MINERAL AND PETROLEUM RESOURCES AND POTENTIAL

NSW WESTERN REGIONAL ASSESSMENTS

FINAL SEPTEMBER 2002

Brigalow Belt South

Stage 2

Resource and Conservation Assessment Council

MINERAL AND PETROLEUM RESOURCES AND POTENTIAL

NSW WESTERN REGIONAL ASSESSMENTS

BRIGALOW BELT SOUTH BIOREGION (STAGE 2)

NSW Department of Mineral Resources
Geological Survey of New South Wales

A project undertaken for the
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Michael Hill was responsible for compilation of the report. Michael Hill, Roger McEvilly and John Watkins edited the report.

Many Departmental staff members and contractors have made significant contributions to the various BBSB geological assessment projects and to the preparation of this report. They are:

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PROJECT SUMMARY

This report describes a project undertaken for the Resource and Conservation Assessment Council as part of the regional assessments of western New South Wales. The Resource and Conservation Assessment Council advises the State Government on broad-based land use planning and allocation issues. An essential process for the western regional assessments is to identify gaps in data information and the best ways in which to proceed with data gathering and evaluation.

Project objective

The Mineral and Petroleum Resources and Potential project for the Brigalow Belt South Bioregion, was implemented by the New South Wales Department of Mineral Resources, Geological Survey of New South Wales branch. The objective of the project is to provide an assessment of the mineral and petroleum resources and potential of the Brigalow Belt South Bioregion.

Methods

The NSW Department of Mineral Resources conducted a largely analytical and interpretive integrated review, but with some important new information gained through associated drilling and mapping projects. It used the best available expert advice to assess mineral resource potential, including contractors where required. It used exploration industry data wherever possible, with permission. The assessment required the assembly and integration of large amounts of information, including the new information, and its critical assessment through a number of established industry standard resource assessment procedures.

Key results and products

The key results of the project are set out in Chapters 7 and 8 and on the accompanying tract maps. Areas of varying potential (potential tract maps) have been identified for relevant metallic and industrial minerals, for construction materials, and for coal, coal seam methane, and conventional petroleum. The tracts are described in detail in the text and are displayed as mineral and petroleum potential tract maps. The maps show the areas within the BBSB with high, moderate and low potential for economic mineral and petroleum discoveries and future mining operations. Figures 27 and 28 summarise the weighted composite and weighted cumulative mineral and petroleum potential for the BBSB. The maps and data sets assembled will assist the development of a whole-of-Government approach to land use options for the bioregion.

INTRODUCTION

In 1999, the NSW Government initiated a regional assessment of western New South Wales co-ordinated through the Resource and Conservation Assessment Council (RACAC). Funding for the various projects was provided by RACAC and the participating agencies. The purpose of the regional assessment is to improve our knowledge of natural resources, to help future land use planning decision-making, and to encourage partnerships to protect the environment. A number of government agencies including the Department of Mineral Resources are involved, as are many local and regional stakeholders. The first area to be assessed, as part of the initiative, is the Brigalow Belt South Bioregion (BBSB) (figure 1).

In October 1999, The Department of Mineral Resources (DMR) commenced the regional assessment of the BBSB. Stage 1 focussed on the Pilliga and Goonoo State Forests and was completed in March 2000. Stage 2 was a detailed regional study comprising two significant projects ie, a "Geology" project (WRA 19) and a "Mineral Potential" project (WRA 20). The primary objective of the "Geology" project was to provide a series of geoscientific datasets on the surface geology to be used in subsequent scientific assessments, including, soil, flora, fauna and mineral assessment modelling.

The primary objective of the "Mineral Potential" project was to assess the mineral and petroleum resources and potential of the BBSB by review of the known data and the collection of new information in selected areas. Two boreholes were drilled; DM Goonoo DDH 1 and DM Goonoo DDH 2, and five reports were commissioned from consultants, on geophysics, and on the petroleum resources of the Bioregion. This Report is the Department's final report on the Stage 2 "Mineral Potential" Project and it incorporates and synthesises the information from the other Departmental BBSB activities and the associated final reports.

Note that the term 'mineral' refers to minerals under the Mining Act 1992 and includes metallic minerals, industrial minerals, some construction materials, and coal. The term 'petroleum' refers to oil, natural gas and coal seam methane gas under the Petroleum (Onshore) Act 1991.

1.1 REPORT OBJECTIVE

The objective of this report is to critically review the metallic and industrial mineral, the construction material, the coal, and the petroleum resources and potential of the BBSB. To achieve this end, a largely analytical and interpretive integrated review has been completed. It used the best available data and expert advice to determine areas of known mineral resources and areas with high, moderate and low mineral resource potential. It also used exploration industry data wherever possible, with permission. It required the assembly and integration of large amounts of information including new information and its critical assessment through a number of established procedures.

This report therefore aims to provide a balanced and objective determination of the comparative mineral, construction material and petroleum importance of different parts of the region. It also aims to provide sufficient background information on important issues such as the geology, mineral economics, exploration history, and current exploration and mining operations. Care has been taken to provide an extensive reference list so that more information on specific topics can be readily accessed. The report is designed to provide a basis for resource potential analysis to inform the development of land use options over the next 10-15 years. New exploration and mining operations will occur during that period, and the new information will be readily integrated with the models herein to further refine them.

1.2 GEOLOGICAL SETTING/DEFINITION

A new integrated and upgraded geological data set for the BBSB area was produced as part of the 'Geology' project (WRA19). This geological mapping upgrade resulted in a significantly more detailed map of the surface geology and an improved geological framework for mineral and petroleum potential studies. A simplified version of the map from this project (figure 2) shows that much of the BBSB is dominated by two sedimentary basins ie, the Sydney-Gunnedah-Bowen Basin and the Surat Basin. The BBSB also includes parts of two major fold belts, the Lachlan Fold Belt to the southwest, and the New England Fold Belt to the east. The basins and fold belts are intruded by younger igneous rocks and overlain by younger volcanic rocks, sedimentary rocks and unconsolidated alluvium.

The two major sedimentary basins cover the southern, central and northwestern parts of the BBSB. They are the Permo-Triassic Sydney-Gunnedah-Bowen Basin, and the Jurassic - Cretaceous Surat Basin. The Gunnedah Basin contains very large coal resources with high value and natural gas resources of regional and possibly national importance. The New South Wales part of the Surat Basin potentially contains valuable oil and gas resources. These have already been found in Queensland near Roma.

To facilitate the review of the mineral and petroleum resources, this report divides the geology of the BBSB into the following regions:

- Lachlan Fold Belt
- New England Fold Belt
- Sydney-Gunnedah-Bowen Basin
- Surat Basin
- Werrie Basin
- Warialda Trough

The Sydney-Gunnedah-Bowen Basin has been further subdivided into the following five resource assessment areas (figure 6):

- Northern Hunter Coalfield
- Northern Western Coalfield
- Gilgandra Sub-Basin
- Gunnedah Basin
- Gunnedah – Bowen Basin.

Discussion of the resources and potential is subdivided into the following major categories:

- metallic minerals
- industrial minerals
- construction materials
- coal
- coal seam methane
- petroleum

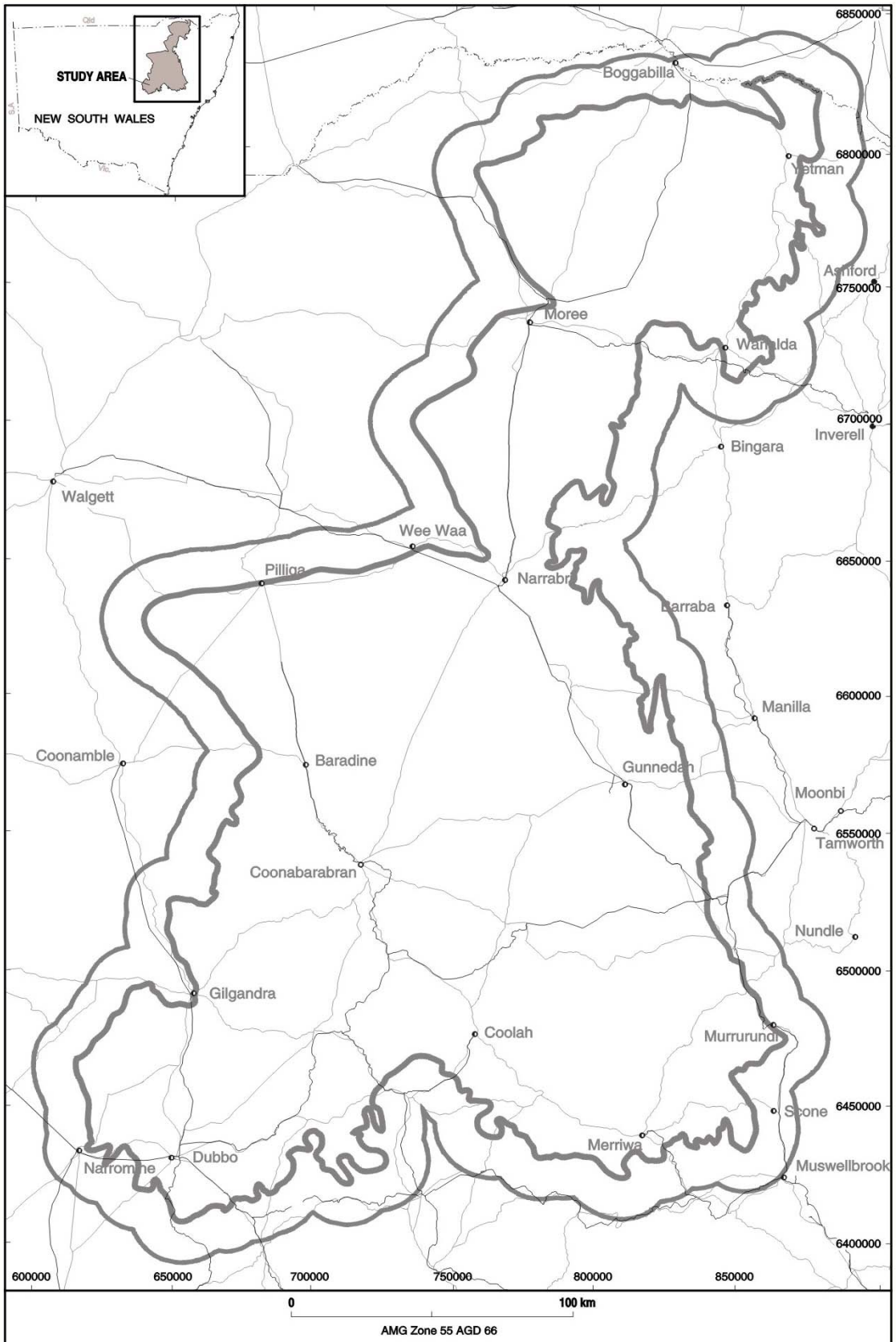

Figure 1 Location of the Brigalow Belt South bioregion

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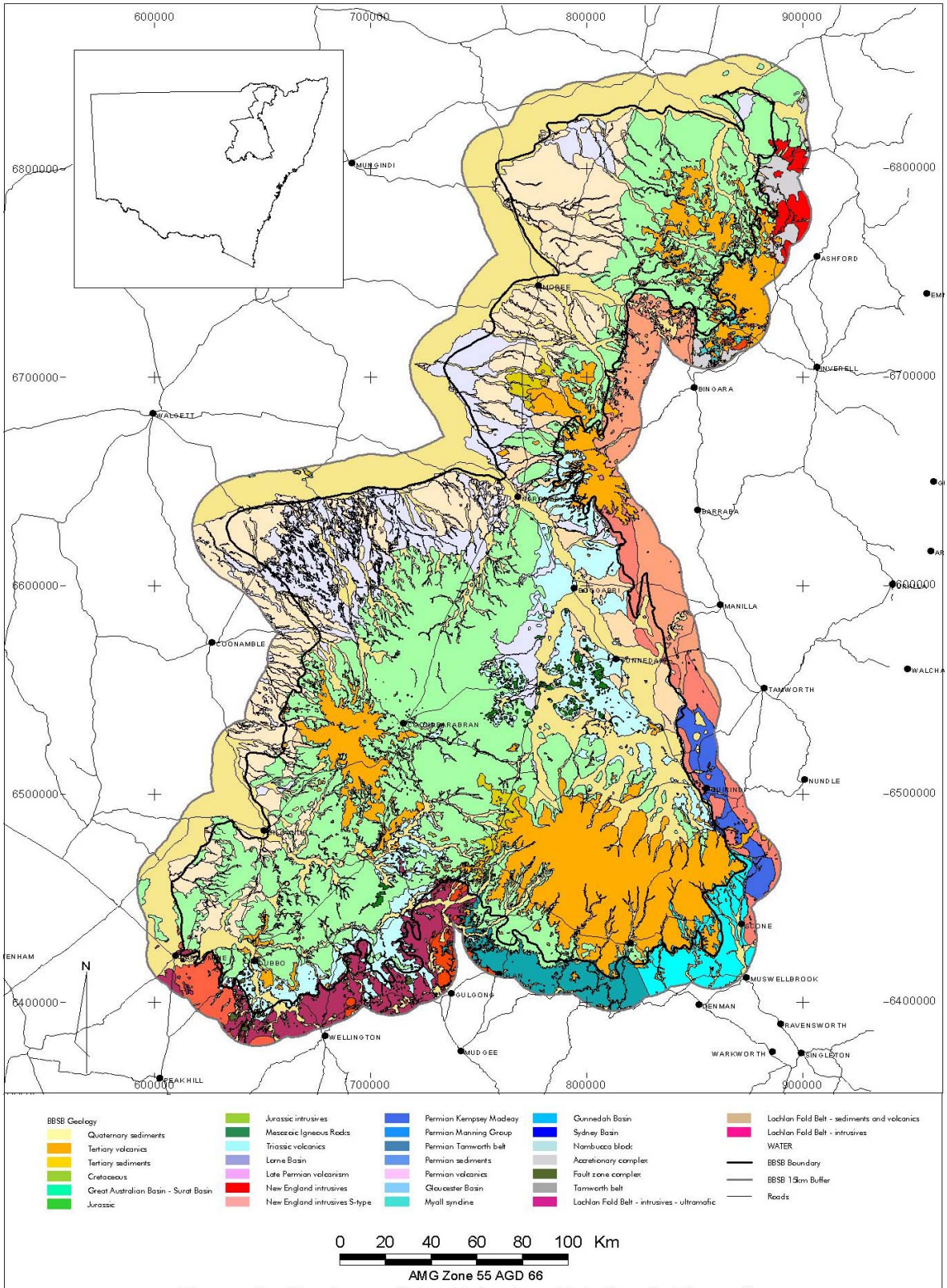

Figure 2. Geology of the Brigalow Belt South Bioregion

1.3 CURRENT LAND USE PRACTICES

Located in central north of the State (figure 1), the BBSB covers 52,409 square kilometres, which is 6.2% of the area of the State. The primary land use in the Bioregion is agriculture and 85% of it is either freehold land or Crown leasehold.

The northern region covering the area north of Narrabri encompasses part of the western plains, including parts of the floodplains of the McIntyre, the Gwydir and the Namoi Rivers. It includes population centres such as Moree and Warialda and has a variety of land-uses including cotton, wheat, summer crop production and livestock production. There are scattered State Forests east of the McIntyre, west of Terry Hie Hie and northeast of Narrabri.

The central region including Coonabarabran, Gunnedah and Narrabri, encompasses the fertile farmlands along the Mooki, the Namoi and the Castlereagh Rivers but also the very extensive Pilliga Forest and the Warrumbungle Mountains. There are two major forestry areas, the West and East Pilliga Forests, and a number of smaller State Forests to the south. The Pilliga Nature Reserve lies at the southeastern end of the forest and the Warrumbungle National Park lies to the west of Coonabarabran. The forests and conservation areas form a very large area covered by mature vegetation including Brigalow, Cypress, and Ironbark.

The southwestern region includes population centres of Gilgandra, Mendooran and Dubbo. It encompasses a variety of land-uses including grain and livestock production. It also includes the extensive Goonoo State Forest and a number of smaller forests. A number of small national parks and reserves are also located within the area. The State Forest areas are covered by vegetation including Brigalow, Cypress, and Ironbark.

The southeaetern region includes the population centres of Muswellbrook, Scone, Murrurundi, Dunedoo Coolah and Merriwa. It encompasses a variety of land-uses including grain and livestock production. It also includes the Liverpool Ranges with a number of National Parks and reserves and small areas of State Forest.

Main access routes into the region are principally via the Newell, the Oxley and the Golden Highways. A series of secondary and tertiary roads criss-cross the area and provide access to smaller centres within the region.

1.4 NATURE OF EXPLORATION

Mineral and petroleum exploration is a long term and ongoing process. Exploration is an extremely costly commercially high-risk activity and areas are often explored many times over before a discovery is made. Exploration activity is cyclic and based on a number of factors including commodity prices, state of the economy, mining technology, exploration methodologies and recent discoveries. New information, new concepts and better understanding of geological processes continually change the perceived potential of areas and regions. New models are continually being developed and refined. Continued access to land is therefore a significant issue for the mineral and petroleum industry and for future development.

The level of knowledge of the mineral and petroleum resources in the BBSB is very uneven. Significant coal exploration only commenced in the late 1970s. Fortunately, the Department of Mineral Resources conducted major coal stratigraphic drilling programs over much of the area during the early 1980s. Further drilling both by the Department and by private explorers has markedly increased the level of confidence in the resource analysis of selected areas. Some parts of the BBSB however, are poorly understood. These include the Gunnedah – Bowen Basin north and west of Narrabri, the Gilgandra Sub-Basin, the deeper parts of the Mullaley Sub-basin, and the Lachlan Fold Belt, adjacent to and under shallow basin cover in the south.

In the early years of exploration less emphasis was placed on the deeper parts of the sedimentary basins because of the additional costs and the lower likelihood of significant returns. Over the last 10 years however, the area has become a centre of exploration for natural gas, following the discovery of gas at Wilga Park, and the growing focus on coal seam methane based on successes in America.

Coal and petroleum exploration licence areas are large because exploration targets are hidden and scattered, and are only located through an understanding of the regional geology. Exploration costs are high and the process is iterative with each step focusing in increasing detail at the areas with maximum resource potential. It is extremely important that regional access for exploration be preserved. The large coal resources of the BBSB have not been assessed and exploited to the level of those in the Sydney Basin to the south. This is largely for economic reasons including the distance from markets and the cost of transport. When the resources to the south are mined out then the high quality resources in the BBSB will be mined. It is important to recognise the long-term (30-50 year) framework for exploration and mining in the bioregion and the strategic nature of the resources.

The discovery and mining of copper-gold resources such as the Cadia-Ridgeway mine, and recent advances in knowledge, have focussed attention on the Merrygoen and Comobella areas in the southern part of the BBSB. Prospective Lachlan Fold Belt rocks crop out here, or are covered by a thin sedimentary basin cover.

1.5 LAND ACCESS ISSUES

The Western Regional Assessment is a broad-based whole-of-government process applying to areas not already covered by NSW forest agreements. It considers environmental, economic and social values of forest and non-forest land systems focusing on conservation, land management and regional planning.

The process aims to achieve conservation outcomes through a range of mechanisms to ensure natural values are protected and at the same time ensure that economic and social objectives can be met. The National Forest Policy Statement and the NSW Biodiversity Strategy require the protection of biodiversity and maintenance of ecological processes and commits NSW to the development of a comprehensive, adequate and representative (CAR) reserve system to help achieve this.

Conservation protection to achieve a CAR reserve system may be provided through different levels of reservation or zoning. In relation to public land the levels are Dedicated Reserves, Informal Reserves and Values protected by Prescription.

Dedicated Reserves include National Parks, Nature Reserves, Forest Management Zones 1 (FMZ1) and Reserves for Environmental Protection. Areas within this category are designed to meet the requirements of JANIS (1997) dedicated (formal) reserves and as such are equivalent to the International Union for the Conservation of Nature (IUCN, 1994) “Protected Area” categories I-IV. Activities not permitted include gravel/hard rock quarrying and mineral and petroleum exploration.

Informal Reserves include Forest Management Zones 2 (FMZ2) and Crown Reserves. Forest Management Zones 2 permits access for mineral and petroleum exploration with conditions that are reviewed by State Forests prior to approval. Exploration and quarrying for construction materials is not permitted in FMZ 2. Management of mineral and petroleum exploration in Crown Reserves is subject to a Memorandum of Understanding between the Department of Mineral Resources and the National Parks and Wildlife Service and recognises situations where there is a conjunction of high conservation and mineral resource values.

The new State Conservation Area (SCA) reserve category was recently created through the National Parks and Wildlife Amendment Bill 2001. The management principles for this new reserve category focus on conservation, while allowing access for new exploration and mining projects to proceed, subject to the consent of the Minister for the Environment. The Department of Mineral Resources is currently working with the National Parks and Wildlife Service to develop a Memorandum of Understanding (and draft protocols) for the management of the new SCA reserve category.

Values protected by Prescription includes Forest Management Zone 3 (FMZ 3). This category is designed to comply with JANIS “values Protected by Prescription” and access for activities such as mineral and petroleum exploration are permitted with standard conditions. Exploration and quarrying for construction materials is not permitted in FMZ 3.

2. LEGISLATIVE & ADMINISTRATIVE FRAMEWORKS

2.1 LEGISLATION

2.1.1 Metallic Minerals, Industrial Minerals and Coal

Exploration and mining in New South Wales is principally governed by the Mining Act 1992, administered by the Department of Mineral Resources, and by the associated regulations and conditions.

Under the Mining Act 1992, there are three principal forms of title**, Exploration Licence, Assessment Lease and Mining Lease**. The **Mineral Claim** is a title that can be granted to cater for smaller operations, prospecting and mining in areas up to two hectares in size. Under the Mining Act, tenures for exploration and mining can be granted over both Crown and private land, and over both Crown and privately owned minerals. Although most minerals are owned by the Crown, there are cases, particularly where original land grants occurred in the 1800s, where the minerals are owned privately.

Exploration Licences enable exploration and prospecting to be undertaken. The size of areas that can be granted, range from about 3 square kilometres (one unit) to about 300 square kilometres (100 units). A unit is an area bounded by a minute of longitude by a minute of latitude. Areas of more than 100 units can be granted in special cases. Exploration licences are normally granted for a period of two years and may be renewed for further periods. These licences allow for geological and geophysical surveying, sampling, drilling, trenching and other exploration techniques as applied for by the applicant.

Before any private lands are entered under an exploration licence the owner and any occupier must be notified and an access agreement entered into by the licence holder and the land owner/occupier. All exploration licences contain conditions, including ones specifying the work program to be completed and the amount required to be expended on exploration during the period of the licence. A security deposit must also be lodged to cover the exploration licence holder's obligations to comply with the licence conditions.

Some current coal exploration licences were granted prior to the 1992 Act and are referred to as **Coal Authorisations**. They sometimes cover the area of an active coalmine where surface access is not provided by the mining lease. This enables the operator to continue exploration and assessment activities during mining operations.

The Assessment Lease is a relatively new title having been introduced by the Mining Act 1992. Its purpose is to enable detailed evaluation of mineral deposits to be carried out after the normal period of exploration has expired, but where, for some special reasons, the project is not ready for a Mining Lease. Such reasons can be of an economic nature, for example, the deposit found is not presently economic to develop, or there could be practical reasons such as a need to develop specific processing methods to extract a particular mineral from the host rock. There is no maximum size for an assessment lease; the dimensions of areas being such as are necessary and appropriate. These titles can be granted for a period of five years and renewed for a further period of five years. Similar conditions on expenditure, reporting

of progress and security are required as for exploration licences. Where access to lands is required, appropriate access arrangements and consents must be obtained.

Mining Leases are granted to enable mining operations to be carried out. There is no maximum size for a mining lease and dimensions and area can be such as are necessary and appropriate for the particular mining operation. Mining leases are generally granted for a period of twenty one years depending upon circumstances, and can be renewed. Mining leases enable operations, subject to appropriate conditions, to be undertaken by open cut (surface) or underground methods. Royalty is payable on all minerals recovered at the rate prescribed by the Mining Act 1992 or at such additional rates as may be specified. The holders of mining leases are required to lodge a security deposit with the Minister commensurate with the size of the mining operation to ensure compliance with conditions of the lease.

Applicants for and holders of titles under the Mining Act 1992 are required to comply with the provisions of other relevant legislation such as the Environment Planning and Assessment Act 1979. In particular, mining lease applicants are required to obtain development consent before a mining lease can be granted. The lodgement of the development consent application normally includes the submission of an Environmental Impact Statement that is put on display for public comment as part of the development process. Depending upon circumstances, a Commission of Inquiry into the development may be required and the recommendations of the inquiry are taken into consideration as to whether or not development consent should be granted and, if so, upon what conditions will be included in the consent and the title. In granting mining leases, the views of all relevant Government agencies are obtained and appropriate conditions to meet respective requirements are formulated for inclusion in the lease documents.

Some coal mining operations are referred to as **Colliery Holdings.** This occurs where a group of mining leases constitute one operation.

2.1.2 Construction Material Extraction

Construction material extraction is controlled by a number of State and Local Government agencies. Some materials, like clay and shale used for brick making, are classed as minerals under the Mining Act 1992 and can be extracted under mining titles issued by the Department of Mineral Resources. Other materials such as sand, gravel and crushed rock, can be extracted from Crown Land under licences issued by agencies such as State Forests and the Department of Land and Water Conservation. In each case, development consent must be obtained from the local Council before extraction can proceed.

Where construction materials are present on private land, they may be extracted by the landowner, or by anyone having an agreement with the landowner, after obtaining development consent from the local Council or other relevant consent authorities. The Department of Mineral Resources has a recognised and accepted role in assessing the State's resources of construction materials and providing advice on their management and extraction. It is also responsible under the Mines Inspection Act 1901 (as amended) for ensuring the safe operation of the State's mines and quarries.

2.1.3 Petroleum

The ownership of petroleum in New South Wales is vested in the Crown. Exploration and production of petroleum (including oil, natural gas and coal seam methane gas) is treated separately to minerals. Petroleum is regulated by the Petroleum (Onshore) Act 1991 and the associated regulations. To-date, no overriding legislation has been introduced to cater for possible development priority conflicts between coal seam methane and coal mining, although this has occurred in some other jurisdictions such as Queensland. Presently any such issues would be resolved by Government policy decisions. As in all mining legislation, best industry practice is required during exploration and production operations for rehabilitation and protection of the environment.

There are three titles that are relevant to the exploration for, and evaluation of, oil and gas. They are, the Exploration Licence, the Assessment Lease and the Special Prospecting Authority. These titles are to be distinguished from a Production Licence which is a separate title permitting the extraction and sale of oil and gas.

An **Exploration Licence** for petroleum can be granted over private or Crown land. The size of any single Exploration Licence ranges from a minimum of 1 block to a maximum of 140 contiguous blocks. One block is 5 minutes of latitude and 5 minutes of longitude along its edges. The term of an Exploration

Licence is up to six years, and renewable, subject to satisfactory work performance of the area, for successive periods. Exploration Licences are designed for exploration over a specific area of land. However, certain parts of the area may be excluded. The standard exclusions of lands are:

- The surface lands within or overlying the external boundaries of colliery holdings as recorded pursuant to Section 163 of the Mining Act 1992.
- National parks, nature reserves, historic sites, Aboriginal areas, state game reserves under the National Parks and Wildlife Act 1974, as at the date of grant of the licence.
- Flora reserves excluded from the operations of the Petroleum (Onshore) Act 1991 under the provisions of the Forestry Act 1916, as at the date of grant of the licence.
- Land vested in the Commonwealth of Australia

Assessment Leases of not greater than four (4) blocks may be granted for a term not exceeding six years to enable exploration companies who have made a discovery to carry out more detailed resource evaluation. **Production Leases** of not greater than four (4) blocks may be granted for a term not exceeding 21 years. However development consent will be required under the Environmental Planning and Assessment Act 1979, along with approvals from other relevant Government agencies before production operations can commence.

State royalty of 10% of wellhead value is payable for production operations. Provision is made for the Government to set the royalty at a lower rate in special circumstances. New discoveries attract a royalty holiday for a period of five years from the start of production. The royalty then commences in year 6 at 6% and increases by 1% for each year to a maximum of 10% in year 10. **Special Prospecting Authorities** are designed to permit scientific research, can be of any size agreed by the Government and may be granted for a term not exceeding twelve months.

2.1.4 Areas under Direction G28 of Section 117 (Environmental Planning and Assessment Act 1979)

Areas identified under direction G28 of Section 117 of the Environmental Planning and Assessment Act (1979) have an identified higher inherent mineral, construction material or petroleum value. Often they are areas with identified resources. In the BBSB, some of these areas do not have identified resources, but are perceived to have higher local mineral or construction material potential. Areas designated as having inherent mineral, construction material or petroleum value under Direction G28 of Section 117 of the Environmental Planning and Assessment Act 1979 cannot be subdivided by local council unless the Minister for Planning gives prior approval, in consultation with the DMR.

There are currently 50 'Section 117' areas in the BBSB area of which 44 are located in the BBSB buffer zone. The location of the Section 117 areas is shown in the attached shapefile b_117_020624.

2.2 CURRENT STATUS OF EXPLORATION AND MINING TITLES

2.2.1 Metallic And Industrial Minerals

There are 27 current exploration licences for metallic and industrial minerals whose boundaries are within or overlap with the BBSB. These are situated mostly in the Lachlan Fold Belt in the far southwest, and the New England Fold Belt in the east and northeast of the BBSB. In the Lachlan Fold Belt, there are 2 for diamonds in the Gulgong area, 10 for gold and/or copper in the Dubbo and Mendooran areas, 2 for rare earth elements south of Dubbo, and 1 for limestone southeast of Dubbo. In the New England Fold Belt, there are 6 for diamonds in the Bingara area, 3 for zeolite in the Quirindi area, and 2 for gold in the Werris Creek and Bingara areas. There is one licence for clay east of Ulan.

There are 13 current mineral/mining leases in the BBSB for metallic and industrial minerals. Most of these are in the buffer zone and are for various industrial minerals. In the Lachlan Fold Belt, there are 2 for iron ore west of Ulan, 1 for gold north of Wellington and 3 for kaolin near Gulgong. In the New England Fold Belt, there is 1 for zeolite near Werris Creek. In the Gunnedah Basin, there is 1 for kaolin near Mendooran, and in the Sydney Basin, there is 1 for bentonite northwest of Scone, and 4 for clay east of Ulan.

There are 2 mineral claims in the buffer zone of the BBSB; one is for gold in the Lachlan Fold Belt near Wellington, the other for gold in the New England Fold Belt near Bingara. There is one mineral purposes lease, in the buffer zone to the far south in the Lachlan Fold Belt, for mine waste from the Tallawang Iron Mine, which is situated just outside the BBSB.

There are 8 private lands leases in the BBSB, most of which are situated in the far south of the BBSB in the Lachlan Fold Belt. Three of the leases are for kaolin near Gulgong and Mendooran, 2 are for iron near Tallawang, and 2 are for copper/gold east of Dubbo. One Lease for clay is in the Sydney Basin east of Ulan. There is one mineral assessment lease for zeolite in the buffer zone east of the BBSB at Quirindi, in the New England Fold Belt.

Figure 3 shows the location of current metallic and industrial mineral titles in the BBSB.

2.2.2 Construction Materials

In May 2002, there were about 175 operating and intermittently operating construction material and industrial mineral quarries and pits in the region. These quarries are mostly operated by local Councils, local construction companies and State Forests of New South Wales as local resource needs arise. Nine of these are for coarse aggregate, 144 for unprocessed construction sand, 2 for clay/shale, 1 for kaolin, 12 for undifferentiated sand and gravel, 5 for construction sand, and 2 for river gravel. A list of all operating and intermittently operating industrial mineral and construction material quarries in the BBSB is given in Appendix 1.

2.2.3 Coal

Current coal exploration and mining titles for the BBSB are shown on figure 4. Discussion of the titles is divided into five parts, the Gunnedah Basin, the Gilgandra Sub-Basin, the Northern Hunter Coalfield, and the Northern Western Coalfield.

Gunnedah Basin

Maules Creek Project

Located 20 km northeast of Boggabri, the Maules Creek Project is an open cut proposal. The project is operated and owned by Namoi Valley Coal Pty Ltd. The project proposes to use dragline and truck and shovel to produce up to 6.50 Mt run of mine coal per year. Current coal titles associated with this project are:

- Coal Lease 375.
- Authorisation 346.

Boggabri Project

Located 17 km northeast of Boggabri, the Boggabri Project is a proposed open cut development. The project is operated by Idemitsu Boggabri Coal Pty Ltd, which is wholly owned by Idemitsu Kosan Co. Pty Ltd. It has development consent to produce up to 4.5 million tonnes of coal per year. Current coal titles associated with this project are:

- Coal Lease 368.
- Authorisation 339.
- Authorisation 355.

Whitehaven Colliery

Located 25 km north of Gunnedah, the Whitehaven mine is an open cut development producing 0.60 million run of mine tonnes of coal per year. The mine is operated and owned by Whitehaven Coal Mining Pty Ltd. As well as the existing mine, Whitehaven Coal Mining Pty Ltd has submitted an Exploration Licence Application (ELA) for the area between the Whitehaven Mine and the Boggabri Project to the north. Current coal titles associated with the Whitehaven Mine include:

- Mining Lease 1464.
- Mining Lease 1471.
- Exploration Licence 4699.
- Exploration Licence 5831.
- Exploration Licence Application 1875.
- Exploration Licence Application 1893.

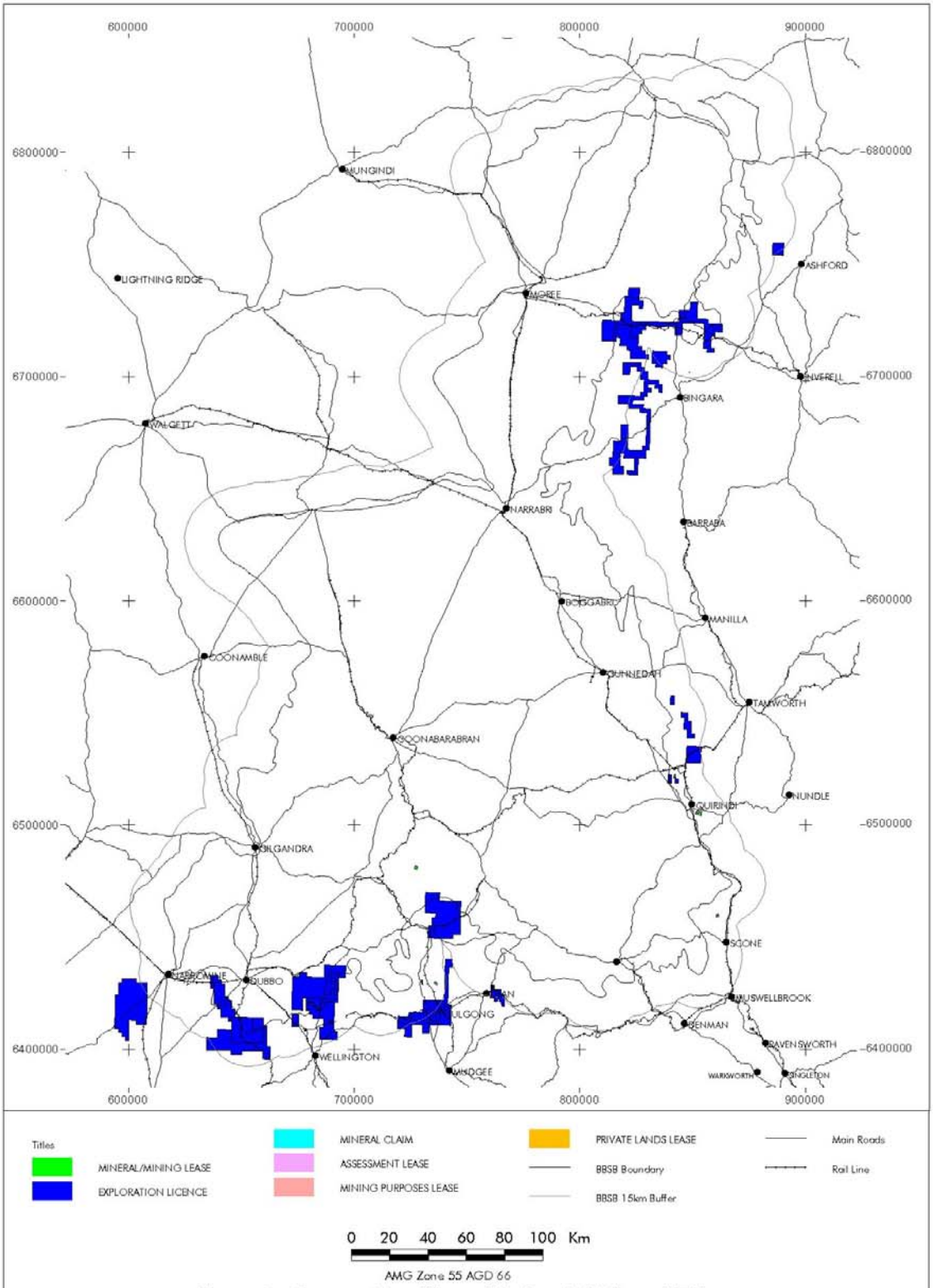

Figure 3. Current Metallic and Industrial Mineral Titles
Brigalow Belt South Bioregion

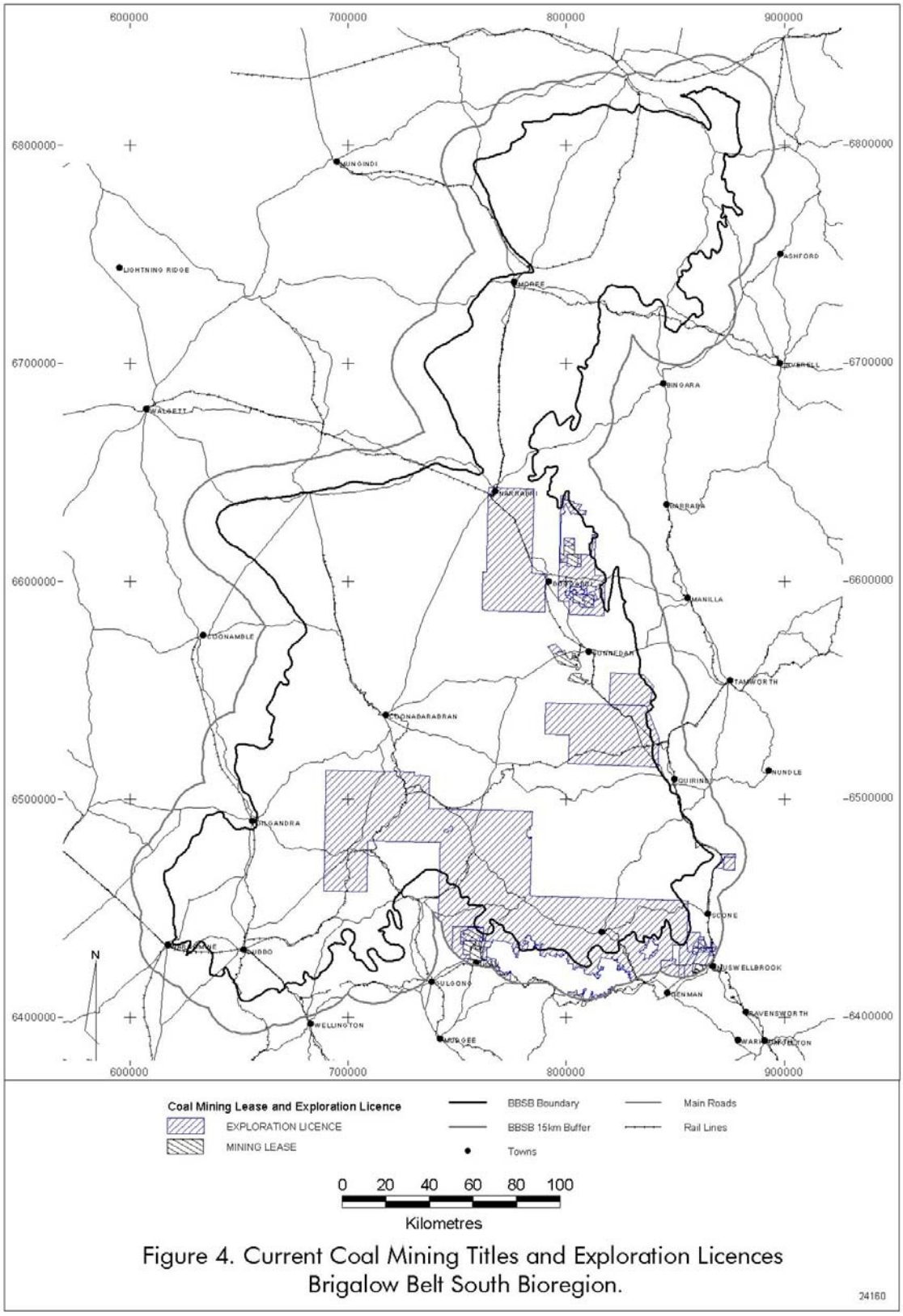

Figure 4. Current Coal Mining Titles and Exploration Licences Brigalow Belt South Bioregion.

Vickery Colliery
Vickery Colliery is located 20 km north of Gunnedah. The open cut mine owned and operated by Namoi Valley Coal Pty Ltd closed in 1998 and rehabilitation of the site commenced in the same year. Current coal titles associated with Vickery Mine are:

- Coal Lease 316.
- Authorisation 406.

Gunnedah Colliery
Located 10 km southwest of Gunnedah, the Gunnedah mine is operated by Namoi Mining Pty Ltd wholly owned by American Metals and Coal International. The mine, which closed in November 2000, used underground bord and pillar methods to extract coal. The company is currently assessing remnant coal resources in the vicinity of the closed mine. Current coal titles for the Gunnedah mine include:

- Consolidated Coal Lease 701.
- Mining Purposes Lease 162.
- Mining Lease 1403.
- Mining Lease 1404.
- Exploration Licence 5183.

Preston Extended Colliery
Preston Extended Colliery was an underground mine located 15 km south of Gunnedah which closed in May 1998. Preston Extended used the bord and pillar mining method to extract coal. The mine was operated by Preston Coal Pty Ltd, which is wholly owned by Centennial Coal Company Ltd. The current coal title for Preston Extended Colliery is:

- Coal Lease 711.

Areas Held Under Title by the DMR
The DMR holds significant resource areas within the Gunnedah Basin under title. Authorisation 216 was granted to the Department in May 1980 over most of the Coalfield. Since that time the Department has continuously undertaken geological investigations in the area and Authorisation 216 has been progressively reduced in size. Today the Authorisation covers three (3) separate areas and these are referred to as:

- The Caroona area located in the south of the basin.
- The Narrabri area located in the north of the basin, south of the town of Narrabri.
- The Maules Creek area, comprising small areas in the Maules Creek Sub-basin in the east of the basin.

Exploration Licence 5833, located to the south of Gunnedah, was granted to the Department of Mineral Resources in April 2001. Recent geological investigations in this area targeted speculative resources in the early Permian coal sequence. Work is ongoing, however, to date results have not been encouraging.

Gilgandra Sub-Basin

Areas Held Under Title by the DMR
The DMR holds a large resource area in the southeast of the Gilgandra Sub-Basin under title. Authorisation 286 was granted to the Department in 1980 and covers the region around Binnaway, Coolah and Merriwa.

Northern Hunter Coalfield

Dartbrook Colliery
Located 10 km northwest of Muswellbrook, Dartbrook Mine is an underground longwall mine producing 3 Mt of saleable coal per year. Dartbrook Coal Pty Ltd is the operating company with major shareholders being Anglo Coal (Dartbrook) Pty Ltd, Marubeni Thermal Coal Pty Ltd, Saang Yong Resources Pty Ltd, and Showa Coal (NSW) Pty Ltd. Current coal titles associated with the mine include:

- Coal Lease 386.
- Mining Lease 1381.
- Mining Lease 1456.
- Mining Lease 1497.
- Authorisation 256.
- Exploration Licence 4574.
- Exploration Licence 4575.

Mount Pleasant Project

Located 5 km west northwest of Muswellbrook, the Mount Pleasant Project is a proposed multi-seam open cut mine. Using dragline and trucks and shovels the proposal will produce up to 10 million tonnes of coal per year. The project is owned and operated by Coal and Allied Operations Pty Ltd. Development Consent for the project was granted in December 1999. Current coal titles associated with the project include:

- Authorisation 459
- Mining Lease Application 100

Bengalla Colliery

Bengalla Mine, located 5 km west of Muswellbrook is an open cut mine producing up to 6 Mt of coal per year, using dragline, trucks and loaders. Bengalla Mining Company Pty Limited operates the mine with major stakeholders being CNA Bengalla Investments Pty Ltd, Wesfarmers Bengalla Ltd, Taipower Bengalla Pty Ltd, and Mitsui Bengalla Investment Pty Ltd. Current coal titles associated with this mine include:

- Mining Lease 1397
- Mining Lease 1450
- Mining Lease 1469
- Authorisation 438

Muswellbrook Colliery

Muswellbrook open cut mine is located 6 km northeast of Muswellbrook. The mine produces 1.7 Mt of coal per year by truck and shovel. The mine is operated by Muswellbrook Coal Company Limited, wholly owned by Idemitsu Kosan Co. Ltd. As well as the existing open cut mine, Muswellbrook Colliery has current Development Consent for an underground development known as Sandy Creek. This proposal is to the north of the existing open cut.

Current coal titles associated with Muswellbrook Mine include:

- Consolidated Coal Lease 713
- Mining Lease 1304
- Mining Lease Application 64
- Authorisation 176

Castlerock – Rosehill Project

The Castlerock - Rosehill Project is located 13 km west and northwest of Muswellbrook. The project is in the exploration phase, targeting open cut coal resources. The project is operated by Muswellbrook Coal Company Limited that is wholly owned by Idemitsu Kosan Co. Ltd.
Current coal titles associated with this project are:

- Exploration Licence 5431
- Exploration Licence 5600

Anvil Hill Project

The Anvil Hill Project is located 20 km west of Muswellbrook. The project is owned and operated by Powercoal Pty Ltd. Recent exploration in the project area has identified an open cut coal resource. The company is currently undertaking environmental and preliminary feasibility studies. The coal titles associated with the project is Exploration Licence 5552.

Areas Held Under Title by the DMR

The DMR holds remaining resource areas within the Northern Hunter Coalfield under Authorisation 102 and Authorisation 286. These titles cover large areas to the west of the area that are known to contain underground coal resources. Only preliminary investigations have been undertaken in this area, particularly in the west.

The Ridgelands Project forms part of Authorisation 286. Recent exploration in the Ridgelands area, north of the Anvil Hill Project, has identified underground coal resources suitable for the thermal coal market. The Department proposed to undertake further geological investigations in the Ridgelands Project area and to “step out” to the north and west within the next few years.

Northern Western Coalfield

Ulan Colliery

Ulan Mine, located 25 km East of Gulgong is an open cut and underground mine producing some 7 Mt of raw coal annually, currently representing 5 per cent of the State's total production. Ulan Coal Mines Pty Limited operates the mine with major stakeholders being Enex Coal Pty Ltd and Mitsubishi Development Pty Ltd:

- Mining Lease 1397
- Mining Lease 1450
- Mining Lease 1469
- Authorisation 438

Areas Held Under Title By The DMR

The DMR holds remaining resource areas within the upper Western Coalfield under title. These titles are Authorisation 449, Authorisation 286 and EL 4948. They cover large areas known to contain potential open cut and underground coal resources. The open cut resources at Wilpinjong have been investigated to a high level. There has been little work within A 286 particularly in the east of the area between Coolah and Merriwa.

2.2.4 Petroleum

Figure 5 shows the current petroleum licences within the BBSB. Details of the licences are as follows.

PEL 1

PEL 1 was granted under the Petroleum (Onshore) Act 1991, to Australian Coalbed Methane Pty Ltd on 11 February 1993 for a 6 year term. It covers 96 blocks (approximately 7,200 km^2) of the Murrurundi and Bando Troughs and the Breeza Shelf to the south of Gunnedah. This licence has been the site of mainly coal seam methane exploration under a co-venture arrangement with Pacific Power. The current term expires on the 13 February 2005, when the title will be subject to the normal processes of renewal.

PEL 4

PEL 4 was granted on 11 November 1993 and is now held by Sydney Gas Operations Pty Ltd. It now covers an area of 96 blocks (approximately 7,200 Km2) of the western Hunter Valley and the Goulburn River area. This licence has been the site of coal-seam methane exploration. The current term expires on the 10 November 2005, when the title will be subject to the normal processes of renewal.

PEL 6

PEL 6 was initially granted to Petroleum Securities Pty Ltd on 9 December 1993 over an area covering 82 blocks (approximately 6,150 km^2) of the northeastern Surat and Gunnedah Basins. This licence was last renewed to Eastern Energy Australia Pty Ltd. Eastern Star Gas Limited, a related company, has actively explored this licence primarily for conventional oil and gas targets. The current term expires on 8 December 2005 when the title will be subject to the normal processes of renewal.

PEL 10

PEL 10 was granted to Australian Coalbed Methane Pty Ltd in November 1994. It covers a small area of some 6 Blocks (approximately 450 km^2) around Merriwa in the Murrurundi Trough of the Gunnedah Basin. The licence was originally sought in order to extend exploration south of PEL 286. The licence has been the site of coal-seam methane exploration. It expires on 10 February 2005 when it will be subject to the normal processes of renewal.

PEL 12

PEL 12 was granted to Australian Coalbed Methane Pty Ltd on 27 September 1995. It now covers an area of 31 blocks (approximately 2325 km^2) to the southwest of Gunnedah in the Gunnedah Basin. The licence is being explored for coal seam methane. The current term expires on the 26 Sept 2007, when it will be subject to the normal processes of renewal.

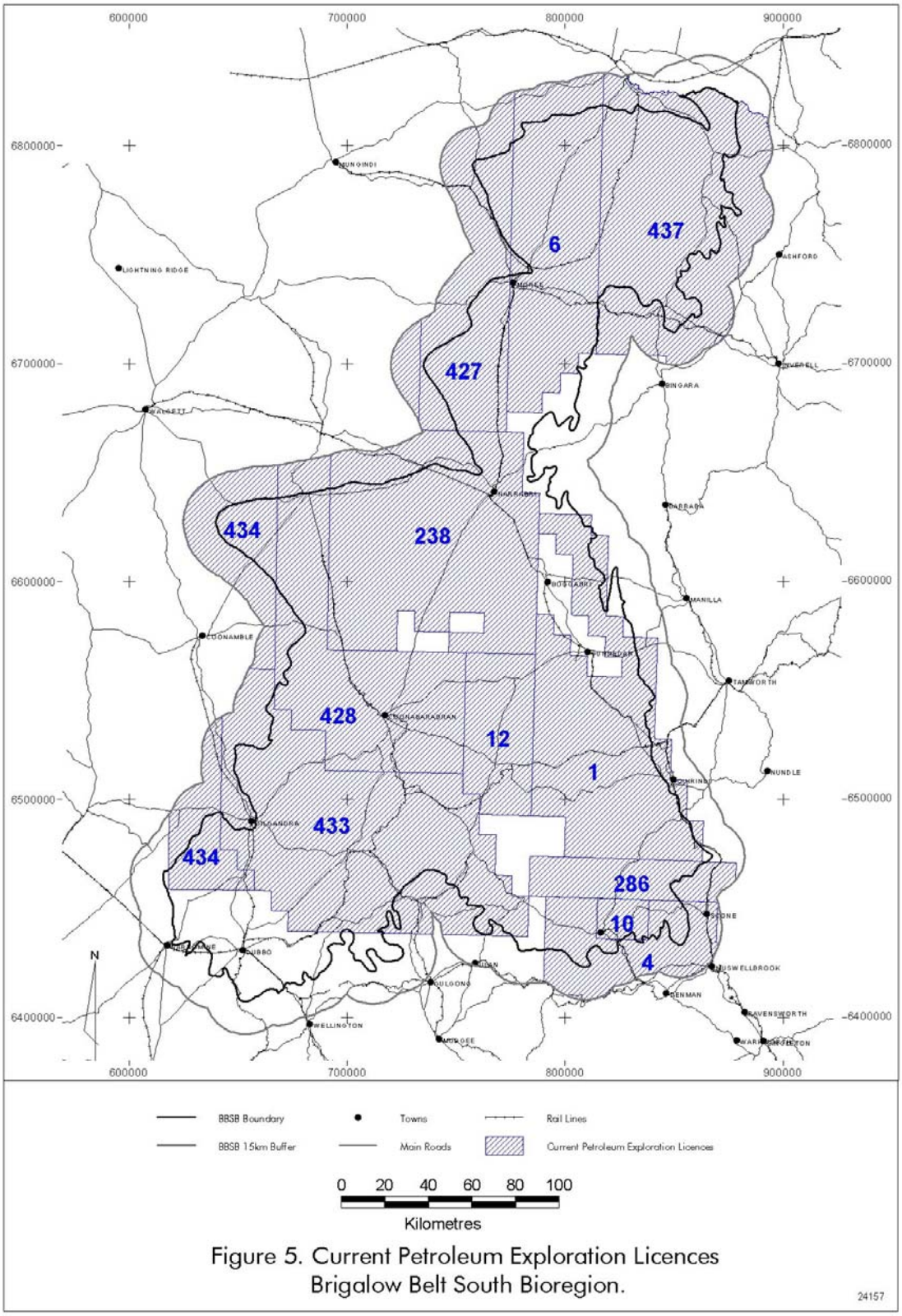

Figure 5. Current Petroleum Exploration Licences
Brigalow Belt South Bioregion.

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PEL 238

PEL 238 was originally granted on 1 September 1980. On 1 November 1997, First Sourcenergy Group Inc farmed into PEL 238. After a series of renewals, transfers, and partial relinquishment, Eastern Energy Australia Pty Ltd now holds the title which covers 132 blocks, (approximately 9900km^2) over the Pilliga State Forest in the northwestern part of the Gunnedah basin. When the current term expires on the 2 August 2007 it will be subject to the normal processes of renewal.

PEL 267

PEL 267 was originally granted on 20th January 1984 and is now held by Sydney Gas Operations Pty Ltd. Following partial relinquishment and renewals, the licence now covers an area of some 92 blocks (approximately 6,900 km^2) in the extreme north and northeastern portions of the Sydney Basin, including the buffer zone of the BBSB. The licence has been the site of both coal seam methane and conventional petroleum exploration. The current term expires on 19 January 2004 when it will be subject to the normal processes of renewal.

PEL 286

PEL 286 was originally granted to Australian Coal Bed Methane Pty Limited on 7 May 1992. Following partial relinquishment and renewals, the Licence now comprises 24 blocks (approximately 1800 km^2) along the crest of the Liverpool Ranges. This licence is being explored primarily for coal seam methane. The current term expires on 10 February 2005, when it will be subject to the normal processes of renewal

PEL 427

PEL 427 was issued to Strike Oil N.L on 21 May 1998. The area covers 122 blocks (approximately 9150 km^2) to the west and northwest of Moree. On 21 August 1998, Forcenergy Australia Pty Ltd and First Sourcenergy Group Inc farmed into the title. The current term expires on 20 May 2004, when it will be subject to the normal processes of renewal.

PEL 428

PEL 428 was granted to Strike Oil N.L. on 15 September 1998. The licence lies to the west of PEL 238 and covers an area of 140 blocks (approximately 10,000 km^2. On 21st August 1998, Forcenergy Australia Pty Ltd and First Sourcenergy Group Inc farmed into PEL 428. The current term expires on 14 August 2004, when it will be subject to the normal processes of renewal.

PEL 433

PEL 433 was granted to Eastern Star Gas Limited 14th February 2001. It covers an area of 140 blocks (approximately 10,500 km^2). It lies to the west and south of PEL 428 and covers much of the northern portion of the Tooraweenah Trough including Mendooran and Dunedoo. The area is being explored for coal seam methane. The licence expires on 13th February 2007, when it will be subject to the normal processes of renewal.

PEL 434

PEL 434 was granted to Eastern Star Gas Limited on 14th February 2001. The area lies to the west of PEL 428, is centred on Coonamble, and covers an area of 140 blocks (approximately 10,500 km^2). It will be explored for coal seam methane. The licence expires on the 13th February 2007 when it will be subject to the normal processes of renewal.

PSPAPP 8

Special Prospecting Authority Application 8 is an application made by Australian Coal Bed Methane Pty Ltd on 4 March 2002 for 200 blocks (approximately 15,000 Km^2) located between Nyngan and Narromine. The application is currently being processed by the DMR.

3. GEOLOGICAL SETTING

3.1 INTRODUCTION

The geological setting of the BBSB is dominated by two sedimentary basin provinces ie, the Sydney-Gunnedah-Bowen Basin and the Surat Basin. The BBSB also includes parts of two major fold belt provinces, the Lachlan Fold Belt to the southwest, and the New England Fold Belt to the east. These four provinces (figure 7) are intruded by younger igneous rocks and overlain by younger volcanic rocks, sedimentary rocks and unconsolidated alluvium.

The following discussion of the geological setting of the BBSB is structured to facilitate the review of mineral and petroleum resources and potential. The Sydney-Gunnedah-Bowen Basin province has been subdivided into a number of resource assessment areas (figure 6).

A comprehensive description of the surficial geology of the BBSB can be found in the report entitled "Geology – Integration and Upgrade" for project WRA19.

3.2 LACHLAN FOLD BELT

The Lachlan Fold Belt extends northwards from eastern Tasmania through Victoria and central New South Wales, disappearing under younger sedimentary basins in the southern part of the BBSB.

The Fold Belt has had a complex geological history with orogenic processes progressively thickening the crust from a deep oceanic environment with volcanic islands (probably an arc-trench association) in the Ordovician, to a continental environment with broad alluvial plains and a shallow sea in the Late Devonian. The Lachlan Fold Belt was accreted or joined onto the older Proterozoic craton to the west and progressively stabilised in a series of deformations involving large-scale faulting and folding from latest Ordovician to Early Carboniferous.

The Lachlan Fold Belt was also the site of very extensive igneous activity during the Silurian and Devonian Periods. Abundant granites and related volcanic rocks were emplaced and now make up about 20 per cent of the total area of the fold belt.

Rock units of the Lachlan Fold Belt comprise the southwestern margin of the BBSB from Narromine, east to Ulan. In this area, it has been subdivided into the Narromine Volcanic Belt in the west, the Cowra Trough, the Molong Volcanic Belt, the Hill End Trough, and the Rockley Gulgong Volcanic Belt in the east (figure 7).

The Narromine, Molong and Rockley-Gulgong Volcanic Belts comprise three segments of a former Ordovician oceanic volcanic island arc termed the Macquarie Volcanic Arc. The Narromine Belt probably represents the core of the arc and the eastern two belts are parts of a large, volcaniclastic apron that was split from the core of the arc during extension in the Silurian. The extension resulted in the formation of the Cowra Trough between the Narromine Volcanic Belt and the Molong Volcanic Belt, and the Hill End Trough between the Molong Volcanic Belt and the Rockley Gulgong Volcanic Belt.

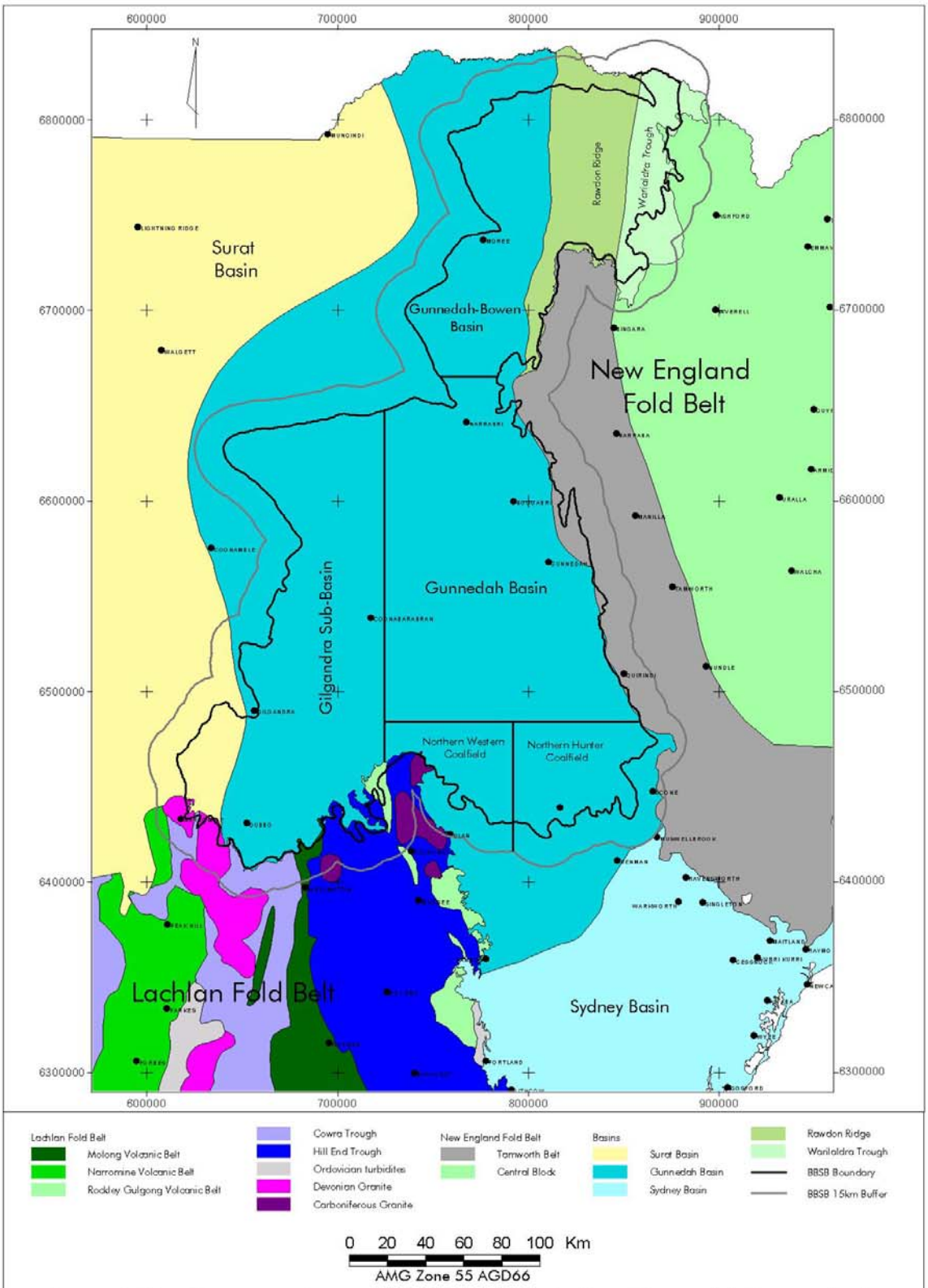

Figure 6. Coal Resource Assessment Areas of the Sydney-Gunnedah-Bowen Basins

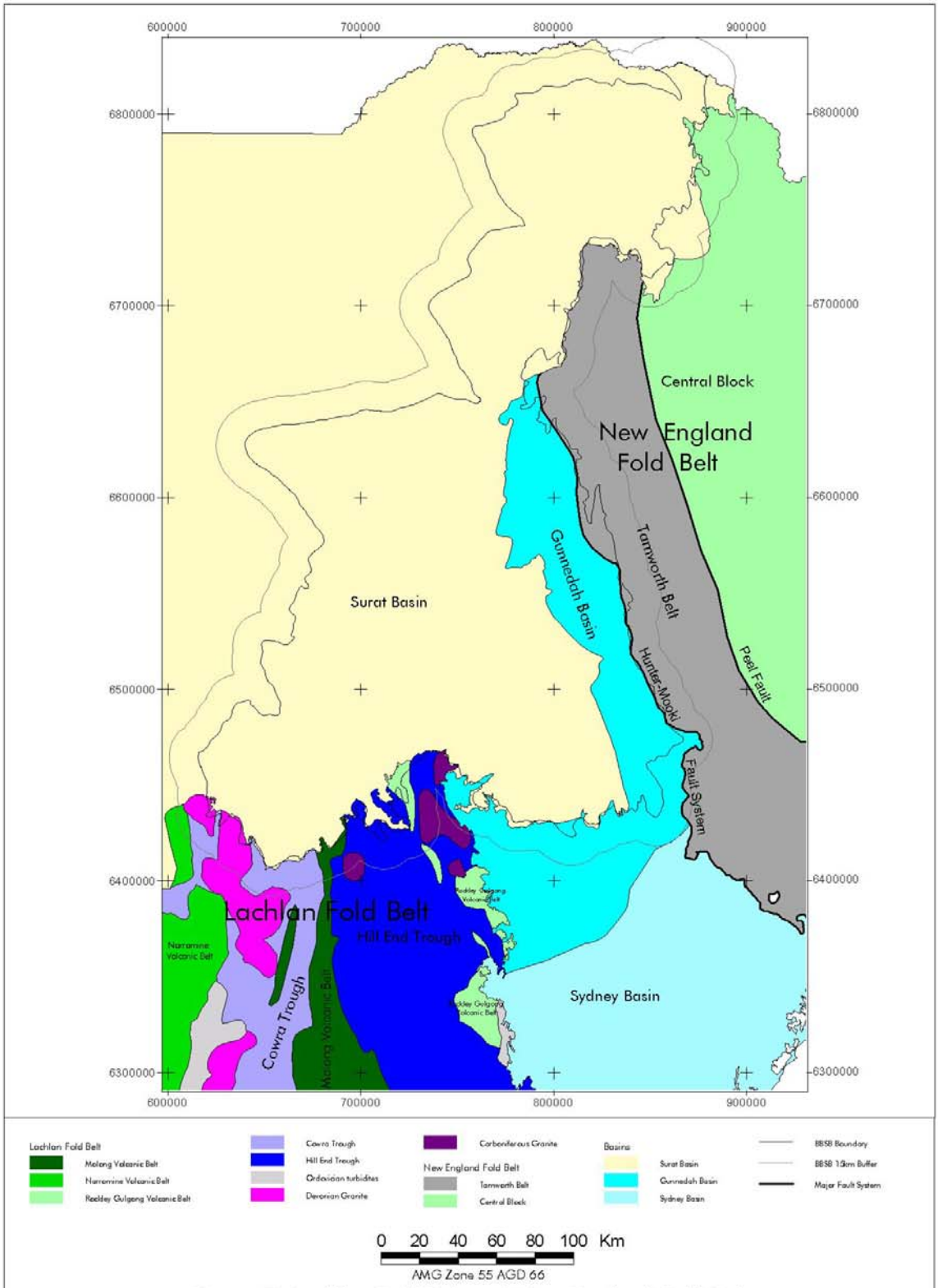

Figure 7. Lachlan Fold Belt and New England Fold Belt
Simplified geological map showing major subdivisions

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The three volcanic belts comprise an association of mostly basaltic and andesitic volcanic and volcaniclastic rocks with lenses of shale and limestone. Volcanic centres, with both coherent lavas and intrusive rocks, are more common in the Narromine and Molong Volcanic Belts, and they often contain rocks such as monzonite that are commonly associated with large porphyry copper-gold deposits.

The Cowra Trough crops out near Dubbo south to Young. The Hill End Trough occupies a north-south area extending east from Wellington to Gulgong. With crustal extension in the Silurian, the region was transformed from deep oceans to basins and platform areas where shallow-water limestone, shale, sandstone and volcanic rocks such as rhyolite and dacite were deposited. Deposits of massive sulphide containing lead, zinc and silver are often associated with the Late Silurian volcanic rocks.

An outpouring of dacite and rhyolitic volcanic rocks, and deposition of volcanogenic sediments was widespread just after the beginning of the Devonian. Thick volcaniclastic deposits were laid down in the Hill End Trough and a minor volcanic episode occurred on the edge of the Molong Volcanic Belt and the Cowra Trough. Large granite bodies such as the Yeoval Granite were also intruded at this time and crop out around the southwestern boundary of the BBSB. Post-volcanic subsidence and a low relief landscape resulted in the deposition of fine grained sedimentary rocks such as shale, in the deep water parts of the basins, with sandstone and limestone on the shallower shelf areas.

During the Middle Devonian, the Lachlan Fold Belt was deformed (folded and faulted) and all moderate to deep water sedimentation ceased. Deposition of sandstone and conglomerate followed in the Late Devonian in a shallow marine and alluvial plain setting. The area was deformed again in the Early Carboniferous and this deformation was followed by the intrusion of numerous granites such as the Bathurst Granite, the Gulgong Granite, and the Wuuluman Granite near Wellington.

The volcanic belts and troughs of the Lachlan Fold Belt all continue northward through the BBSB but are unconformably overlain by increasing thicknesses of younger sedimentary rocks of the Surat and Sydney-Gunnedah Bowen Basin. Rock units of the Lachlan Fold Belt comprising a variety of volcanic, plutonic and sedimentary rocks form basement beneath most of the BBSB. The exception is along the eastern portions of the BBSB where rock units of the New England Fold Belt form basement.

Important mineral commodities found in the Lachlan Fold Belt include copper, gold, silver, lead, zinc and rare earths. Mineralisation styles for the area are summarised by Downes (1999b) and are particularly relevant not only for exposed sections of the Lachlan Fold Belt, but also for areas of shallow cover on the margins of the Surat and Sydney-Gunnedah Basins. Porphyry copper-gold, structurally controlled (orogenic) gold and volcanic-hosted massive sulphide mineralisation styles are particularly important in the southern parts of the BBSB.

3.3 NEW ENGLAND FOLD BELT

The New England Fold Belt is a major geological province that extends from the Newcastle area north to Far North Queensland. It comprises many rocks that formed in complex geological settings where sediments from the deep ocean were being subducted and thrust into the Australian landmass. They were mixed with sediments formed from the eroding mountains and volcanoes that existed on the margins of the continent. Like the Lachlan Fold Belt, the New England Fold Belt has had a complex structural history with the rocks undergoing a series of deformations involving large-scale faulting and folding from the Late Carboniferous to Triassic time. The Fold Belt also includes several major suites of granitic rocks as well as numerous related intrusive and extrusive volcanic rocks. It is faulted against and thrust over the eastern part of the Sydney-Gunnedah-Bowen Basin along the Hunter-Mooki-Goondiwindi Fault system.

The New England Fold Belt in the area of the BBSB comprises rocks of the Tamworth Belt and a small part of the Central Block. Central Block rocks are separated from the Tamworth Belt by the Peel Fault System. Figure 7 shows the extent of the New England Fold Belt in the BBSB area.

The Central Block of the New England Fold Belt occurs to the east of the Peel Fault and is comprised of a Cambrian to Silurian ophiolitic sequence (ocean crust), which was emplaced in the Late Carboniferous (Aitchison and Island 1995). Middle Silurian to Early Carboniferous deepwater marine strata occur to the east of the ophiolite sequence. Granites of the Late Carboniferous Bundarra Plutonic Suite intrude the Palaeozoic sediments. Late Permian and Early Triassic granites of the Clarence River Suite and other

undifferentiated granites intrude the sediments.

The Tamworth Belt is separated from the Central Block on the east by the Peel Fault and disconformably underlies and overthrusts rocks of the Surat and Sydney-Bowen Basins as well as the Warialda Trough to the north and west. The Tamworth Belt is comprised of gently folded and mildly metamorphosed Devonian to Carboniferous sedimentary and volcanic rocks. These rocks represent a protracted marine regression culminating in continental and shallow-marine sedimentation during Late Carboniferous time. Generally a westerly source of sediments and volcanics prevailed. This belt is usually interpreted as a forearc basin to the east of a (now buried) volcanic arc.

Mineralisation styles in the Tamworth Belt and Central Block are discussed in Brown and Stroud (1997), Brown et al (1992), and Gilligan and Brownlow (1986). Of particular importance are structurally controlled orogenic (metahydrothermal) gold deposits, tin veins, and placer deposits of sapphire, tin and diamond. A number of zeolite and diatomite prospects are also present.

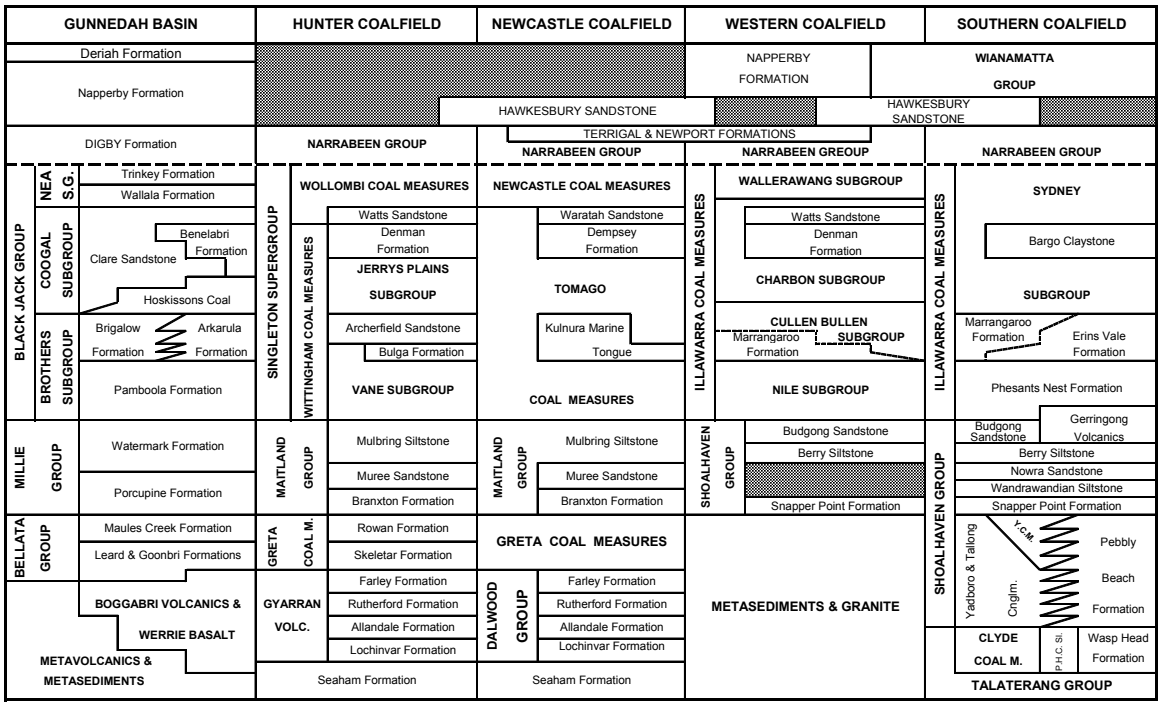
3.4 SYDNEY - BOWEN BASIN

The Sydney-Bowen Basin extends for 1700 km along the eastern margin of Australia from central Queensland in the north to the edge of the continental shelf off southeastern New South Wales. It is divided into three parts, the Sydney, Gunnedah and Bowen Basins. The BBSB area, including the buffer zone, covers the northern Sydney Basin, the entire Gunnedah Basin and the southern-most part of the Bowen Basin. Study of the Sydney-Bowen Basin has traditionally been concentrated in coalfields established around each of the coal exploration and mining centres.

Individual stratigraphies (rock unit naming systems) have been developed for each of the coalfields but these do not coincide with the structural boundaries of the basins as now defined. For example, the Ulan – Binnaway area is defined as being within the structural Gunnedah Basin but is included for historic and economic reasons within the Western Coalfield and uses a modified Western Coalfield stratigraphy instead of the Gunnedah Basin stratigraphy. Likewise, the Upper Hunter area is defined as part of the structural Gunnedah Basin but a modified Hunter Coalfield stratigraphy is used.

To assist the review of the geology and mineral resources, and to assist the reader, the portion of the Sydney – Bowen Basin relevant to the BBSB assessment has been subdivided into resource assessment areas. They are, the Gunnedah Basin, the Gilgandra Sub-Basin, the Northern Hunter Coalfield, the Northern Western Coalfield, and the Gunnedah – Bowen Basin, (figure 6). A stratigraphic chart comparing the stratigraphies used in the various parts of the Sydney and Gunnedah Basins is provided in table 1. The following discussion of the geological and tectonic history of the NSW portion of the Sydney – Bowen Basin is provided to form a context for the more detailed discussions set out below. Reference is also made to the development of the Warialda Trough and the Werrie Basin, two small Permo-Triassic basins in the east of the BBSB.

TABLE 1 CORRELATION OF LITHOSTRATIGRAPHIC UNITS, GUNNEDAH AND SYDNEY BASINS



3.4.1 Tectonic And Depositional History

The Sydney-Bowen Basin was initiated by Late Carboniferous and Early Permian volcanic rifting between the Lachlan and the New England Fold Belts (Scheibner 1974; 1976). This was followed by a mid-Permian stage of thermal relaxation, and then a final Late Permian-Triassic stage where a foreland basin developed (Murray, 1990).

The earliest Permian sediments in the Sydney Basin consist of isolated occurrences of fluvial, coastal plain and marine sediments deposited on the older Palaeozoic basement. These are represented in the south by the Talaterang Group, consisting of the Clyde Coal Measures, Pigeon House Creek Siltstone and the Wasp Head Formation (Fielding and Tye, 1994; Tye and Fielding, 1994), and in the Newcastle and Hunter regions by the fluvio-lacustrine sediments of the Seaham Formation. The fluvial sediments of the Temi formation in the Werrie basin were also deposited at this time.

Rifting caused the initial basin subsidence and initiated a widespread marine transgression throughout the Sydney Basin. This resulted in the formation of the Shoalhaven Group, including the Yadbro and Tallong Conglomerates, and the Pebbly Beach Formation, in the south and west, and the Dalwood Group in the Newcastle region. The Yarrunga Coal Measures were deposited at this time in the southern Sydney Basin, in a coastal plain environment (Tye and Fielding, 1994) that moved westwards as the transgression took place (Herbert, 1980a). The thick basaltic and rhyolitic sequences of the Lochinvar Formation and Gyarran Volcanics in the Sydney Basin, and the Boggabri Volcanics and Werrie Basalts in the Gunnedah Basin, were also formed.

A marine regression, which started late in the Early Permian, terminated the deposition of the Dalwood Group and allowed the accumulation of a thick fluvio-deltaic sediment wedge (the Greta Coal Measures). This wedge prograded southwards from tectonically active areas in the New England region. It reached the Hunter Valley and Newcastle areas but did not prograde to the southern part of the Sydney Basin. Marine conditions continued uninterrupted in the south, forming the sequence from the Wasp Head Formation to the Snapper Point Formation and the Wandrawandian Siltstone. Deposition also commenced in the western part of the basin at this time, with a thick transgressive shoreline and near-shore deposit (Snapper Point Formation) which was mainly derived from the Late Devonian quartzite of the Lachlan Fold Belt (Herbert, 1980a).

The equivalents of the Greta Coal Measures in the Gunnedah Basin, the Leard, Goonbri and Maules Creek Formations, were deposited over the sequence of weathered basal volcanics. Basin fill was localised in small, rapidly subsiding troughs. Highlands and ridges separated the troughs. Fine-grained

lacustrine sediments (Goonbri Formation), accumulated in the most rapidly subsiding areas in the troughs (the Maules Creek Sub-basin, Bohena and Bando Troughs in the Gunnedah Basin, (Tadros, 1993c), whereas prograding volcanic - lithic alluvial fan and piedmont deposits accumulated on the flanks of the highs and ridges and on the trough margins and ultimately filled the lakes and covered the trough areas with thick sequences of fluvial sandstones and conglomerates (Tadros, 1993b). Small amounts of quartz-rich sediments derived from the Lachlan Fold Belt were also deposited in the trough areas. Equivalents of the Greta Coal Measures are also found in the Werrie Basin. They are the Willow Tree and the Koogah Formations.

Rapid subsidence followed this phase of deposition and led to a transgressive marine inundation of the Greta Coal Measures and its equivalents. The transgression was developed first in the Sydney Basin, with deposition of the Branxton Formation of the Maitland Group in the Hunter Valley region, and the deposition of the Wandrawandian Siltstone in the Illawarra region. It subsequently spread northwards and resulted in deposition of the Porcupine Formation in the Gunnedah Basin and the Borambil Creek and lower Bickham Formations in the Werrie Basin. The presence of ice-rafted dropped pebbles and boulders in these formations is thought to indicate a cold climate, which persisted until at least the end of deposition of the Maitland Group (Brakel, 1984).

A regressive-transgressive episode interrupted the open marine shelf deposition and formed near-shore sand sheets (the Muree Sandstone in the north and the Nowra Sandstone in the south). These beds were overlain by the finer-grained offshore sediments of the Mulbring Siltstone in the north, the Berry Siltstone and lower Cumberland Group in the south and west, and the Watermark Formation in the Gunnedah Basin. Sandy sedimentary units are common in the upper part of the sequence, indicating the onset of a marine regression that acted as the initiator of the main period of peat formation in the Sydney - Gunnedah Basins. The Toll Bar and upper Bickham Formations are the equivalents of these units in the Werrie Basin.

The regression commenced very early in the Late Permian. Uplift and volcanism in the New England region resulted in increased erosion and transportation of sediment west and southwest into the Sydney and Gunnedah Basins. Prograding fluvio-deltaic systems formed the Tomago, Wittingham and Illawarra Coal Measures in the Sydney Basin and the Black Jack Group in the Gunnedah Basin.

The Sydney and Gunnedah Basins also received sediments from the Lachlan Fold Belt as the result of periodic uplift caused by the developing collision with the New England Fold Block. Alluvial systems prograded north and east across the Sydney Basin and southeast across the Gunnedah Basin. The sediments formed the Marrangaroo and Blackmans Flat Formations in the lower part of the Illawarra Coal Measures in the Western and Southern Coalfields, and the Brigalow Formation and Clare Sandstone within the Black Jack Group.

Two marine incursions interrupted terrestrial sedimentation in the Basins for short periods during this depositional episode. The first incursion, caused by tectonic subsidence (Brakel, 1986), deposited the Kulnura Marine Tongue and its lateral equivalents, the Bulga and Archerfield Formations in the northern Sydney Basin, the Erins Vale Formation in the southern Sydney Basin, and the Arkarula Formation in the Gunnedah Basin (Mullaley Sub-basin). This marine incursion did not reach the western margins of the Basins. Instead, the braided fluvial wedge of the Marrangaroo Formation was deposited in the Sydney basin and quartz-rich, bed-load fluvial sediments of the Brigalow Formation were deposited in the Gunnedah Basin.

The return to terrestrial sedimentation in the east of the Sydney and Gunnedah Basins marked a very important event: the establishment of basin-wide swamps. Peat accumulated in a succession of nearly continuous blankets over the subdued relief resulting from the infilling of the preceding marine embayment (Brakel, 1984), and the emergent extensive platform of marine-reworked deltaic sediments (Hamilton, 1987).

The peat swamps formed the Lithgow Coal and the Lidsdale Coal in the southern and central Western Coalfield, and the Ulan Coal in the northern Western Coalfield. To the south, they formed the Bayswater Coal in the Hunter Coalfield and the Woonona Coal Member in the Southern Coalfield. In the Gunnedah Basin, they formed the Hoskissons Coal.

A second marine incursion which was probably eustatically controlled (Brakel, 1986) then affected the basins. It resulted in the deposition of the Watts Sandstone and Denman Formation in the Hunter and Western Coalfields, the Waratah Sandstone/Dempsey Formation sequences in the Newcastle area, and the Darkes Forest Sandstone/Bargo Claystone sequence in the Illawarra.

From the widespread nature of the Dempsey/Denman incursion, abundance of acritarchs and the presence of foraminifera, Bembrick (1983) interpreted a marine open bay environment for this interval. The Dempsey/Denman incursion did not reach the Gunnedah Basin, but its lateral equivalents are freshwater lacustrine sedimentary rocks, the organic-rich, mudstone-dominated Benelabri Formation, to the east, and the westerly derived fluvial sandstones of the Brigalow Formation in the west (Tadros, 1986a, b; 1993c).

Coal measure sedimentation resumed after a marine regression ended the incursion, with the southward progradation of major fluvio-deltaic systems from the north of the Sydney Basin. This resulted in deposition of the Wollombi and Newcastle Coal Measures in the north; the upper part of the Illawarra Coal Measures (the Wallerawang Subgroup) in the west; the upper part of the Sydney Subgroup in the Illawarra; and the uppermost part of the Black Jack Group (the Nea Subgroup) in the Gunnedah Basin.

The encroachment of conglomeratic braided fluvial systems influenced sedimentation during that interval particularly towards the upper part, throughout the Sydney-Gunnedah Basin. There was also an abundance of air-fall tuff and pyroclastic detritus, derived from the tectonically active New England Fold Belt region. Tuff and pyroclastic detritus in the Newcastle Coal Measures were apparently derived from the "Northumberland Ridge" to the east of the present coastline (Brakel, 1984).

A major depositional break and a period of structural readjustment, uplift and erosion followed at the end of the Late Permian, and are evident across the Sydney - Bowen Basin. An angular unconformity is present in the northern Gunnedah Basin between the Triassic Digby Formation and the Permian rocks of the Millie and Black Jack Groups (Tadros, 1986b; Tadros in Tadros et al. 1987b).

In the Hunter Valley, a significant depositional break occurred between the Late Permian coal measures and the overlying basal Narrabeen Group. An unconformity is also present over the Lochinvar Anticline where the Newcastle–Tomago Coal Measures sequence has been completely eroded and the Triassic Munmorah Conglomerate (Narrabeen Group) rests directly on the underlying marine Maitland Group (Herbert, 1980a). Locally, in the area northwest of Ulan, the upper part of the Illawarra Coal Measures has been eroded and the Narrabeen Group rocks rest unconformably and erosively on the Ulan Coal. Further west, the Narrabeen Group rests directly on the Ulan Quartz Monzonite.

Deposition in the Sydney-Bowen Basin resumed in the Early Triassic when major alluvial systems generated by erosion in the uplifted New England Fold Belt prograded south and southwest over the eroded surfaces of the Permian sediments. Thick conglomerate sequences formed by large alluvial fans and the associated outwash sediments spread across the Hunter–Mooki Fault System to create the Munmorah and Widden Brook Conglomerates in the Hunter Valley, and the Bomera Conglomerate Member of the Digby Formation in the southeastern Gunnedah Basin. These conglomerates pass laterally into pebbly sand outwash deposited ahead of the fans, and gradually becoming sandier along the western margins of the Sydney Basin (Herbert, 1980a).

In the south, the Triassic Scarborough and lower Bulgo Sandstones are finer grained with an increased proportion of interbedded shaly units. Red, green and grey claystone and siltstone, representing fine-grained outwash and overbank sediments, are often intercalated with or overlain by conglomeratic sediments deposited by the advancing braided streams and alluvial fans; the Stanwell Park Claystone and Wombarra Claystone in the south, the Dooralong Shale in the east, and the Caley Formation in the west.

Deposition continued during the Triassic in the Sydney Basin, but with significant changes in stream gradient and flow direction. In the northern part, low-gradient streams flowed to the southeast parallel to the basin axis and deposited large quantities of fine-grained red and green overbank sediments, the Tuggerah Formation and Patonga Claystone. The western margin received more quartzose sediments at that time resulting from reactivation of uplift in the Lachlan Fold Belt in the west, with deposition of the Banks Wall Sandstone in the western Sydney Basin (Bembrick, 1980) and the upper part of the Digby Formation. Widespread palaeosol horizons formed on top of the Gunnedah Basin deposits at the end of that phase (Jian 1991). These have been attributed to equilibrium conditions between loading by the overthrust New England Fold Belt and a fore bulge development in the craton (Jian and Ward, 1993).

Renewed basin subsidence resulted in deposition of the Triassic Napperby Formation in the Gunnedah Basin. The basal section comprises laminated siltstone and claystone deposited in a very extensive lake. Well-developed upward-coarsening sequences of laminated siltstone/claystone, interbedded sandstone/siltstone laminites to sandstone, derived from the New England Fold Belt, form the middle part of the sequence. Those units represent progradation of lacustrine deltas. The upper part consists of fluvially deposited, irregularly interbedded sandstone and siltstone sequences. Jian and Ward (1993) believed that contemporaneous volcanic activity in the New England Fold Belt produced the very distinctive green sandstone of the Deriah Formation at the top of the Triassic sequence.

Subsidence in the Sydney Basin caused limited transgression and an upward transition to fluvio-deltaic deposition of the upper Narrabeen Group (Newport and Terrigal Formations). Sediments derived from the New England Fold Belt did not reach the southern and western basin areas. Instead, thick claystone-siltstone red beds of the Bald Hill Claystone and Wentworth Falls Claystone Member were deposited. These are likely to have been formed as terrestrial piedmont deposits (Herbert, 1980a).

Uplift of the Lachlan Fold Belt to the southeast of the Sydney Basin caused tilting and erosion of the Late Permian and Early to Middle Triassic sedimentary units in the southern Sydney Basin, and the subsequent deposition of coarse quartzose sand (Hawkesbury Sandstone). The sand was probably derived from Late Devonian quartzites in the Lachlan Fold Belt. Tilting of the Basin to the northeast resulted in easterly and northeasterly current directions (Standard, 1964; Herbert, 1980a), which indicate that sediment was supplied from immediately west of the Sydney Basin.

Lithologies equivalent to the Hawkesbury Sandstone are not present in the Gunnedah Basin. This is because the New England Fold Belt remained the dominant source of sediments to that part of the basin complex at that time (Jian & Ward, 1993).

The last phase of tectonic development of the Sydney Basin is attributed to "shutting-off" of quartzose sand supply from the Lachlan Fold Belt, and to rapid subsidence of the Hawkesbury alluvial plain. This resulted in the deposition of the Wianamatta Group. Herbert (1980a, b) related the deposition of the Wianamatta Group to a single regressive cycle. The Napperby Formation in the Gunnedah Basin is a gross regressive cycle from lacustrine to delta and ultimately to fluvial sedimentation, with the main sediment source being the New England Fold Belt.

Hamilton et al. (1988) noted that a major mid-to Late Triassic episode of compressive deformation caused reverse faults and uplifted small blocks from which the upper part of the Napperby Formation was removed. They also suggested that up to 2000 m of Triassic and Permian sedimentary section had been removed in the southeastern part of the Gunnedah Basin during that period of erosion. This episode of deformation terminated deposition in the Sydney-Gunnedah Basin.

3.5 GEOLOGY OF THE GUNNEDAH BASIN

3.5.1 Introduction

The Gunnedah Basin forms the central section of the larger Sydney-Bowen Basin that extends for 1,700 km along the eastern margin of Australia, from central Queensland in the north to the edge of the continental shelf off southeastern New South Wales. The Sydney, Gunnedah and Bowen Basins are considered as the preserved parts of one continuous depositional system that now has prominent large-scale structural subdivisions. The Sydney-Bowen Basin comprises rocks of Permian and Triassic age and is the major source of black coal in Australia. The surface extent of the Gunnedah Basin is shown in figure 7 and its subsurface extent is shown in figure 6. The surface geology is shown in figure 2.

The Gunnedah Basin is bounded on the east by the Mooki Thrust Fault System, where the older New England Fold Belt rocks have been thrust over the Gunnedah Basin strata. The Basin overlies rocks of the Lachlan Fold Belt and its boundary is defined as the western limit of Triassic strata. The northern and southern boundaries of the basin are both subject to debate, particularly as the Gunnedah Basin is contiguous with the Bowen and Sydney Basins respectively. The most widely accepted boundaries at present are the Moree High (north of Moree) in the north and the Mount Coricudgy Lineament in the south.

In this section of the report, the discussion of the Gunnedah Basin will be restricted to the area south of Moree, north of the Liverpool Ranges, west of the Mooki Thrust, and east of the Rocky Glen Ridge. The Western, southern and northern sections are discussed separately.

3.5.2 Overview of Basin History

The following overview of the Basin geology has been modified after Tadros (1993a, 1999), Pratt (1998), Upstream Petroleum Consulting Service (2002b) Vanibe (2000), and Maloney (2002).

Basal Sedimentary units of the Gunnedah Basin overly Late Carboniferous to Early Permian volcanics, except in the far west and southwest where they unconformably overly rocks of the Lachlan Fold Belt. The patterns of post-Carboniferous deposition were largely controlled by a basement geometry, developed by the beginning of the Permian. This geometry was modified by tectonic events in Late

Permian to Early Triassic time, in the Jurassic, and finally by the emplacement of major volcanic complexes in the Tertiary.

Initial formation of the Gunnedah Basin was accompanied by the out-pouring of silicic and mafic lavas of the Boggabri Volcanics and the Werrie Basalt, during a period of extensional tectonism in the Late Carboniferous to Early Permian. This extension controlled the deposition of the Leard and Goonbri Formations in the Early Permian (Stage 4). These units correlate with the Reids Dome Beds of the Dennison Trough in the Bowen Basin of Queensland. The terrain at the end of the volcanism consisted of a series of valleys and ridges. The weathered volcanic surface was preserved in places forming the Leard Formation. A series of shallow lakes and swamps formed in the deepest parts of the Basin, the Maules Creek Sub-Basin and the Bellata Trough, the resulting deposits forming the Goonbri Formation.

In the late Early Permian a period of lacustrine and fluvial sedimentation resulted in the accumulation of thick coals (Maules Creek Formation). These coals are the primary target of the current coal seam methane exploration and future potential economic production within the basin. The thickest development of the formation was in the fastest subsiding parts of the basin, the Maules Creek Sub-Basin and the Bellata, Bohena and Bando Troughs. In the Maules Creek Sub-Basin, periods of subsidence marked by the renewed shedding of sediments from the Boggabri Ridge, were interspersed with quiet periods when coal swamps formed.

The onset of Late Permian deposition was marked by a marine transgression during which the Porcupine and Watermark formations (equivalent to the Shoalhaven and Maitland Groups of the Sydney Basin) were deposited. The transgression may have resulted from continued subsidence of the basin resulting from thermal relaxation and/or from a eustatic sea level rise. Intermittent but dominant sediment supply from the east produced fan deltas that were spread over the marine shelf forming the Porcupine and lower Watermark Formations.

An east-west compressional event caused by the collision with and eventual over thrusting of the New England Fold Belt affected the basin in Late Permian to Early Triassic times. The first evidence of the uplift to the east is the development of deltas in the east of the basin which gradually prograde to the west and southwest across it. The marine parts of the delta form the upper Watermark Formation. The lower and upper delta plain sediments, and the associated extensive coals that developed in the east and southeast, form the Pamboola Formation, the base of the Black Jack Group. A eustatic marine transgression then covered much of the basin forming the Arkaroola Formation, with beach, lagoonal and near shore facies common in the south and deeper shelf sediments occurring in the north. The transgression did not reach the west of the Basin. Uplift of the Lachlan Fold Belt resulted in the development of the quartz-rich, braided fluvial sediments of the Brigalow Formation.

A marine regression initiated peat formation in a nearly continuous blanket over the subdued relief resulting from the infilling of the preceding marine embayment. This formed the Hoskissons Coal. A period of widespread peat formation followed, interrupted by the effects of a second marine incursion and fluvial sedimentation both from the east and the west. The extensive Dempsey/Denman marine incursion in the Sydney Basin did not reach the Gunnedah Basin, but its lateral equivalents are freshwater lacustrine sedimentary rocks, the organic-rich, mudstone-dominated Benelabri Formation, in the eastern half of the Mullaley Sub–basin. In the west, further uplift of the Lachlan Fold Belt led to the formation of the quartz rich Clare Sandstone Member, deposited as the bed load of a braid channel system which gradually prograded east across the basin.

Significant uplift now occurred in the New England Fold Belt. Alluvial fans developed in the east, and braid outwash streams flowed to the southwest and south across the basin forming the Wallala Formation. The following quiescent period was dominated by peat formation and volcanic activity. Major volcanic centres developed in the New England uplands at this time. Repeated major eruptions produced extensive and often thick deposits of airfall tuff that blanketed large tracts of the basin and were most commonly preserved in association with the coal seams.

The east-west compressional event caused by the over thrusting of the New England Fold Belt, reached its peak at the end of the Permian. West verging thrust faults and high angle reverse faults and folds developed, and the eastern part of the Basin was uplifted and eroded. The northern part of the Rocky Glen Ridge was probably subject to reactivation and differential uplift of the Permian sediments at this time.

A major period of uplift occurred in the New England Fold Belt at the commencement of the Triassic with a sheet of coarse lithic fluviatile sediment being deposited over the Permian sediments in the east and centre of the Basin (the Bomera Member of the Digby Formation). As the erosion of the New England block waned, uplift began in the Lachlan Fold Belt, and a braid channel system deposited quartzose sediments from the west (the Wollar Member of the Digby Formation). Mixing of the easterly and westerly-derived material occurred in a trunk stream flowing to the south. This stream progressively prograded to the east as the western channel system became dominant. This was followed by a period of quiescence, where soil horizons developed over the basin.

The Napperby Formation was then deposited. A vast lake formed which was dammed at the southern end of the Basin but the process of its formation is still conjectural. This lake began to fill with fine silts but increasing quantities coarser material was supplied by deltas prograding west and southwest out from the edge of the New England Fold Belt. Eventually, a flood plain with a number of active fluvial channels covered the basin.

A late Triassic compression event affected eastern Australia and it marks the boundary between Permo-Triassic Sydney-Bowen Basin system and the overlying Jurassic-Cretaceous Surat and Eromanga Basin systems. Uplift and erosion occurred in the east, and up to 2000 metres thickness of Gunnedah Basin sedimentary rocks were removed. Following uplift there was a prolonged period of igneous activity in the Early Jurassic, forming the Garrawilla Volcanics. They consist of volcanic flows, tuffs, domes and intrusives and are widespread across the area. Fluvial sediments of the Purlawaugh and Pilliga Formations overlie the Garrawilla Volcanics. The last major geologic event took place in the Tertiary, when the Warrumbungle, Liverpool Range, and the Nandewar volcanic complexes were emplaced.

Structural Elements

The major structural elements of the Gunnedah Basin (figure 8) are based on the interpretation of surface geology combined with interpretation of various other geological and geophysical data sets. Most notably these sets include the regional gravity and magnetic data coverages, as well as seismic and borehole control. The following overview has been modified after Tadros 1993a and 1999, Pratt 1998, Vanibe 2000, Upstream Petroleum Contracting Services 2002b, and Gunn, 2002a.

The structural elements resulted initially from the Carboniferous -Early Permian tectonic episode. Subsequent tectonic episodes reactivated and enhanced them, and also influenced the depositional patterns. The elements therefore comprise the principal controls on depositional style, structuring and lithofacies development, all of which are important for understanding the distribution of coal seams, and of source, seal, reservoir, and trapping mechanisms for conventional oil and gas generation. A brief description of them follows.

Maules Creek Sub-basin
The Maules Creek Sub-basin is bound by the Mooki Fault to the east, and the Boggabri Ridge to the west. It is a remnant basin structure that originally probably covered areas to the east of the boundary with the New England Fold Belt.

Boggabri Ridge
This structural high separates the Maules Creek Sub-basin from the Mullaley Sub-basin to the west. The ridge was a high during the Early Permian, and Early Permian sediments on-lap both the eastern and western flanks. It is formed by the Boggabri Volcanics in the south and centre, and the Werrie Basalt to the north.

Mullaley Sub-basin
The Mullaley Sub-basin extends the entire length of the Gunnedah Basin from Moree, in the north, to the Mount Coricudgy Anticline, in the south. It is divided by prominent transverse highs, shelfs and troughs.

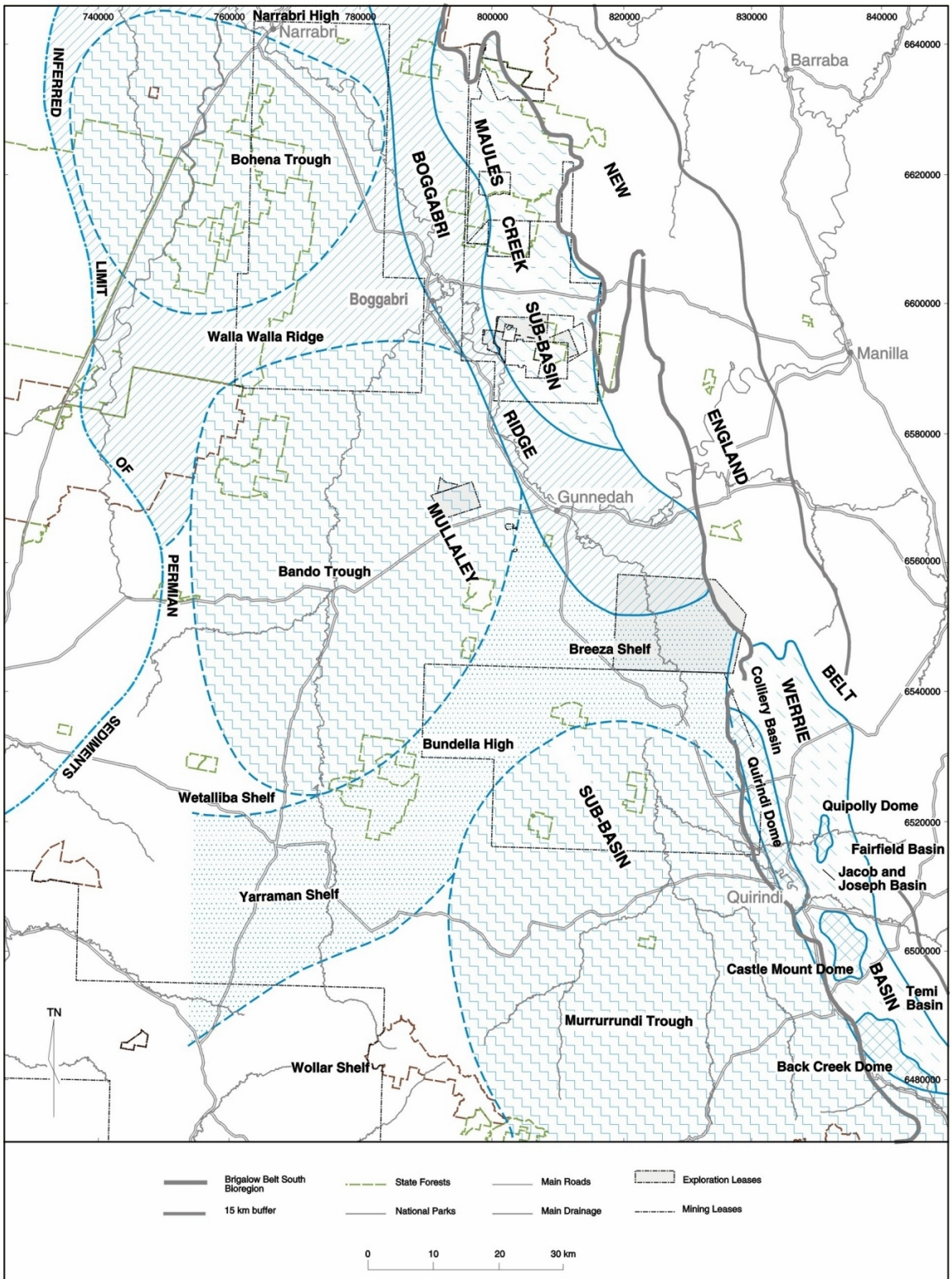


Figure 8 Gunnedah and Werrie Basins Major Structural Elements

AMG Zone 55 Australian National spheroid

Rocky Glen Ridge
The Rocky Glen Ridge is a meridionally trending basement high which separates the Gilgandra Sub-Basin in the west from the Mullaley Sub-basin in the east. Its eastern edge occurs close to the western edge of the thick Werrie Basalt and Boggabri Volcanics basement. It is now believed that uplift commenced in the Late Permian after the deposition of the Gunnedah Basin sequence. Permian sediments were variably eroded along the high, prior to and during the deposition of the Wollar Sandstone Member.

Bellata Trough
Lying north of the Narrabri High, this is the northernmost of the depocentres comprising the Mullaley Sub-basin. It is an area, approximately 40 km wide and 70 km long, of thickened sedimentary pile overlying a basement deep, bound in the west by the Rocky Glen Ridge and in the east by the Boggabri Ridge. Basement depths lie between 600 m and 900 m below sea level.

Narrabri (or Culgoora) High
The Narrabri High separates the Bellata and Bohena Troughs. It is located north of the Wilga Park area and is oriented NE-SW to E-W. It separates Lower Permian sedimentation in the troughs and also had some impact on subsequent Upper Permian, Triassic and Jurassic sedimentation.

Bohena Trough
The Bohena Trough lies south of the Narrabri High where it covers an area of approximately 3,500 km^2. It is bounded to the south by the Walla Walla Ridge, but there is doubt whether this structure had any significant effect on sedimentation. Depth-to-basement mapping, based on drilling and seismic coverage, implies continuity of deposition between the Bohena Trough and the Bando Trough during the Lower Permian. This trough contains an active petroleum system as indicated by the occurrence of conventional gas in the Coonarah, Wilga Park and Bohena wells.

Walla Walla Ridge
The Walla Walla Ridge is a transverse basement high which locally forms the boundary between the Bohena and Bando Troughs. Small silicic volcanic outcrops north of Coonabarabran mark the continuation of this Ridge across the Rocky Glen Ridge. On regional basement maps, the Walla Walla Ridge has a relief of approximately 500 m. It was probably formed during the Late Permian and earliest Triassic. Later sedimentation thins and is draped over it.

Bando Trough
The Bando Trough is a 3,500 km^2 area of thickened Gunnedah Basin sedimentary units located south of the Walla Walla Ridge and north of the Bundella High. Depth-to-basement mapping indicates basement depths within the range of 100 m to 600 m below sea level, within the trough, which contains an extensive sequence of Lower to Late Permian sediments.

Bundella and Yarraman Highs
The Bundella and Yarraman Highs are interpreted northeast trending basement highs separating the Bando and Murrirundi Troughs. Although there is some slight magnetic signature associated with it, it is most readily delineated by a residual gravity high some 25 km wide, and particularly, by an offset of approximately 12 km in the axis of the Meandarra Gravity Ridge beneath the adjacent Bando and Murrurundi Troughs. The Bundella High stands some 200 to 300 m above the floor of the adjacent Bando Trough.

Breeza Shelf
The Breeza Shelf is a broad high shelf area located on the extreme southeastern edge of the Bando Trough. It is considered to be the margin edge development off the Bundella High. It is an area of slightly negative local gravity response and higher magnetic response, presumably reflecting the shallower nature of underlying volcanic basement.

Wollar Shelf
The Wollar Shelf is a shallow area between the main Mullaley Sub-basin and the Rocky Glen Ridge, in the southwest. It is distinguished by stability and lower subsidence rates than the neighbouring trough. In the current study it is defined as the shelf area west of the Murrirundi Trough connecting the Mt Coricudgy Anticline and Bundella – Yarraman High. It is an area that includes a conspicuous gravity low

but a higher magnetic response than adjacent gravity lows, interpreted by Gunn (2002a) as shallow granitic basement.

Weetaliba Shelf
The Weetaliba Shelf is located west of the Bando Trough, adjacent to the Rocky Glen Ridge. It flanks the Baradine High, and Permian sediments thin across the crest of this feature. It probably coincides with a disruptive northwest trending zone between the southernmost extension of the Rocky Glen Ridge and the Capertee High, to its south. Gravity values are intermediate between those to the west and east, although the polarity is reversed. That is, the shallow granitic basement has lower gravity values than the trough where intrusives have given rise to the Meandarra Gravity Ridge.

Murrurundi Trough
The Murrurundi Trough is a major north-south trending infra-basin or depocentre south of the Breeza Shelf, east of the Wollar Shelf and north of the Mt Coricudgy Anticline. Regional structure and isopach contours indicate a rapid increase in thickness of the Permo-Triassic rocks within this Trough, which is probably the deepest of the Gunnedah infra-basins. It coincides with a conspicuous positive gravity feature to the west of Quirindi, Murrurundi and Scone. It is dominated by a strong gravity low along its eastern margin and a north trending gravity high along its axis. Thick sequences of Boggabri and/or Werrie Basalts floor the sedimentary section within the Trough, which is interpreted to be approximately 100 km long and 120 km wide. Much of it is masked by the Liverpool Ranges.

3.5.4 Stratigraphy

A summary of the stratigraphic sequence of rock units, their ages and lithologies is presented in table 2. The following discussion focuses on the formations within the sequence and where relevant, the members within the formations. The complete stratigraphy is described in Tadros (1999). Figures 9 and 10 are west-east and north-south cross sections of the basin, showing the principal units of the basin sequence.

Early Permian and older Basement
The basement of the western side of the Mullaley Sub-basin and the Rocky Glen Ridge is comprised of meta-sedimentary and meta-volcanic rocks and intrusives of the Lachlan Fold Belt, of Ordovician to Carboniferous age (see Section 3.2).

Werrie Basalt/Boggabri Volcanics
The basement rocks of the majority of the Gunnedah Basin are felsic lavas of the Early Permian Boggabri Volcanics and the mafic (basaltic) lavas of the Werrie Basalt. The Boggabri Volcanics were extruded from several volcanic centres at Boggabri and Gunnedah, their remnants forming the Boggabri Ridge and the Warrigundi Volcanics, at Piallaway and Werris Creek in the Werrie Basin. Elsewhere, the Werrie Basalts covered the basin floor to an estimated depth in excess of 1500 m. The top of the Boggabri Volcanics and Werrie Basalt assemblage is erosional, with the upper part of the basaltic rocks in particular, showing evidence of deep weathering. All rock types are commonly overlain by colluvium, poorly sorted conglomerate or breccia.

Leard Formation
The Leard Formation is the basal unit in the Gunnedah Basin sedimentary sequence and forms a thin veneer a few metres thick on the basal volcanics in the Maules Creek Sub-basin. In the Mullaley Sub-basin, the unit is discontinuous and ranges in thickness up to 17.5 m. The Leard Formation comprises pelletoidal claystone, conglomerate, sandstone and siltstone commonly interbedded with coal. The formation was deposited through colluvial and alluvial processes from material derived from the breakdown of the underlying basal volcanic rocks.

Goonbri Formation
The Goonbri Formation, although known only from drill core, has been recognised in the Maules Creek Sub-basin, the Bohena Trough and the Bellata Trough. The formation consists mainly of organic rich siltstone, thin layers of coal, laminites and fine to medium grained moderately well sorted sandstones. The lacustrine depositional environment of the Goonbri Formation was terminated by the prograding fluvial sedimentation of the Maules Creek Formation.

Table 2. Gunnedah Basin and Overlying Stratigraphy

Basin	Years (Ma)	Period		Stratigraphy: Group	Stratigraphy: Formation	Lithology
	2	QUATERNARY			undifferentiated sediments	Undifferentiated alluvial deposits of gravel,sand, silt and clay.
		TERTIARY			Nandewar Volcanic Complex	Felsic, intermediate and mafic sills, dykes, plugs and flows
					Liverpool Range Beds	Basaltic lavas and pyroclastics with minor fluviatile sediments
	65	CRETACEOUS				
Surat Basin Units	141	JURASSIC			Orallo Formation	Clayey sandstone with interbedded siltstone and mudstone
					Pilliga Sandstone	Quartz pebble and quartzose sandstone with minor siltstone
					Purlawaugh Formation	Thinly bedded lithicsandstone interbedded with siltstone and mudstone
					Bulga Complex	Erosional residuals of massive felsic flows and lava domes
					Glenrowan Intrusives	Sills and dykes of mafic rocks
	205				Garrawilla Volcanics	Basaltic lavas and pyroclastics
Gunnedah Basin Units		TRIASSIC	MIDDLE		Napperby Formation	Coarsening-up sequences of dark-grey siltstone/sandstone laminite overlain by parallel bedded or low-angle crossbedded quartzose sandstone
			EARLY		Digby Formation	Poorly sorted volcanic-lithic pebble conglomerate overlain by coarse to fine grained quartz-lithic and then quartzose sandstone
	251	PERMIAN	LATE	Black Jack Group, Nea Subgroup	Trinkey Formation	Claystone, siltstone and fine grained sandstone intercalated with tuff, carbonaceous claystones and tuffaceous stoney coal seams
					Wallala Formation	Fining up sequence of dominant lithic conglomerate, sandstone, siltstone, claystone and coal with minor tuff and tuffaceous sediments.
				Black Jack Group, Coogal Subgroup	Clare Sandstone	Medium bedded, cross stratified medium to coarse grained quartzose sandstone. Quartzose conglomerate locally developed
					Benelabri Formation	Interbedded organic rich mudstone, siltstone, coal and quartzose sandstone.
					Hoskissons Coal	Coal with subordinate layers of fine grained sandstone, carbonaceous siltstone and claystone, and tuff
				Black Jack Group, Brothers Subgroup	Arkarula Formation	Fining-up sequence from medium grained sandstone with sub-vertical worm burrows to alternating sequences of poorly sorted sandstone and siltstone
					Pamboola Formation	Lithic sandstone, siltstone, claystone, conglomerate and intercalated coals in generally coarsening-up sequences
				Millie Group	Watermark Formation	Bioturbated silty sandstone to siltstone/claystone laminite
					Porcupine Formation	Basal conglomerate passing upward into bioturbated silty sandstone and minor siltstone with dropped pebbles
	270		EARLY	Bellata Group	Maules Creek Formation	Basal carbonaceous claystone, pelletoidal clay sandstone, passing into fining-up cycles of sandstone, siltstone and coal. Conglomerate dominant towards top
					Leard Formation	Buff coloured pelletoidal claystone, conglomerate, sandstone and siltstone
					Werrie Basalt	Basaltic lavas with intervening palaeosols
					Boggabri Volcanics	Felsic to intermediate lavas and ashflow tuffs with interbedded shale.
	298	CARBONIFEROUS			Currububula Formation	Conglomerate, feldspathic and lithic sandstone, siltstone, mudstone and minor limestone. Felsic and intermediate ashflow and airfall tuff.

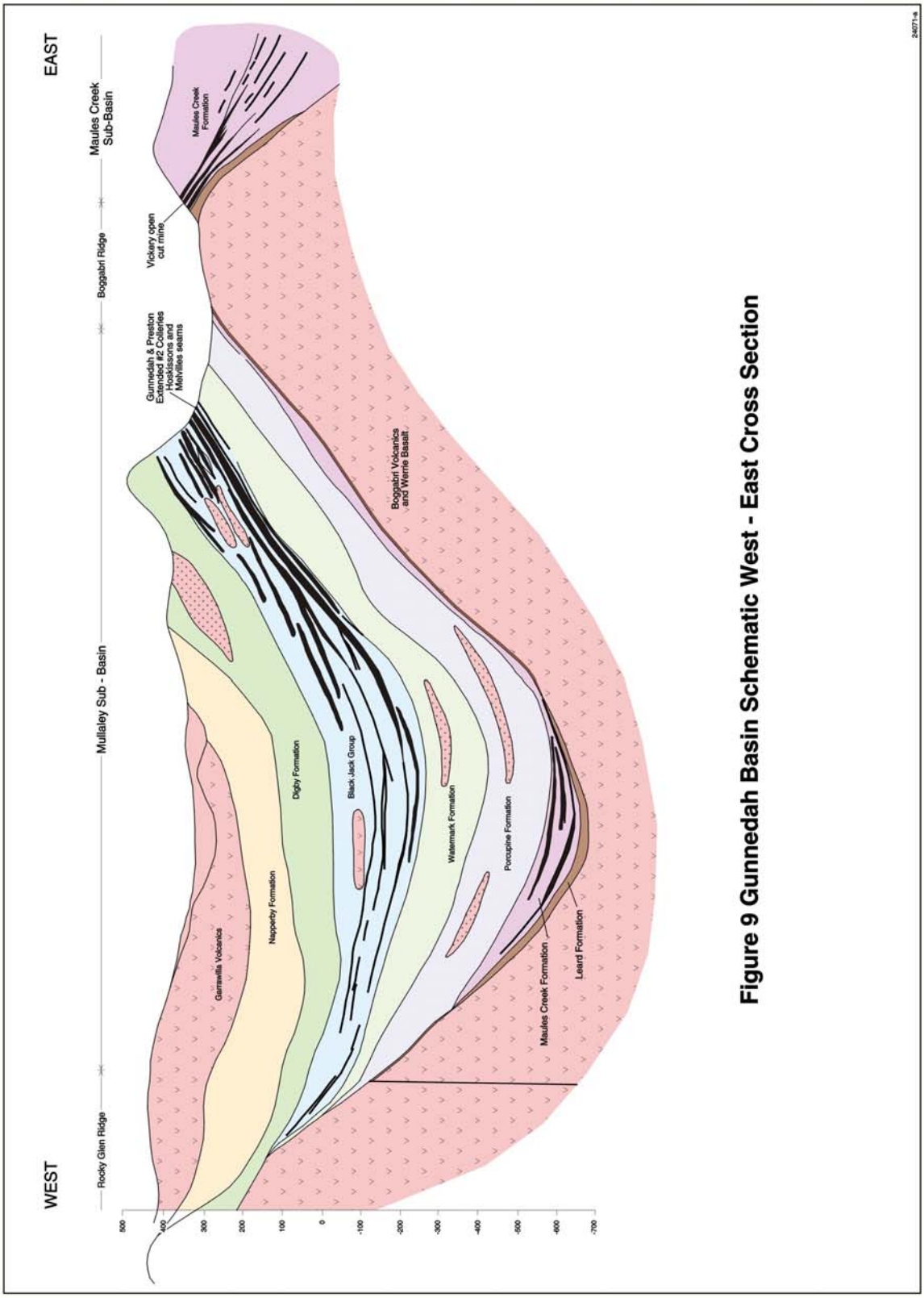


Figure 9 Gunnedah Basin Schematic West - East Cross Section

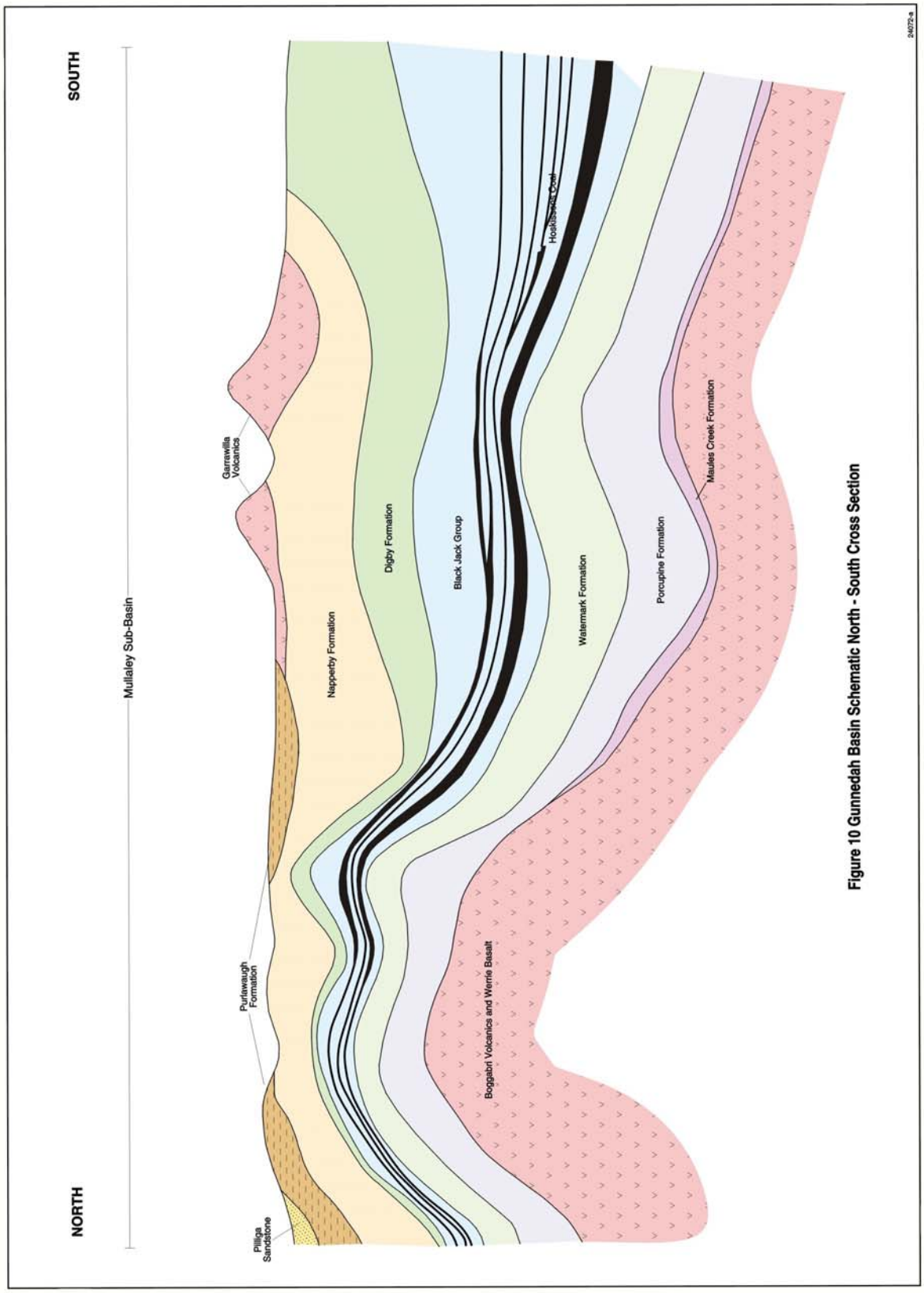


Figure 10 Gunnedah Basin Schematic North - South Cross Section

Maules Creek Formation
The Maules Creek Formation is an important coal-bearing unit. In the Maules Creek Sub-basin, it thickens eastwards to in excess of 800 m and is dominated by conglomerate with lesser amounts of sandstone, siltstone, claystone and coal. In the Mullaley Sub-basin, the formation is generally less than 100 m in thickness and it comprises a northern zone of quartz-rich cratonic sandstones, a central zone of volcanogenic sedimentary rocks derived from the Boggabri Ridge, and a southeastern zone characterised by fine grained sedimentary rocks and coal.

Porcupine Formation
The Porcupine Formation is widespread throughout the Mullaley Sub-basin where it attains a maximum thickness of 170 m. In the central part of the sub-basin, the formation conformably overlies the Maules Creek Formation, while around the Sub-basin margins, the formation unconformably overlies the Werrie Basalt or Boggabri Volcanics. The Porcupine Formation is dominated by conglomerate in the lower part and by silty sandstone in the upper part. The rocks are extensively bioturbated, contain marine fossils and represent a Late Permian marine incursion into the Gunnedah Basin.

Watermark Formation
The Watermark Formation overlies the Porcupine Formation with a gradational boundary and attains a maximum thickness of 230 m. This marine formation comprises siltstone, claystone, silty sandstone and laminites. The rocks weather readily and outcrop is rare. The Watermark Formation exhibits extensive bioturbation, consistent with its marine and deltaic origins.

Black Jack Group
The Black Jack Group is widely distributed throughout the Mullaley Sub-basin and conformably overlies the Watermark Formation. This Late Permian sequence consists of lithic sandstone, quartzose sandstone, siltstone, conglomerate, tuff and coal. The Black Jack Group averages 200 m in thickness over the Mullaley Sub-basin, thickening from less than 50 m in the west to greater than 470 m in the southeast. In the Caroona area, up to eight coal seams can be recognised in the Black Jack Group, the Melvilles, Hoskissons, Caroona, Howes Hill, Breeza, Clift, Springfield and Doona seams. The Black Jack Group consists of three Sub-groups: the Brothers, Coogal and Nea Sub-groups.

Pamboola Formation
The Pamboola Formation ranges in thickness up to 206 m in the southeast and up to 89 m in the north. The Pamboola Formation comprises mainly lithic sandstone, siltstone, claystone, conglomerate, and intercalated coals, in generally upward coarsening and sporadic upward-fining sequences. Sediments of the Pamboola Formation represent deposition of the subaerial component of a major delta system, mainly from distributary channels and crevasse splays and in interdistributary bay, lagoon and marsh areas of the lower delta plain environment with deposition accompanied by favourable peat-forming conditions.

Arkarula Formation
The Arkarula Formation overlies the Pamboola Formation in the east and consists of burrowed silty sandstone. It extends over the central and south central parts of the Mullaley Sub-basin and attains a thickness of 51 m in the north of the Mullaley Sub-basin. The Formation consists of an upward fining sequence of fine to medium grained lithic sandstones characterised by very distinctive sub-vertical mud-lined worm burrows and sporadic zones of very coarse detritus. Sediments of the Arkarula Formation have been interpreted as a wave dominated delta system, a southern component of the basin wide Arkarula shallow marine system, and consisting of barrier-beach, near shore sands and lagoonal deposits.

Brigalow Formation
The Brigalow Formation overlies the Pamboola Formation in the west and consists of medium to coarse grained and pebbly quartz rich sandstone. It ranges up to 28 m in thickness. The formation has an overall fining-upward character and consists of mainly medium and coarse-grained to pebbly, medium bedded quartzose sandstone with minor fine-grained sandstone finely interbedded with siltstone and carbonaceous siltstone. The Brigalow Formation sediments were deposited by easterly and southeasterly flowing bed-load channel systems that emanated from the Lachlan Fold Belt in the West.

Hoskissons Coal
The Hoskissons Coal is the major economic seam in the Mullaley Sub-basin. It extends over much of the Mullaley Sub-basin from just north of Narrabri to Quirindi in the southeast and Coonabarabran in the

West. The thickness of the Coal ranges from less than 1 m in the west, to more than 12 m in the north and to approximately 18 m in the southeast.

The Hoskissons Coal maintains a consistent lithotype profile over the basin, consisting mainly of vitrinite-poor, inertinite-rich dull coal with minor layers of fine-grained sandstone, carbonaceous siltstone/claystone and tuff. It represents a significant period of negligible deposition of terrigenous clastics. Peat accumulated in vast swamps that developed on the extensive plain formed by marine regression. Westerly sourced quartzose channel fills disrupted peat accumulation along the western margin of the sub-basin. The Hoskissons Coal is overlain in the east and central part of the Mullaley Sub-basin by the Benelabri Formation and, in the west, by the Clare Sandstone.

Benelabri Formation
The Benelabri Formation is dominated by organic-rich mudstone. It is present over much of the eastern part of the Mullaley Sub-basin from Turrawan near Narrabri in the north, to west of Caroona in the south, except for a 10 km-15 km wide south easterly trending zone between Gunnedah and Quirindi. The formation averages 20 m-30 m in thickness and reaches 35 m in the north and is up to 68 m thick in the Caroona area. Sediments of the Benelabri Formation are thought to have their origin in a large lake system that extended over the eastern half of the Mullaley Sub-basin.

Clare Sandstone
The Clare Sandstone consists of up to 86 m of medium to coarse grained quartz rich sandstone with quartz conglomerate locally developed. It crops out as a cliff-forming unit in the Breeza to Curlewis area and is recognised in the subsurface from Narrabri to Quirindi, and westwards to the east of Coonabarabran. The sediments of the Clare Sandstone were deposited mainly by an easterly and southeasterly flowing bedload channel system that emanated from the Lachlan Fold Belt.

Wallala Formation
The Wallala Formation comprises beds up to 5 m thick of lithic conglomerate interbedded with subordinate thin beds of sandstone, siltstone, claystone and coal, with only minor amounts of tuff and tuffaceous sediments. The sediments were derived from the New England Fold Belt by westerly and southwesterly flowing braid channels.

Trinkey Formation
The Trinkey Formation is dominated by finely bedded claystone, siltstone and fine grained sandstone, interbedded with tuff, tuffaceous sediments and abundant coal. The unit reaches a thickness of 258 m in the southeast around Quirindi, and extends over much of the Mullaley Sub-basin. Sediments were derived from the New England Fold Belt and deposited over much of the Mullaley Sub-basin by mixed-load streams in point bars, levees, crevasse splays and as suspended-load in back swamp areas. Tuff and tuffaceous sediments were derived from tephra ejected contemporaneously from volcanoes in the New England region.

Digby Formation
The Early Triassic Digby Formation unconformably overlies the Black Jack Group in the Mullaley Sub-basin, and the Maules Creek Formation in the Maules Creek Sub-basin, where the Black Jack Group has been eroded away. The Formation ranges up to 204 m in thickness and consists of two members, the basal Bomera Conglomerate Member and the overlying Wollar/Ulinda Sandstone Member.

The Bomera Conglomerate Member comprises lithic clast-supported pebble conglomerate with subordinate lithic sandstone, generally in the upper part. The member is a lithostratigraphic correlative of the Munmorah and Widden Brook Conglomerates in the lower part of the Narrabeen Group of the Sydney Basin.

The Wollar Sandstone Member attains a thickness in excess of 100 m south of Spring Ridge and thins northwards to its northern limit near Boggabri. The member comprises mainly quartzose sandstone with subordinate quartzose conglomerate, and claystone. The top of the member is marked by a basin-wide mudstone horizon, a palaeosol, a few centimetres to a metre thick.

Napperby Formation
The Napperby Formation ranges from 30 m to 250 m in thickness, and is present over much of the Gunnedah Basin except in the Maules Creek Sub-basin south of the Deriah Forest. The Formation is an

overall coarsening upwards sequence composed of three units. The lowest unit ascends from dark grey silty claystone to laminated and thinly interbedded lithic sandstone. Burrows and bioturbation are common. The middle unit is dominated by dark grey silty claystone, laminite and lithic sandstone but towards the northeast the unit consists mainly of small coarsening upwards sequences of claystone to lithic sandstone. Burrows and bioturbation are again common in this unit. The upper unit consists mainly of off-white lithic sandstone, with claystone paleosols becoming common at the top of the unit.

Deriah Formation
The late Middle Triassic age Deriah Formation ranges in thickness from 5 m in the west to 160 m in the north. The lower part of the Formation consists dominantly of fine to medium grained green lithic sandstone rich in volcanic fragments, while the upper part consists of off-white lithic sandstone and dark grey to grey-brown mudstone with minor plant rootlets and coaly layers.

3.5.5 Structure

The major folds and faults in the Gunnedah Basin are presented in Figure 11. The most significant fault within the Basin is the Boggabri Thrust that is located mostly within the Boggabri Volcanics of the Boggabri Ridge and approximately underlies the Namoi River between Gunnedah and Narrabri. This fault raises the Maules Creek Sub-basin strata several hundred metres higher than equivalent strata in the Mullaley Sub-basin. Erosion associated with the deposition of the Triassic Digby Formation has removed much of Black Jack Group at its unconformable contact west of Boggabri in the Mullaley Sub-basin, and may have removed almost all of the strata, including the Black Jack Group above the Maules Creek Formation in the Maules Creek Sub-basin.

In the Maules Creek Sub-basin, faulting is generally orientated in a north-northwest direction, such as the Karu and Whitehaven Faults in the Vickery area, or southwest such as the Driggle Draggle Fault also in the Vickery area. The latter trend is strongly evident in the aeromagnetic data of the sub-basin and this trend often extends well into the Mooki Thrust Fault to the east, and possibly across the Boggabri Ridge and into the Benelabri area of the Mullaley Sub-basin to the west.

In the Mullaley Sub-basin, several minor folds have been identified in the region from Willow Tree northwest towards Mullaley and Gunnedah. These include the south to southwest plunging New Windy, Caroona, Tribella, Watermark and Curlewis Anticlines and associated synclines, and the northwest trending Milroy and Mirrabooka Anticlines and associated synclines. These structures were identified from surface mapping, air photo interpretation, seismic and gravity surveys and from borehole data. Further drilling in the Breeza area identified the Nea and Clift Anticlines and the Springhurst Dome. It is probable that most of the structures to the west and south of Curlewis are created by underlying intrusions.

The southerly plunging Watermark Anticline is the largest anticlinal structure exposed at the surface. Its limbs dip at less than 8 degrees and are composed of the more resistant sediments of the Black Jack Group while its core is composed of the more readily eroded silty Watermark Formation.

Although the folding is gentle, the most significantly folded area lies south of the intersection of the Boggabri Thrust with the Mooki Thrust. This point, near Piallaway, also approximates the intersection of the Kelvin Thrust with the Mooki Thrust, and the sudden change to an easterly strike. It is considered that the Boggabri Ridge protected the Permian sediments of the Mullaley Sub-basin from the folding and faulting that accompanied the Mooki thrusting, and that crustal shortening was accommodated by movements on the Kelvin, Mooki and Boggabri Thrusts. Recent work by the Department of Mineral Resources has identified several west-north-westerly trending faults in the area of the Tribella, Caroona and New Windy Anticlines.

A detailed geophysical study by the Department of Mineral Resources and NEDO (New Energy Development Organisation) of a small area between Caroona and Breeza has revealed a pattern of minor northeast and northwest striking faults. Recent airborne survey and drilling data suggest that there may be some major structural disturbance in the Pine Ridge area.

3.5.6 Volcanic Activity

There are three main periods of volcanic activity in the Gunnedah Basin following emplacement of the Early Permian basal volcanics. They are, the Late Triassic to Early Cretaceous Garrawilla Volcanics, the

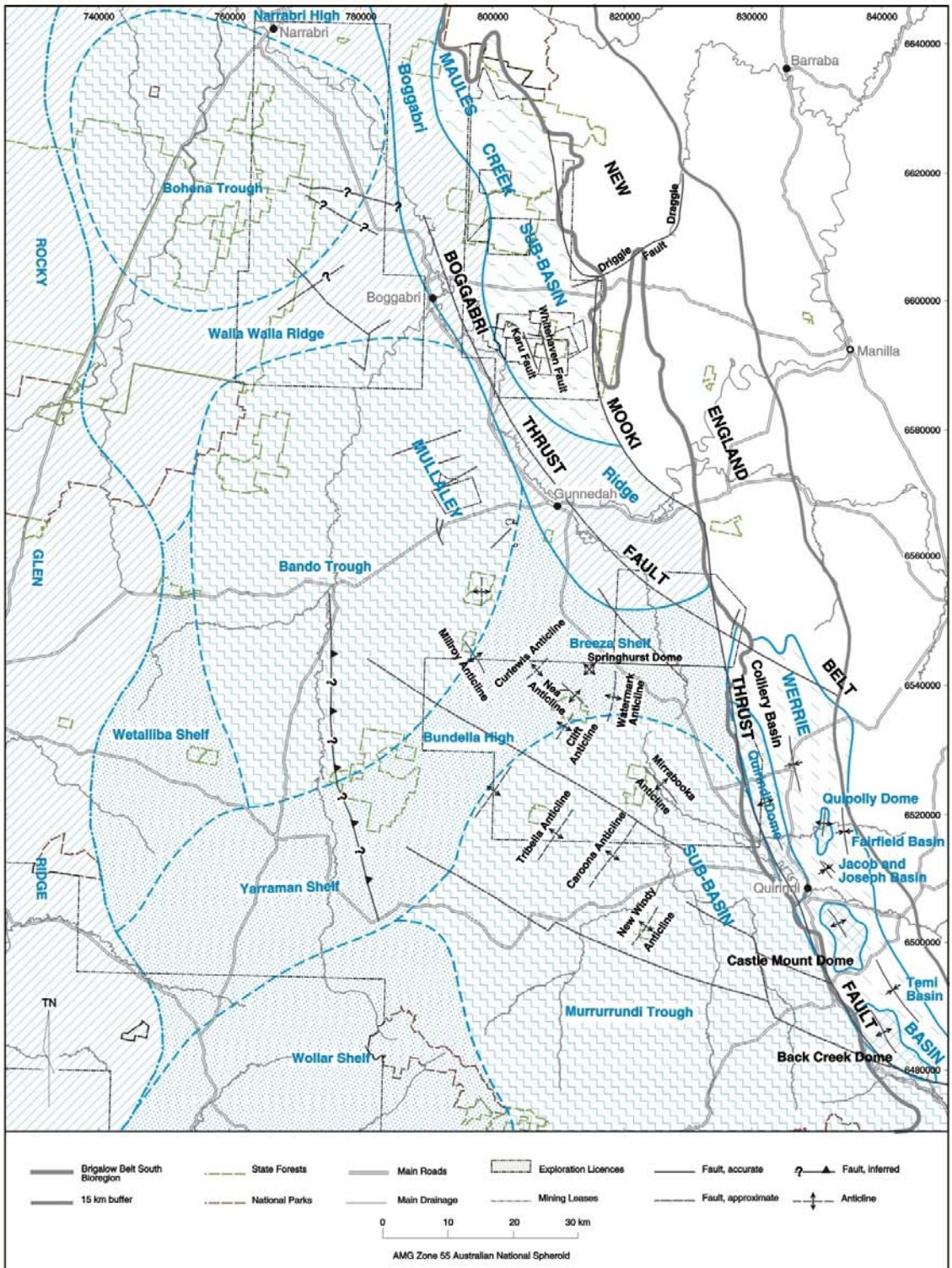


Figure 11 Gunnedah and Werrie Basins Structure

Tertiary (Eocene) Liverpool Range Volcanic Province, and the Tertiary (Miocene) Nandewar Volcanic Complex.

The Garrawilla Volcanics

The Garrawilla Volcanics were emplaced in the late Triassic in the area to the east of Narrabri, from at least 218 Ma and continued with regular activity, although in widely separated areas, for at least the next 99 Ma, to the Early Cretaceous. The Garrawilla Volcanics are part of a more widespread volcanic event which extends through much of Eastern Australia and indeed through all continents in the southern hemisphere, in association with the breakup of Gondwana (Veevers 2000).

The Garrawilla Volcanics includes two recognised and sometimes contemporaneous units: the Glenrowan Intrusives and the Bulga Complex. The volcanics usually disconformably overlie Triassic rocks of the Deriah or Napperby Formations, in places with a widespread basal bed of finely bedded unlithified volcanic ash and lapilli. The Garrawilla Volcanics, where not exposed at the surface, are overlain by sedimentary units of the Surat Basin, the Purlewaugh Formation in the lower part of the Garrawilla topography, and the Pilliga Sandstone in the more elevated parts.

The Glenrowan Intrusives appear less widespread both temporally and spatially than the Garrawilla Volcanics. The known intrusives are confined to the area between Gunnedah and Mullaley and were probably intruded over a period of about 10 Ma from 180 Ma to 170 Ma. The distribution and aggregate thickness of intrusions intersected in boreholes through Permian strata in the Gunnedah Basin indicates that the most intensely intruded area with greater than 50 m aggregate thickness of intruded rocks occurs in a 60 km diameter area with Gunnedah on the north-eastern perimeter.

The Bulga Complex appears to be restricted both temporally and spatially. The complex is located mostly to the south and west of Mullaley and was emplaced over a period of about 21 Ma from 170 Ma to 149 Ma. Residuals of massive flows and lava domes of felsic rocks form prominent topographical features in the area. Sills and volcanic plugs are minor constituents of the complex. The lava domes are regarded as the product of slow eruption of viscous lava from central vents.

The Liverpool Range Volcanic Province

The Tertiary Liverpool Range Volcanic Province forms the Liverpool Range, the largest volcanic province in New South Wales. It adjoins the early Eocene Mount Royal Range to the east and the mid-Miocene Warrumbungle Range to the west.

The Liverpool Range Volcanic Province comprises predominantly mafic lavas, with a surprisingly small range in rock compositions, together with minor interbedded conglomerate, quartzose sandstone and shale. A thickness in excess of 500 m of flat lying interbedded lavas and pyroclastics is exposed at the western end of the Liverpool Range near the headwaters of Coxs Creek.

The Liverpool Range forms a topographical and lithological surface boundary to the Gunnedah Basin and also separates the nomenclature of the Gunnedah and Hunter Coalfields. There is an abrupt change in topography from a highly dissected spine or ridge in the eastern part to a broader plateau with only marginal dissection in the western part. Considering the topographic, age, and minor geochemical differences between the two parts, two distinct volcanic sources may have existed in the east and the west.

The Nandewar Volcanic Complex

The lower Miocene Nandewar Volcanic Complex is located astride the Mooki Fault, east and northeast of Narrabri. It forms both part of the Nandewar Range and the northeastern boundary of the Gunnedah Basin. The Nandewar Volcanic Complex is the remnants of an originally low-angled shield volcano with stratiform flanks surrounding two complex centralised systems of eruptive vents. They are, the Killarney Gap volcano (21–20 Ma) and the Mount Kaputar volcano (17–16 Ma). The complex is now a mature erosional caldera with dykes, plugs, sills, and domes of felsic rocks exposed. Unlike the lava fields of the Liverpool Ranges, there is a considerable range of igneous lithologies and morphologies present in this shield volcano complex.

3.6 GEOLOGY OF THE GILGANDRA SUB-BASIN

3.6.1 Introduction

The Gilgandra Sub-basin is located to the west of the main part of the Gunnedah Basin (Figure 12). It has a north-south orientation, parallel to and west of the Rocky Glen Ridge, and extends from the Cobar-Inglewood Lineament in the north to Mudgee in the south. It contains a thick sequence of Permo-Triassic sediments. Until recently, the relationship between the Sub-basin and the Sydney-Gunnedah Basin was uncertain and poorly known. The results of project work undertaken as part of the BBSB assessment now indicate that it was part of one unified depositional system that was later partially separated from the Gunnedah Basin by uplift and erosion of the Rocky Glen Ridge.

3.6.2 Overview of Basin History

Sedimentation in the Gilgandra Sub-basin was initiated by weathering and erosion of the rocks of the Lachlan Fold Belt. In the Early Permian, grabens developed along existing N-NE trending faults. Where subsidence was sudden, thick alluvial fan wedges accumulated. Where subsidence was slow, meandering streams laid down the thick flood plain deposits of the Cobbora Formation. Further subsidence related to the basin rifting to the east lead to the deposition of the Mirrie Formation by a braid channel system entering into a swamp or lacustrine environment.

In the late Early Permian, there was a period of fluvial sedimentation that resulted in the accumulation of coals of the Maules Creek Formation. In the stable western part of the area, thick coals were deposited in swamps with little sediment input. In the east, coals are thinner and are associated with channel and flood plain deposits. The onset of Late Permian deposition was marked by a marine transgression during which the Porcupine and Watermark formations were deposited. In the southeast, in DM Mirrie DDH1, the marine units are replaced by a fluvial channel system flowing to the north from the Lachlan Fold Belt. One small interval in the top of one channel cycle is bioturbated and was affected by the transgression.

An east-west compressional event caused by the collision with and eventual over thrusting of the New England Fold Belt affected the basin in Late Permian to Early Triassic times. The first evidence of the uplift to the east is the development of deltas in the east of the basin which gradually prograde to the west and southwest across it. The marine parts of the delta form the upper Watermark Formation. Lower and upper delta plain sediments, and the associated coals form the base of the Black Jack Group. Uplift of the Lachlan Fold Belt then resulted in the development of the Brigalow Formation, quartz-rich, braided fluvial sediments that prograde to the east and northeast. The Trinkey Formation sediments were derived from the New England Fold Belt and deposited over much of the Mullaley Sub-basin by mixed-load streams in point bars, levees, crevasse splays and as suspended-load in back swamp areas. Tuff and tuffaceous sediments were derived from tephra ejected contemporaneously from volcanoes in the New England region.

Uplift and erosion of Late Permian units occurred at the end of the Permian on the northern end of the Rocky Glen Ridge, north of the Baradine High, and possibly on other highs further to the west. This was followed by the deposition from the west of the Triassic Wollar Sandstone Member (Digby Formation), an alluvial fan and braided stream deposit. After a period of quiescence, where a basin-wide soil horizon developed, a large lake formed leading to the deposition of the Napperby Formation.

Uplift and erosion marks the boundary between the Triassic and Jurassic. There is evidence of erosional truncation at the base of the Pilliga Sandstone level between Ballimore Hill-2, Soda-1, DM Mirrie DDH1 and DM Pibbon DDH1. Following uplift there was a prolonged period of igneous activity throughout the Jurassic, when the Garrawilla volcanic episode occurred. The volcanics consist of flows, tuffs, domes and various forms of intrusive. The volcanics are overlain by fluvial sediments of the Purlawaugh and Pilliga formations.

The last major geologic event took place in the Tertiary, when the Warrumbungle Volcanic Complex was emplaced. Sills and dykes of Jurassic-Early Cretaceous and Tertiary age have been penetrated by about 50% of the bores drilled in the region.

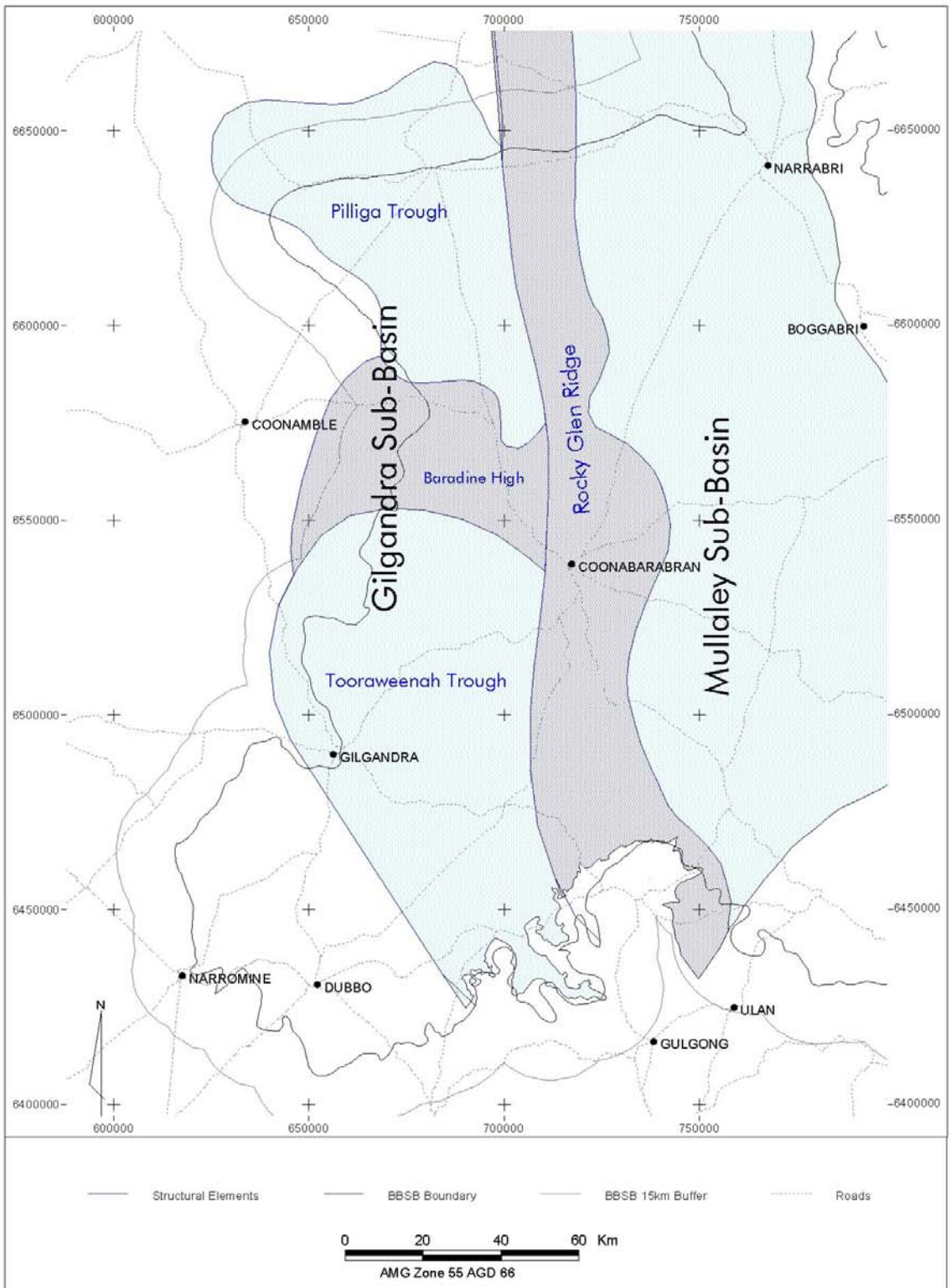


Figure 12. Gilgandra Sub-Basin
Interpreted Major Structural Elements

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3.6.3 Structural Elements

The structural elements of the Gilgandra Sub-Basin are illustrated on Figure 12. These have been compiled from regional gravity coverages, as well as seismic, borehole and surface geology (Yoo, 1988, Tadros, 1993a and 1999, Vanibe, 2000 and 2002b, and Gunn, 2002a).

These structures developed at the end of the Late Carboniferous and Early Permian tectonic event and were reactivated and enhanced by the subsequent tectonic events. They affected depositional patterns and they comprise the principal controls on depositional style, structuring and lithofacies. A brief description of each of the principal elements follows.

The Tooraweenah Trough

The Tooraweenah Trough is bounded by the Baradine High in the north and the Rocky Glen Ridge in the east, having an area of some 2300 km ^{2}. It closely follows a strong aeromagnetic high. The western boundary is overlain by the Surat Basin and is not clearly defined. The magnetic data indicates a gradual decrease in depths to the Lachlan Fold Belt across the western portion of the area. The Warrumbungle Range occurs over the northern part of the Trough.

Rocks of the Lachlan Fold Belt form the basement of the Trough. In the south at Cobbora and Yarindury, Early Permian sediments, older than the earliest known to the east, were deposited in grabens formed by north-south fault systems. Gunn (2002a) confirmed the broad shallow nature of the Trough, and the probable presence of other grabens within it.

The results of the drilling of DM Goonoo DDH1 indicate that the Tooraweenah Trough and the Mullaley Sub-Basin formed a unified depositional system during the Permian until partially separated by uplift of the Rocky Glen Ridge.

Rocky Glen Ridge

The Rocky Glen Ridge is a meridionally trending basement high which separates the Pilliga and Tooraweenah Troughs in the west, from the Bohena and Bando Troughs in the east. The Ridge is interpreted to comprise shallow basement of Ordovician to Carboniferous metasedimentary rocks, Carboniferous and inferred Devonian granites and volcanic rocks. Aeromagnetic and gravity data coverages confirm that it is coincident with the western edge of the Werri Basalt and Boggabri Volcanics in the Gunnedah basin. The southern termination of the Rocky Glen Ridge coincides with a northwest trending fault system along which the Liverpool Range Volcanics are developed.

Two boreholes have been drilled into the northern part the Rocky Glen Ridge. DM Arrarownie DDH1 and DM Hall DDH1 did not penetrate Permian sediments, as both terminated in volcanics below the Triassic strata. DM Worigal DDH1, located 10 km to the west of DM Hall DDH1, intersected 40m of Late Permian coal measure sediments below the Triassic strata.

It is likely that the Rocky Glen Ridge was reactivated during periods of compression in the Late Permian, Triassic and possibly the Tertiary, resulting in its having acted both as a depositional barrier as well as having been subject to cycles of erosional truncation.

The Pilliga Trough

The Pilliga Trough forms the northern part of the Gilgandra Sub-Basin and coincides with a negative gravity anomaly of 40 to 50 milligals. A stratigraphic borehole DM Drildool DDH1A, drilled on the shallow north-eastern portion of the Pilliga Trough, was terminated at 222m in the middle of the Cretaceous Bungil Formation. To check the negative anomaly, the NSW DMR Gurley (Moree) seismic survey was conducted in 1996 with two lines shot in the northern part of the Pilliga Trough. From the seismic data it became apparent that the sedimentary section was very thin with little or no indications of the expected deeper features predicted by the magnetic data. Apart from that information, the Pilliga Trough is still largely unknown.

Baradine High

The Baradine High is a basement high separating the Gilgandra Sub-Basin into the northern Pilliga Trough and the southern Tooraweenah Trough. Gravity data indicates that the eastern portion of the Baradine High coincides with a positive anomaly, where basement depths lie in the range of 100 to 100 m below sea level. Little more is known of this structure.

3.6.4 Stratigraphy

A summary of the stratigraphic sequence of rock units, their ages and lithologies is presented in table 3.

Pre-Permian Basement

Siluro-Devonian and Ordovician metasedimentary and volcanic rocks of the Lachlan Fold Belt, intruded by Carboniferous and inferred Devonian granitic rocks, form much of the basement underneath the Tooraweenah Trough. Outcrops of Palaeozoic talcose schist, phyllite and slate are present to the north of Coonabarabran and represent the exposed part of the Rocky Glen Ridge. Ignimbritic volcanic rocks were intersected at the base of DM Arrarownie DDH1 northeast of Coonabarabran. Metasedimentary rocks consisting of laminated pale-grey and black phyllite and schist were intersected in DM Worigal DDH1. DM Hall DDH1 intersected 40m of light green, strongly altered agglomerate followed by 15m of acid volcanic rocks. Oil exploration wells AMOSEAS Baradine West 1 and 2 intersected similar low grade rocks described as “indurated sandstone, siltstone and shale” and “slate” respectively. In DM Goonoo DDH1 the basement rocks intersected were 12m of phyllite and metamorphosed, quartz-veined sandstone interbedded with siltstone (light green schist facies). The age of these rocks is thought to be Early Middle Devonian. Palaeozoic basement rocks were also encountered in CRA exploration drillholes. In RC96CC015 situated in the Cobbora graben, the basement was represented by 23m of schist; in RDPD98YY02 situated in the Yarindury graben, Ordovician volcanics of the Oakdale Formation were intersected. In Soda-3, 6m of “basaltic volcanics and some altered metasediments” were intersected.

Cobbora Formation (New Name)

Early Permian sediments of the Cobbora Formation have been recorded in Soda–3, and CRA boreholes in the Cobbora-Yarindury area. Palynological dating indicates that the sediments are older than the Maules Creek Formation and equivalent (APP 2) to the Reids Dome Beds of the Denison Trough in Queensland (CRA, 1998).

TABLE 3: GILGANDRA SUB- BASIN AND OVERLYING STRATIGRAPHY

Basin	Years (Ma)	Period		Stratigraphy: Group	Stratigraphy: Formation	Lithology
	2	QUATERNARY			undifferentiated sediments	Undifferentiated alluvial deposits of gravel,sand, silt and clay.
		TERTIARY			Warrumbungle Volcanic Complex	Felsic, intermediate and mafic sills, dykes, plugs and flows
	65	CRETACEOUS				
Surat Basin Units	141	JURASSIC			Orallo Formation	Clayey sandstone with interbedded siltstone and mudstone
					Pilliga Sandstone	Quartz pebble and quartzose sandstone with minor siltstone
					Purlawaugh Formation	Thinly bedded lithicsandstone interbedded with siltstone and mudstone
	205				Garrawilla Volcanics	Basaltic lavas and pyroclastics
Gunnedah Basin Units		TRIASSIC	MIDDLE		Napperby Formation	Coarsening-up sequences of dark-grey siltstone/sandstone laminite overlain by parallel bedded or low-angle crossbedded quartzose sandstone
			EARLY		Digby Formation	Poorly sorted volcanic-lithic pebble conglomerate overlain by coarse to fine grained quartz-lithic and then quartzose sandstone
	251	PERMIAN	LATE	Black Jack Group, Nea Subgroup	Trinkey Formation	Claystone, siltstone and fine grained sandstone intercalated with tuff, carbonaceous claystones and tuffaceous stoney coal seams
					Wallala Formation	Fining up sequence of dominant lithic conglomerate, sandstone, siltstone, claystone and coal with minor tuff and tuffaceous sediments.
				Black Jack Group, Coogal Subgroup	Clare Sandstone	Medium bedded, cross stratified medium to coarse grained quartzose sandstone. Quartzose conglomerate locally developed
					Benelabri Formation	Interbedded organic rich mudstone, siltstone, coal and quartzose sandstone.
					Hoskissons Coal	Coal with subordinate layers of fine grained sandstone, carbonaceous siltstone and claystone, and tuff
				Black Jack Group, Brothers Subgroup	Arkarula Formation	Fining-up sequence from medium grained sandstone with sub-vertical worm burrows to alternating sequences of poorly sorted sandstone and siltstone
					Pamboola Formation	Lithic sandstone, siltstone, claystone, conglomerate and intercalated coals in generally coarsening-up sequences
				Millie Group	Watermark Formation	Bioturbated silty sandstone to siltstone/claystone laminite
					Porcupine Formation	Basal conglomerate passing upward into bioturbated silty sandstone and minor siltstone with dropped pebbles
	270		EARLY		Maules Creek Formation	Basal carbonaceous claystone, pelletoidal clay sandstone, passing into fining-up cycles of sandstone, siltstone and coal. Conglomerate dominant towards top
					Mirrie Formation	Pebble conglomerate with carbonaceous claystone matrix
					Goondi Formation	Colluvial/alluvial deposits from weathering of basement metasedimets
					Cobbora Formation	Conglomerate, breccias, arcose sandstone, coaly siltstone, mudstone
	298	PRE-CARBONIFEROUS			Lachlan Fold Belt	Phyllite, slate, schist, ignimbritic volcanic and metasedimentary rocks

Soda-3 intersected an Early Permian section 184 m thick comprising conglomerate, pebble, cobble fan conglomerates and breccias which may indicate proximity to basement surface. This section was probably deposited at the neck of an alluvial fan in a high relief environment. An east-west seismic survey carried out over the hole indicates a fault zone (the "Kalonga Fault") beneath the drill hole, upthrown to the east. The fault is considered to have been active during the deposition of the Early Permian sequence. If this is so, then the Kalonga Fault could be correlated with the Early Permian extensional tectonics which caused the generation of grabens and half grabens in the other parts of the Sydney- Bowen Basin.

In the Cobbora area, the Formation is over 234 m thick, and comprises two siltstone and claystone flood plain sequences separated by a meandering fluvial sandstone channel sequence. In the Yarindury Graben, it is over 407 m thick, and comprises arkose sandstone, carbonaceous/coaly siltstone and mudstone.

Goondi Formation (New Name)

The Goondi Formation is a colluvial/alluvial deposit derived mainly from weathering of the basement rocks. It is the direct equivalent of the Leard Formation that forms a discontinuous veneer on the basement volcanic units further to the east. In DM Goonoo DDH1, this formation comprises 2.8 m of subangular broken pieces of basement metasediments in a light grey sandstone matrix. The clasts have tabular shape and bimodal sorting.

Mirrie Formation (New Name)
Mirrie Formation sediments were intersected at the base of DM Mirrie DDH 1, and conformably above the Goondi Formation in DM Goonoo DDH1. They comprise 7 m of pebbly conglomerate in a black carbonaceous claystone matrix. The clasts of conglomerate were formed from the basement metasediments and are off-white to grey, subangular to subrounded, poorly sorted, siliceous and have equant shape. The matrix is formed from organic rich swamp or lake sediments.

Maules Creek Formation
Maules Creek Formation sediments were encountered in DM Goonoo DDH1. They comprise a 23 m section of interbedded sandstone, claystone, siltstone, conglomerate and coal. The conglomerate is lithic, pebbly, sandy in parts, and poorly sorted. The Siltstones are grey to dark grey, partly carbonaceous, and laminated. The Claystones are dark grey and usually carbonaceous. Three coal seams greater than 1.7m in thickness were encountered below 381 m. The Coal is dull lustrous and dull, with minor bright bands, sometimes interbedded with claystone and sandstone. DM Mirrie DDH1 intersected a 25 m thick section of mudstone, carbonaceous claystone, sandstone and coal.

Porcupine Formation
The Porcupine Formation was intersected in DM Goonoo DDH1 conformably overlying the Maules Creek Formation. It consists of strongly bioturbated silty lithic sandstone and siltstone with “dropped pebbles”.

Watermark Formation
The Watermark Formation has only been recognised in DM Goonoo DDH 1. It comprises a thin sequence of laminated Siltstone interbedded with sandstone and claystone.

In DM Mirrie DDH1, the Watermark Formation is replaced by a sequence of medium to coarse-grained and pebbly quartzose sandstone with subordinate claystone and carbonaceous claystone. The sequence is a series of fining-upward fluvial channel cycles. A band of mudstone at the top of one of the cycles contains acritarchs, abundant worm burrows and bioturbation. Below this band the sandstones are sparsely pyritic, indicating a short marine/brackish transgression. This layer is a lateral equivalent to the Watermark Formation.

Black Jack Group
The Black Jack Group crops out along the flank of the basement high from north of Dunedoo to east of Saxa. It appears to dip gently toward the northwest, and is assumed to extend at least as far west as the Ballimore – Biddon area. Coal has been found in outcrop on the western side of the Warrumbungles. The best developed Late Permian coal outcrop is situated at the junction of Laheys Creek and Sandy Creek where a 1.5 m thick coal seam is exposed.

Pamboola Formation
The Pamboola Formation is absent in DM Pibbon DDH1 and DM Goonoo DDH1 but is 20 m thick in DM Mirrie DDH 1. It is likely that the formation thickens towards the Mullaley Sub-Basin in the east. The Formation comprises mainly lithic sandstone, siltstone, claystone, conglomerate, and intercalated coals in generally upward coarsening and sporadic upward-fining sequences. The sediments were deposited from distributary channels and crevasse splays into interdistributary bay, lagoon and marsh areas of the lower delta plain environment, with deposition accompanied by favourable peat-forming conditions.

Brigalow Formation
The Brigalow Formation overlies the Pamboola Formation in the west, and consists of medium to coarse grained and pebbly quartz rich sandstone. It is 4 m thick in DM Goonoo DDH1 and consists of light grey sandstone. The formation has an overall fining-upward character and was deposited by easterly and southeasterly flowing bed-load channel system that emanated from the Lachlan Fold Belt.

Hoskissons Coal
The Hoskissons Coal in DM Mirrie DDH1 comprises 2.4 m of dull coal. DM Pibbon DDH1 intersected two seams with thicknesses of 2.4 m and 2.6 m, at depths of 557.6 m and 563.80 m respectively. These seams are tentatively correlated with the Hoskissons Coal. In DM Goonoo DDH1, the coal is absent, replaced by quartz sandstones.

Clare Sandstone
The Clare Sandstone comprises medium to coarse grained quartz rich sandstone with quartz conglomerate locally developed. The sediments of the Clare Sandstone were deposited mainly by an easterly and

southeasterly flowing bedload channel system. The unit reaches a thickness of 2 m in DM Mirrie DDH 1, 4m in DM Pibbon DDH 1, and 10 m in DM Goonoo DDH 1.

Wallala Formation
The Wallala Formation comprises thin beds of lithic sandstone, siltstone, claystone and coal, with only minor amounts of tuff and tuffaceous sediments. Sediments were derived from the New England Fold Belt by a westerly and southwesterly flowing fluvial system.

Trinkey Formation
The Trinkey Formation is dominated by finely bedded claystone, siltstone and fine grained sandstone, interbedded with tuff, tuffaceous sediments and abundant coal. The unit reaches a thickness of 20 m in DM Mirrie DDH 1 and 21 m in DM Pibbon DDH 1. Sediments were derived from the New England Fold Belt and deposited by mixed-load streams in point bars, levees, crevasse splays and as suspended-load in back swamp areas. Tuff and tuffaceous sediments were derived from tephra ejected contemporaneously from volcanoes in the New England region.

Digby Formation
Outcrops of the Digby Formation and its equivalents are present in the southwest of the Binnaway – Wollar area of the Gunnedah Basin. It is also reasonably well exposed along the southern edge of the Trough. This unit overlies the Black Jack Formation with a significant regional unconformity, which reflects the renewed tectonism in the New England Fold Belt. It is conformably overlain by the Napperby Formation. The Digby Formation was deposited by a fluvial system and braided channel sandstone deposits are common.

The Digby Formation can be divided into three units, a conglomerate facies at the base, a quartz lithic sandstone facies in the middle, and a quartzose sandstone facies at the top, the Wollar Sandstone Member. The quartz content increases up the sequence and quartz becomes dominant and better sorted in the upper part. The Digby Formation is thinner on the west of the Rocky Glen Ridge than it is in the east.

The Wollar Sandstone Member is 20 m thick southwest of Mendooran, and the conglomerate and sandstone facies are absent. In DM Pibbon DDH1, DM Mirrie DDH1, and DM Goonoo DDH 1, the three facies are present and the unit is 50 m thick, 20 m thick and 20 m thick respectively.

Napperby Formation
The Napperby Formation conformably overlies the Wollar Sandstone Member. The top of the Formation is marked by a regional unconformity with overlying units either of the Garrawilla volcanics or the Purlawaugh Formation of the Surat Basin. The Napperby Formation is well developed west of the Rocky Glen Ridge with a maximum thickness of 193 m northwest of Coonabarabran, thinning to 89 m towards the southern margin. In DM Pibbon DDH1 the unit is 181m thick and is intruded by a dolerite sill. In DM Mirrie DDH1, the Napperby Formation is 91 metres and in DM Goonoo DDH1 it is 122 m thick. The Napperby Formation can be subdivided into three facies, a very finely laminated dark grey claystone at the base, a finely banded siltstone and sandstone laminae in the middle, and lithic sandstone interbedded with bioturbated siltstone at the top.

Jurassic Units
Between the Triassic and Jurassic, uplift and erosion took place, followed by a period of igneous activity resulting in the widespread deposition of the Garrawilla Volcanics**.** This unit consists of mafic volcanic flows, tuff and various forms of intrusives and volcanoclastics up to 135 m thick. The unit was not intersected in the DM Goonoo DDH1. The Garrawilla Volcanics is overlain by fluvial sediments of either the Purlawaugh Formation or the Pilliga Formation.

Structure

There is limited structural data available for the Gilgandra Sub-Basin. Significant folding and faulting is indicated in recently completed geophysical studies.

3.6.6 Volcanic Activity

During the Early to Middle Jurassic, a series of lavas and other extrusives associated with the Garrawilla Volcanics erupted in the Surat Basin. This unit is represented by a sequence of dark grey sharp based mafic volcanics and dark grey, pelletoidal sharp based claystones. The thickness of this unit increases from 6 m in the southwest to 135 m in DM Pibbon DDH1. Individual flows commonly have weathered tops indicating subaerial exposure for long periods.

The Warrumbungle Volcanic Complex is located in the northern part of the Tooraweenah Trough and represents the eroded remnants of a roughly circular shield volcano (Scheibner 1999). The approximate diameter is 50km, but lavas extruded from this volcano occur much further to the north. Felsic lavas and pyroclastics dominate the central part, with mafic lavas constructing the thin peripheral apron. The central portion has many dykes, plugs and domes of feldspathoid and quarts-bearing trachytes intruding a relatively poor bedded sequence of tuffs and breccias. K/Ar data indicates a range in age of 17 to 13 Ma (Tertiary).

A 48 m thick dolerite sill was intersected in DM Pibbon DDH1. It was probably associated with Jurassic volcanic activity. Petrologically lavas of the Garrawilla Volcanics and the Tertiary volcanics are very similar, both being generally mafic in composition.

Gunn (2002a) and Slater and McEvilly (2001) identified a number of plugs within the Tooraweenah Trough although some of these may be related to the Jurassic to Early Cretaceous Garrawilla Volcanics. Most of the intrusives appear to be concentrated in the eastern portion of the Goonoo area and may be structurally controlled by a crustal lineation, trending west-northwest, along volcanics forming the eastern part of Liverpool Ranges (Upstream Petroleum Consulting Services, 2002B).

3.7 GEOLOGY OF THE NORTHERN HUNTER COALFIELD

3.7.1 Introduction

The Northern Hunter Coalfield extends from Murrurundi to Denman and is that part of the Hunter Coalfield lying north of the Coricudgy Lineament. The area lies within the buffer zone of the BBSB. The Northern Hunter Coalfield is divided into two parts based on stratigraphy and coal resource potential (figure 13). North of Scone there is a low coal resource potential while south of Scone there is a high potential. The surface geology of the Northern Hunter Coalfield is shown on figure 2.

3.7.2 Basin Setting

The basement of the Murrurundi Trough has not been intersected in boreholes so its nature is not certain. Deep boreholes have terminated in mafic lavas of the Early Permian Gyarran Volcanics of the Dalwood Group, a predominantly marine unit. These volcanics are approximate equivalents of the terrestrial Werrie Basalt in the Gunnedah and Werrie Basins.

Overlying the Gyarran Volcanics are the Greta Coal Measures, comprising the Skeletar and Rowan Formations. The Skeletar Formation has lithological similarities to the Leard Formation in the Gunnedah Basin while the Rowan Formation contains economic coal seams that are equivalents of the Maules Creek and Willow Tree Formations in the Gunnedah and Werrie Basins respectively. This coal-forming period was followed, as in the Gunnedah and Werrie Basins, by a marine incursion that deposited the Maitland Group in the Hunter Coalfield. Sedimentation again reverted to a terrestrial mode as the sea retreated and the Late Permian Wittingham and Wollombi Coal Measures were deposited.

North of Aberdeen, the Watts Sandstone, the boundary between the Wittingham and Wollombi Coal Measures, is not developed so that the Hunter Coalfield stratigraphic nomenclature is difficult to apply. A nomenclature exists for the Permian rocks in the structurally complex area between Scone and Blandford where the north-trending Hunter Thrust approaches the east-trending Mooki Thrust. This nomenclature recognises the basal Early Permian terrestrial Temi Formation overlying the Carboniferous basement rocks. The overlying Werrie Volcanics are in turn overlain by the Koogah Formation containing coal seams equivalent to the Greta Coal Measures. A marine incursion followed to deposit the Bickham Formation, an equivalent of the Maitland Group. Reversion to terrestrial sedimentation then deposited the Murulla Beds, equivalent to the Wittingham and Wollombi Coal Measures and the Black Jack Group of the Hunter Coalfield and Gunnedah Basin respectively.

During the Late Permian compressional tectonic event, the Carboniferous and Devonian rocks of the New England Fold Belt were thrust over the Permian strata. A complex system of faults developed in the north probably associated with splays from the Hunter Thrust, and in the south with the Mount Ogilvie Fault

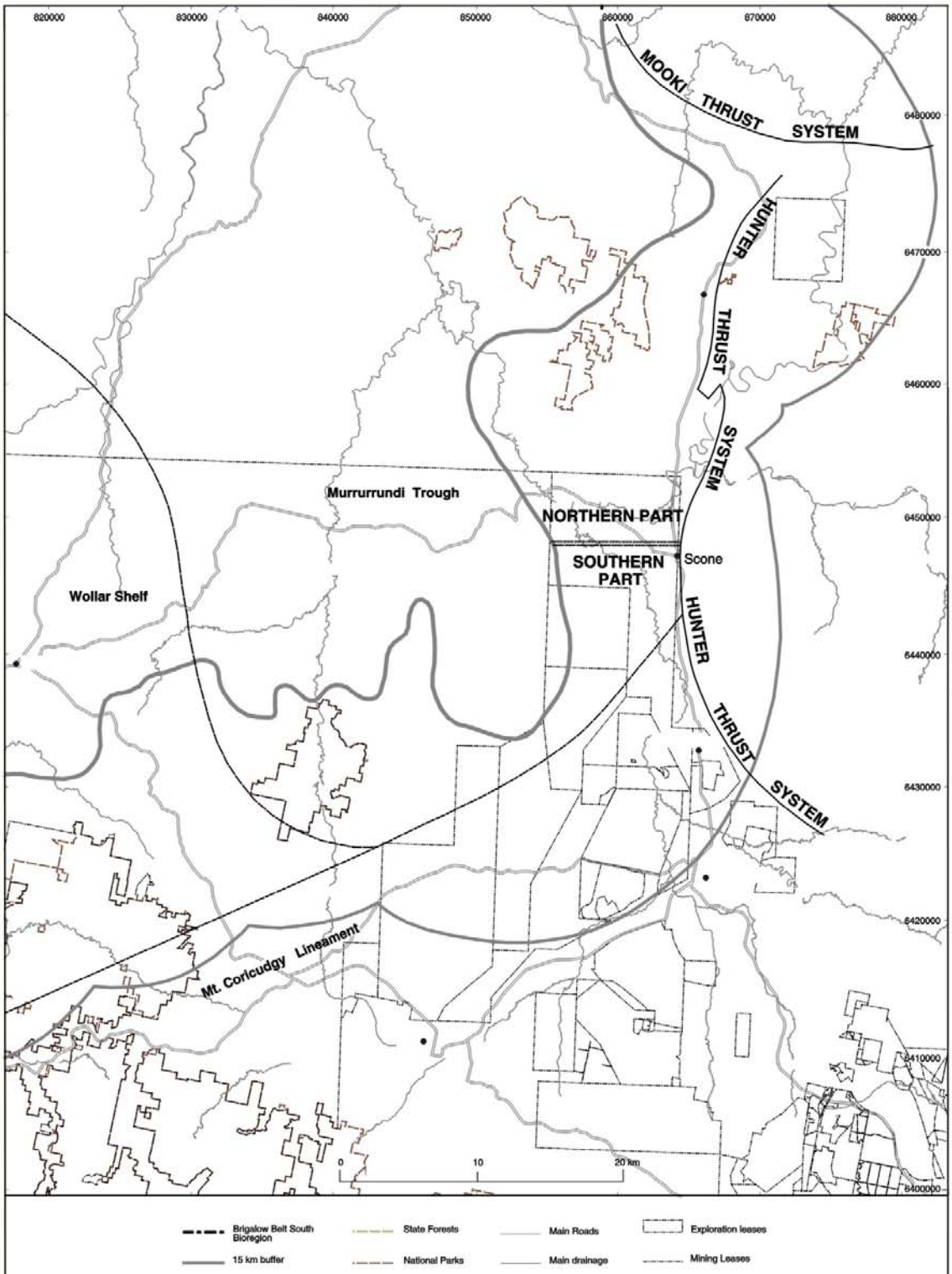

Figure 13 Upper Hunter Coalfield Subdivisions and Structural Elements

AMG Zone 55 Australian National Spheroid

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system. In the area where the Hunter Thrust approaches the Mooki Thrust some localised folding produced the Sandy Creek Syncline. The Early Triassic Narrabeen Group sedimentary rocks were then deposited, as uplift in the New England Fold Belt continued providing the source for these lithic sediments. Sedimentation may have continued through to the Early Cretaceous, after which a major denudation event removed much of the existing sedimentary cover down to the Triassic rocks. During the Tertiary (Eocene) the flood basalt lavas of the Liverpool Range Volcanics were extruded over the land surface.

3.7.3 Structural Elements

The Northern Hunter Coalfield is bounded on the east by the Hunter Thrust, on the north by the Murrurundi Fault, on the west by a geographical line extending north-south to the east of Merriwa, and the south by the Coricudgy Lineament. This area covers the southern half of the Murrurundi Trough, a basement structure of the Gunnedah Basin (figure 13).

3.7.4 Stratigraphy

North of Scone

A summary of the stratigraphic sequence north of Scone, their ages and lithologies is presented in table 4.

Temi Formation
The Temi Formation is comprised of mudstones, sandstones, pebble conglomerate and coaly horizons in places up to 6m thick.

Werrie Volcanics
The base of the Werrie Volcanics consists largely of basaltic pyroclastics and lavas. Higher in the sequence, mafic volcanism gives way to more silicic volcanism, initially lavas, then pyroclastics. Fluvial sediments form minor interbedded components. The lack of redeposited material, the presence of near-vent basaltic pyroclastics, silicic pyroclastics, high level intrusives and rapid lateral and vertical lithological changes, indicate that the Werrie Volcanics near Wingen represents the preserved flanks and core of a dominantly basaltic stratovolcano.

Koogah Formation
The Koogah Formation consists of friable lithic sandstones, shale and coal, and is correlated with the Greta Coal Measures of the Lower Hunter Valley. The formation attains a maximum thickness of approximately 40 m near Mt Wingen and thins northwards, becoming coarser in the same direction. One of the coal seams attains a maximum thickness in excess of 10 m. Coal was once mined at the Bickham Colliery on the banks of the Pages River.

TABLE 4. UPPER HUNTER COALFIELD STRATIGRAPHY – NORTH OF SCONE

Basin	Years (Ma)	Period	Formation	Lithology
UPPER HUNTER COALFIELD		QUATERNARY	Undifferentiated	Undifferentiated alluvial deposits of gravel,sand, silt and clay.
	2	TERTIARY	Liverpool Range Beds	Basaltic lavas and pyroclastics with minor fluviatile sediments
	65	CRETACEOUS		
	141	JURASSIC ?	Murulla sill	Dolerite intrusive
	205	TRIASSIC	Napperby Formation	Coarsening-up sequences of dark-grey siltstone/sandstone laminite overlain by parallel bedded or low-angle crossbedded quartzose sandstone
			Narrabeen Group	Poorly sorted volcanic-lithic pebble conglomerate overlain by coarse to fine grained quartz-lithic sandstone
	251	PERMIAN	Murulla Beds	Lithic sandstone, shale and coal with subordinate conglomerate and limestone
			Bickham Formation	Lithic and feldspathic sandstone with minor conglomerate and shale
			Koogah Formation	Lithic sandstone, shale and coal
			Werri Volcanics	Basaltic to felsic lavas and pyroclastics with minor fluviatile sediments
			Temi Formation	Lithic tuffaceous sandstone with conglomerate lenses and carbonaceous shale
	298	CARBONIFEROUS	Undifferentiated	Conglomerate, feldspathic and lithic sandstone, siltstone, mudstone and minor limestone. Felsic and intermediate ashflow and airfall tuff.

Bickham Formation

In this marine unit, lithic and feldspathic sandstones with abundant carbonate cement are accompanied by shales and occasional polymictic conglomerates. Plant debris are accompanied by abundant marine shell debris in carbonate cemented sandstone. The Bickham Formation is more conglomeratic than the Koogah Formation and also coarsens northward.

Murulla Beds

The topmost Permian coal measure strata, the Murulla Beds, are comprised of predominantly lithic sandstone, shale and coal, with subordinate conglomerate and limestone high in the sequence. Several horizons of coal have been encountered in bores and wells, and one seam has been worked in the Pioneer Coal Syndicate mines near Wingen.

South of Scone

A summary of the stratigraphic sequence south of Scone, their ages and lithologies is presented in table 5.

Undifferentiated Carboniferous

Undifferentiated Upper Carboniferous rocks have been thrust over the Permian rocks by the Hunter Thrust and crop out along the eastern edge of the buffer zone.

Maitland Group

The Maitland Group is the Lowest Permian strata exposed at the surface in the Northern Hunter Coalfield south of Scone, and here it is approximately 300 m in thickness.

The basal Permian Dalwood Group, a marine unit and the overlying Greta Coal Measures do not crop out but have been intersected in boreholes. The Greta Coal Measures are exposed and mined at the surface a few kilometres beyond the buffer zone boundary.

Branxton Formation

The Branxton Formation, the lowest formation in the Maitland Group, crops out east of the Hunter River between Muswellbrook and Aberdeen and is in turn overlain by the Muree Siltstone, the highest formation in the Group. The Branxton Formation typically consists of sandstone, siltstone and conglomerate with some probable ice-rafted detrital clasts. In the Northern Hunter Coalfield the unit is considerable thicker and coarser in the south. East of Aberdeen, the Branxton Formation has been thrust over the Jerrys Plains Subgroup by the Aberdeen Thrust, a splay thrust off the Hunter Thrust.

TABLE 5. UPPER HUNTER COALFIELD STRATIGRAPHY - SOUTH OF SCONE

Basin	Years (Ma)	Period	Group	Sub-group	Formation		Lithology
		QUATERNARY		Undifferentiated			Undifferentiated alluvial deposits of gravel,sand, silt and clay.
	2	TERTIARY	Liverpool Range Beds				Basaltic lavas and pyroclastics with minor fluviatile sediments
	65						
	141	CRETACEOUS					
	205	JURASSIC					
		TRIASSIC		Napperby Formation			Coarsening-up sequences of dark-grey siltstone/sandstone laminite overlain by parallel bedded or low-angle crossbedded quartzose
			Narrabeen Group				Poorly sorted volcanic-lithic pebble conglomerate overlain by coarse to fine grained quartz-lithic and then quartzose sandstone
	251						
UPPER HUNTER COALFIELD		LATE PERMIAN	Wollombi Coal Measures	Glen Gallic Sub-group	Greigs Creek Coal		Durain rich coal
					Redmanvale Creek Formation		Predominantly conglomerate
					Dights Creek Coal	Hillsdale Coal Mbr Naleeen Tuff Hobden Gully Mbr	Durain rich coals separated by tuffaceous claystone
				Doyles Creek Sub-group	Waterfall Gully Formation		Tuffaceous cherty claystone
					Pinegrove Formation	Hambledon Hill Sandstone Wylies Flat Coal Mbr Glengowan Shale	A sequence of shale and sandstone with minor tuffaceous claystone. Contains a vestigial coal member comprising inferior coal plies and bands
				Horseshoe Creek Sub-group	Lucernia Coal	Eyriebower Coal Mbr Longford Creek Siltstone Rombo Coal Mbr Hillsdale Claystone Carramere Coal Mbr	A rich coal-bearing sequence comprising distinctive phases of coal and tuffaceous claystone
					Strathmore Formation		Carbonaceous shale with minor claystone and sandstone
					Alcheringa Coal		A distinctive coal rich sequence with tuffaceous claystone beds
					Clifford Formation		A dominantly sandstone sequencewith minor tuffaceous claystone and vestigial coal beds
				Apple Tree Flat Sub-group	Charlton Formation	Stafford Coal Mbr Monkey Place Tuff	Sandstone, siltstone and minor shale, bounded at the top by inferior coal and at the base by a distinctive biotite rich tuffaceous claystone
					Abbey Green Coal		Bright to vestigial coal rich in carbonaceous shale
				Watts Sandstone			A distinctive massive sandstone
			Wittingham Coal Measures	Jerrys Plains Sub-group	Denman Formation		Dark grey striped sandstone - siltstone laminite with abundant burrows
					Mt Leonard Formation	Whybrow Coal Mbr	Massive sandstone to conglomerate with intercalated coal seams
					Althorpe Formation		Light green to white tuffaceous claystone
					Malabar Formation	Redbank Creek Coal Mbr Wambo Coal Mbr Whynot Coal Mbr Blakefield Coal Mbr	Sandstone, siltstone, conglomerate, minor claystones and coal seams
					Mt Ogilvie Formation	Saxonvale Mbr Glen Munro Coal Mbr Woodlands Hill Coal Mbr	Sandstone, siltstone, carbonaceous siltstone, minor claystone and coal seams
					Milbrodale Formation		Waxy white tuffaceous claystone to cherty siltstone
					Mt Thorley Formation	Arrowfield Coal Mbr Bowfield Coal Mbr Warkworth Coal Mbr	Sandstone, siltstone and coal seams
					Fairford Formation		A distinctive off white tuffaceous claystone to volcanogenic sandstone
					Burnamwood Formation	Mt Arthur Caol Mbr Piercefield Coal Mbr Vaux Coal Mbr Broonie Coal Mbr Bayswater Coal Mbr	Sandstone, siltstone and coal seams
				Archerfield Sandstone			Massive well sorted sandstone
				Vane Sub-group	Bulga Formation		Laminated siltstone and fine grained sandstone with abundant burrows
					Foybrook Formation	Wynn Coal Mbr Edderton Coal Mbr Clanricard Coal Mbr Bengalla Coal Mbr Edinglassie Coal Mbr	Lithic sandstone, siltstone, shale, conglomerate and coal seams
				Saltwater Creek Formation			Passes upwards from dark marine siltstone to quartz-lithic sandstone with minor siltstone and claystone bands
		EARLY PERMIAN	Maitland Group	Mulbring Siltstone			Siltstone, claystone and minor fine grained sandstone
				Branxton Formation			Conglomertate, sanstone and siltstone
			Greta Coal Measures	Rowan Formation			Sandstone, siltstone and coal seams
				Skeletar Formation			Pellet claystone, siltstone and chert
			Dalwood Group	Gyarran Volcanics			Felsic to mafic volcanics and pyroclastics
	298						
		CARBONIFEROUS		Undifferentiated			Conglomerate, feldspathic and lithic sandstone, siltstone, mudstone and minor limestone. Felsic and intermediate

Mulbring Siltstone

The Mulbring Siltstone overlies the Branxton Formation in the Northern Hunter Coalfield, as the Muree Sandstone is not developed. The Mulbring Siltstone is dominated by siltstone with subordinate claystone and thin sandy lenses. The unit is generally about 300 m in thickness.

Singleton Supergroup

The Singleton Supergroup overlies the Maitland Group and is generally about 1500 m in thickness. The Supergroup is divided into the Wittingham Coal Measures (1200 m thick) and the overlying Wollombi Coal Measures (300 m thick).

Wittingham Coal Measures
The Wittingham Coal Measures include the major coal producing units in New South Wales, the Vane and Jerrys Plains Subgroups which are bounded by coal-barren units, the Saltwater Creek Formation at the base, the Archerfield Sandstone separating the Subgroups and the Denman Formation at the top.

Saltwater Creek Formation
The Saltwater Creek Formation is the basal unit of the Wittingham Coal Measures and is transitional in character, passing upwards from dark marine siltstone to a sandstone dominant unit at the base of the coal-bearing sequence. The lithology is characteristically quartz-lithic sandstone with minor siltstone and claystone bands. The unit varies in thickness from 10 m to 100 m.

Foybrook Formation
The Foybrook Formation contains up to six mineable seams in the Northern Hunter Coalfield, the basal Ramrod Creek, Edinglassie, Bengalla, Clanricard, Edderton and Wynn seams. The interseam sediments include siltstone, lithic sandstone and conglomerate. The type section is 240 m in thickness.

Bulga Formation
The Bulga Formation overlies the Foybrook Formation and consists of laminated siltstone and fine-grained sandstone. The unit is usually less than 20 m in thickness and is not always developed.

Archerfield Sandstone
The Archerfield Sandstone, a regionally significant marker unit, overlies the Bulga Formation and is a massive well sorted sandstone. The unit is best developed in conjunction with the Bulga Formation but is more extensive. It is typically between 15 m and 25 m in thickness.

Burnamwood Formation
The Burnamwood Formation is the lowermost unit in the Jerrys Plains Subgroup and comprises sandstone and siltstone and five named coal seams, the Bayswater, Broonie, Vaux, Piercefield and Mount Arthur seams. The standard section in JEM Mount Arthur DDH 1 is 97.1 m thick.

Fairford Formation
The Fairford Formation overlies a consistently dulling section of the Mount Arthur seam. The formation is usually about 2 m thick and forms a distinctive off white tuffaceous claystone to lithic (volcanogenic) sandstone over most of the Hunter Coalfield.

Mount Thorley Formation
The Mount Thorley Formation represents a continuation of the same coal bearing sequence as the Burnamwood Formation. The formation contains the Warkworth, Bowfield and Arrowfield seams and averages about 100 m in thickness.

Millbrodale Formation
The Millbrodale Formation is a waxy white tuffaceous claystone to cherty siltstone that averages less than 1.0 m in thickness. The formation occurs throughout the coalfield and is usually associated with the base of the Woodlands Hill seam.

Mount Ogilvie Formation
The base of the Mount Ogilvie Formation coincides with the base of the Woodlands Hill seam, and the top of the formation coincides with the base of the Blakefield seam. The formation is generally about 100 m thick and consists of sandstone, siltstone, carbonaceous siltstone and minor claystone. The formation includes the Glen Munro and Woodlands Hill seams.

Malabar Formation
The Malabar Formation overlies the Mount Ogilvie Formation and typically consists of sandstone, siltstone, conglomerate and minor claystone. The formation is about 160 m thick and contains the Blakefield, Whynot, Wambo and Redbank Creek seams.

Althorpe Formation
This is a tuffaceous claystone that averages 2 m in thickness. The underlying Redbank Creek seam is usually associated with the formation and assists in correlation of the unit.

Mount Leonard Formation
The Mount Leonard Formation is a coal-bearing mainly clastic unit which forms the uppermost unit of the Jerrys Plains Subgroup. Lithologies range from massive sandstone to conglomerate with interbedded thin coal seams. The Whybrow seam is contained within this formation. The formation is generally less than 12 m thick in the Northern Hunter Coalfield.

Denman Formation
The Denman Formation is the uppermost unit of the Wittingham Coal Measures. There is a distinct lithological change from the underlying sandstone and conglomerate of the Mount Leonard Formation to the interbedded siltstone and minor sandstone of the Denman Formation. The formation is typically burrowed and bioturbated and is approximately 20 m in thickness.

Wollombi Coal Measures
The Wollombi Coal Measures are about 180 m thick 3 km west of Denman. The Coal Measures differ from the Wittingham Coal Measures in that they contain a greater number of tuffaceous claystones; the coal seams are more banded; there is a decrease in the number of economic coal seams; and the seams become increasingly duller towards the top of the sequence. The Coal Measures are currently the subject of a stratigraphic review which, when completed and ratified, may significantly change the present stratigraphic nomenclature.

Watts Sandstone
The coal-barren Watts Sandstone is the lowermost unit of the Wollombi Coal Measures. The formation varies from 30 m to 60 m in thickness and is generally massive, medium grained, even textured sandstone. The formation has a resistant lithology relative to the surrounding coal-bearing sequences and often forms a prominent linear outcrop.

Abbey Green Coal
The Abbey Green Coal is the lowermost coal of the Wollombi Coal Measures. The formation is very widespread and ranges from a metre or more of bright coal to vestigial coal development rich in carbonaceous shale, sometimes associated with minor splitting.

Charlton Formation
The Charlton Formation comprises sandstone, siltstone, with minor shale. The Monkey Place Tuff Member comprises a biotite rich tuffaceous claystone and occurs at the base of the formation overlying the Abbey Green Coal. The top of the formation is bounded by the Stafford Coal Member, a persistent bed of inferior coal.

Clifford Formation
The Clifford Formation comprises a dominantly sandstone sequence containing minor tuffaceous claystone and vestigial coal beds occurring between two widely correlated coal sequences.

Alcheringa Coal
The Alcheringa Coal is a distinctive coal-rich sequence comprising a number of tuffaceous claystone beds.

Strathmore Formation
The Strathmore Formation comprises a dominantly shaly sequence, richly carbonaceous, with minor claystone and sandstone beds occurring between two thick and distinctive coal sequences.

Lucernia Coal
The Lucernia Coal is a rich coal-bearing sequence comprising distinctive units of coal and tuffaceous claystone recognised in a number of boreholes. The units include the Carramere, Rombo, and Eyriebower Coal Members, and these are respectively separated by two distinctive beds nominated as the Hillside Claystone and the Longford Creek Siltstone Members.

Pinegrove Formation
The Pinegrove Formation is a sequence of shale and sandstone with minor tuffaceous claystone. A vestigial coal member comprising inferior coal plies and bands, called the Wylies Flat Coal Member, is underlain by a predominantly shaly phase and overlain by a predominantly sandstone phase called respectively the Glengowan Shale and Hambledon Hill Sandstone Members.

Waterfall Gully Formation
The Waterfall Gully Formation comprises mainly chert-like claystone and shale defined at the base by sandstone and at the top by coal.

Dights Creek Coal
The Dights Creek Coal has been divided into two members, the Hobden Gully and Hillsdale Coal Members, which are separated from each other by a marker bed of tuffaceous claystone called the Naleen Tuff Member.

Redmanvale Creek Formation
The Redmanvale Creek Formation is a coarse conglomerate containing rounded boulders and pebbles.

Griegs Creek Coal
The Griegs Creek Coal comprises a dull durain-rich coal and the formation delineates the top of the Wollombi Coal Measures. The formation is not always present.

3.7.5 Structure

The northern part of the area appears to be heavily faulted with steep dips being apparent. This faulting is believed to be associated with the nearby Hunter Thrust. Further south, major faults appear to be associated with splays from the Hunter Thrust, while in the southern part of the area the major faulting appears to be associated with the Mount Ogilvie Fault system which terminates the western end of the Hunter River Cross Fault (figure 14). In the southern part of the area there is also a northeast to southwest faulting trend which is present in the lower Hunter Coalfield and has influenced the placement of major igneous dykes.

Structure contours of the top of the Wollombi Coal Measures in the area southwest of Denman indicate a shallow north-north-westerly plunging syncline with an axial plane fault developed at Myambit.

3.7.6 Volcanic Activity

While intrusions related to volcanism are widespread and common in the area, they tend to cluster into more intensely intruded areas leaving other areas relatively free. While there does not appear to be any significant structural control on the distribution of the intrusions, recent intensive exploration work by mining companies indicates that the structural setting of the area is very complex. The largest area of intrusions extends from midway between Aberdeen and Scone northwards to Wingen.

The age of the intrusions is uncertain but their likely range is from Late Triassic to Tertiary. Most of the large sills in the Hunter Coalfield have given Jurassic ages, except the Fordwich sill which is Tertiary.

Samples from a sill intersected at Mount Arthur gave a late Middle Triassic age while Mt Dangar, 7 km south of Gungal, gave a Late Triassic age, which is consistent with the onset of the Garrawilla Volcanics.

The Tertiary basalts of the Liverpool Volcanics almost certainly covered most of the area and have been stripped away by erosion. The extrusion of this lava field also would have produced localised dykes and sills.

3.8 NORTHERN WESTERN COALFIELD

3.8.1 Introduction

The Northern Western Coalfield covers the area between Ulan and Merriwa in the southwestern part of the BBSB. The Ulan-Merriwa area is part of the structural Gunnedah Basin but for historical reasons it is created as the northernmost part of the Western Coalfield (figure 15). There is a major operating coalmine at Ulan within the buffer zone in the south and large coal resources have been identified atBylong, Wollar, Wilpinjong, and Moolarben. The area is bounded to the south by the buffer zone boundary, to the west by the limit of the Illawarra Coal Measures, to the north by an east-west line extending west from the Liverpool Ranges, and to the east by a north-south line to the east of Merriwa.

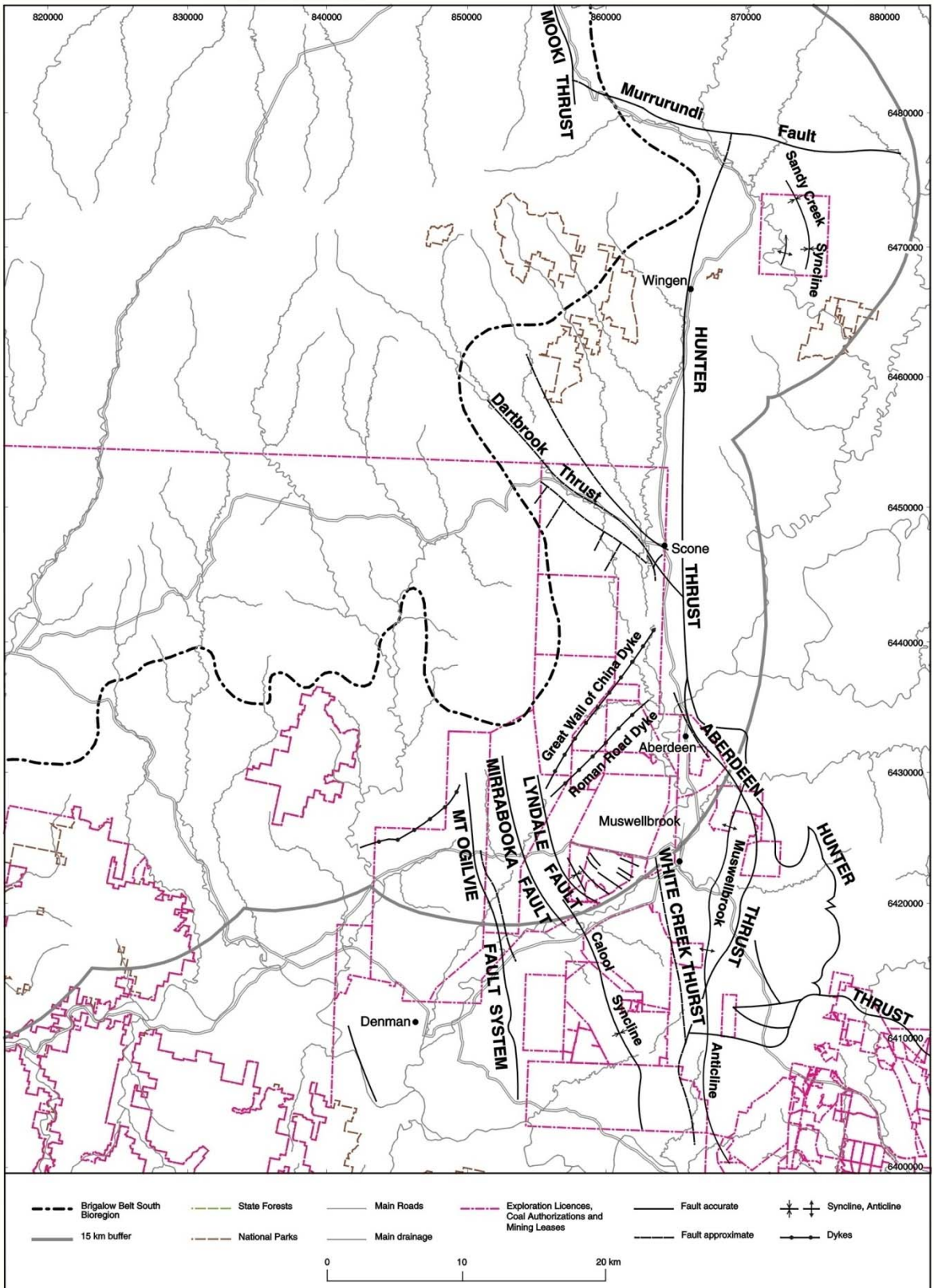

Figure 14 Upper Hunter Coalfield Structure

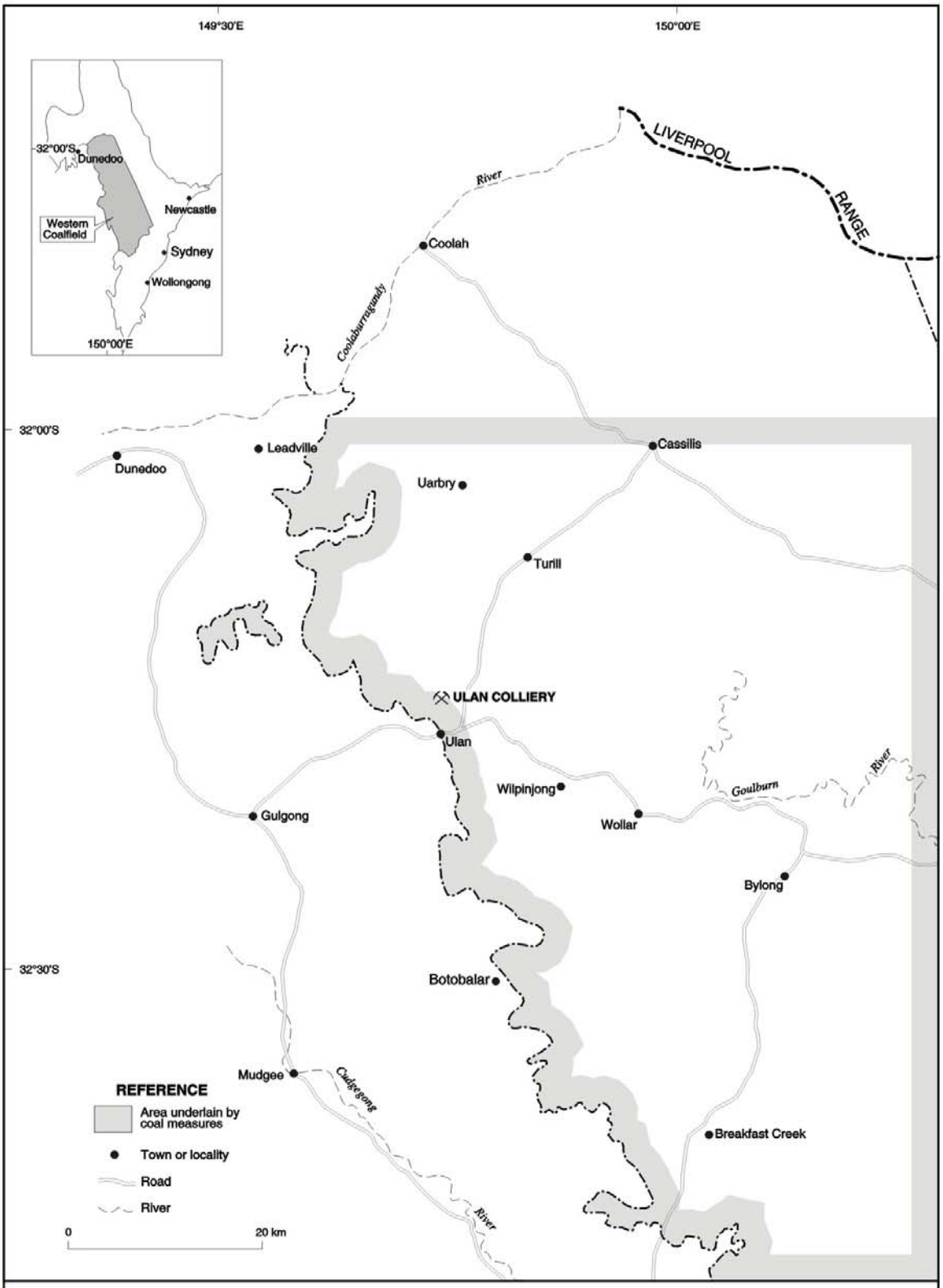

Figure 15 Northern Western Coalfield Location

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3.8.2 Tectonic and Depositional History

The following overview has been modified after Tadros (1988, 1993a, and 1999), Vanibe (2000), and Upstream Petroleum Consulting Services (2002b).

The basement rocks of the Northern Western Coalfield consist of rocks of the Lachlan Fold Belt; including folded Palaeozoic metamorphosed sediments, Late Carboniferous granites, and Early Permian Rylstone Volcanics. The Late Permian Illawarra Coal Measures unconformably overlie the basement rocks in the Kandos–Moolarben–Ulan area. The Measures are thin in the western half of the region maintaining a relatively uniform thickness of 100 m to 200 m (figure 16). In the eastern half of the area, the basement is composed of viscous felsic lavas of the Early Permian Boggabri Volcanics and the mafic (basaltic) lavas of the Werrie Basalt. The Coal Measures thicken rapidly from 200 m to 900 m eastwards towards the trough areas of the Sydney and Gunnedah Basins.

Deposition commenced in the east of the area with the marine Shoalhaven Group as part of a marine transgression that covered most of the Sydney-Gunnedah Basin. The transgression may have resulted from continued subsidence of the Basin resulting from thermal relaxation and/or from a eustatic sea level rise. A regressive phase commenced very early in the Late Permian. Uplift and volcanism in the New England region resulted in increased erosion and transport of sediment west and southwest into the Basin. Sedimentation was by prograding fluvio-deltaic systems. Uplift of the Lachlan Fold Belt produced alluvial sediments which prograded north and east into the Basin. Those sediments formed the lower part of the Illawarra Coal Measures in the Western Coalfield (Marrangaroo and Blackmans Flat Formations.

The return to terrestrial sedimentation in the Basin marked a very important event, the establishment of basin-wide swamps. Peat accumulated as successive, nearly continuous blankets over the subdued relief of the emergent surface resulting from infilling of the preceding marine embayment. The earliest peat swamps formed the Lithgow Coal, followed by the Lidsdale Coal in the south of the Coalfield and the lower part of the Ulan Coal in the Ulan area. West-derived quartz-rich alluvial sandstone and conglomerate wedges of the Blackmans Flat Formation interrupted the Lithgow/Lidsdale sequence. Peat swamp environments extended northwards over much of the Gunnedah Basin and formed the upper part of the Ulan Coal.

This period of peat formation was followed by southward progradation of the lower part of the Charbon Subgroup, the Long Swamp Formation to Glen Davis Formation interval. It was characterised by a lower deltaic depositional environment with associated distributary mouth bar and crevasse splay sands. A marine incursion, probably eustatically controlled, resulted in the deposition of the overlying Watts Sandstone and Denman.

Coal measure sedimentation resumed after the incursion, with the southward progradation of major fluvio-deltaic systems from the north. This resulted in the deposition of the Wallerawang Subgroup in the Western Coalfield. Deposition of the Subgroup commenced with a fluvial channel system, the Gap Sandstone. It prograded from the northeast, possibly via a trunk stream which flowed southwards parallel to the Lachlan Fold Belt, and discharged into a delta front area south of Lithgow. In the north, this Subgroup thickens progressively to the east.

The upper part of the Wallerawang Subgroup, the Farmers Creek Formation, formed in an alluvial system associated with extensive peat swamps (the Middle River, and Woodford Coal Members and the Katoomba Coal). Contemporaneous volcanism in the New England area provided thick tuff layers within the sequence, notably the Middle River Coal Member. Volcanism appears to have temporarily ceased during the formation of the Katoomba Coal.

A major depositional break and a period of structural readjustment, uplift and erosion followed. Northwest of Ulan, the upper part of the Illawarra Coal Measures has been eroded, and the Narrabeen

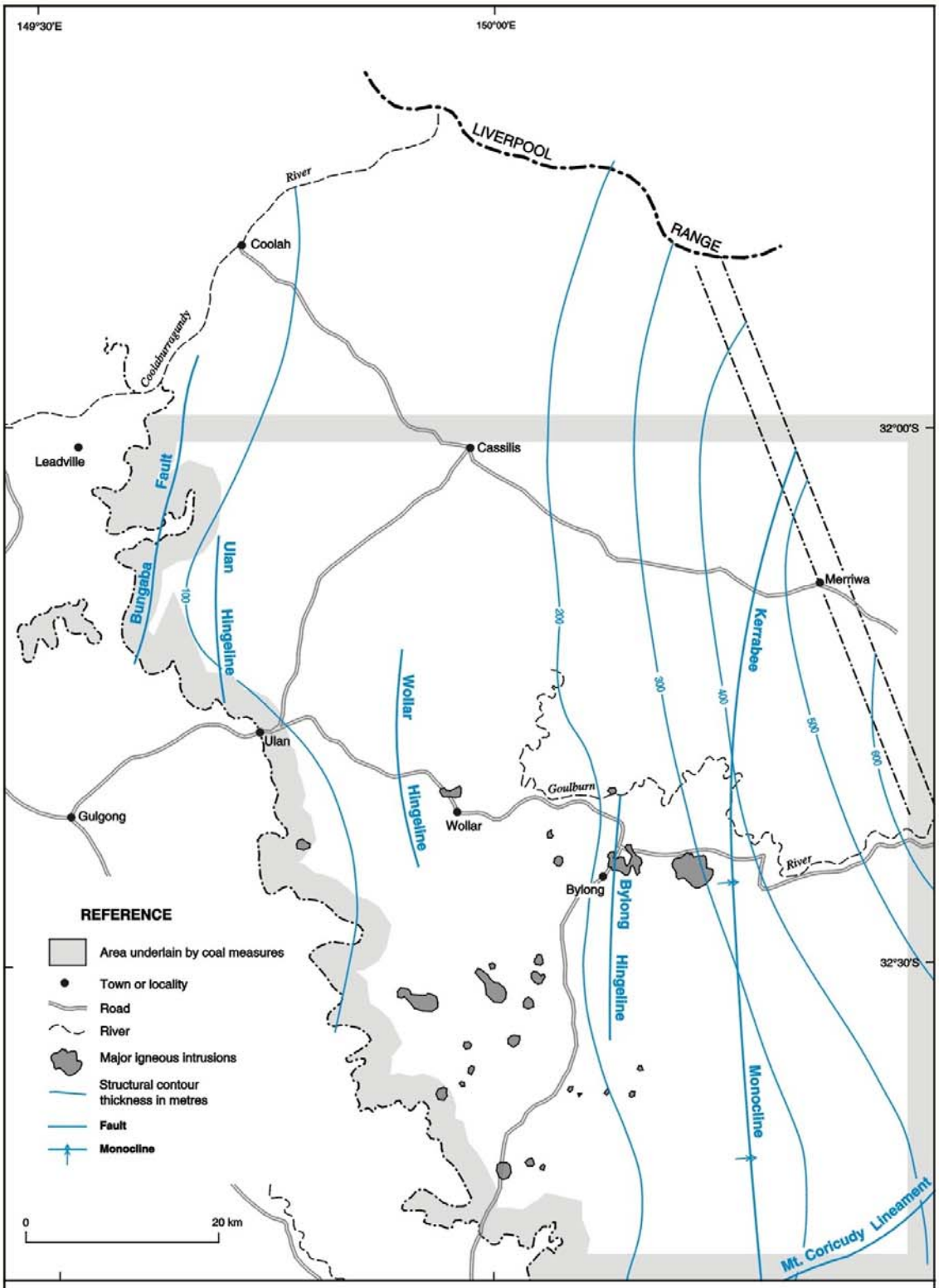

Figure 16 Northern Western Coalfield Structure and Isopachs of the Illawarra Coal Measures

Group rocks rest unconformably and erosively on the Ulan Coal. Further west, the Narrabeen Group rests directly on the Ulan Quartz Monzonite. In the Northern Western Coalfield, initial Triassic deposition formed the Wollar Sandstone Member of the Digby Conglomerate. This comprises quartzose fluvial sediments derived from uplift of the Lachlan Fold Belt. Widespread palaeosol horizons formed on top of the unit at the end of the phase. Renewed basin subsidence resulted in deposition of the Triassic Napperby Formation. Well-developed upward-coarsening sequences of laminated siltstone/claystone, interbedded with sandstone, derived from the New England Fold Belt, form the lower part of the sequence. Those units were formed by the progradation of lacustrine deltas. The upper part consists of fluvial irregularly interbedded sandstone and siltstone sequences.

The Jurassic Purlawaugh Formation and Pilliga Sandstone of the Surat Basin successively overlie the Illawarra Coal Measures in the area. Tertiary basalts occur on topographic ridges in many parts of the area, but more commonly in the northern part towards the Liverpool Range.

3.8.3 Structural Elements

The Northern Western Coalfield is located mainly on the Wollar Shelf (figure 16), a basement structural element of the Gunnedah Basin (Tadros 1988, 1993a, 1993b, and Bayly (1997). The meridional Mount Tomah Monocline, a major structure located in the middle of the Coalfield and extending along its full length, separates the Shelf from the Murrurundi Trough.

3.8.4 Stratigraphy

The stratigraphy of the Western Coalfield is shown in table 6 (Bayly 1997).

Early Permian
A thinly laminated pale green varved claystone of Early Permian Stage 2 age occurs in the Cockabutta Creek area northwest of Ulan underlying the Illawarra Coal Measures. This unit grades upward into medium-bedded to thinly-bedded breccia, consisting of broken, sharply angular clasts of the varved claystone in a dark grey muddy matrix.

Shoalhaven Group
The Shoalhaven Group is absent in the far west but unconformably overlies the Lachlan Fold Belt basement further to the east. It consists of the Snapper Point Formation and Berry Siltstone. The Berry Siltstone is up to 41 m thick and consists mainly of bioturbated marine, dark grey, micaceous mudstone, and contains shell fragments and abundant isolated drop pebbles. White siliceous worm tubes are common throughout the unit.

Marrangaroo Formation
The Marrangaroo Formation crops out persistently throughout the western edge of the Coalfield. In outcrop, it forms characteristic “benches” up to several metres high. In the Ulan area, it ranges in thickness from 3m to 8m and consists of upward-fining units of quartz-lithic to quartzose pebbly sandstone.

Lithgow Coal
The Lithgow Coal ranges in thickness from less than 1m to 9m and consists of dull coal with minor bright layers, generally increasing towards the base and top of the formation. A few thin carbonaceous or tuffaceous claystone layers are present in the upper half. In the Ulan area, the Lithgow Coal is 0.2m to 1.1m thick and deteriorates to a carbonaceous claystone layer at Wollar.

Blackmans Flat Formation
The Blackmans Flat Formation is a coarse grained, pebble-bearing, quartzose sandstone, which progressively includes finer grained sedimentary units to the east. The Formation is persistent along the western margin of the Basin ranging in thickness from 3.5 m to 10.6 m at Bylong, and from 2 m to 5 m in the Ulan area. Here, Lithgow Coal locally wedges out and the Blackmans Flat and Marrangaroo Formations merge into one unit.

Lidsdale Coal
The Lidsdale Coal consists of predominantly dull coal, thin claystone, carbonaceous and tuffaceous claystone and siltstone. The unit ranges in thickness from 0.5m to 5m subdivided into upper and lower sections by a persistent thin tuffaceous claystone layer. The lower section generally contains an economic coal 1.5 m to 2.7 m thick. It is considered to be equivalent to part of the Ulan Coal in the Ulan area.

TABLE 6. STRATIGRAPHY OF THE ILLAWARRA COAL MEASURES IN THE NORTHERN PART OF THE WESTERN COALFIELD

Ulan - Coolah			**Rylstone Area**		
DIGBY FORMATION			NARRABEEN GROUP	NARRABEEN GROUP	
	Katoomba Coal		Katoomba Coal		ILLAWARRA COAL MEASURES
Farmers Creek Formation			Farmers Creek Formation	WALLERAWANG	
			Middle River Coal Member	SUBGROUP	
			Gap Sandstone		
Middle River Coal Member					
State Mine Creek Formation			State Mine Creek Formation		
Moolarben Coal Member - upper			*Moolarben Coal Member*		
			Watts Sandstone		
Moolarben Coal Member - lower			Denman Formation		
	Kaolinitic claystone			CHARBON	
Glen Davis	*Bungaba Coal Mb.*		Glen Davis Formation		
	Cockabutta Creek Ss.Mb.				
Formation					
Newnes Formation			Newnes Formation	SUBGROUP	
			Irondale Coal		
			…..		
	Upper		Mount Brace seam		
Ulan					
			Seam A		
		C Marker ^^ ^^	^^^ ^		
	Lower		Upper Rider		
Coal					
			Lidsdale Upper		
				CULLEN	
		F Ply ^^ ^^	^^^ ^ *Tuffaceous Marker*		
		G Ply	Lidsdale Lower	BULLEN	
Blackmans Flat Formation			Blackmans Flat Fm.	SUBGROUP	
			Lithgow Coal		
Marrangaroo Formation					
			Marrangaroo Formation		
Undifferentiated Nile Subgroup			Gundangaroo Formation	NILE SUBGROUP	
			Coorongooba Creek Sandstone		
			Mount Marsden Claystone		

Ulan Coal

The Ulan Coal consists of two sections. The upper section consists of three plies, and the lower section consists of five plies. The Ulan Coal is approximately 14 m thick at Ulan, divided approximately equally between the upper and lower sections. The lower section maintains its thickness over the area. The upper section, totalling up to 7 m thick between Ulan and Wilpinjong, splits eastwards into thin multiple, discontinuous coals. At Bylong, this interval is 20 m thick.

Long Swamp Formation

The Long Swamp Formation consists of commonly bioturbated claystone and siltstone, tuff, sandstone and thin discontinuous coal layers. The Formation generally thins out near the western margin of the basin and it is more than 60 m thick in the east. West of the Wollar Hingeline, the Formation consists of a thin tuffaceous claystone layer within the Ulan Coal. East of the Hingeline, the Formation contains thick, fining-upward sandstone lenses with green and red volcanic pebbles and granules.Irondale Coal

The Irondale Coal consists of a thin (1.3 m to 1.5 m) but persistent unit mainly of bright coal that tends to be brighter and thicker at top of unit and contains two or three stone layers. The Irondale Coal can be correlated with the Coolah seam intersected in two holes drilled southeast of Coolah where the seam is about 1.5 m thick and consists of dull coal with minor bright layers.

Newnes Formation

The Newnes Formation consists generally of a fine to medium grained, lithic sandstone, with interbedded siltstone and claystone west of the Wollar Hingeline, and an upward fining lithic sandstone east of the Wollar Hingeline. The Formation ranges from 8 m to 14.5 m in thickness.

Glen Davis Formation

The Glen Davis Formation is 17 m to 26 m thick and consists of coal, carbonaceous claystone, claystone and siltstone and sandstone. In the Ulan-Wollar area, the upper part of the Formation contains the Cockabutta Creek Sandstone Member. There are two uneconomic coal seams within the formation; the upper one is the Bungaba Coal Member, which is up to 3.47 m thick. It consists of dull/minor bright coal and numerous carbonaceous and tuffaceous claystone layers. The Coal Member is overlain by the Denman Formation east of the Ulan Hingeline and by 0.7 m-thick kaolinitic claystone west of the Hingeline. Farther west, the Coal Member has coalesced with the Moolarben Coal Member forming a layered coal seam up to 13.6 m thick northwest of Ulan.

Denman Formation and Watts Sandstone

Marine rocks of the Denman Formation grade vertically upwards from dark grey claystone through laminated claystone and fine sandstone with common bioturbation, into fine-grained lithic sandstone. The Formation is 10 m thick near Ulan and 1 m thick near Coolah but thickens gradually in an easterly direction, from 20 m at Bylong to 50 m at Denman.

The Watts Sandstone is a coarsening up, cross-bedded lithic sandstone with calcareous cement. North of Ulan, the base of the sandstone is often marked by coarse, cross-bedded lithic sandstone or, in some cases, a basal conglomerate, above which the sequence fines upwards. The Watts Sandstone ranges in thickness from 5 m to a maximum of 15.5 m but thins to 2 m at Coolah.

State Mine Creek Formation

The State Mine Creek Formation consists of claystone, mudstone, siltstone, minor sandstone and coal seams with common worm burrows and plant remains. The Formation ranges in thickness from 5 m to 10 m in the western margin and thickens gradually to the east. Three coal seams are generally present in State Mine Creek Formation: the Moolarben Coal Member at the base; the Turill Coal Member in the middle; and the “Lennox seam” or “Goulburn seam” at the top.

The Moolarben Coal Member consists of dull coal with minor bright layers, particularly in the lower part, and numerous carbonaceous claystone layers. It is 3.17 m thick 8 km east of Ulan. Northwest of Ulan, it coalesces with the underlying Bungaba Coal Member. The Turill Coal Member is 1.5 m thick near Turill and 4 m near Cassilis. It consists of dull coal with bright layers and numerous thin carbonaceous claystone layers in the lower half, and moderately thick carbonaceous and tuffaceous claystone layers in the upper half. The Coal Member is 600 m deep at Cassilis.

Gap Sandstone
The Gap Sandstone is an off-white upward fining, medium to coarse grained, high-angle cross-bedded quartz-lithic to lithic sandstone with a pebbly base. The Formation is generally 3 m to 5 m thick but is up to 11 m in the Wilpinjong area and thins rapidly northwest of Ulan, where the State Mine Creek and Farmers Creek Formations coalesce. In some areas, the Gap Sandstone truncates the entire State Mine Creek Formation and part or all of the underlying Watts Sandstone.

Farmers Creek Formation
The Farmers Creek Formation consists of claystone, carbonaceous claystone, siliceous claystone, siltstone, sandstone, coal and oil shale. It includes the Middle River Coal Member at the base and several thin coal layers, some of which may coalesce to form the "Woodford seam". The Farmers Creek Formation is 20 m thick along the Basin margin and 60 m thick south of Mount Coricudgy. In parts of the Ulan area, the Formation has been almost entirely eroded.

The Middle River Coal Member consists of a sequence of coal and argillaceous sedimentary rocks and oil shale. Coal is basically dull with bright layers. The sedimentary bands are thicker in the upper part of it. The Katoomba Coal consists of dull coal with minor bright coal layers, carbonaceous claystone and sporadic thin tuff lenses. It can be divided into an upper section, up to 2.92 m thick, with low to medium mineral matter content, and a few thin stone layers, and a lower section, up to 1.4 m thick, with high mineral matter content and a few but thicker tuff layers.

Digby Formation
The Triassic Digby Formation consists of conglomerate at the base, overlain by a quartz-lithic sandstone, which gradually changes into a quartzose sandstone unit consisting of cross-bedded sandstone with well-rounded quartz pebbles. A siltstone/sandstone and grey/purple claystone palaeosol is present at the top.

Napperby Formation
The Napperby Formation consists of an overall coarsening upward sequence of a finely laminated dark grey claystone at the base; finely layered siltstone/sandstone laminite containing abundant bioturbation, burrows, shrinkage cracks and ripples in the middle; and lithic sandstone at the top.

3.8.5 Structure

Interpretation of drill hole information suggests that there are three north-trending hingelines on the Wollar Shelf that have influenced sedimentation of the Illawarra Coal Measures. The effects of these structures are shown on figure 17, which is a west–east cross section across the coalfield. Several significant faults have been mapped, but there is insufficient information on the structure over most of the area.

Mount Tomah Monocline
The Mount Tomah Monocline extends along the full length of the Coalfield through Kelgoola, some 20 km east of Rylstone, to join the Kerrabee Monocline, east of Bylong, and possibly further north to the Liverpool Range. To the east of Mount Tomah Monocline, the Illawarra Coal Measures thicken significantly towards the basin centre. Most probably, the monocline originated as a hingeline during sedimentation and was subsequently reactivated during the Late Pliocene or Early Pleistocene (the Kosciusko Epoch) uplift of the Blue Mountains Plateau. It is also possible that the uplift was initiated towards the end of Cretaceous or Late Paleocene time.

Ulan Hingeline
The Ulan Hingeline is east of Ulan, close to the western limit of the Denman Formation and the Watts Sandstone. West of the hingeline, the basal plies of the "Ulan seam" are absent. The Bungaba Coal Member in the Glen Davis Formation coalesces with the Moolarben Coal Member of the State Mines Creek Formation; and the State Mine Creek Formation converges with the Farmers Creek Formation.

Wollar Hingeline
The Wollar Hingeline is a prominent structural feature located further east of Ulan, near Wollar. The northern segment of the hingeline is north trending, whereas the southern segment appears to trend southeasterly through Wollar, Berrigan and Growee. East of the Wollar Hingeline, the upper section of the "Ulan seam" expands in thickness and the coal plies split widely. The Denman Formation, Watts Sandstone and Farmers Creek Formation increase substantially in thickness across this hingeline.

The lower and upper sections of the Ulan Coal (equivalent to the Lidsdale Coal and the interval including the Long Swamp Formation and the Irondale Coal, respectively) generally maintain a uniform thickness

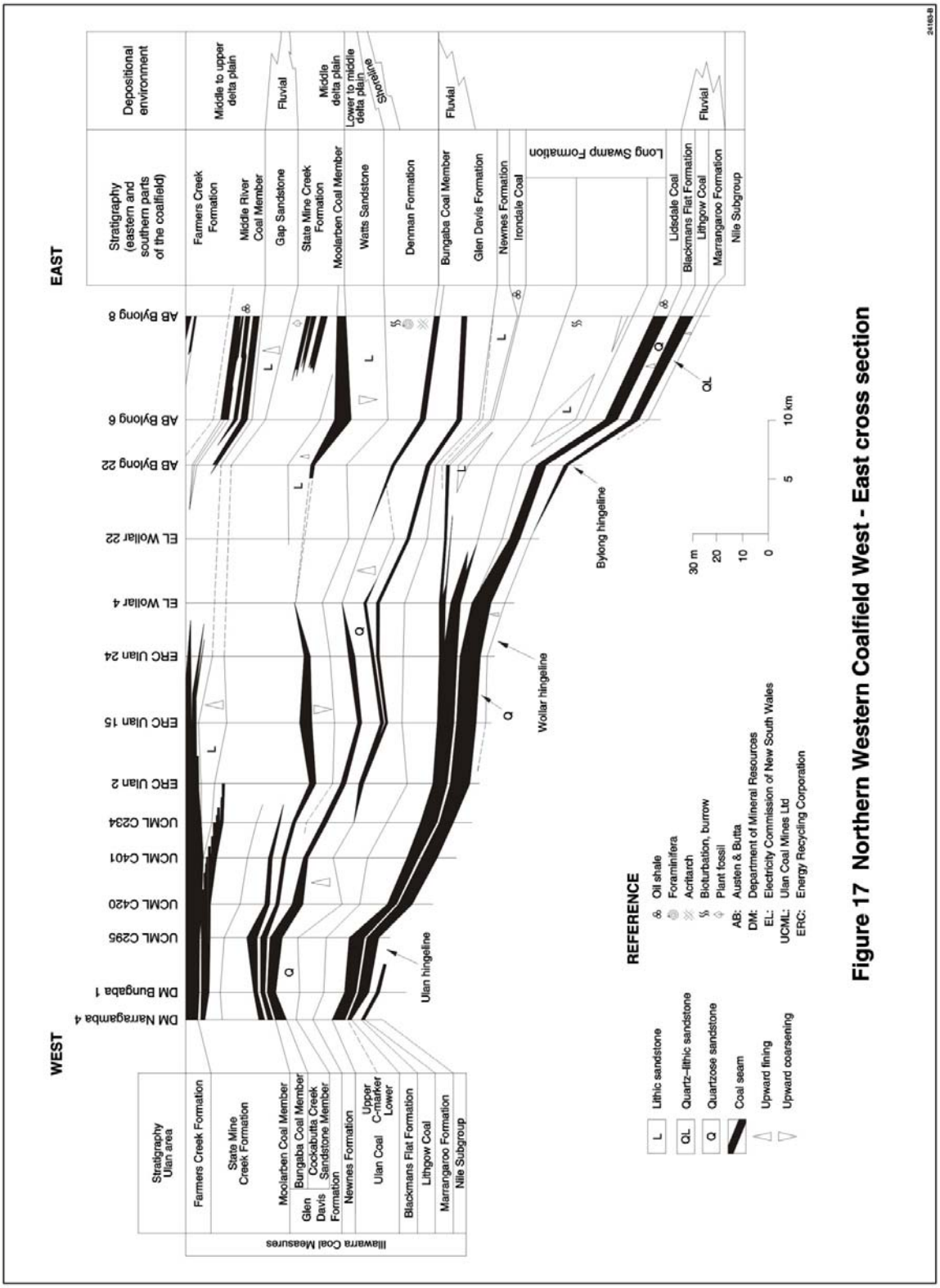

Figure 17 Northern Western Coalfield West - East cross section

in the area between the Ulan and the Wollar Hingelines. This area also marks the western limit of the Gap Sandstone, and the State Mine Creek Formation contains a relatively higher proportion of fine to medium, lithic sandstone.

Bylong Hingeline

The Bylong Hingeline is east of Bylong, where the Lithgow Coal begins to thicken eastwards. The Long Swamp Formation, Denman Formation, Watts Sandstone and Farmers Creek Formations also increase substantially in thickness east of this hingeline. West of the Bylong Hingeline, the State Mine Creek Formation becomes thinner and the Cockabutta Creek Sandstone Member of the Glen Davis Formation wedges out.

Faults

Recent drilling in the north Ulan area has revealed several probable normal faults. For example, a set of faults at Uarbry Pinnacle 8 km west of Uarbry forms a graben with a displacement of over 100 m. The displacement of the coal measures, the overlying Narrabeen Group, and the Pilliga Sandstone immediately west of the fault suggests a long history of faulting which probably spanned the Jurassic to Tertiary extensional phases of eastern Australia.

Northeast of Ulan, there is a graben trending approximately northwest. The Curra Creek Fault and Green Hills Fault bound this structure with a maximum displacement of 50 m. These faults appear to extend to the Talbragar River. The limit of any southeastern extensions of the faults beyond the Goulburn River is not known. The Spring Gully Fault is near the eastern margin of the Ulan Coal Mine and trends in a north-northeasterly direction. The eastern side is upthrown with a displacement ranging from 2 m to 7 m. This fault and several others recorded in the western margin of the Coalfield are also probably related to extensional rifting in the western margin of the Sydney and Gunnedah Basins.

3.8.6 Volcanic Activity

Volcanic rocks in the Northern Western Coalfield include the Early Permian Rylstone Volcanics, and the major volcanic intrusions and extrusions of Mesozoic and Cainozoic age. Triassic to Jurassic intrusions, Jurassic to Tertiary diatremes, and Tertiary basalt have had the most effect on the region, particularly where they are in contact with or intrude the coal seams. However, some of these rocks, such as basalt, are important construction materials.

Rylstone Volcanics

The Rylstone Volcanics crop out along the western margin of the Wollar Shelf, mainly in the Dunedoo, Cumbermelon Creek valley, Botobolar, Kandos, and Rylstone areas, and as outliers to the southwest. The Rylstone Volcanics have been intersected in a number of drillholes under the Permian rocks, also in the Wollar Shelf area. The Volcanics are of earliest Permian age and non-conformably overlie Carboniferous basement granites. The unit has widely variable composition of rhyolitic to dacitic pyroclastic and ignimbrite sheets, flow-layered lavas and epiclastic units, which may show ripples, cross beds and parallel laminations.

Tuffs within the Coal Measures

The Illawarra Coal Measures sequence contains numerous airfall tuffs, probably derived from an active volcanic arc in the New England region during the Late Permian period. Some of these tuffs, particularly within coal seams, are persistent over very large areas of the region. This is most probably because of the physical characteristics of the peat-forming environments. They are largely stable and protected areas capable of accommodating and preserving airfall tuffs as discrete layers within the coal seams.

Post-Permian Intrusions and Extrusions

The Triassic–Jurassic igneous intrusions in the region occur randomly in an area bounded by Rylstone, Botobolar, Wollar and Bylong. Jurassic volcanism in the Rylstone area was concentrated along the edge of the Lachlan Fold Belt. It included basalt flows, teschenite sills and large, late-stage phonolitic laccoliths. In general, igneous activity appears to have started in the north and west of the area, and spread to the southeast.

Surface geological mapping, drilling investigations and airborne magnetic and radiometric surveys in the Ulan area have identified a number of igneous sills, dykes, plugs and diatremes. However, only a few of these bodies intersected and/or affected the economic Ulan seam.

Exploration drilling in the north Ulan area has not encountered sills and dykes. However, surface mapping has indicated the presence of flow basalts particularly in the northwest of Ulan mine. It is reasonable to assume that these basalts could be masking diatremes and plugs that could impact on the coal resources of the Ulan seam, although in the area around Uarbry where basalts and their likely associated feeder pipes are present, the seam is thin and potentially uneconomic.

3.9 WERRIE BASIN

3.9.1 Introduction

The Werrie Basin is located adjacent to the eastern side of the Gunnedah Basin, on the eastern side of the Hunter-Mooki Fault System on New England Fold Belt basement. It is not considered to be a part of the Gunnedah Basin although the age and stratigraphic similarities between them suggest a close association and a probable direct physical link during deposition. The Werrie Basin lies within the buffer zone of the BBSB.

3.9.2 Overview of Basin History

There are some significant differences between the Gunnedah and Werrie Basins particularly with regard to the basal rocks and to the early depositional history. The basal rocks of the Werrie Basin are generally those of the Temi Formation. The unit averages 200 m in thickness of which the bottom 150 m is composed of conglomerates comprising predominantly felsic volcanic clasts. These conglomerates overlie very similar conglomerates of the Upper Carboniferous Currabubula Formation and the boundary is often difficult to identify. The upper 50 m of the Temi Formation consists of fluviatile sandstones and coaly horizons.

The Werrie Basalt overlies the Temi Formation. It is estimated to exceed 1000 m in thickness and it has been exposed by the intensive folding. In the northern part of the basin, the Temi Formation is not developed and the Werrie Basalt unconformably overlies the Carboniferous Currabubula Formation. The mafic Werrie Basalt has been extruded from the Piallaway and Mount Terrible volcanic centres around which more viscous felsic lavas of the Warrigundi Volcanic Complex occur.

The Werrie Basalt is overlain by the Willow Tree Formation, a terrestrial coal-bearing unit that correlates with the Maules Creek Formation in the Gunnedah Basin and the Greta Coal Measures in the Hunter Coalfield.

The Willow Tree Formation is overlain by the Borambil Creek Formation, a marine unit containing fossils which correlate with the Watermark Formation of the Gunnedah Basin and the Muree Sandstone and Mulbring Siltstone of the Hunter Coalfield. The Late Permian Toll Bar Formation, a readily eroded unit which forms poor outcrops, overlies the Borambil Formation. The formation was deposited by westerly prograding deltas and is equivalent to the Black Jack Group but it does not contain significant coal seams.

Both the Borambil and Toll Bar Formations are known only from the Willow Tree area while the Willow Tree Formation occurs at Willow Tree and also at Werris Creek where it occurs as small outlier preserved in the core of an eroded syncline.

3.9.3 Structural Elements

The Werrie Basin is a north-north-west trending synclinal structure in the southwestern part of the New England Fold Belt (figure 8). The curving Mooki Fault System terminates the basin at each end. It was originally far more widespread and probably extended westwards to form the eastern margin of the Gunnedah Basin during deposition.

Located above the Carboniferous and Devonian rocks of the New England Fold Belt, the Werrie Basin has been intensely folded during the Hunter – Bowen Orogeny at the close of the Permian. The folding and thrusting of the Mooki thrust system steepened the limbs of the Werrie Syncline, and the Permian sedimentary units were eroded from the anticline which formed to the west on the leading edge of the thrust (Quirindi Dome). On the western limb of this anticline the Permian strata were steepened to an almost vertical attitude and have been preserved along the leading edge of the thrust at Willow Tree.

A more northerly orientated compressive movement created a series of basins and domes within the Werrie syncline and the Permian sediments were also eroded to expose the Carboniferous basement rocks on the crests of the domes (figure 11). These structures are described in Section 3.9.5.

3.9.4 Stratigraphy

A summary of the stratigraphic sequence of formations, their ages and lithologies is presented in table 7.

Temi Formation
The Early Permian Temi Formation consists of about 150 m of pebble conglomerates overlain by up to 60 m of sandstones, mudstones and coaly horizons. The coaly horizons occur to the northwest of the New England Highway while to the southeast, torbanite (oil shale) is found. Extensive exploration of the basin northwest of the New England Highway by Rio Tinto in the mid 1990s failed to locate any coal seams with economic potential.

TABLE 7. WERRIE BASIN STRATIGRAPHY

Basin	Years (Ma)	Period		Formation	Lithology
Werrie Basin Units	251	PERMIAN	LATE	Toll Bar Formation	Claystone, lithic sandstone, conglomerate and limestone
				Borambil Creek Formation	Lithic sandstone, conglomerate
	270		EARLY	Willow Tree Formation	Shale, lithic sandstone, conglomerate, coal
				Warrigundi Igneous Complex	Felsic and intermediate lavas and intrusions
				Werrie Basalt	Basaltic lavas with intervening palaeosols
	298			Temi Formation	Conglomerate, lithic sandstone, shale and coal

Werrie Basalt
The Werrie Basalt consists of greater than 1000 m of mafic lavas with intervening palaeosols. In the southern part of the basin the unit consists of tuffs, substantial amounts of intermediate and felsic volcanic rocks, conglomerates and sandstones. The sandstones contain marine fossils that correlate with the Dalwood Group of the Hunter Coalfield. In the Werris Creek to Quirindi area the Werrie Basalt is usually deeply weathered and forms gently undulating topography.

Warrigundi Volcanic Complex
The Warrigundi Volcanic Complex consists of intermediate and felsic rocks that are in part interbedded with the upper parts of the Werrie Basalt.

Willow Tree Formation
The Willow Tree Formation consists of shales, sandstones, conglomerates and coal seams. At Willow Tree, the formation is estimated to be in excess of 300 m in thickness while at Werris Creek the formation is about 160 m in thickness. The Werris Creek coal seams were mined by underground workings and, after these closed the shallow resources were mined by open cut methods.

Borambil Creek Formation
The marine Borambil Creek Formation comprises sandstone and conglomerates with subordinate shales. The maximum thickness is estimated at about 100 m. The formation is found only at Willow Tree where the beds dip at angles in excess of 65 degrees to the southwest and steepen westwards toward the Mooki Fault.

The Toll Bar Formation
The Toll Bar Formation, approximately 600 m thick consists of claystones, sandstones, conglomerates and thin beds of limestone. Again the beds dip steeply, in places vertically, to the south-west and steepen westwards toward the Mooki Fault.

3.9.5 Structure

The Werrie Basin is a synclinal structure, which under lateral compression, has been folded internally into a western anticline along the leading edge of the Mooki Fault and an eastern syncline. Subsequent

longitudinal compression has produced a series of domes with intervening basins. These structures trend southeast to northwest and include the Back Creek Dome, the Temi Basin, the Castle Mount Dome, the Jacob and Joseph Basin, the Quipolly Dome, and the Fairfield Basin to the east, and the Colliery Basin and Quirindi Dome to the west (figure 11).

Compression has developed major faults, including backthrusts, associated with the Mooki Fault in the more resistant rocks of the Carboniferous basement exposed along the western anticline. These faults tend to anastomose and some probably have a component of lateral slip. Minor local faults have also been mapped throughout the basin. As all of the Permian rocks have been affected by folding, compression must have occurred subsequent to the deposition of the Toll Bar Formation.

3.9.6 Volcanic Activity

There are few recorded occurrences of volcanic activity in the Werrie Basin after the Early Permian Warrigundi Volcanics, until the Tertiary (Eocene) when the Liverpool Range Volcanics was extruded over the southern part of the basin. An intrusive complex dated as Late Permian to Early Triassic occurs at Bald Hill, which could belong to the Moonbi Suite of the New England Fold Belt.

3.10 GUNNEDAH-BOWEN BASIN

3.10.1 Introduction

The following overview of the Gunnedah-Bowen Basin is summarised from Green et al. (1997), Tadros (1993a, 1999), Pratt (1998), Upstream Petroleum Consulting Services (2002c), and Vanibe (2000). The Surat Basin and the underlying Gunnedah-Bowen Basin comprise the northern part of the BBSB. Units from these basins unconformably overly Palaeozoic rocks of the Lachlan Fold Belt and the New England Fold Belt. The main units, together with their age, are shown in table 7.

The Bowen Basin forms the northern extension of the Bowen-Gunnedah-Sydney Basin system in eastern Australia and it is the southern part of this Basin and its connection with the Gunnedah Basin that is covered by this discussion. Sedimentary rocks of shallow marine and terrestrial origin and volcanics of Permian-Triassic age comprise the deposits in the Gunnedah-Bowen Basin. They reach thicknesses up to 10 km in the Taroom and Denison Troughs in Queensland. Southwards, into New South Wales they thin dramatically to a maximum of approximately 2500 – 3000 m. The basin crops out near Collinsville. To the south, the Bowen Basin is unconformably overlain by the Surat Basin and continues in the subsurface into New South Wales, where it is contiguous with the Gunnedah Basin.

3.10.2 Overview of Basin History

Murray (1990) identified three phases of basin formation for the Bowen Basin and these phases apply to the whole Bowen-Gunnedah-Sydney Basin system (Scheibner, 1993). They are:

- An Early Permian igneous rift phase.
- Mid-Permian sag phase.
- A Late Permian-Middle Triassic foreland basin phase.

The Sydney-Bowen Basin rift phase developed as an extensive north-south trending back-arc basin to the west of the continental Camboon Volcanic Arc. This arc developed as the result of continent- ocean plate convergence (Murray et al, 1987, Fielding, 1990, and Fielding et al, 1990b). Early Permian back-arc rifting (extension) on the western margin of the Bowen Basin produced a series of half-grabens, such as those of the Denison and Arbroath Troughs. These were the sites of initial deposition. A similar origin is anticipated for the grabens recognised in the Goonoo Area and at Collarenebri and Goodooga. Contemporaneously, andesite and volcanoclastics associated with the arc were laid down on the eastern margin of the basin, where they occur as the Boggabri and Werrie basalts.

The Early Permian rift phase resulted in the development of thick basal volcanic sequences. Major grabens, such as the Denison Trough, were mostly filled with Early Permian terrestrial sediments. They include the Reids Dome Beds and equivalents in the Taroom Trough (Elliot and Brown, 1988, Totterdell and Krassay, 1995), and the Goodooga and Collarenebri Grabens in northwest NSW (Bamberry and Kouzmina, 1995). Initial deposits of the lower Back Creek Group were also deposited in the graben structures.

A phase of thermal subsidence followed in the latest Early Permian to earliest Late Permian, allowing the incursion of the sea over the arc and westwards across the basin (Fielding et al, 1990). The upper Back Creek Group, Porcupine and lower Watermark Formations were deposited. Deltaic facies developed around the western and northern edges of the basin, as well as adjacent to the eastern margins. These deltas persisted into the Late Permian resulting in the formation of coastal swamps and the subsequent accumulation of extensive coal deposits.

The Late Permian-Middle Triassic foreland basin phase marks a period of major structuring of the Gunnedah- Bowen Basin sedimentary units. During this phase, the Bowen-Gunnedah-Sydney Basin developed its asymmetric geometry as a foreland basin of the New England Fold Belt. Within the BBSB, the Basin effectively formed a half-graben shape, dipping towards the eastern thrust faulted margin. Deformation in the basin sediments is greatest adjacent to the foreland thrust belt (Hunter-Mooki-Goondiwindi Thrusts). This phase produced north-trending compressional structures, including high angle reverse faults and folding. Faults bounding graben were reactivated as reverse faults eventually leading to positive inversion of graben and half-graben.

Sedimentation during the foreland phase involved deposition of widespread coal measure and alluvial successions forming the Blackjack Group and its equivalent, the Kianga Formation. During the Late Permian, large quantities of volcanlithic sediments were shed from upland areas to the east, resulting in a prograding fluviodeltaic depositional system. Craton derived sediments were deposited by fluvial systems along the western margins of the basin providing quartzose sandstones with good reservoir potential.

During the latest Permian, following the onset of a contractional tectonic event, initial deposition of the volcanolithic alluvial sediments of the lower Rewan Group (Digby Formation) occurred across the basin from the eastern margin to the west. The quartzose sandstones of the overlying Middle Triassic Clematis Group (Wollar Sandstone Member) reflect a change in provenance, with sediments being sourced predominantly from the uplifted western craton instead of the arc in the east (Fielding et al. 1990a,b). The Showgrounds Sandstone, an important petroleum reservoir and subsurface equivalent of the upper part of the Clematis Group on the western side of the basin, shows evidence of being deposited in a body of standing water such as a lake or a sea (Butcher, 1984).

TABLE 8. GUNNEDAH-BOWEN AND SURAT STRATIGRAPHY

Age		Palynolog. Zone	Gunnedah - Bowen and Surat Basins Stratigraphy: Southern Bowen Basin (NSW)	Bellata area	Gunnedah Basin	Basin
Cretaceous	Late	APK 7				Surat Basin
	Early	APK 6				
		APK 5	Rolling Downs Group: Griman Creek Formation			
		APK 4	Surat Siltstone Wallumbilla Formation: Coreena Member Doncaster Member			
		APK 3				
		APK 2	Blythesdale Group: Bungil Formation	Blythesdale Group: Bungil Formation	Blythesdale Group: Bungil Formation	
		APK 1	Mooga Sandstone	Mooga Sandstone	Mooga Sandstone	
Jurassic	Late	APJ 6	Orallo Formation Gubberamunda Sandstone Injune Creek Group: Westbourne Formation Springbok Sandstone Pilliga Sandstone	Orallo Formation Pilliga Sandstone	Orallo Formation Pilliga Sandstone	
	Middle	APJ 5				
		APJ 4	Walloon Coal Measures Bundamba Group: Hutton Sandstone	Purlawaugh Formation / Walloon Coal Measures and Hutton Sandstone	Purlawaugh Formation: Digilah Mbr Ukebung Mbr	
		APJ 3				
	Early		Evergreen Formation			
		APJ 2	Precipice Sandstone			
		APJ 1				
					Garrawilla Volcanics	
Triassic	Late	APT 5				Gunnedah / Bowen Basin
		APT 4				
	Middle	APT 3	Moolayember Formation/ Wandoan Group Snake Creek Mudstone Member Clematis Group: Showgrounds Sandstone	Moolayember Formation Snake Creek Mudstone Mbr T1&T2 units/ Napperby Formation	Deriah Formation Napperby Formation	
	Early	APT 2				
		APT 1	Rewan Group / Cabawin Formation (only in Glencoe-1)	Digby Formation	Digby Formation	
Permian	Late	APP 6	Blackwater Group / Kianga Formation (McIntyre-1)		Black Jack Group: Trinkey Formation Wallala Formation	
		APP 5			Clare Sandstone Benelabri Mudstone Mbr Hoskissons Coal Brigalow Formation Arkarulla Formation Pamboola Formation	
		APP 4	Back Creek Group Upper Lower	Porcupine Formation	Millie Group: Watermark Formation Porcupine Formation	
	Early	APP 3	Maules Creek Formation	Maules Creek Formation	Bellata Group: Maules Creek Formation	
		APP 2	Goonbri Formation? / Reids Dome beds (Lantern-1 and McIntyre-1)	Goonbri Formation	Goonbri Formation Leard Formation	
		APP 1				
Basement			Kuttung Formation / Boggabri Volcanics Timburry Hills	Werrie Basalt	Boggabri Volcanics and Werrie Basalt	Basement

The Middle Triassic Moolayember Formation (Napperby Formation) is the youngest unit in the Gunnedah-Bowen Basin and its lithology reflects a return to sourcing from a volcanic province in the east. The Formation consists mainly of fluvial and lacustrine deposits. The dark, fine-grained Snake Creek Mudstone Member at the base of the Moolayember Formation is believed to have been deposited in a marginal marine or tidal-flat environment (Butcher, 1984).

Major compressive deformation during the Middle-Late Triassic resulted in regional uplift, folding, and the erosion of up to 3000m of section along some portions of the basin (Fielding et al, 1990a,b). As the developing thrust front propagated westwards, it brought about a termination of sedimentation within the Basin (Korsch and Totterdell, 1994). This event resulted in erosion of the Permian sequence and erosion and angular truncation of mid-Triassic sequence beneath the Surat Basin.

3.10.3 Structural Elements

The following overview of the structural elements of the Gunnedah-Bowen Basin is modified after Upstream Petroleum Consulting Services (2002c), and Vanibe (2000), see figure 18.

Maules Creek Sub-Basin

The Maules Creek Sub-basin is located on the eastern side of the Gunnedah Basin, between the Tamworth Belt of the New England Fold Belt, to the east and the Boggabri Ridge to the west. Deformation associated with crustal shortening, during the Permian and Triassic, has produced thrust

faults that have deformed and faulted the basin sediments and thrust the western edge of the New England Fold Belt over the eastern side of the Maules Creek Sub-basin for distances of up to 15km. This has resulted in Carboniferous (basement) rocks of the New England Fold Belt covering at least the eastern third of the Maules Creek Sub-basin.

Moree High

The Moree High is an east-west trending basement high that separates the Bellata Trough from the Boomi Trough to the north and terminates the Rocky Glen Ridge at its north. It lies near latitude 29° 30'S, and is approximately 50-60 km wide. It may be an easterly projection of the Lightning Ridge High.

Taroom Trough

The Taroom Trough is a narrow, deep, north-south oriented trough, located between the Gil Gil Ridge and the Moonie-Goondiwindi Fault. It extends southwards to the approximate position of the Moree High. It contains a thick Permo-Triassic sequence that may merge northwards with the Boomi Trough. It has a complex basement geometry including structurally reactivated basement ridges and grabens.

3.10.4 Stratigraphy

Principal stratigraphic units are shown in table 8**,** and are summarised as follows.

Early Permian and Older Basement

In the west, basement is comprised of a variety of Ordovician to Devonian geological units. They include granites, volcanogenic metasediments, volcanics, and sediments. Pre-Carboniferous basement intersected in drillholes, in the eastern half of the basin, comprises metasediments (Devonian Timbury Hills Formation) and generally non-magnetic granites. This is overlain by Late Carboniferous to Early Permian volcanic rocks, which are the initial deposits of the Gunnedah-Bowen Basin. The volcanics are bimodal and include the Camboon and Combargno Volcanics (Bowen Basin) and the Boggabri Volcanics and Werrie Basalt (Gunnedah Basin).

The volcanic sequence is very thick in the Taroom Trough and the eastern part of the Gunnedah Basin, and thins westwards onto the Lachlan Fold Belt, where only thin remnants remain. These have recently been modelled by Gunn (2002b) as part of the current review of the BBSB. The volcanics have been eroded with the upper part of the basaltic rocks in particular, showing evidence of deep weathering. All units are commonly overlain by Early Permian colluvial deposits, poorly sorted conglomerate or breccia.

Early Permian: Reids Dome Beds (Maules Creek, Goonbri & Leard Formation equivalents)

The Early Permian Reids Dome Beds sedimentary rocks were deposited in alluvial plain to lacustrine environments within the initially developing depocentres of the Taroom Trough and Denison Trough. Sediment input was predominantly from the northwest with additional input off the flanks to the east. In the Bowen Basin, the section comprises an initial course grained terrestrial sequence overlain by paralic and fluvial sequences capped by a shallow marine sequence which culminate in the Cattle Creek Formation. These units lap onto the flanks of the Taroom Trough and have only been positively described in Macintyre-1, located near the border with Queensland. Early Permian sediments penetrated

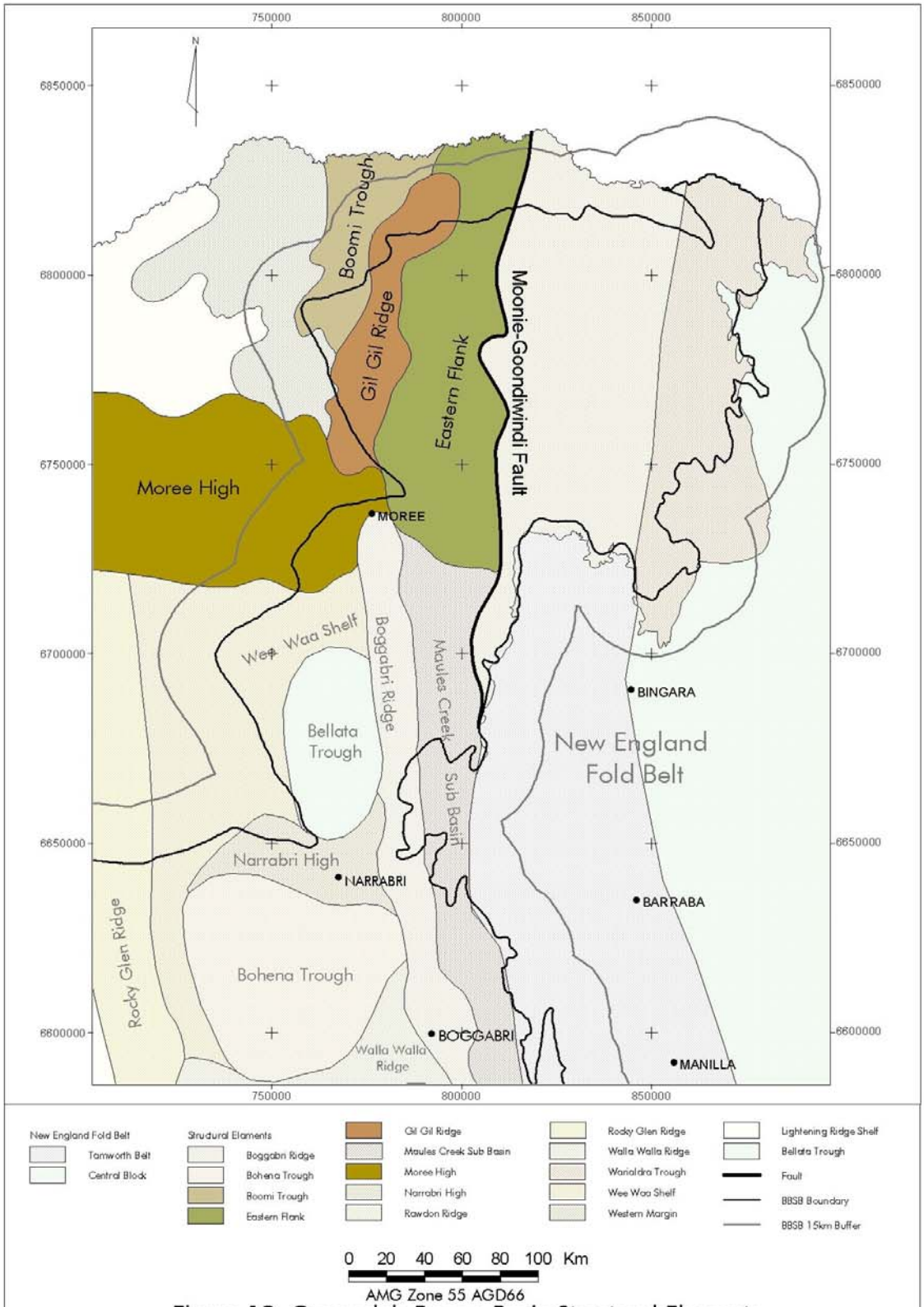

Figure 18. Gunnedah-Bowen Basin Structural Elements

in Goondiwindi-1, Mt Pleasant-1, and in Bellata-1 are thought to be slightly younger (Totterdell & Korsch, 1995) and constitute the Leard and Goonbri Formation equivalents.

Back Creek Group (Watermark and Porcupine Formation equivalents)

The Mid to Late Permian Back Creek Group, which unconformably overlies the Kuttung / Reids Dome Beds, can be divided into an upper and a lower part on the basis of the dominant lithology. The lower part is a wholly marine sequence of shale, siltstone, minor sandstone, and limestone, which is equivalent to the Porcupine Formation of the Gunnedah Basin. Some of the units within this section are very fossiliferous. The upper part is a marginal marine to non-marine sequence of dominantly sandstone with minor shale and siltstone. The sandstone appears to have had a local easterly provenance. The Upper Back Creek Group is equivalent to the Watermark Formation of the Gunnedah Basin.

At the southern end of the Gunnedah-Bowen Basin, north of Moree, the lower part of the Back Creek Group contains interbedded conglomerate, sandstone, siltstone, shale and coal, which have been attributed to deposition in an alluvial fan setting (OCA, 1985). In Mt Pleasant-1, the lower Back Creek Group attains a thickness of 635m. The unit thins easterly, towards the Goondiwindi Fault, and thins westerly where it is eventually overlapped by the upper part of the Back Creek Group sediments. South of Moree, lower Back Creek Group sediments extend as far south as Gurley where they are overlapped by Jurassic sediments against the Moree High. South of the Moree High, equivalents of the lower Back Creek Group continue southwards into the Gunnedah Basin and were intersected in DM Bellata DDH 1.

Kianga Formation (Black Jack Group equivalent)

Conformably overlying the Back Creek Group is the Late Permian Kianga Formation. This formation onlaps to the south and is only present in the extreme northeast of the basin. It is a coal measure sequence, comprising coal, tuff, siltstone, shale and sandstone. It was deposited in low energy streams in a non-marine environment consisting of fluvial channel to flood plain and peat swamp deposits. It has a thickness of 86 m in Macintyre-1, which is the only, well that it has been recognised in New South Wales.

The Black Jack Group is extensively developed in the Bellata Trough and south of the Narrabri High. At its thickest, the section is 162 m in the southeast.

Rewan Group (Digby Formation equivalent)

The Triassic Rewan Group unconformably overlies the Kianga Formation. It is only present in the very north of the basin, onlapping to the south. It has only been identified at Glencoe-1 where it unconformably overlies the Late Permian Blackwater Group and is unconformably overlain by the Showgrounds Sandstone. It is a volcanogenically derived, terrestrial conglomerate, sandstone and siltstone sequence and was deposited as a meandering stream and flood plain sequence. It is the equivalent of the lower Digby Formation in the Gunnedah Basin and at Glencoe-1 it has a thickness of 65 m.

Showgrounds Sandstone

Conformably overlying the Rewan Group is the Mid Triassic Showgrounds Sandstone, a west-northwesterly derived quartzose sandstone sequence that is a major hydrocarbon reservoir on the western flank of the basin in Queensland. The unit is equivalent to the quartzose westerly sandstone facies of the Digby Formation in the Gunnedah Basin. It consists of up to 42m of quartzose sandstone, conglomerate, siltstone and shale and is equivalent to the upper part of the Clematis Group, which crops out in the northern part of the Bowen Basin.

The Showgrounds Sandstone rests unconformably over the older Rewan Group, Kianga Formation or older Permian sediments and basement rocks. Facies reconstruction of the Showgrounds Sandstone by OCA (1985) suggested the presence of a northeasterly flowing fluvial system that passes basinward into a restricted marine or lacustrine succession via near-shore and deltaic facies. The Showgrounds Sandstone was intersected all deep petroleum wells except for Werrina-1 and Mt Pleasant-1, where the development of emergent highs has restricted deposition of the Showgrounds Sandstone and Snake Creek Mudstone.

Snake Creek Mudstone Member

The Showgrounds Sandstone is conformably overlain by the Mid Triassic Snake Creek Mudstone Member, a uniform dark grey-black shale. The Member has been interpreted as deposits of a restricted marine to lacustrine environment (OCA, 1985). The Snake Creek Mudstone provides a good regional seal for the underlying Showgrounds Sandstone reservoir and is considered a potential oil source rock. It is the time equivalent to the lower Napperby Formation in the Gunnedah Basin.

Moolayember Formation
Triassic deposition ceased with deposition of the Mid Triassic Moolayember Formation. This formation conformably overlies the Snake Creek Mudstone Member and is the same age as the upper Napperby Formation in the Gunnedah Basin. It consists of marine and non-marine interbedded sandstone, siltstone, shale and coal. The formation is a major hydrocarbon reservoir on the western side of the Surat Basin. In the southern Surat Basin it has little reservoir potential but does have good oil source rock potential. It is more widespread than the underlying Triassic units although it also onlaps along the western margin of the basin.

3.10.5 Structure

Recent reviews of exploration data suggest that there is a complex pattern of faulting within the Basin. There is evidence for strike-slip movement along major faults developed as part of the Late Permian-Triassic compressional event. The sense of direction, whether dextral or sinistral, is still the subject of debate as is their primary direction (Scheibner and Basden, 1996, and Gunn 2002). Some normal growth faults have been reactivated to become reverse faults. The present eastern margin of the Bowen Basin is bounded by a series of north-south trending faults that are generally westerly directed thrusts. Some of these may be thin-skinned, and parallel basement across the Basin, emerging as a ramps along the western side forming structures analogous to the Rocky Glen Ridge.

3.10.6 Volcanic Activity

There are two main periods of volcanic activity affecting the Gunnedah-Bowen Basin following the emplacement of the basal volcanics.

Garrawilla Volcanics
The Garrawilla volcanics were emplaced in the Late Triassic, circa 218 Ma, in the area to the east of Narrabri and continued with regular activity, although in widely separated areas, for at least the next 99 Ma to the Early Cretaceous.

Tertiary Volcanics
Tertiary volcanic and intrusive rocks are widespread in the south and east of the area and include the large eroded volcanic complexes of the Warrumbungle Mountains and the Nandewar Ranges. Intrusions intersected within Permian sediments to the north of Moree, have locally affected adjacent strata (e.g., Lantern-1), which have consequently passed through the main phase of hydrocarbon generation. Sill-like intrusions have also been encountered in Triassic strata, west of Narrabri (e.g., Wee Waa 1) and in places, intrude main reservoir targets (Coonarah 1). Many sills are relatively thin and their impact on maturation appears to be largely local (Othman and Ward, 1999, and 2002).

3.11 SURAT BASIN

3.11.1 Introduction

The Surat Basin is part of the Great Australian Basin, a Jurassic-Cretaceous intracratonic basin that covers 1.7 million square kilometres of Eastern Australia. The Surat Basin covers the north-central part of New South Wales with an area of approximately 108 000 square kilometres that extends from the Queensland border as far south as Dubbo, to the east of Moree, and nearly as far west as Bourke.

The western and central parts of the Surat Basin sequence unconformably overlie Palaeozoic rocks of the Lachlan Fold Belt. The eastern part overlies the Permo-Triassic Sydney-Gunnedah-Bowen Basin system. The BBSB covers much of the central and eastern Surat Basin.

3.11.2 Overview of Basin History

The Surat Basin extends across southeast Queensland into New South Wales and unconformably overlies the Bowen and Gunnedah Basins. Initial sedimentation in the Surat Basin was centred in the Mimosa Syncline above the Taroom Trough in Queensland, which overlies the thickest Permo-Triassic rocks.

After a long period of erosion and peneplanation at the end of the Triassic, a large intracratonic sag was initiated, which eventually formed the Great Australian Basin. It is a composite basin system including the Surat, Carpentaria, Clarence-Moreton, and Eromanga Basins. Deposition occurred in these basins until the Early Cretaceous.

The driving force for the formation of these basins remains controversial. Korsch et al (1989) have suggested that the basins formed as a result of thermal sag after the cessation of rifting associated with the Camboon Volcanic Arc. Alternatively, Kingston et al (1983) have described similar extensive intracratonic sags developing under a tensional regime resulting from divergent plate motion. Subsidence of the Surat Basin was extensive, slow and relatively even (Exon, 1976). Later deformation of the Basin sequence comprised mild compression producing flexures above older faults.

The Garrawilla Volcanics were first deposited in the southeast of the Basin at the end of the Triassic. However, activity continued across a wide area into the late Jurassic. Sedimentation in the Basin commenced in the Early Jurassic with deposition of the alluvial Precipice Sandstone. This was succeeded by lacustrine to coastal plain sediments of the Evergreen Formation, age equivalent to the fluvial and lacustrine sediments deposited in the Eromagna Basin. Widespread deposition of quartzose fluvial sediments of the Middle Jurassic Hutton Sandstone was succeeded by lacustrine to deltaic sedimentation resulting in the deposition of organic rich shales and siltstones in the Birkhead Formation, and coals in the laterally equivalent Walloon Coal Measures. Deposition of laterally extensive thick braided fluvial sandstones of the Pilliga Sandstone directly followed. Fluvial, alluvial and lacustrine sediments of the Orallo Formation in turn overlie these.

Sedimentation in the Surat Basin ceased in the Middle Cretaceous. This cessation coincided with a compressional event which was responsible for the uplift and erosion of the Bowen and Surat Basins and their associated volcanic arcs in the Middle Cretaceous (Elliott, 1994). Deformation also occurred during the Late Cretaceous and Tertiary due to epeirogenic movements as well as forces relating to divergent plate motion during the break up of Gondwana (Exon, 1976, Veevers et al, 1982, Fielding et al, 1990b, Elliott, 1993).
Late Cretaceous to Early Tertiary compressional events rejuvenated existing structures and created new high angle reverse faults and anticlinal closures which are the targets for petroleum traps throughout the northern BBSB. Intrusion of Tertiary plugs, dykes and sills have caused uplift, doming and normal faulting of the Permian and Triassic succession and in some cases, form a significant component of structures targeted for hydrocarbons (eg. Wilga Park).

3.11.3 Structural Elements

There is no clear structural feature that separates the Eromanga Basin from the Surat Basin in New South Wales. In Queensland, the Nebine Ridge forms the barrier between these two basins. Bamberry and Kouzmina (1995) noted that thickening of the basin fill near longitude 1470E marks an arbitrary division between these basins.

The Surat Basin in New South Wales is generally a more shallow extension of the main basin sequence developed in Queensland. It has been divided into six units in NSW, three of which occur within the BBSB ie, the Boomi Trough, Lightning Ridge Shelf, and the Coonamble Embayment (Bourke, Hawke and Scheibner, 1974, Scheibner, 1993), (figure 19).

Boomi Trough
The Boomi Trough is the southern extension of the Mimosa syncline and its boundaries are approximately the same as the underlying Taroom Trough. As the Boomi Trough shallows westward it merges with the Lightning Ridge Shelf.

Lightning Ridge Shelf
Only the eastern part of the Lightning Ridge Shelf is within the BBSB. It is a stable area extending west of Walgett. It coincides with the southerly extension of the Dirranbandi Syncline, but as that basement structure is not well known, the more general term “shelf” is preferred.

Coonamble Embayment
The Coonamble Embayment is a broad, shallow, fairly uniform area forming most of the south and southwest of the Basin. It merges with the Cunnamulla Shelf of the Eromanga Basin, the Lightning Ridge Shelf and the Boomi Trough. Its northern boundary is taken as the Walgett Lineament Zone.

3.11.4 Stratigraphy

The stratigraphy of the Surat Basin is shown in table 8.

Precipice Formation
The Precipice Formation is comprised of Early Jurassic braided stream sandstones with their provenance in northwestern central Queensland. The Formation gradually thins to the south, being absent over most of the southern Surat Basin. The main axis of deposition was in Queensland via a braided fluvial system that flowed southerly down the axis of the Taroom Trough then east through the Tara Trough to the Cecil Plains Depression and out to the east via the Clarence-Moreton Basin. It was only deposited in the far northern part of New South Wales.

Evergreen Formation
The Precipice Formation is conformably overlain by a major lacustrine shale, siltstone and sandstone sequence of the Early Jurassic Evergreen Formation**.** In New South Wales, the Precipice Sandstone and Evergreen Formation are confined to a small area between Boomi and Goondiwindi within the Boomi Trough. A high proportion of sandstone in the Evergreen Formation makes differentiation of the two formations difficult in this area, although both formations can be identified in Limebon-1, Goondiwindi-1, Chester-1 and Macintyre-1. The maximum thickness of this sequence in New South Wales is 114 m in Limebon-1. Drilling and palynological evidence demonstrated the presence of a combined Evergreen Formation-Precipice Sandstone sequence in Quack-1.

Hutton Sandstone
The Middle Jurassic Hutton Sandstone is a thick sequence of stacked quartzose braided stream sandstones. The unit often contains an appreciable thickness of siltstone and shale, particularly in its basal part. It conformably overlies the Evergreen Formation where present, and disconformably overlies Triassic rocks elsewhere. Its southern subsurface limit runs approximately southeast from Mungindi towards Moppin, 32km northwest of Moree, and then eastwards towards Warialda (Bourke, 1980). Etheridge (1987) interpreted a basal Jurassic quartzose sandstone intersected in DM Bellata DDH 1 as a Hutton Sandstone correlative suggesting that the Hutton may extend as far south as Bellata.

Walloon Coal Measures
The Hutton Sandstone is conformably overlain and overlapped by the southward thinning Mid Jurassic Walloon Coal. These are a coal measure sequence composed of coal, sandstone, siltstone and shale that have excellent oil source rock characteristics.

Purlawaugh Formation
The Purlawaugh Formation unconformably overlies the Garrawilla Volcanics where present, or unconformably overlies the Napperby Formation in the Coonamble embayment. It extends across the whole area from the Goulburn River Valley in the east to Dubbo in the west to Narrabri in the north. The Purlawaugh Formation is comprised of siltstone, mudstone, kaolinitic claystone, interbedded with carbonaceous or coaly shale, thin coal seams and fine to medium grained lithic-labile sandstone. The coal is stratigraphically equivalent to the Walloon Coal measures.

Pilliga Sandstone
Conformably overlying the Walloon Coal Measures/Purlawaugh Formation are fluvial braid channel quartzose sandstones of the Middle to Late Jurassic Pilliga Sandstone. The Pilliga Sandstone is conformably overlain by the Late Jurassic to Early Cretaceous clastics of the Orallo, Mooga, Bungil, and Wallumbilla Formation.

Orallo Formation
The Late Jurassic to Early Cretaceous Orallo Formation consists of medium-grained sub-lithic sandstone and interbedded siltstone and mudstone with minor thin coal seams. The formation thins westwards, eventually pinching out west of Lightning Ridge. The base of the formation is gradational with the underlying Pilliga Sandstone. The top of the formation is marked by the disconformable base of the Mooga Sandstone. The Orallo Formation does not often crop out in New South Wales, as outcrops are usually concealed beneath alluvial deposits.

Mooga Sandstone
The Early Cretaceous Mooga Sandstone consists mainly of quartz sandstone with subordinate beds of mudstone. Exon (1976) recognised three sub units in the formation: a basal unit consisting of sub-lithic to quartzose conglomeratic sandstone, a middle unit comprising dark grey mudstone, a top unit consisting of fine- to medium-grained sub lithic sandstone with pebble and mudstone lenses.

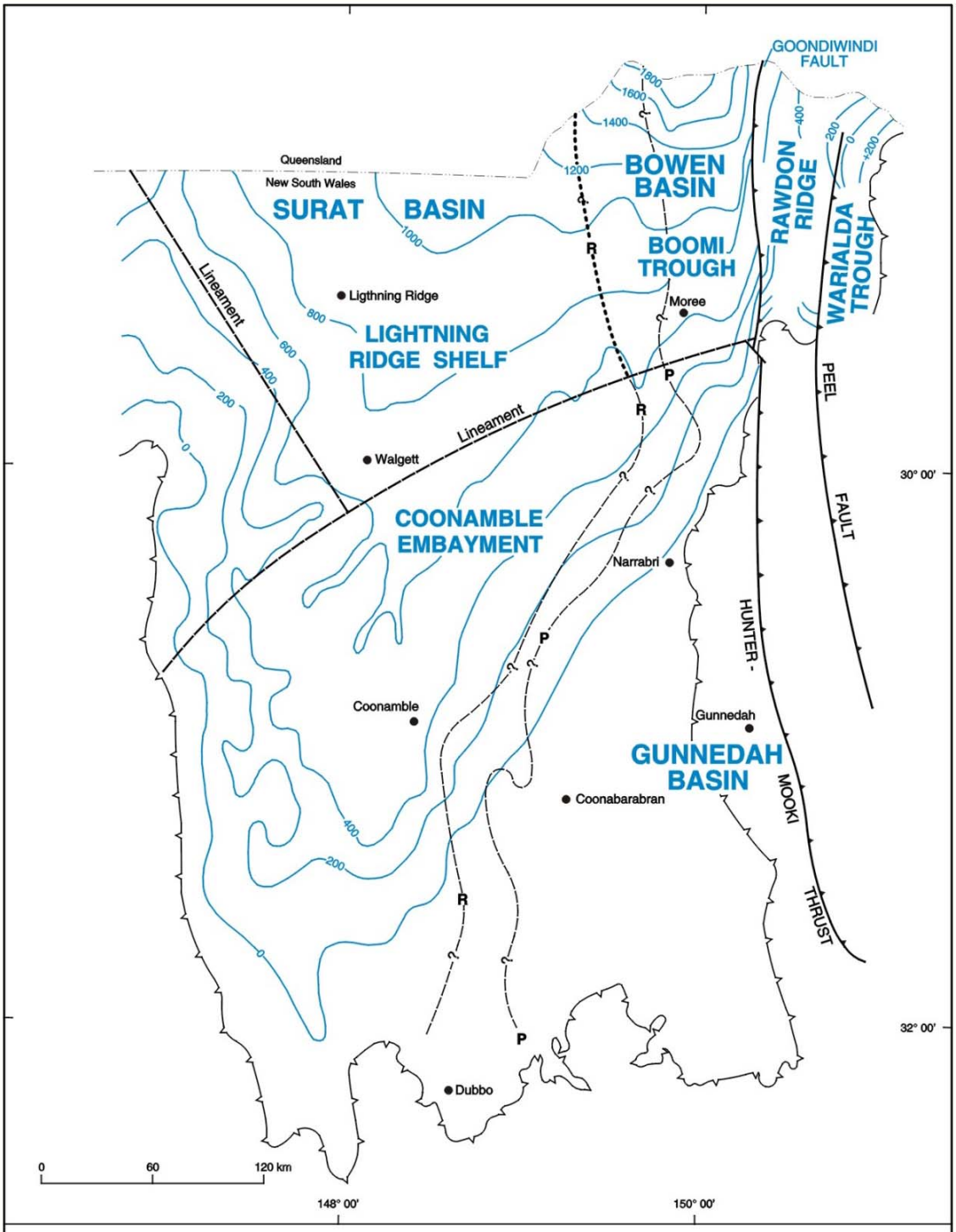

Figure 19 Surat Basin Structural Elements

Bungil Formation
The Early Cretaceous Bungil Formation comprises a succession of fine-grained lithic sandstone, siltstone and mudstone with subordinate coarse-grained quartzose sandstones. Siltstone and mudstone beds are commonly carbonaceous and, in places, the formation contains thin coal seams. Glauconite-bearing beds and calcareous concretions are present in the upper part of the unit.

Keelindi beds
The latest Jurassic to Early Cretaceous Keelindi beds (stratigraphic equivalents of the Orallo Formation, Mooga Sandstone and lowermost Bungil Formation) conformably overlie the Pilliga Sandstone in places. They represent the transition from the terrestrial braided stream environment of the Pilliga Sandstone to the floodplain of a meandering river system. In the Early Cretaceous, regional subsidence allowed the sea to invade most of the Surat Basin. The uppermost part of the Keelindi beds are marginal marine in nature, indicating an Early Cretaceous regression.

Drildool beds
The late Early Cretaceous Drildool Beds are the lateral equivalent of the dominantly marginal marine Bungil Formation. The unit was deposited in a coastal plain to intertidal environment, containing mudflats, tidal channels and marshy areas inshore from the tidal mud flats. The unit consists of grey, fine grained lithic sandstone, laminated, interbedded, and intermixed with siltstone, mudstone, and minor thin seams of coal. There are sporadic pebbles and fragments of mudstone and coal, and also rare beds of mudstone breccia.

3.11.5 Structure

The Surat Basin has been subjected to Early-Middle Jurassic compression with associated folding and high angle reverse faulting, rejuvenating existing faults and other structures. Drape over basement highs and compaction induced subsidence over the thick Permian and Triassic succession characterised structuring of the Surat Basin. The next phase of structuring occurred in the Late Cretaceous – Tertiary which was also a period of compression with regional uplift and erosion. Older structures were once again rejuvenated. Tertiary igneous intrusions, which are common throughout the Surat Basin, often complicate structural interpretations. Tertiary intrusions, dykes and sills have cause uplift, doming and normal faulting of the Permian and Triassic strata.

3.11.6 Volcanic Activity

Tertiary volcanic and intrusive rocks are widespread in the areas south and east of the Surat Basin and include the large eroded volcanic complexes of the Warrumbungle Mountains, the Liverpool and the Nandewar Ranges. Borehole data in the Gunnedah Basin (Martin 1993) showed that volcanic rocks commonly intrude the Permian and Triassic rocks, whereas intrusions in the Purlawaugh Formation are less common.

3.12 WARIALDA TROUGH

3.12.1 Introduction

The following overview of the Warialda Trough is modified from Bourke (1980). The Warialda Trough is a Mid to Late Triassic sedimentary sequence which rests unconformably over the New England Fold Belt, and is unconformably overlain by the Surat Basin and Tertiary Volcanics. Units of the Warialda Trough crop out southeast of Warialda and continue as a series of parallel belts to the north in the subsurface. The trough sequence is of terrestrial origin with thickness up to 200 metres.

3.12.2 Overview of Basin History

The Mid-Triassic Gunee Formation nonconformably overlies rocks of the New England Fold Belt including the Early to early Middle Triassic Dumboy-Gragin Granite. The implications for this observed discordance is that there was a high rate of erosion of up to 2 kilometres of the New England Fold Belt in the Early to Middle Triassic. This erosion was concurrent with the deposition of high-energy braided stream sediments of the Digby Formation to the west.

A high-relief land surface prevailed in the Middle Triassic for the initial deposition of the trough sediments. The palaeogeography consisted of narrow river valleys surrounded by hills of the New England Fold Belt Central Block (Bourke 1980). This high-relief palaeogeography is manifest as coarse

conglomerates derived locally from the Dumboy-Gragin Granite and the Woolomin Group. As the narrow valleys filled, the source areas of the detritus became more distant and the energy of the depositional system decreased. Small lakes, well-vegetated swamps, and marshy areas developed in the partly filled valleys. Deposition of the overlying Gragin Conglomerate is believed to have been in a piedmont environment sourced from Permian volcanics with relatively little input from the Woolomin Group (Chesnut and Cameron 1971). Uplift during the Late Triassic ended sedimentation of the Warialda Trough and it was covered by the Surat Basin in the Early to Mid Jurassic.

3.12.3 Structural Elements

There is insufficient drilling and geophysical data on the Warialda Trough to determine wether it can be subdivided into structural elements.

3.12.4 Stratigraphy

Mid Triassic and Older Basement
The basement is composed of a variety of Cambrian-Permian to early Mid Triassic geological units. They include the Dumboy-Gragin Granite and the Woolomin Group of the New England Fold Belt Central Block in the south, as well as Permian-Triassic Bowen Basin sedimentary units in the north.

Gunee Formation
The Gunee Formation overlies the basement nonconformably and is comprised of a clastic sequence grading upwards from paraconglomerate to carbonaceous shale and coal. Clasts range in composition from chert to meta-siltstones to granite. The thickness of this unit is generally less than 50 metres but may thicken in the north beneath cover to over 100 metres.

Gragin Conglomerate
The Gragin Conglomerate unconformably overlies the Gunee Formation and is predominantly composed of orthoconglomerates with minor sandstones. Clasts are comprised mostly of Permian felsic volcanics, presumably from the Wandsworth Volcanic Group. The thickness of this unit, where exposed, is generally less than 100 metres but it may thicken to the north. The unit has been attributed to deposition in a piedmont setting.

3.12.5 Structure

The sedimentary sequences in the Warialda Trough are generally undeformed. However, minor drape folding during deposition has inclined the sediments, with dips of up to twenty degrees recorded.

3.12.6 Volcanic Activity

Alkaline basalts of the Central Volcanic Province intrude and unconformably overlie the sedimentary rocks of the Warialda Trough. Volcaniclastic sediments of the Central Volcanic Province also overlie units of the Warialda Trough, which are an important source of sapphires in the New England Fold Belt.

3.13 TERTIARY VOLCANIC AND SEDIMENTARY UNITS

Tertiary volcanic and sedimentary rocks are widespread throughout New South Wales and other eastern Australian states. The Tertiary volcanic units within the BBSB are genetically related to four separate provinces. These provinces contain volcanic rocks that were erupted in a continental intraplate setting and form part of an extensive volcanic belt that stretches along the highlands of Eastern Australia from Victoria to northern Queensland.

Within the BBSB, Tertiary volcanic and intrusive rock units contain a variety of rock types including basalt, trachyte, dolerite, pyroclastic breccias and tuffs. They have intruded or in part unconformably overlie many of the older units within the BBSB and are in part overlain by younger Quaternary sediments.

The Tertiary volcanic activity within the Sydney-Bowen Basin is described in detail in earlier sections. The northwestern end of the Central Volcanic Province lava field also lies within the northeastern part of the BBSB near Warialda. The province forms an elongate belt about 240 km long and up to 70 km wide, capping the New England Fold Belt, and parts of the Surat Basin and Warialda Trough. This lava field is

dominated by alkali olivine basalt, with subordinate trachybasalt, picrite basalt, analcamite, basanite, nephelinite, and minor volcaniclastics.

Tertiary volcanic rocks are sometimes an important source of construction materials, and in places also have important economic implications with regard to sapphires. Furthermore, weathering of Tertiary volcanic rocks has produced most of eastern Australia's best soils, including those throughout the BBSB.

Tertiary sediments are generally spatially related to the volcanic rocks and comprise clay-rich quartz and lithic sand as well as gravel, silt, kaolin-rich clay, pebbly clay, diatomaceous earth, and laterite.

3.14 QUATERNARY SEDIMENTS

Large areas of unconsolidated Quaternary sediments of fluvial, colluvial and residual origin dominate the northern two thirds of the BBSB. The fluvial sediments were deposited by present day and abandoned river systems that comprise the Darling Riverine Plain. The Liverpool Plains, which cover much of the central portion of the BBSB, comprise a well-defined part of the Darling Riverine Plain north of the Liverpool Ranges. The unconsolidated Quaternary sediments overlie rocks of the Gunnedah and Surat Basins, as well as rocks of the Lachlan and New England fold belts.

The present day alluvial landscape is dominated by the abandoned Quaternary river systems, which have remnants slightly elevated with respect to the modern systems. They vary in character from bed-load systems in the older units through mixed-load systems to the modern suspended-load systems. Rare source bordering dunes (lunettes) are found adjacent to small lakes. The deposits comprising each system can be broadly subdivided into meander plain and flood plain sediments. Common fluvial features include scroll bars, oxbows, depressions and scalds.

Narrow belts of colluvial material fringe the hill lands surrounding the riverine plain. They represent transitional landscapes between the elevated landscapes and the lower depositional floodplains. The belts slope gently towards the riverine plains and often represent relict small-scale alluvial fans and braid plains shedding into the fluvial zone.

In the area southwest of Narrabri, the riverine plain is flanked by slightly elevated erosional surfaces developed on pre-Cainozoic rock that are blanketed by Quaternary residual material. They consist mostly of deeply weathered sediments of the Jurassic Pilliga Sandstone and Cretaceous Keelindi beds that form slightly undulating low hill lands of up to 20 m relief, with well-defined dendritic drainage lines.

Widespread but uneconomic deposits of heavy mineral sands occur within small to medium sized present and abandoned stream channels between Narrabri and Baradine. These rutile, zircon and leucoxene bearing sands have been derived from the weathering and reworking of heavy minerals within the Early Cretaceous Keelindi beds and Jurassic Pilliga Sandstone.

4. EXPLORATION AND MINING HISTORY

4.1 METALLIC MINERALS

There are 29 metallic mineral occurrences in the BBSB (figure 20). Details of occurrences are found in the metallic mineral occurrence database of the Geological Survey of New South Wales (Downes 1999a). Copper, gold, silver and other base metals have been mined on a small scale in the BBSB, in the Wongoni and Glengarry areas. Scattered copper and gold occurrences have been prospected just within or south of the BBSB boundary east of Dubbo. Scattered small alluvial gold occurrences occur throughout the BBSB, but production has never been significant. Tin and bismuth occurrences have been mined on a small scale close to the margins of the BBSB in the Warialda area. Metallic mineral exploration within the BBSB since the 1960s has focused primarily on gold, copper, lead, zinc, and silver. Areas around the southern margins of the BBSB, such as Quirindi, Comobella, Dubbo and Merrygoen have received the most attention. Perceived prospectivity, commodity prices, accessibility and metallurgical technology are factors that have a marked influence on the level of exploration expenditure.

4.2 INDUSTRIAL MINERALS AND CONSTRUCTION MATERIALS

There are 364 industrial mineral and construction material occurrences recorded in the BBSB (figure 20). Details of occurrences are found in the industrial mineral occurrence database of the Geological Survey of New South Wales (Ray et al 2001). Diatomite has been mined intermittently at Chalk Mountain near Bugaldie. Kaolin has been mined as 'flint clay' in the Merrygoen area since the 1950s and near Boggabri. Extensive deposits of zeolite occur in the eastern parts of the BBSB, and a small operating mine has been established at Escott near Werris Creek, just outside the BBSB eastern boundary.

Alluvial diamonds have been recovered within the BBSB east of Narrabri, however production has been very limited. The Bingara, Copeton, and Cudgegong Diamond Fields are situated close the margins of the BBSB, which together have produced in excess of 236,000 carats. However the total production of gemstones within the BBSB itself has been small. A small operating alluvial diamond mine called the Monte Christo is situated at Bingara, just east of the BBSB.

Numerous other commodities have also been recorded within the BBSB. These include: heavy mineral sand (Narrabri), bauxite (Dubbo), clay/shale (Coolah), loam (Narrabri), nepheline syenite (Dubbo), ochre and other mineral pigments (Merrygoen and Boggabri), bentonite and fullers earth (Boggabri and Dubbo), emery (Quirindi), volcanic opal (Tooraweenah), zircon (Bugaldie), and soda ash (Pilliga State Forest). Petrified wood and other semi-precious stone is sold locally in several places.

Recent industrial mineral exploration has focused on rare earth elements (including niobium, yttrium, tantalum, and zirconium), zeolite, kaolin, heavy mineral sands (rutile, zircon, and monazite), and diamonds. Areas around the southern margins of the BBSB near Quirindi, Comobella, Dubbo and Merrygoen have received the most attention from exploration companies. Diamond exploration within the BBSB has been intermittent since the 1960s, notably in areas west of Bingara, and in the extreme southern margin near Ulan and Cudgegong. Exploration for heavy mineral sand has received modest

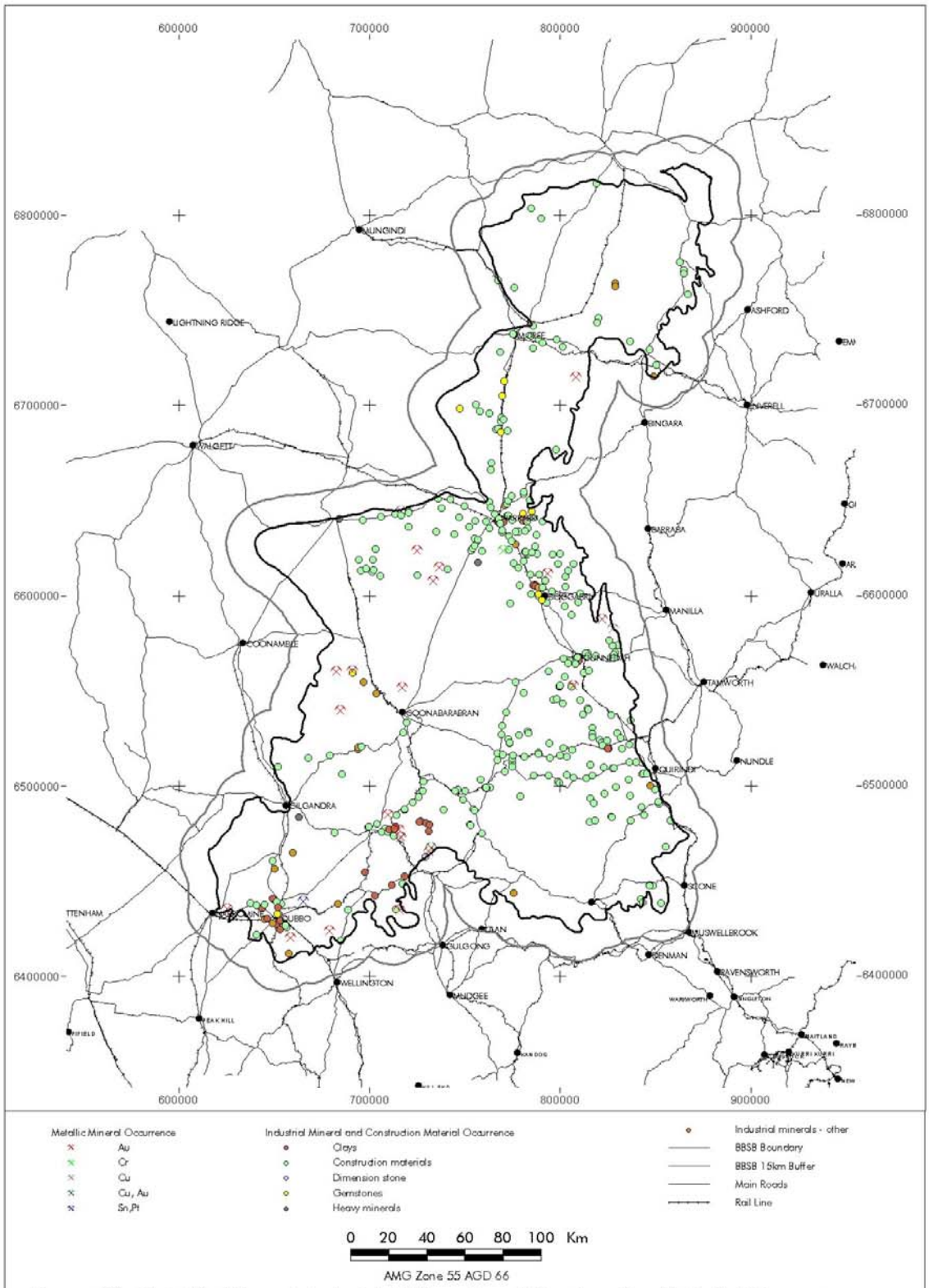

Figure 20. Metallic Mineral, Industrial Mineral and Construction Material Occurrences Brigalow Belt South Bioregion (Excluding the Buffer Zone)

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attention throughout the BBSB since the 1960s, notably in the area around Narrabri. There has also been limited exploration for sodium bicarbonate in recent years near Dubbo and Narrabri.

Construction materials are quarried across the BBSB. A list of all operating and intermittently operating quarries in the BBSB (excluding the buffer zone) is shown in Appendix 1.

4.3 COAL, PETROLEUM AND COAL SEAM METHANE

4.3.1 The Gunnedah Basin

The following discussion has been modified from reviews of the exploration history of the Gunnedah Basin by Tadros (1993a) and Morton (1995, 2000).

Oil Shale (torbanite) from Murrurundi (the Temi deposit in the Werrie Basin) was exhibited at the London International Exhibition in 1862. Coal was discovered in the Gunnedah area in 1877 in a well sunk on the property "Thornberry", followed by several other discoveries during the following few years. In 1880, Barney McCosker discovered a coal seam on "Black Jack Hill" and produced small quantities of coal which he transported to Gunnedah. Samuel Melville acquired the "Thornberry" property, employed McCosker to prospect for coal and sank a shaft to the coal seam in 1887.

The Centenary (Preston) Colliery at Curlewis commenced production of coal in 1889. Coal mining at Gunnedah also commenced in the 1890's and the Gunnedah Colliery and Black Jack Collieries were opened soon after. They produced coal for the railways and local industry, including the Tamworth power station. Coal production from both of the Gunnedah Coalfield mines dropped considerably in the 1960's due to the railways converting to diesel locomotives and to the closure of the Tamworth power station following expansion of the State Electricity Grid. In 1984, an expansion program commenced at Gunnedah Colliery that included development of two open cut pits to mine the Melvilles seam.

In the Boggabri - Maules Creek area, coal was discovered early this century during water drilling operations. In 1971, Sunshine Gold Pty Ltd (now Vickery Coal Pty Ltd) conducted a reconnaissance drilling program in the vicinity of the Vickery State Forest. In 1985, Vickery Coal Pty Ltd (a Novacoal Australia subsidiary) was granted Coal Lease 316 for the Vickery mine.

In 1980, Pacific Coal Pty Ltd (a CRA subsidiary) was granted Exploration Permit Tender Area No. 4 in the Maules Creek area. A Coal Lease was granted for the Maules Creek Project in 1991 which is now held by Queensland Coal Pty Ltd. Mining at the Maules Creek Project is yet to commence. Exploration Permit Tender Area No. 1 was awarded to a joint venture comprising BHP Minerals Ltd and AMAX Pacific Inc in 1975. A trial box cut into the Merriowen seam was constructed in 1979. In 1984, A355 was granted over an area adjacent to the west and in 1990 the Joint Venture was granted Coal Lease 368. Mining has yet to commence.

The Department of Mineral Resources has maintained a strong involvement in resource assessment of the Basin since 1974. Thirteen major programs have been completed with 186 boreholes being drilled and geophysical surveys being recorded. These programs have provided the framework of our understanding of the regional geology and the energy resources of the Basin (figure 21).

There have been four main phases of petroleum exploration in the Gunnedah Basin, the mid-1960s, the mid-1980s, 1993-1995 and 1998 to the present. The first three periods exclusively involved conventional petroleum exploration, whereas the last has involved an increasing proportion of coal seam methane related exploration and development drilling. To date, only 19 conventional petroleum exploration wells have been drilled, 15 of these during the first period in the mid-1960s, two in the mid-1980s and one in each of 1993 and 1995. In total, 7 wells were drilled within PEL 238. The most recent phase is partially a response to increased awareness of coal seam methane potential following exploration campaigns in the Bowen Basin.

One seismic reflection survey and numerous other geophysical surveys, including gravity and magnetics, were conducted in the 1960s. Coal assessment during the 1970s and 1980s clarified the distribution of coal and petroleum source rock sequences. At the time, numerous small gas shows were reported during

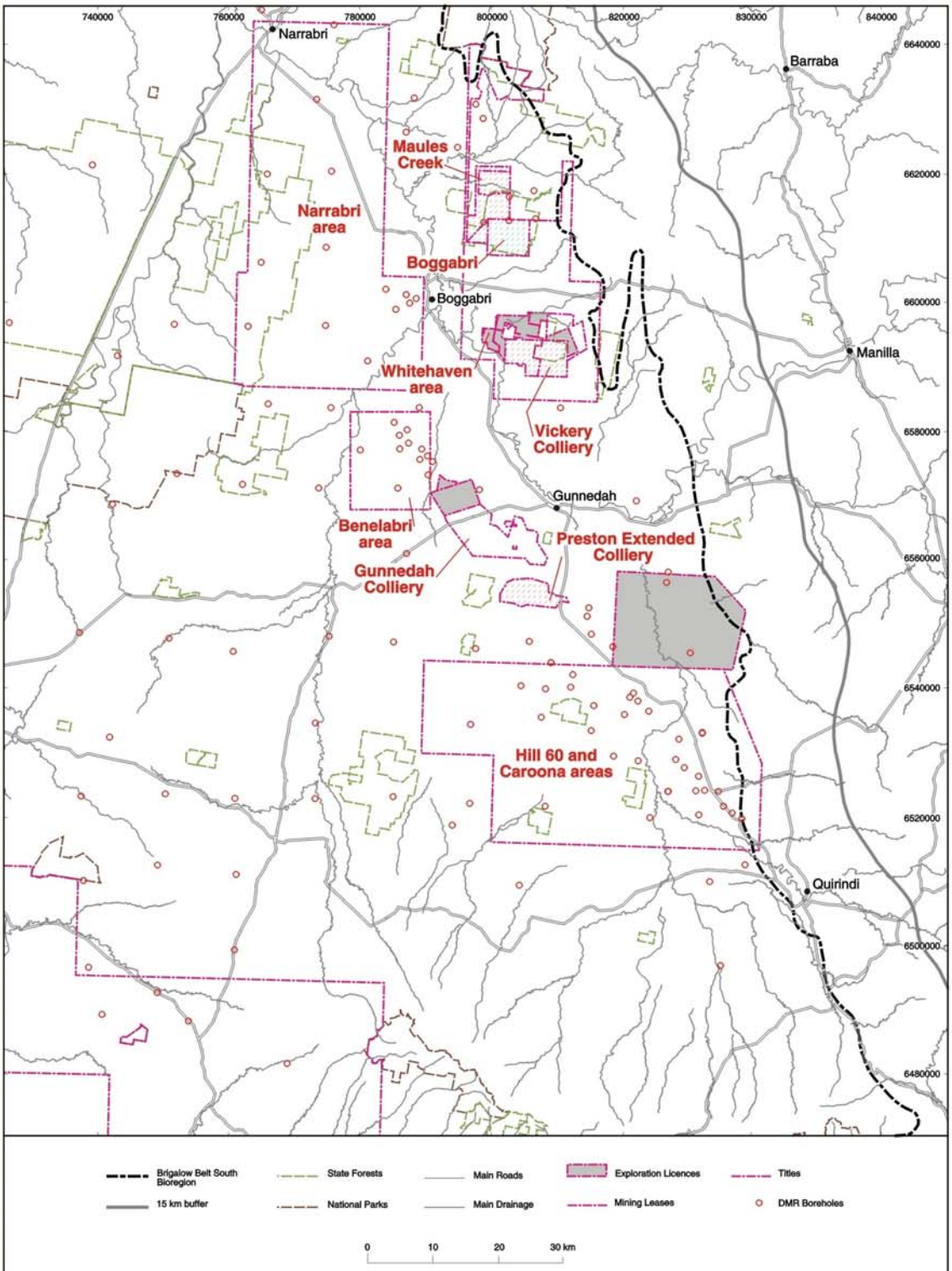

FIGURE 21 Gunnedah Basin - DMR Boreholes and Mining Titles

the drilling of boreholes, including the DM holes, Blake DDH1, Parsons Hill DDH1 and Dampier DDH1. The majority of gas flows emanate from the Permian Black Jack Group, however shows were also reported from the Porcupine Formation in Bando DDH1 and the Digby Formation in DM Dampier DDH1.

In the early 1980s, Hartogen Energy Ltd, as operator of three conventional petroleum exploration licences, acquired several surveys of high fold seismic data and drilled two wells. Wilga Park-1, drilled in October 1985, resulted in the first successful exploration well, and the first well to discover conventional gas within NSW. It was completed as a new field gas discovery, although the accumulation was then thought to be sub-commercial. The second well, Nyora-1 drilled in 1986, was a dry hole.

Coonarah-1 and 1A, drilled by Petroleum Securities Pty Limited in late 1993, resulted in a new gas pool discovery in the Digby Formation. Natural gas was tested at a rate of 340 Thousand Cubic Feet/Day, which was sub-commercial, notwithstanding that it contained 1.14% Helium, considered to be very high by world standards. A minimum 37 m gross gas column was penetrated by the well with an estimated 80% net/gross ratio. Coonarah-2 was located 1.8 kilometres northeast of the discovery well and drilled in August 1995, with disappointing results. The Digby Formation, although gas bearing, was fine grained and tight. The Black Jack Formation sandstones were also tight with a drillstem test conducted over the lower part of this formation flowing gas to surface at a rate too small to measure.

In October 1997 First Source Energy Inc. farmed into PEL 238 and commenced an active coal seam methane exploration programme targeting mainly coals within the Early Permian Maules Creek Formation. From February 1998 to February 1999, First Source drilled 15 wells, conducted 7 hydraulic fracture stimulations, 2 open hole cavity stimulations, recorded 486 kilometres seismic data and reprocessed existing seismic data (figure 22). This exploration work has not only confirmed the huge gas potential within the coal seams but it has also discovered conventional gas reserves within the Digby Formation in the Bohena area. Bohena-2 flowed gas to surface from the Digby Formation at rates in excess of 2 Million Cubic Feet /Day and Bohena-7 also flowed gas to surface at high but unmeasured rates. In addition, gas has been produced from almost every formation intersected within the Permian and Triassic section. Well locations in the Bohena area have been sited without seismic data and therefore without the benefit of any structural control.

Work in the Southern part of the Basin commenced in the early 1960s with reconnaissance aeromagnetic surveys, followed later by gravity surveys. In 1968, a gravity survey, was completed for Alliance Petroleum Australia N.L. A further survey was undertaken in 1968. That survey revealed a number of anomalies, the two major meridionally trending gravity highs centred in the vicinity of Yarraman North and Windy Station. The Yarraman – Dimby survey in 1975 confirmed the presence of a complex gravity high possibly due to relief on the surface of the Werrie Basalt at a depth of about 1,250 m.

The first seismic surveys were conducted following the acquisition of aeromagnetic data. The Coolah-Merriwa Seismic Survey was a reconnaissance reflection survey completed in August 1962. Near surface basalts and isolated lines made mapping of very regional data difficult.

In 1964 Namco International Inc acquired the 1964 Caroona refraction survey. In 1965, 7 lines totalling 45km (28 miles) were recorded during the New Windy Seismic Survey run to test the continuity of surface anticlines at depth. Closure was indicated on the New Windy Anticline and Quirindi No 1 was drilled on the New Windy geological, gravity and seismically defined high.

Mirrabooka-1 drilled to a total depth of 342 m was the first of a number of holes drilled in the vicinity of an aeromagnetic high at the northwestern end of the structure. Other stratigraphic holes included Waverton1, 2 and 3. These wells penetrated a coarse unsorted sandstone and conglomeratic unit in the Digby Formation. New Windy-1, 2 and 2C were drilled to test the New Windy Structure. Small traces of gas, probably methane, were observed when the Permian strata were cemented off in the Waverton-2 well. It was concluded that the Mirrabooka structure resulted from intrusion of quartz diorite magma which uplifted the late Permian and Early Triassic sequence. In contrast the New Windy structure appears to be of Jurassic or post-Jurassic age.

The Breeza Seismic Survey was recorded for Alliance Petroleum, in 1968. This was followed by the Blackville and Bundella seismic surveys in 1969 and 1970 respectively. The Blackville Seismic Survey was one of the first multi-fold seismic surveys conducted in the region, the intention being to acquire the

first reliable seismic control of the deeper portions of the Bando Trough. The Bundella Seismic Survey comprised a total of four lines (74km) of multi-fold data. There has been no follow-up drilling within the Southern Basin area following this survey.

Recently, Australian Coalbed Methane Pty Ltd, holder of PELs 1 and 12 has undertaken the drilling of a number of deep coal seam methane wells. These include West Quirindi-1 in 1993, Goodgerwirri-1 and Pine Ridge-1 drilled in 1997, and Calalah-1 in 1998. The most recent exploration in the area was a seismic survey conducted across the extreme western portion of the Weetabila Shelf in PEL 428. Undertaken by Eastern Star Gas Limited in 2001, the survey was primarily designed to acquire the first significant seismic coverage across the Tooraweenah Trough.

4.3.2 Gilgandra Sub-Basin

Early last centaury, four shafts were sunk in the bed of Spicers Creek, near Saxa to mine coal (Jones, 1919). Permian coal 1.2 m thick with a thin claystone band at the top was intersected at a depth of 7.6 m.

Coal assessment drilling in the study area commenced with the DMR 1981-1982 Gunnedah Basin Regional Drilling Programme. The boreholes in the southwest of the area established the eastern edge of the Rocky Glen Ridge. The drilling of DM Hall DDH1, DM Worigal DDH1 and DM Arrarownie DDH1 confirmed the existence of the Rocky Glen Ridge as a prominent basement topographic feature in the north and suggested the uplift and erosion of Permian sediments by the Digby Formation.

Later, the DMR Coolah – Binnaway Drilling Programme assessed the geology and coal resources to the north of Ulan. Two boreholes were drilled in the Tooraweenah Trough encountering Late Permian sediments.

In 1989 three boreholes Soda-1, 2 and 3 were drilled by Denison Australia Pty Ltd for the exploration of sodium bicarbonate bearing groundwaters. The main objective was to drill through the Mesozoic sediments and into an Upper Permian artesian in westerly derived sandstones below Hoskissons Coal Member. Soda-1 failed to reach the drilling target and was terminated in the Wollar Sandstone. Soda-2 encountered the target aquifer at 166-167m, underlying the Huskisson Coal. Soda-3 encountered 190m of Early Permian sediments.

In 1996-1998, CRA Exploration Pty Ltd acquired four titles situated on the southern margin of the Gunnedah and Surat Basin. Its target was a large export quality, thermal coal deposit analogous to the Early Permian Blair Athol coal deposit on the western margin of the Bowen Basin. This exploration identified an extensive area of shallow, thick Late Permian coal. More importantly, several deep boreholes penetrated Early Permian sediments unconformably underlying the Late Permian coal measures in the Cobbora and Yarindury grabens.

Interest in petroleum exploration within the Gunnedah Basin began to grow in the early 1990s in response to the success in the Pilliga area, and to renewed interest in coal seam methane. This renewed exploration effort has gradually extended into the western portions of the basin, including the Gilgandra Sub-Basin.

In 2001 Eastern Star Gas Limited acquired the first significant seismic coverage across the Tooraweenah Trough. This seismic data shows that the Rocky Glen Ridge is a complex structural feature with variable horst and graben development. A conspicuous angular unconformity is interpreted between the pre- and post- Surat Basin sediments consistent with the Ridge having undergone a number of discrete periods of uplift (Upstream Petroleum Consulting Services, 2002b).

In November 2001 the NSW Department of Mineral Resources completed the drilling of DM Goonoo DDH1 as part of the assessment activities being conducted for the BBSB. The borehole was drilled in the Goonoo State Forest area and intersected Jurassic to Cretaceous sediments of the Surat Basin and Triassic to Permian sediments of the Gunnedah Basin. The borehole was terminated in the Early to Middle Devonian sandstone. In April 2002, a second borehole, DM Goonoo DDH2, was commenced on the Rocky Glen Ridge in order to provide further information about this area.

4.3.3 Northern Hunter Coalfield

The following history of the Hunter Coalfield is modified from J Beckett et al, 1995. The earliest reports of coal in the Northern Hunter River and its tributaries begin with the first exploration parties in the early

1820s and from the farmers and graziers who quickly followed. By the 1830s coal occurrences were being reported from many properties in the Hunter Valley, extending from east of Singleton through the Muswellbrook and Scone areas to Burning Mountain at Wingen.

The first coalmines in the Northern Hunter Valley developed largely in response to the energy requirements of the early dairy industry. The first successful mine in Muswellbrook area was the Kayuga Mine which was opened in 1892. The Muswellbrook Mine opened in 1908. The markets were firstly domestic, with the main supplies going to the railways and the gas plant. By 1923 the company had built a local power station which eventually supplied Muswellbrook, Aberdeen, Scone and Denman with electricity. Open cut mining at the Muswellbrook mine commenced in 1944 with Thiess Bros. initially contracted to commence the operation.

The period from 1940-1970 saw the intervention of the Federal and State Government, with major investment in the coal mining industry. The Joint Coal Board and the Department of Mines were involved in the geological investigations and development of open cut coal mining and in the declaration and development of State Coal Mine Reserves. During the period between 1947 and 1951 investigations were carried out by the Joint Coal Board, the New South Wales Department of Mines and Bureau of Mineral Resources in the Foybrook and Ravensworth areas. This led to the establishment of Foybrook (March 1951), Pikes Gully (March 1951) and Foybrook North (November 1951) open cut projects. At the same time the Liddell State Mine underground operation and the Ravensworth open cut project were developed on adjoining State Coal Mine Reserves.

It will be more than 20 years before major dragline and truck and shovel opencut mines are replaced as the major form of production. However, the last major open cut deposits in the Hunter Valley at Mt Arthur North and Saddlers Creek are now allocated. The group of open cut mines proposed for the Muswellbrook area, Bengalla, Mt Pleasant and Kayuga will be the last major open cut mines. Future coal production will come increasingly from new underground multi-seam highly efficient longwall operations.

There has been very limited petroleum exploration in this area. To the south of the Liverpool Ranges, the Denman Seismic Survey was recorded in 1973 in order to extend the seismic reconnaissance control northwest through what was then PEL 103 and which now constitutes portion of PEL 4. The work was undertaken for Australian Oil and Gas Corporation Limited. A few anticlines were partially defined by this survey and subsequently one of them was drilled as Martindale 1-1A, without successfully encountering any hydrocarbons. From 1993 until 1997, Amoco Australia Oil Company Drilled 5 regional stratigraphic wells and conducted a seismic survey and an aeromagnetic survey in PEL 4, in the Merriwa-Sandy Hollow-Muswellbrook area. The exploration program was aimed at coal seam methane. Although moderate gas contents were found in some of the holes, the company withdrew from Australian operations.

4.3.4 The Northern Western Coalfield

Coal deposits at Ulan were first worked in the mid 1920s by a small underground bord and pillar operation and were mined sporadically through the 1950s for domestic and small-scale commercial uses after the establishment of the No. 1 Underground Mine in 1946. The No. 2 Ulan Underground Mine was developed in 1957 to meet the fuel demand of an electricity generating station at Ulan village but the station closed in 1969. The underground mine was fully mechanised in 1977. A high-productivity longwall system is currently employed at the mine with an annual production capacity of around 4 million tonnes. In 1982, Ulan Coal Mines Limited established its large opencut mine to the southeast of the underground mine. Current annual production of the open cut mine is around 3 million tonnes.

There have been seven Government drilling programmes in the area since 1950, with 174 boreholes drilled, mostly in the Ulan-Wollar area. The Department also carried out aeromagnetic and radiometric surveys over the larger Wilpinjong–East Ulan area in 2000 and 2001. There has also been extensive private exploration near Ulan including geophysical surveys. Petroleum exploration has been limited to the drilling of two stratigraphic wells near Merriwa by Amoco to test coal seam methane potential.

4.3.5 Gunnedah - Bowen Basin and Surat Basin

There is a long history of exploration in the Bowen and Surat Basins, gas having been discovered in the southern Queensland town of Roma in 1900 in the Jurassic sandstones on Hospital Hill. This was used to

light the town in 1906. Following proclamation of the area as an Oil Reserve in 1916 and later Government initiated exploration spasmodic and unsuccessful exploration took place until the 1960s when the then Bureau of Mineral Resources carried out the first systematic geophysical surveys involving gravity, magnetic and seismic coverages of the area.

The gas fields on the Roma Shelf and the oil fields at Moonee were discovered during the 1960s. This triggered significant interest both in the Queensland and adjacent northern New South Wales portions of the basin. There is now of the order of 40 economic gas fields, 16 oil fields and several oil and gas fields in the Queensland portion of the Surat and Bowen Basins.

In comparison with Queensland, exploration in New South Wales has always been at a low level. Large areas of the Surat Basin were leased during the 1960's. The main explorers in New South Wales during this period were the Union Group, whose activities were largely concentrated about the State border, and American Overseas Petroleum who explored the southeastern part of the basin. Esso Exploration Australia Inc. undertook further exploration in the Moree-Goondiwindi area in the 1960s as a farm-in from the Union Group's tenement.

Only 31 wells (Bamberry & Kouzmina, 1995) have been drilled in the Surat Basin in NSW, contrasting with over 1300 drilled in the Queensland portion of the Basin. The most explored part in NSW is in the northeast close to productive areas in Queensland. The 20 wells drilled in this part of the basin recorded nil to minor hydrocarbon shows. Seven wells further to the south intersected the Surat Basin succession where the main drilling targets were deeper Permian and Triassic reservoirs. Only four wells have been drilled in the western two-thirds of the Surat Basin in NSW, Baradine West-1, and 2, Sandy Camp-1 and Collyblue-1. As with drilling the major seismic coverage is also in the Boomi Trough region of the State. As indicated, outside of this area, regional coverage is lacking, except for surveys around the Lightning Ridge area.

Following successful discoveries in Queensland, the Union Group drilled several wells in northern New South Wales, mainly to test basal Jurassic units, and sandstones in the Permian succession. Additional seismic exploration by Esso Exploration Australia identified further drilling targets in the basal Jurassic units, and in Permian sandstones.

Later exploration focused on possible pinch out plays of the Hutton Sandstone, at depositional edges and against basement highs. Drilling in the 1980s examined a range of prospects, ranging from Permian sandstones (Gunnedah Basin), the Triassic Showgrounds Sandstone (Quack 1), through to the Mooga Sandstone (Collyblue 1).

Oil Company of Australia (OCA) (1985) suggested that the major cause for the lack of exploration success in the Surat Basin in New South Wales is the location of many wells outside structural closure at critical levels. Exploration in the area is hindered by poor reservoir development and presence of Tertiary intrusives in the prospective sections over large areas of the eastern edge of the Basin.

Union Oil Co and Esso were active in the mid to late 1960s when they drilled a number of wells, primarily on structural highs targeting Showgrounds reservoirs. Following the lack of success there was only minor exploration activity in the 1970s. However in the early 1980s OCA instituted an active program which led to the drilling of a number of new wells, again without success. OCA attempted to intersect the Showgrounds and Evergreen Formation reservoirs that formed the fields immediately to the north in Queensland. Stewart & Alder (1995) believed that few of the wells were sited on valid traps or if they were, the objective reservoir targets were tight or absent. Minor fluorescence, indicating the presence of oil, was noted in the Mooga Formation in Barb-1 and a drillstem test flowed fresh water with a thin film of oil noted on the surface of the water where it collected in the flare pit. A trace of fluorescence was noted in a sample from the top of the Hutton Sandstone in Boomi-1, which also recorded gas increases in drilling mud from coals in the Bungil Formation, Walloon Coal Measures, Moolayember Formation and Permian sequences. Minor fluorescence and low level gas shows have been encountered in the Showground Sandstone, Orallo Formation, Pilliga Sandstone, and lower Back Creek Group in several wells.

Most of the topography in the area of the Surat Basin area of New South Wales is very flat and presents little opportunity for outcrop studies. Airborne geophysical surveys have increased insight into the subsurface geology of the Surat Basin although a recent study (Encom, 1995) suggests that the

geophysical data provides very little information on the characteristics of the Permian-Triassic and Mesozoic sedimentary sections. Gunn (2002) undertook a major re-interpretation of geophysical coverages in the area for the Department of Mineral Resources.

5. MARKETS AND COMMERCIALISATION

5.1 METALLIC AND INDUSTRIAL MINERALS, AND CONSTRUCTION MATERIALS

No metallic mineral production was recorded in the BBSB during the 2000-2001 financial year.

There were about 175 operating and intermittently operating quarries for industrial minerals and construction materials in the BBSB as at May 2002; of which 9 are coarse aggregate, 144 unprocessed construction sand, 2 clay/shale, 1 kaolin, 12 undifferentiated sand and gravel, 5 construction sand, and 2 river gravel. The value of production for construction materials in the BBSB is estimated at $15.23 M, for the 2000-2001 financial year. The actual value of production is greater than the amount reported because some operations have not provided data to the Department. Construction material production was made up of crushed and broken stone (coarse aggregate) at $9.78M, construction sand at about $0.348M, clay/shale at about $105,000, loam $10,255, river gravel $403,000 and unprocessed construction materials at $4.574M.

The Dubbo Zirconia Project (Toongi) is located in the buffer zone, about 25 km south of Dubbo. The project is at the advanced exploration and mine feasibility stage. Pilot plant tests are underway and an EIS and feasibility study are due for completion in 2002. Zirconia is used mainly as refractories, abrasives, and ceramic pigments however the project will also produce a number of rare earth elements including yttrium (used in colour televisions and computer monitors), niobium (steel industry) and tantalum (capacitors for mobile phones). The mine proposal involves a small open cut operation.

Resources reported from company exploration reports and environmental impact statements are given in table 9. The reported amounts do not necessarily constitute reserves as defined by the Australasian Code for Reporting of Identified Mineral Resources and Ore Reserves.

The NSW Department of Mineral Resources keeps detailed records of exploration expenditure undertaken by exploration licence holders. These records indicate that the total exploration expenditure for current exploration licences in the BBSB for metallic, industrial mineral, and construction materials for the last full year of each licence amounts to $1,817,340. This figure is also lower than actual expenditures, because for a few exploration licences only the most recent 6 month figures are available. Actual figures vary considerably from year to year. The variation relates to prevailing economic conditions, commodity prices, the development of new geological and mineral deposit models, accessibility, and the availability of new data such as detailed geophysical or geological and metallogenic data.

Exploration expenditure for some metallic and industrial minerals has increased over recent years in the BBSB because of increased perceptions of prospectivity. For example, rare earth element (REE, including yttrium, zirconium, tantalum, and niobium) exploration has been significant in the southern parts of the BBSB following the discovery of the large Toongi deposit in recent years. Prior to this, rare earth elements were not being investigated in the area at all. Exploration for zeolite, gold, copper, and silver has also followed a similar pattern, following the recognition of prospective areas within or close to

the eastern and southern margins of the BBSB. There has also been increased exploration for sapphires and diamonds in the north-east parts of the BBSB in recent years.

TABLE 9. IDENTIFIED METALLIC AND INDUSTRIAL MINERAL, AND CONSTRUCTION MATERIAL RESOURCES IN THE BBSB

Operation Name	Commodity	Resource	Unit	Category	Average Grade
Bakers Quarry	coarse aggregate – sandstone	0.18M	m3	Exploration result	na
Bohena Creek	heavy mineral sand - undifferentiated	100M	tonne	Exploration result	0.4% HM (0.009% leucoxene, 0.279% rutile, 0.1035% zircon, +zirconium, +baddeleyite
Boomley South Clay	kaolin - flint clay	5.7M	tonne	Exploration result	30% Al_2O_3, <1.4% Fe_20_3
Braeside Hardrock Quarry	coarse aggregate - hard rock	15,000	tonne	Exploration result	na
Connecticut Gravel Pit	unprocessed construction materials	6,000	m3	Exploration result	na
Dubbo, Sheraton Road	coarse aggregate - hard rock	70M	tonne	Exploration result	
Durkins Pit	unprocessed construction materials	15,000	m3	Exploration result	na
Rocky Dam No 1 Pit	unprocessed construction materials	45,000	tonne	Exploration result	na
Rocky Dam No 2 Pit	unprocessed construction materials	10,000	tonne	Exploration result	na
*Toongi REE Deposit	Rare Earth Elements	83M	tonne	Indicated and inferred	83Mt at 1.91% ZrO_2, 0.041% HfO_2, 0.448% Nb_2O_5, 0.027% Ta_2,O_5, 0.138% Y_2O_3, 0.720% REO
Willow Tree, Pollocks Lane	coarse aggregate - hard rock	2M	tonne	Exploration result	na
Willow Tree, Pollocks Lane	unprocessed construction materials	6.6M	tonne	Exploration result	na

*Toongi is located in the BBSB buffer zone, but is included due to its importance to the nearest township of Dubbo, within the BBSB.
Note: Resource data is not available for all operating and intermittently operating quarries in the BBSB; available data is derived from environmental impact statements or resource assessment studies.

5.2 COAL

The Gunnedah Coalfield covers the Gunnedah Basin north of the Liverpool Ranges. The coalfield contains substantial resources of open cut and underground coal suitable for use as both a domestic and an export thermal coal. Mining operations are currently limited to one open cut mine. The recovery of these resources is not likely to occur on a significant scale in the short to medium term. There are

extensive resources in the Hunter Coalfield and the Northern Western Coalfield that are, at present, more economic.

The Hunter Coalfield is New South Wales's most important coalfield producing 60% of the 110 million tonnes of saleable coal in 2000-01. Approximately 85% of this production is by high volume low cost open cut operations. Ulan Mine located 25 km East of Gulgong in the Northern Western Coalfield is an open cut and underground mine which produced 6 Mt of saleable coal in 2000-01, representing approximately 5.4% of the State's total production.

The future of the Gunnedah Coalfield is dependent on the cost of mining and transport to market becoming competitive with operations in the Hunter Valley and Western Coalfield. Future coal mining in the Gunnedah Coalfield will be dependent on:

- Depletion of coal reserves amenable to open cut mining in the Hunter Coalfield over the next 20 years.
- Increasing costs of mining in the other coalfields associated with the increasing level of production from underground mines.
- Changes to rail transport infrastructure that will reduce the cost of transport to domestic coastal markets, and to the Newcastle coal terminals for export.
- Availability of markets that are beyond the maximum production capacity of the Hunter, Western and Newcastle Coalfields to fulfil.

The substantial coal resources of the Gunnedah Coalfield will be required at increasing levels over the next few decades to replace diminishing production from the other coalfields. In the interim it is essential that these resources remain available for exploration and mining when required and are not made unavailable by incompatible landuses. In the long term, (30-50 years), they represent the State's major strategic coal resource.

5.3 COAL SEAM METHANE AND PETROLEUM

Coal seam methane (csm) is the natural gas formed during the coalification process whereby peat and other organically rich sediments are transformed into coal, as a consequence of compaction and heat associated with the processes of on-going deposition and burial. Coal seam methane is essentially similar to natural gas found in conventional sedimentary reservoirs, although it is generally higher in methane concentration. However, unlike conventional natural gas reservoirs, where gas is trapped in the pore or void spaces of a rock, such as sandstone, methane trapped in coal is adsorbed onto the coal grain surfaces or micropores of the coal and is held in place by reservoir (water) pressure.

The coal therefore acts as a source, reservoir and seal for the methane and as such is to be distinguished from a conventional gas accumulation within a sandstone reservoir rock. Because the micropore surface area is very large, coal can potentially hold significantly more methane per unit volume than most conventional reservoirs such as sandstone. Csm is generally regarded as an "unconventional" source of natural gas, and is distinguished from conventional gas, which is produced from reservoir rocks that are typically not the origin of the gas.

Discoveries of conventional gas and csm have recently been made in the Narrabri region of the Gunnedah Basin. Although exploration is in its early stage, independent assessment of these discoveries has indicated that total possible reserves within the Basin are very large and if recoverable, could supply the State's needs for over 100 years.

The viability of any conventional or csm gas project is ultimately dependent upon finding markets. New South Wales is Australia's largest domestic market for oil and natural gas but has no conventional oil or gas production and only very limited coal seam methane production from coal mines in the Southern Sydney Basin (Mullard, 2000). As such it is the only mainland state to have developed a distribution system based on supplies from other states.

To supply the market in New South Wales, gas has been piped from Moomba (in South Australia) to Sydney, Wollongong, Newcastle and several country centres since 1976. Within the state, AGL Gas Companies (New South Wales) Ltd and its subsidiaries, were until recently responsible for supplying more than 95% of the natural gas requirements. In 1998, a link from Victoria to the NSW gas distribution system was completed via Wodonga and Wagga Wagga. A second pipeline was completed by Duke

Energy in 2000. It will supply gas from the Bass Strait fields to Sydney via Longford then along the east coast.

Oil is to be distinguished from gas in that the former may be sold on a well-established international commodity market that enables both forward selling and hedging. Gas on the other hand is generally sold on a one to one basis, at rates negotiated between specific producers and suppliers. Whilst New South Wales' energy requirements are large, the gas component of the overall energy budget is relatively small. Coal fired power stations generate 94% of the State's electricity.

Natural gas demand in NSW levelled out from the mid 1980s after early growth. Recently, demand has jumped, principally as a result of the conversion to gas in 1997, of the former ICI chemical plant near Botany. NSW now consumes around 151 Peta Joules (PJ) per year. Because of the previous supply constraint, NSW has one of the lowest gas usages per capita of Australian states. One of the major factors cited for future market expansion is the lack of assured long-term stable supplies.

In a significant development for the Gunnedah region, Eastern Star Limited announced to the Australian Stock Exchange on 29 April 2002 that it had entered into a Deed of Co-operation with Country Energy in relation to the investigation of means to develop a power generation project in Narrabri, fuelled by gas from Eastern Star's Coonarah Gas Field, in PEL 239. This may facilitate early commercialisation of the Coonarah Field, which has independently accredited, proved and probable reserves of 11.3 Peta Joules (PJ). Country Energy is Australia's largest regional energy business and third largest electricity retailer with annual revenues of $1.3 billion. Eastern Star Limited is now involved in exploration to enhance their gas reserves base throughout the Gunnedah region, to extend this alliance.

There are several factors that make the discovery and development of new gas supplies in NSW and Australia important. There is increasing pressure to reduce, or contain, greenhouse gas emissions. Natural Gas is an efficient fuel and in comparison with other hydrocarbons produces lower emission levels.

The contracted supply of natural gas to NSW is scheduled to begin to decline this year, and contracts with SANTOS are due for renewal in 2006. This places uncertainty on existing supply but does open opportunities for new suppliers to enter the market. The explosion and fire at Longford in Esso's Victorian facilities associated with the Gippsland Basin and the serious impact on the Victorian economy, has emphasised the need for both stability and diversity of gas supply. To this end, relevant State authorities throughout Australia are implementing policies to ensure increased competition in exploration and production.

Currently, NSW and SA are both supplied from the SANTOS operated gas plant located at Moomba. With declining reserves in South Australia, dependence will be transferred within 10 years to Victoria. This reliance on one gas supply for at least 80 percent of the combined gas market is unwise and could be economically damaging if further interruption to supply was to occur. The development of additional gas supplies for the NSW energy market will not only increase the size of the market due to competitive forces, but also will significantly strengthen its security of supply.

Recently, there has been a freeing up of the NSW gas distribution system as well as significant expansion of pipelines, particularly in regional areas. In NSW, a 283 km spur-pipeline off the Moomba-Sydney trunk pipeline has been constructed to supply the towns of Forbes, Parkes, Narromine, Dubbo and Wellington. Importantly for projects in the BBSB, this pipeline will be extended through to Gunnedah and Tamworth. This means that initial discoveries will not require the construction of a large and expensive pipeline infrastructure in the initial stages.

The 1997, the Australian Gas Association (AGA) demand forecast for the eastern states of Australia suggests that gas demand will increase from 474 PJ per annum in 1998 to 787 PJ per annum by 2010. Natural gas will be Australia's fastest growing energy source to the year 2030, with average annual projected growth of around 3% with the gas component of the national primary energy share rising from 18 % to 28%.

The development of NSW gas resources therefore fits in well with both state and national energy planning. Gas derived from the Gunnedah Basin has the advantage of proximity compared to other potential sources and hence would be cheaper. Moreover, most gas developments require large initial

project funding. However, the development of the Gunnedah Basin reserves, would require less pipeline construction and substantially lower capital costs.

The development of a domestic gas supply will provide investment and long term employment to regional NSW, it will increase competition in gas supply, it will increase surety and dependability in supply, and it will assist in the lowering of green house emissions.

6. EXPLORATION AND LAND ACCESS

6.1 METALLIC AND INDUSTRIAL MINERALS

Mineral exploration is a long term and ongoing process. Exploration is an extremely costly commercially high-risk activity and areas are often explored many times over before the initial clue that leads to a discovery is found. Exploration activity is cyclic, based on a number of factors including commodity prices, state of the economy, mining and exploration technology, exploration methodologies, recent discoveries, etc.

The advent of Carbon-In-Pulp and Carbon-In-Leach gold extraction technologies in the 1970s provide examples of the way in which technological (and economic) change can affect exploration. These technologies dramatically changed the costs of gold recovery and also reduced the risks associated with exploration for gold-oxide ores by allowing gold to be mined profitably at much lower grades. This triggered intensive, Australia-wide exploration for large tonnage gold oxide deposits at considerably lower cut off grades than were previously considered economic (Blain 1992). Carbon-In-Pulp and Carbon-In-Leach processing are also used for treatment of low-grade primary gold ores. Persistent exploration and re-evaluation of the geology can also lead to discoveries. The Ridgeway gold-copper deposit near Cadia Hill is concealed by a blanket of Tertiary basalt and was recently discovered by a drilling program, 140 years after the first discoveries in the area.

New information, new concepts and better understanding of geological processes continually change the prospectivity of areas and regions. New models are continually being developed and refined. Continued access to land is therefore a significant issue for the mining industry and for future mineral development. In order to examine the implications of alternative land access arrangements for exploration and mining in the region it is important to understand both the nature of exploration and its likely costs and benefits. The typical sequence of events of a modern exploration program is described below.

1. Global considerations
   - Assessment of political stability
   - Assessment of security of title
   - Assessment of access and restrictions
   - Assessment of financial climate, restrictions or inducements
   - Determination of geoscientific framework and availability of information

2. Preliminary investigations
   - Review regional geoscientific data (geology, geophysics, satellite imagery)
   - Formulation of geological concepts and selection of prospective areas
   - Examination of known mineralisation

3. Reconnaissance exploration
   - Acquisition of exploration tenements
   - Collection and assessment of geoscientific data over the tenement
   - Examination of available regional geoscientific data
   - Conducting of geoscientific surveys required to augment available data

- Selection of target areas, for more detailed exploration

4. Detailed exploration
   - Detailed geoscientific surveys to detect and delineate anomalies
   - Drilling of anomalies in search of significant mineralisation
   - Delineation of mineral deposits by further drilling and other methods to determine configuration, approximate tonnage, grade, metallurgical characteristics of the deposits
   - Pre-feasibility studies
   - Acquisition of mining tenements, if justified, at the appropriate stage of program.

The cost and duration of exploration programs will vary from company to company and across commodities. Clark (1996) suggests that the development of a typical major deposit (worldwide) involves a 5-20 year lead-time. This estimate results from a typical 3-10 years exploration program prior to the mine development phase.

It is important to note that the exploration process starts with assessments of very large regions and is then systematically narrowed down as the exploration target becomes better defined. The direct costs facing explorers increase as the target area becomes smaller and exploration methods more intense. The cumulative cost of a single major metallic mineral exploration project at an advanced stage of exploration may reach figures of the order of tens of millions of dollars or more, with no certainty of success or approval, however the potential returns may also be very much higher. The environmental impact associated with exploration also increases as the area being explored becomes smaller and the exploration methods used become more invasive (for example, drilling).

Modern exploration, which is increasingly using remote sensing from satellites or aircraft, is able to proceed to surface phases with no physical surface disturbance. The early stages of a surface exploration program involve activities such as mapping, geophysical measurements and geochemical sampling of stream sediments that have little or no effect upon the environment. Follow-up investigations that would require other techniques that could have some localised and temporary effects may include:

- Rock chip sampling.
- Collecting soil samples.
- Electrical, gravity, magnetic, seismic or radiometric ground surveys.

If the results of this work were positive, additional follow-up work would probably include some drilling. Drill holes are required to be rehabilitated to best practice standard by the Mining Act and by the title conditions.

6.2 CONSTRUCTION MATERIALS

Exploration for construction material resources typically involves an initial identification of “target” areas which may contain suitable deposits, based on an assessment of geological, socio-economic and environmental factors, including in particular, distances to markets and road access. Because construction materials are high-bulk, low unit value commodities, transport costs are a major component of the final price and hence resources should ideally be as close to the intended markets as possible.

Potential sources of construction materials within the target area are identified by evaluating available geological and technical data including geological maps, topographic maps, air photos, geological reports, existing quarries, and constraints on quarrying. This is followed by field reconnaissance, including examination of outcrops and exposures such as road cuttings, and quarries, as well as preliminary assessment of potential access routes, current land use and broad environmental constraints.

Once a potential resource has been identified, more detailed exploration is normally conducted to determine its size and quality. The extent and method of such exploration depends on the commodity involved, the intended use(s), the proposed scale of the quarrying operation, and the complexity of the geology. Drilling is generally used to assess the size, thickness, amount of overburden, and other characteristics of the deposit. Samples obtained from drillholes are tested to determine the suitability of the material for the intended applications. Bulldozers or backhoes may be used to obtain sub-surface data and samples from deposits of sand, gravel and other unconsolidated materials. In some cases, larger test pits may be excavated to obtain bulk samples for testing. Further drilling and sampling may be undertaken to assist in quarry design.

Unprocessed construction materials for local use in roads and fill are not generally required to meet very stringent specifications. Exploration for such deposits may be limited to reconnaissance inspection and sampling to identify potential extraction sites, followed by limited backhoe testing or auger drilling.

6.3 COAL

Coal exploration differs from metallic and industrial mineral exploration in several significant ways. Firstly, the extent of the coal measure sequences is reasonably well understood in most localities. Secondly, the Department of Mineral Resources usually has the role of conducting the initial phases of resource assessment to the point where minable resources have been identified. Areas are then tendered to private industry for detailed assessment and ultimately, mining.

Drilling is the fundamental tool throughout most phases of assessment. In the initial stage, boreholes are drilled on a wide spaced grid (12-16 km spacing) to establish the presence, depth and thickness of the coal seams. The boreholes are fully cored and they provide sufficient sample for detailed chemical analysis of the coal. If the target seams are within basic parameters, ie, less than 600 m in depth, greater than 1.5 m in thickness, and less than 35% ash (mineral residue after combustion), then "infill" drilling will be conducted down to a spacing of 4 km in selected areas.

Further exploration and assessment then depends on whether the resource is suitable to be mined by open cut or underground methods. In most cases, drilling for open cut resources will be conducted to 0.5 km centres. Detailed drilling will also be conducted along any seam subcrop line to determine its location and the extent of oxidation. Large diameter boreholes are often drilled to recover bulk samples for analysis and plant design. Drilling for underground resources is usually conducted to 2 km centres but additional holes will be drilled where required.

Geophysical techniques are now routinely used in coal exploration. Aeromagnetic surveys help to determine the presence of igneous bodies at depth, which may have damaged or destroyed the coal. Seismic surveys help to locate any structures affecting the coal that may impact on mine design or viability.

Coal exploration activities are required to be conducted to industry best practice with minimal surface impact. Drilling operations require a 5 m by 10 m cleared space but usually can be sighted in established clearings without damage to trees. Seismic lines can usually be conducted along established roads or across cleared land. Where lines cross bush areas, line clearing is no longer used, ground cover is slashed to provide access to the equipment and to assist regrowth. Rehabilitation of all exploration activities is required under the Mining Act (1992) and the licence conditions.

6.4 COAL SEAM METHANE

Coal seam methane exploration has similarities both to coal and to petroleum exploration. The target reservoirs are coal seams and drilling using coal rigs is used to investigate important parameters such as the number, thickness and quality of the coal seams. Coal samples are tested for gas content and composition, for permeability, and other reservoir characteristics. Regional studies including geophysical surveys are important to locate areas with high gas contents and high production potential.

Drilling operations will concentrate on the most prospective areas and gas production testing will commence. This will usually involve a pilot production operation with between 3 and 15 boreholes spaced on a 250 to 500 m grid. There are several stimulation (completion) techniques used to produce the gas from the coal, the main ones being hydraulic fracturing, and cavity completions. Sites for these operations are larger than normal drill sites and there is additional equipment and staff needed during the stimulation operations. After stimulation, water flows from the holes and after a period up to six months, gas production will commence. If the results of the pilot field are positive, planning for full-scale production will commence including design for water disposal and gas collection and treatment. Ultimately, the rates of flow over time of methane to the surface will control costs of the gas and the economic development of gas fields.

Tables 10 and 11 give a summary of the land access requirements of a standard coal seam methane drainage exploration program and production test facility.

TABLE 10. LAND ACCESS REQUIREMENTS OF A STANDARD COAL SEAM METHANE DRAINAGE EXPLORATION PROGRAM

OPERATION	TIME REQUIREMENT	IMPACT & COMMENTS
Geological Mapping	1-3 months (depending on area)	Minimal impact - no surface disturbance
Drilling (Coal Exploration)	2-4 weeks/hole (depending on depth and drilling conditions)	Localised impact - 500m^2 area required for each drill site. Rehabilitation required.
Drilling (Methane Targets)	3-5 weeks/hole (depending on depth and range of tests required)	Localised impact - 500 – 100m^2 square area required for each drill site. Rehabilitation required.
Drilling (Conventional Oil and Gas Targets)	2-6 weeks/hole (depending on depth and range of tests required)	Localised impact 500- 1,500m^2 square area required for each drill site. Rehabilitation required.
Seismic Survey: *(a) High Resolution* *(b) Vibroseis*	 0.5-4 line kms/day (dependent on terrain and landuse) 5-15 line kms/day (dependent on terrain and landuse)	 Localised impact line kms by 3m Rehabilitation required. Localised to minimal impact line kms by 3m. Can use existing access-ways although rehabilitation required.
Ground Geophysics	1-8 weeks (dependent on area)	Localised to minimal impact - up to 20 sq.kms. Minimal rehabilitation required.
Airborne Geophysics	1-7 days (dependent on area)	Minimal impact. Up to 10,000 km^2. No rehabilitation required

TABLE 11. LAND ACCESS REQUIREMENTS OF COAL SEAM METHANE PRODUCTION TEST FACILITIES

OPERATION	TIME REQUIREMENT	IMPACT AND COMMENTS
Installation Phase:		
a) Site Preparation	1-5 days	Preparation of access tracks and provision of level surfaces for drillsites and frac-pad
b) Drilling	3-5 weeks/hole	Localised impact - 1,000m^2 area required for each site (up to 5 sites). Rehabilitation required.
c) Frac-Pad	1-2 days/hole	Localised impact - 2,500m^2 pad (located centrally to service 5 drillsites). The site may be used for production phase, otherwise rehabilitation will be required.
Production Phase: (Subject to separate Environmental Assessment)		
a) Access/Utilities/ Corridors	1.5-3 years	Access roads to each production site and central production facility (if required)
b) Production Sites	1.5-3 years	Very localised impact - 50m^2 Infrastructure includes concrete pad, pump, gas and water reticulation systems, monitoring system, security fence.
c) Detention Basin (Optional)	1.5-3 years	Localised impact-up to 200m^2 Infrastructure includes basin and water treatment facility.

6.5 PETROLEUM

Petroleum exploration involves a number of different processes for searching for and assessing petroleum deposits. Today, sophisticated techniques rely upon identifying subtle physical properties of deposits or the geological conditions that might host deposits. Although discovery and delineation are the primary reasons for exploration, lack of discovery from an exploration program does not imply that the effort yielded no benefit. Information gained from each stage will increase the understanding of a region's geology and enable refinement of future exploration techniques. Typically, the exploration history in a region involves several phases, the results of each providing a steady increasing knowledge base. Some exploration techniques rely on naturally occurring phenomena such as slight variations in the earth's gravity and magnetic fields are acquired passively by simple field readings (figures 23 and 24). These are

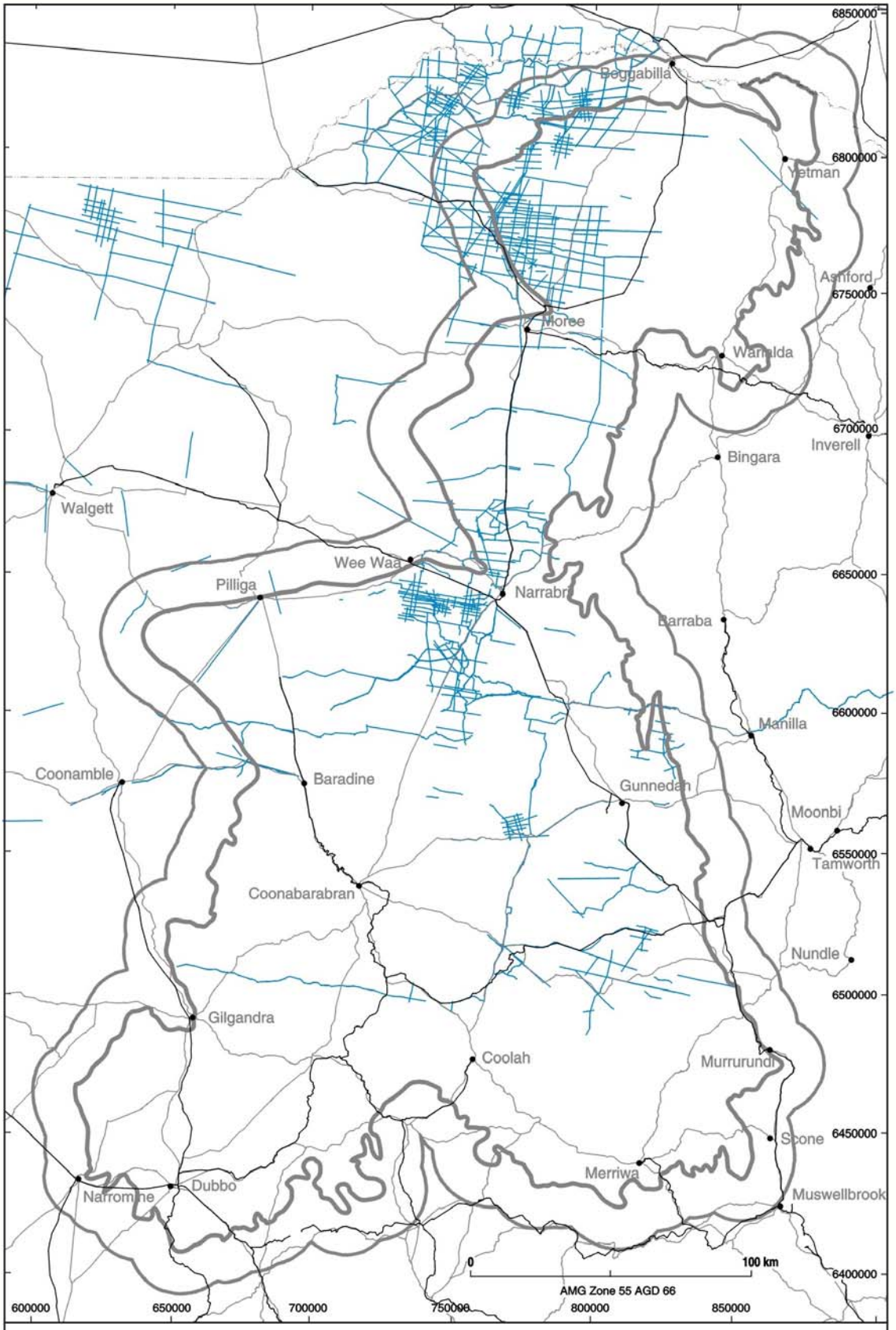

Figure 22 Seismic Lines, Brigalow Belt South Bioregion

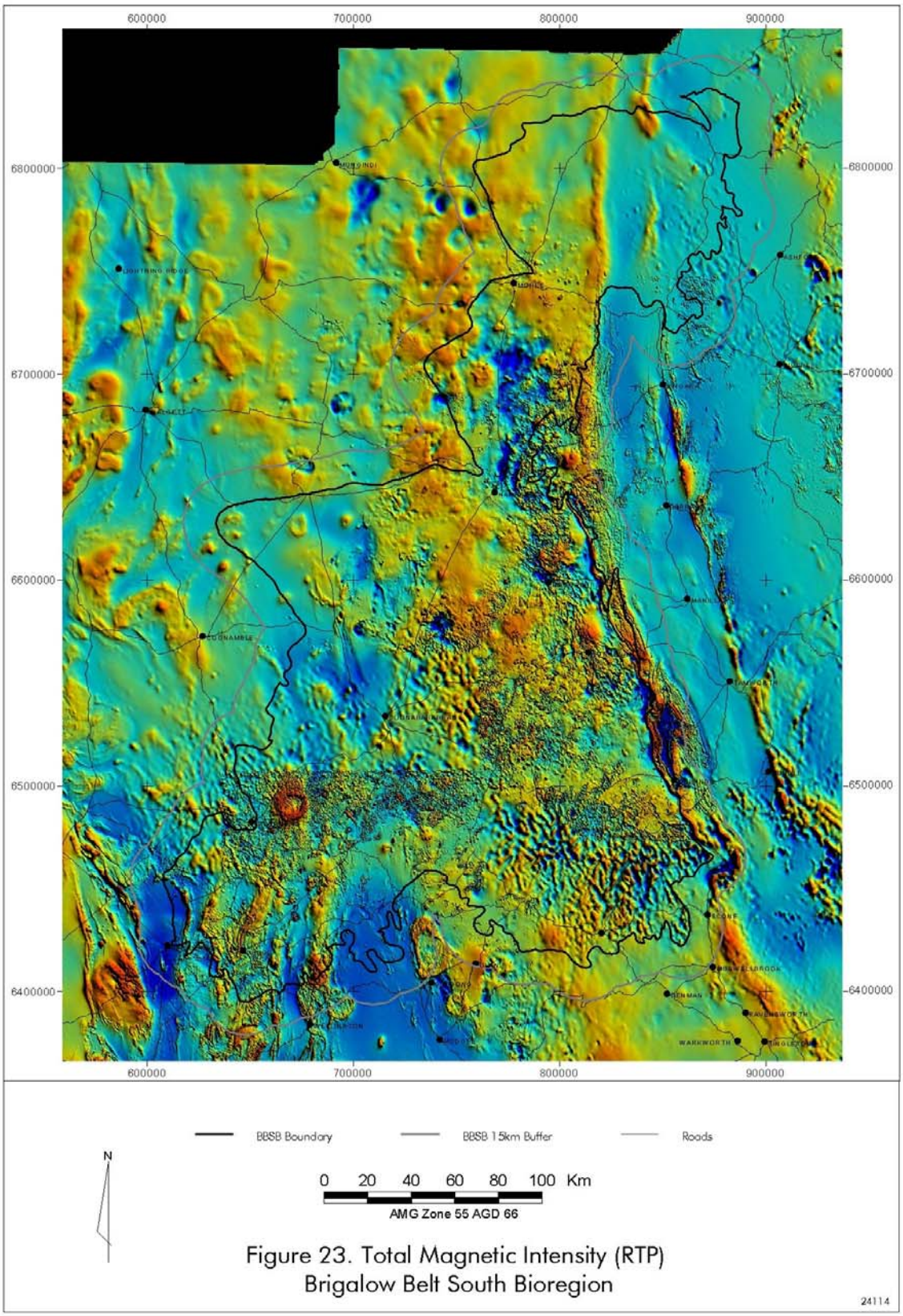

Figure 23. Total Magnetic Intensity (RTP)
Brigalow Belt South Bioregion

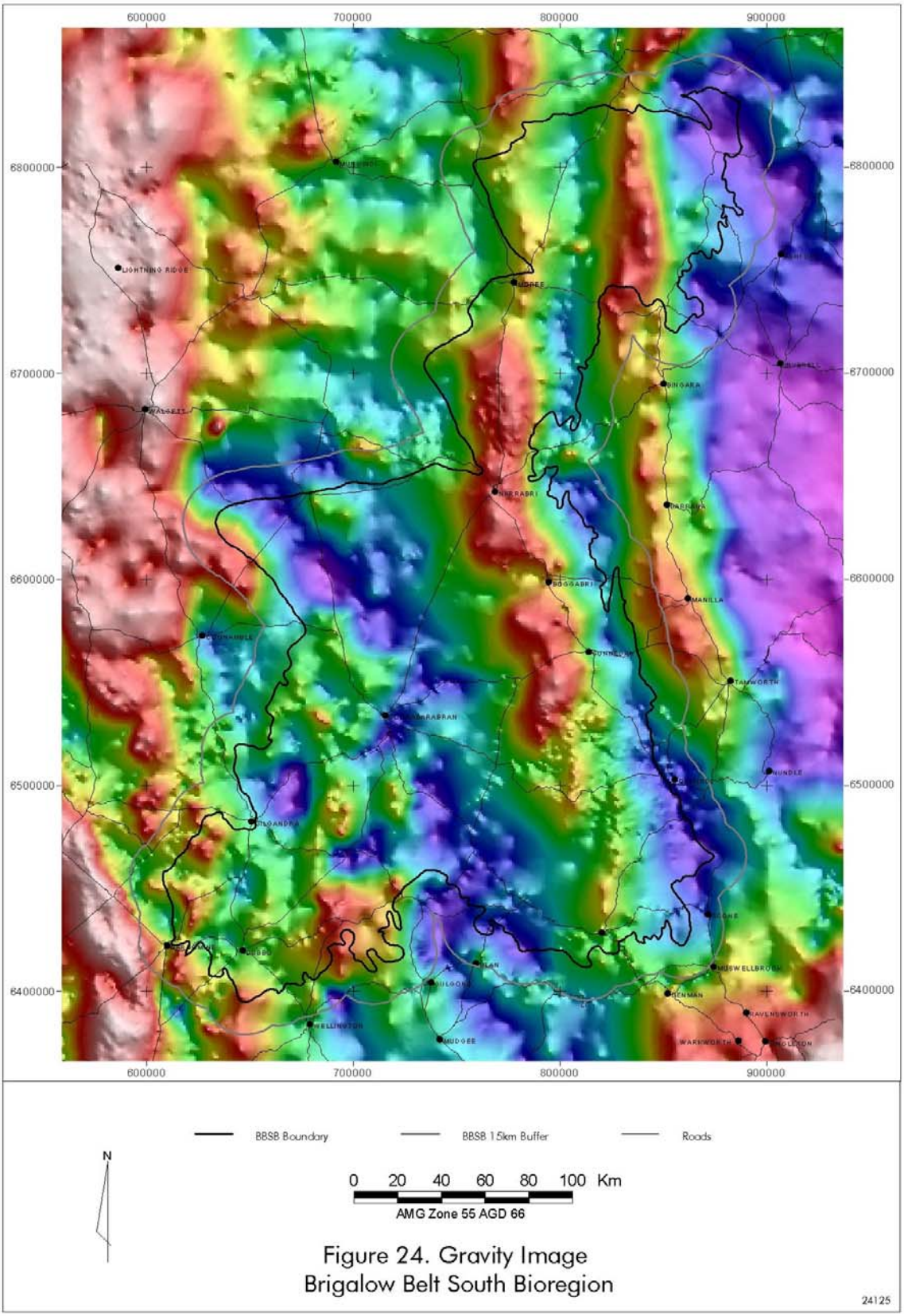

Figure 24. Gravity Image
Brigalow Belt South Bioregion

relatively cheap methods that can be interpreted to provide a good overview of the regional geology and assist in identifying those areas likely to contain hydrocarbons. Techniques, such as seismic reflection, are more active and require the introduction of an energy pulse into the ground. The results once computer processed, provide images of the sub-surface in much the same way that the ultra-sound technique provides images of the human anatomy (figure 22).

There are numerous reasons why exploration might continue in some areas over many years, without a discovery being made. New technology, changes in economic climate, and better understanding of geological processes that control the distribution of petroleum, all influence the location and intensity of exploration activity. The exploration history of the BBSB, outlined in Chapter 4, is typical of that experienced in many sedimentary basins in onshore Australia. Exploration occurs in distinct phases, the initial phase usually involving the collection of reconnaissance or regional data; surface mapping, acquisition of remote sensing data, magnetics, and gravity data, all of which are used to define broad scale geological features and highlight areas of interest that might be worthy of more intensive future investigations. Subsequent phases of exploration tend to focus on specific targets or "sweet-spots" along "fairways" where both perceived exploration risk is lowest and prospectivity highest. At present exploration for conventional oil and gas in the BBSB is only at the initial phase.

Conventional petroleum, and increasingly csm exploration make extensive use of seismic reflection techniques which involve an energy source on the surface (previously dynamite, now a mechanical vibratory source) passing a pulse of energy into the subsurface. This energy is reflected off the various geological layers and upon bouncing back to the surface is detected by a series of listening devices (geophones) spread out over distances of up to 4-5 km. In order to reduce distortion the geophones are usually placed along a straight traverse, hence seismic data is usually collected along "lines", the introduction of energy at vibration points being repeated many times along each traverse in order to amplify the weak geological reflections against other "white" noise. The laying out and collection of geophones usually requires some vehicular access. In the initial stages, seismic lines are often recorded along pre-existing thoroughfares.

Because many geophones are used (often over 2,000 per recording) there is considerable statistical redundancy. This means that geophone positioning can accommodate local vegetation and terrain conditions. Clearing seismic traverses of grass and other vegetation, a common practice 30 years ago, is no longer necessary with modern digital telemetry recording systems. Moreover, modern processing techniques now also accommodate "crooked" line recording, so that in open forest country lines and geophones can be located around trees. Surface clearing is minimal and sufficient only for access by geophone, source and recording vehicles. Seismic acquisition is a transient process, with daily production rates of 5 - 15 km. Typically lines are scouted, surveyed and pegged at regular intervals for source and geophone positioning. Once recording is complete, pegs are removed. Individual lines are subject to sporadic traffic movements for a maximum of 2-3 days for any given survey. Remedial work nowadays is usually not required following the survey.

Currently there is no technology available to define, using measurements at the earth's surface, the presence of commercial quantities of hydrocarbons within the underlying rock units. Accordingly, once surface based geological and geophysical studies have identified an area of extreme interest (prospect) it is necessary to drill to recover rock samples and any contained fluids in order to assess whether economic quantities of oil and gas might exist at depth.

Exploration drilling for petroleum requires a drilling rig considerably larger than for coal exploration because the diameter of the holes drilled is larger. Drilling requires the clearing of a well site and levelling of the land surface for the safe installation of drilling equipment. An earth dam for water and drilling mud supply and detention is also usually built, the total area involving approximately 1 ha. Clearing of surrounding vegetation is also necessary in the event of controlled release of gas and liquids that may be encountered whilst drilling. Facilities to flare any gas tested also need to be in-place.

Exploration wells are usually drilled over a period 2-3 weeks. If the well is dry then it will be plugged and abandoned and the site rehabilitated, so that there are no permanent impacts of the drilling activity. Development drilling to assess a discovery has a longer-term impact, with wellhead infrastructure being put in place. Production testing may occur over a period of several months during which time the reservoir and gas characteristics are monitored and evaluated. Once production operations are approved,

pipelines connecting wellheads to the collection facilities are constructed and the surrounding areas are rehabilitated. Access to the wellhead must be maintained for routine monitoring, maintenance and servicing.

Because exploration is primarily a data gathering process it is necessarily dynamic, so that most regions can never be regarded as being completely explored. The direct costs facing explorers increase as the target areas become smaller and exploration methods become more expensive. The environmental impact associated with exploration also increases as the areas being explored become smaller and the applied exploration methods become more invasive, such as close space development drilling, or 3D seismic programs). All activities are required to be carried out to best practice standard and on completion of the operations rehabilitation of all sites is required and monitored. The long-term impact of petroleum exploration and production operations is minimal.

7. MINERAL, CONSTRUCTION MATERIAL AND PETROLEUM POTENTIAL ASSESSMENT METHODOLOGY

7.1 GENERAL ASSESSMENT METHODOLOGY

The mineral, construction material, and petroleum potential of the BBSB has been assessed by determining the types of deposits likely to be found within the geological framework known or interpreted to be present. The general methodology used was developed by the United States Geological Survey (USGS), and has been used successfully for resource assessments of the Upper and Lower North East, Eden and Southern Regional Forest Agreement areas. This approach identifies geological areas (tracts) which could contain particular types of deposits. A summary of the qualitative assessment methodology is described by Marsh et al (1984), Taylor and Steven (1983), and by Dewitt et al (1986).

A qualitative assessment of the potential resources of an area is an estimate of the likelihood of occurrence of deposits that may be of sufficient size and grade to constitute a resource. The term 'resource' is restricted to deposits judged to be potentially viable in the next 25 years. Only the deposit types judged to be most likely to constitute significant resources in the region have been assessed in detail.

Resource assessment of an area combines knowledge of its geology, geophysics, geochemistry, and deposit occurrences, with current theories of deposit genesis and results of previous exploration. The assessment process requires a study of available geoscientific data to determine the history of geologic processes and environments. Geological environments judged to have characteristics that are known to be associated with specific types of deposits are then identified. In particular, the assessment draws on regional and local characteristics of deposit models to establish whether or not specific types of deposits are likely to occur, and whether they occur in economic grades and sizes.

The potential of an area is its likelihood of having a particular type of deposit, ranked as high, moderate, low or unknown, based on expert judgments of geoscientists involved in the assessment. To reflect the differing amounts of information available, the assessments of potential are also categorised according to levels of certainty, denoted by letters A to D in order of increasing certainty (table 12).

TABLE 12. RELATIONSHIP BETWEEN LEVELS OF RESOURCE POTENTIAL AND LEVELS OF CERTAINTY

Decreasing level of potential ↓	D	C	B	A
	H/D HIGH POTENTIAL	H/C HIGH POTENTIAL	H/B HIGH POTENTIAL	U/A UNKNOWN POTENTIAL
	M/D MODERATE POTENTIAL	M/C MODERATE POTENTIAL	M/B MODERATE POTENTIAL	
	L/D LOW POTENTIAL	L/C LOW POTENTIAL	L/B LOW POTENTIAL	
	N/D NO POTENTIAL			

→ Decreasing level of certainty

Similar assessment procedures are commonly used by private explorers to choose the selection of exploration areas. It is important to note, however, that the assessment of potential resources is subject to the amount and the quality of data available to the assessors. As geological knowledge of an area is never complete, it is not possible to have a 'final' assessment of potential mineral, construction material and petroleum resources at any given time. The resource potential needs to be monitored and reassessed periodically to take account of new data and advances in geological understanding including relevant new discoveries. Advances in exploration, mining, production and quarrying technologies, and changes in market prices are other factors that may change the resource potential of an area.

7.2 SPECIAL ASSESSMENT CRITERIA FOR COAL

Coal resource deposits differ markedly from most other mineral deposits in that they have a relatively low dollar per tonne ratio, are only suitable for relatively large scale operations, are generally in relatively flat lying strata and hence involve a large aerial extent of the land surface. The mining potential of a coal resource is dependent on a large number of factors but there are five characteristics that can be used to provide an initial assessment potential. They are; depth, seam thickness, coal quality, lateral continuity, and constraints to mining.

Depth. The DMR considers that for the foreseeable future, the maximum depth for the economic underground mining of thermal coals to be 600 m.

Seam thickness. In determining an open cut coal resource, the DMR considers the minimum economic seam thickness to be 0.3 m and the maximum coal to overburden linear ratio to be 1:10. For an

underground resource, the Department considers the minimum economic seam thickness to be 1.5 m. However, most longwall operations require a minimum working section of 1.8-2.0 m for economic viability.

Coal quality. Coal quality involves many coal characteristics that affect its end use and value. The first significant property is the raw ash content, that is, the percentage of non-combustible matter (ash) within the seam or working section. A raw ash of 35% is considered the maximum for an underground or open cut coal resource. Coal quality can be upgraded by washing out the rock material to lower the ash content of the coal and some seams respond better to this process than others. Typical utilisation categories for coal based on ash % are set out below.

Raw Coal Ash % (ad)	Utilisation Category
<15%	**Prime Export (Thermal, PCI, Coking)**
15% to 20%	**Prime Export and Standard Export (beneficiated)**
	Domestic Thermal (raw and beneficiated)
20% to 30%	**Domestic Thermal, Cement Manufacture (raw)**
>30%	**Cement Manufacture (raw)**

Lateral continuity. The lateral continuity determines the extent of the mineable deposit and is primarily established by points of observation (usually boreholes). As the seam thickness and quality can vary considerable between points of observation, confidence in the assessment is largely dependent on the distance between points of observation.

Constraints to Mining. External factors may also place constraints on where mining can take place. These may be geological such as faults or igneous intrusions, topographical such as proximity to cliffs, rivers, dams and lakes, economic such as transport, industrial and agricultural infrastructure, environmental such as National Parks or other conservation reserves, or social such as proximity to dwellings, etc.

The industry has a clearly defined code for reporting coal resources to the market, referred to as the JORC (Joint Ore Reserve Committee) code. This categorises and assigns a specific status to a coal deposit. The categories are: Coal In Situ, Coal Resources and Coal Reserves.

Coal In Situ, includes any occurrence of coal in the Earth's crust which can be estimated and reported, irrespective of thickness, depth, quality, mineability or economic potential; and by definition, includes all Coal Resources. 'Coal Resource' is that part of the Coal In Situ category in such form and quantity that there are reasonable prospects for eventual economic extraction. A Coal Resource must be reported in terms of Inferred, Indicated or Measured status, depending on specific levels of confidence based on information gathered from points of observation that may be supported by interpretive data (such as aeromagnetic surveys). Trends may be extrapolated from Points of Observation up to 2 km for Inferred Resources; 1 km for Indicated Resources; and 500 m for Measured Resources.

A Coal Reserve is the economically mineable part of a Measured or Indicated Coal Resource at the time of reporting. It includes diluting materials and allowances for losses that may occur when the coal is mined. Coal Reserves are further categorised again depending on levels of confidence as Probable, Proved and Recoverable and then, depending on washing or other preparation as Marketable (Probable and Proved).

7.3 SPECIAL ASSESSMENT CRITERIA FOR COAL SEAM METHANE

Coal seam methane (csm) is the natural gas formed during the coalification process whereby peat and other organically rich sediments are transformed into coal, as a consequence of compaction and heat associated with the processes of on-going deposition and burial. Coal seam methane is essentially similar to natural gas found in conventional sedimentary reservoirs, although it is generally higher in methane concentration. However, unlike conventional natural gas reservoirs, where gas is trapped in the pore or

void spaces of a rock, such as sandstone, methane trapped in coal is adsorbed onto the coal grain surfaces or micropores of the coal and is held in place by reservoir (water) pressure.

The coal therefore acts as a source, reservoir and seal for the methane and as such is to be distinguished from a conventional gas accumulation within a sandstone reservoir rock. Because the micropore surface area is very large, coal can potentially hold significantly more methane per unit volume than most conventional reservoirs such as sandstone. Csm is generally regarded as an "unconventional" source of natural gas, and is distinguished from conventional gas which is produced from reservoir rocks that are typically not the origin of the gas.

In New South Wales, exploration activity has been carried out for some years in the Gunnedah Basin and in the Sydney Basin, further to the south. The potential for csm is not governed exclusively by the presence of coal (Vanibe, 2000). In order to establish viable, commercial production it is necessary to evaluate the coal seams in order to establish their potential to produce adequate gas volumes on production. The general criteria relevant to the successful discovery and development have been stated as follows by Brown et al (1996), with appropriate modification.

Areal extent. This depends on the permeability and gas content and varies from area to area. Typically a producing field would comprise at least 250 wells at an "80 acre" (approximately 32 ha) spacing, requiring between 80 and 100 km^2, depending upon site conditions.

Ash. A low ash content is generally better for csm recovery. Coals with high (incipient, or detrital) ash content tend to have fewer fractures. Fractures can be filled to varying amounts with "mineral matter" and such mineral matter can also contribute to the ash content of the coal. Coals with high ash content also tend to have less adsorbed gas by volume.

Depth. In general terms, coal seams in the range of 250m to 1000m in depth are favoured for coal seam methane production, otherwise overburden pressures are either too small or too great.

Cleat. Cleat is a fracture, or fracture system, developed in coal. Face cleat is the fracture system developed parallel to bedding, and butt cleat is the fracture system at right angles to the bedding. Good cleat development is generally more common in coals with high vitrinite and bright clarain. High cleat density is related to higher permeability.

Structuring. Csm prospectivity is enhanced when the coal seam has extensive lateral continuity. Significant fault displacement can restrict production potential from a coal reservoir. This is caused by the dislocation of the reservoir into small unconnected or poorly connected blocks. In some cases faulting can act to permit the escape of methane from the coal, which is deleterious for csm reservoirs but could allow migration of methane to another reservoir, such as a conventional gas-in-sandstone reservoir. In this respect, there might be an inverse relationship between csm and conventional oil and gas prospectivity in such areas. The presence, frequency, orientation and intensity of folds, faults, joints, and cleats influence the permeability and continuity of a coal reservoir. The presence of a tensional structural regime is preferred to enhance production potential, because such a regime favours dilation of cleats etc and hence facilitates greater permeability.

Density. - There is a preference for coals, which have low bulk density or specific gravity. Specific gravities of less than 1.45 gm/cc are generally regarded as being more suitable for csm prospectivity, whereas coals with densities of greater than 1.6 gm/cc have lower prospectivity.

Igneous Intrusions. - Igneous intrusions can affect the composition of the gas in the coal reservoir by raising the proportion of carbon dioxide present. In some areas, the thermal maturity of the coals present may be altered, the consequences of which can be either favourable or unfavourable.

Insitu Stress. This expressed in terms of effective stress, is a major control on the cleat and fracture dilation and consequently coal seam permeability. Low effective stress favours good permeability.

Permeability. Permeability is a fundamental parameter for CSM production. Ideally, this should be greater than 5 millidarcies, but sometimes permeability values as low as 1 millidarcy can yield satisfactory gas flows.

Reservoir pressure. Generally, depths below 250m are required to develop the hydrostatic pressure to ensure the gas is held adsorbed onto the coal, and also to promote production from the wells. If the pressure is low then a considerable amount of gas may have been lost.

Overpressuring. Although not prevalent in Australia, it is important because well completion techniques have been developed in the USA to produce gas from overpressured reservoirs.

Seam thickness. Generally, the preferred values for coal seam and reservoir thickness are greater than 10 m for single and closely spaced completions, and greater than 15m for multiple completions.

Thermal maturity. The maturation of the coal should be in the range of Ro of 0.7 to 2.0% vitrinite reflectance. Peak maturity for csm is around 1.2%.

7.4 SPECIAL ASSESSMENT CRITERIA FOR PETROLEUM

The principles of conventional oil and gas prospectivity outlined in Upstream Petroleum Consulting Services (2002a, 2002b, and 2002c), and Vanibe (2000), are used to assess BBSB conventional petroleum resources.

Most sedimentary rocks contain some organic material, although not all rocks are capable of generating petroleum. Typically, rocks capable of generating conventional petroleum have at least 0.5 % and preferably more than 1.0%, total organic carbon content. Coals and fine grained sedimentary rocks, such as shales and siltstones, are the most common rock types containing sufficient organic material to constitute potential petroleum source rocks.

When subjected to appropriate depths of burial (associated with increased temperature), and for sufficient time, source rocks will generate and expel liquid or gaseous hydrocarbons. These hydrocarbons move through the microscopic voids in rocks under the influence of buoyancy and congregate in traps where their further movement is impeded by permeability barriers. Structural traps typically are associated with anticlines or faulting.

The most prospective traps involve very porous and permeable rock types, reservoirs, such as sandstone in which significant quantities of petroleum may be contained. Seismic reflection surveys are used by explorers to image potential traps in the subsurface so that they may subsequently be drilled to test whether they contain petroleum bearing reservoirs. Unlike csm, expelled conventional oil and gas may move tens of kilometres under the influence of buoyancy (a process called migration) out of the deep basin areas in which they were generated and across the flanks of adjoining structural highs.

A pod of actively generating source rock (kitchen area) and all related oil and gas, together with all of the essential elements and processes needed for oil and gas accumulations is referred to as a petroleum system (Magoon & Dow, 1994, Magoon, 1997). The occurrence of genetically related oil and gas accumulations implies that migration pathways exist, either now or in the past, connecting the kitchen with the accumulations. Using the principles of petroleum geochemistry and geology this fluid system can be mapped in order to better understand how it evolved. The goal of the explorer is to use seismic data, well data and other geophysical data, to map and delineate specific petroleum systems in order to locate undiscovered petroleum. This approach can be applied at both the basin and continental-wide scale (eg. Bradshaw, 1993, Bradshaw et al, 1994, and Boreham and Summers, 1999).

Traps are described as prospects or leads, depending upon the degree of confidence of their delineation. Typically the play fairway comprises a group of areally defined prospects and leads, which share similar or common trap type, seal, reservoir, and petroleum source within a petroleum system. Thus they share common elements of exploration risk relating to the possible occurrence of oil and gas. Exploration strategies are geared to targeting specific traps in a play fairway and previous exploration results in a specific fairway reflect the geological risk associated with that play type. That is, within the same fairway sourcing, migration and entrapment are similar, whereas they are to some degree different to those of adjacent fairways.

7.5 SUMMARY OF POTENTIAL METALLIC AND INDUSTRIAL MINERAL, CONSTRUCTION MATERIAL AND COAL AND PETROLUEM RESOURCES, SEPTEMBER 2002.

Tracts in the BBSB judged to contain potential for the formation of specific types of deposits are delineated and their potential is ranked in table 13.

TABLE 13. SUMMARY OF POTENTIAL METALLIC AND INDUSTRIAL MINERAL, CONTRUCTION MATERIAL, AND COAL AND PETROLEUM RESOURCES, SEPTEMBER 2002

		LEVELS OF POTENTIAL & STANDARD POTENTIAL SCORES (b)				
		High 18	M-H 12	Moderate 6	L-M 2	Low 1
DEPOSIT MODELS	DEPOSIT INDEX (a)	WEIGHTED POTENTIAL SCORE (a x b)				
Coal	10	180	120	60	20	10
Coal Seam Methane	10	180	120	60	20	10
Petroleum (includes conventional gas)	10	180	120	60	20	10
Porphyry Cu-Au	8	144	96	48	16	
Rare Earth Element	7	136		42		7
Kuroko VHMS	7	136		42		7
Epithermal Au-Ag	7	136	84	42		7
Orogenic Gold	5			30	10	
Alluvial Sapphire	5	90	60	30	10	5
Weathered profile-hosted Opal	5		60		10	5
Heavy Mineral Sand (fluvial and beach placer)	5				10	5
Construction Materials and Dimension Stone	2	36		12		2
Alluvial Diamond	2		24		4	2
Zn-Pb Skarn	2	36		12		2
Besshi/Cyprus VHMS	2	36	24		4	2
Tin (greisen and vein)	2	36	24		4	2
Alluvial tin	1		12		2	1
Zeolite	1	18		6		
Kaolin	1		12	6		1

(NB: Even though a single index has been used for each deposit type, some of the deposit types have more than one index, which reflect factors such as sub-types and different stratigraphic positions of host rocks. Where possible these factors have been incorporated into the levels of potential (b) for each tract).

To facilitate the review, all the metallic and industrial mineral, construction material, and coal and petroleum tracts were combined (overlain) to produce four types of summary maps of mineral and petroleum potential (figures 25 to 28), of which the most significant are figures 27 and 28. (Note: construction materials can here be taken to read as minerals, and coal is a mineral).

Figure 25 is a composite of mineral and petroleum potential for the BBSB and shows the highest level of potential assessed for areas in the region. Where tracts for different deposit types overlap, the area is assigned the highest potential level of all the overlapping tracts. In this approach, the tract having the highest potential in any particular area obscures tracts of lower potential. It is important to note that the different types of mineral and petroleum deposits do not have equal economic values.

Figure 26 shows the cumulative mineral and petroleum potential for the BBSB. In constructing this figure, standard scores were allocated according to a subjective ranking of levels of potential as follows:

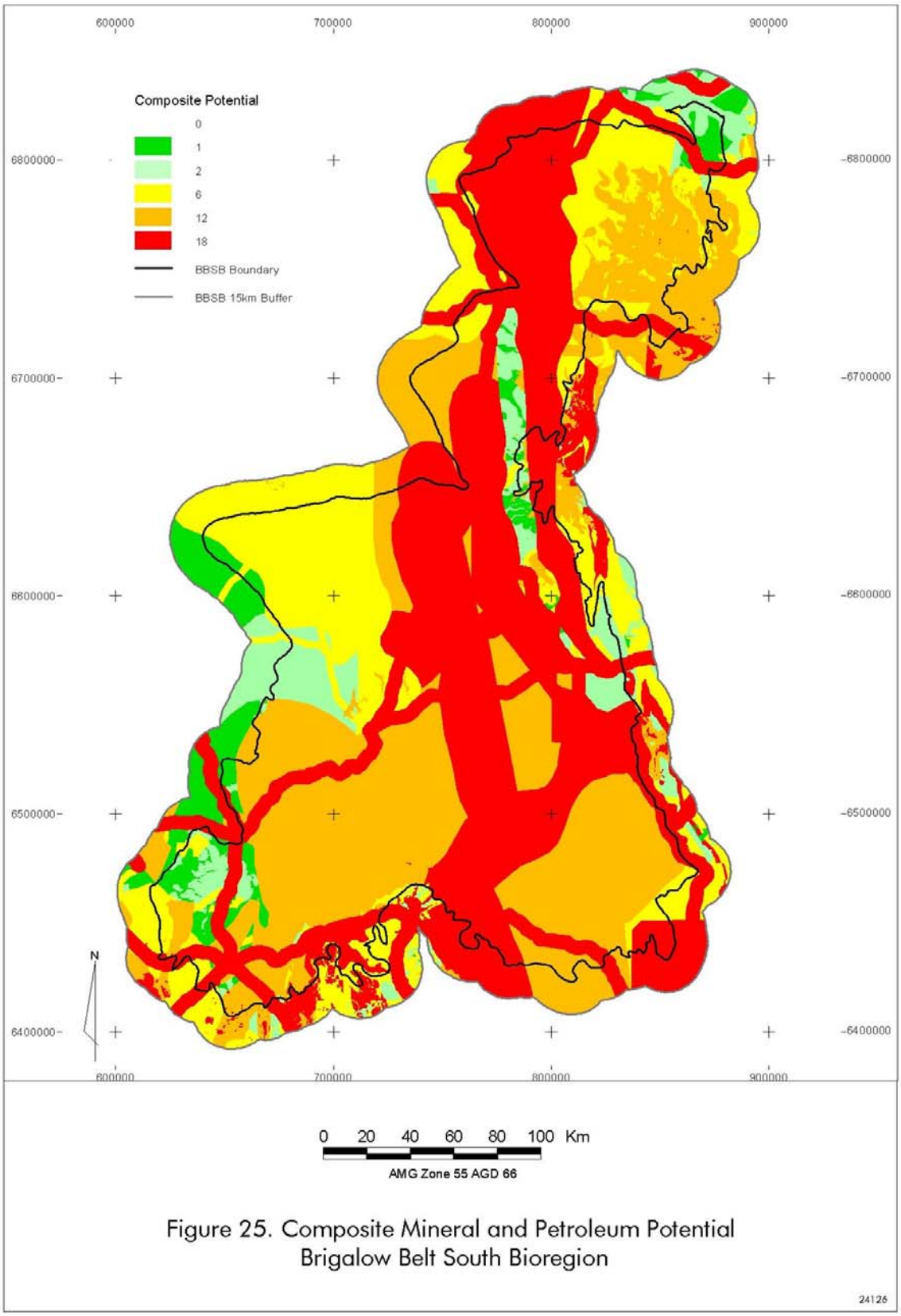

Figure 25. Composite Mineral and Petroleum Potential
Brigalow Belt South Bioregion

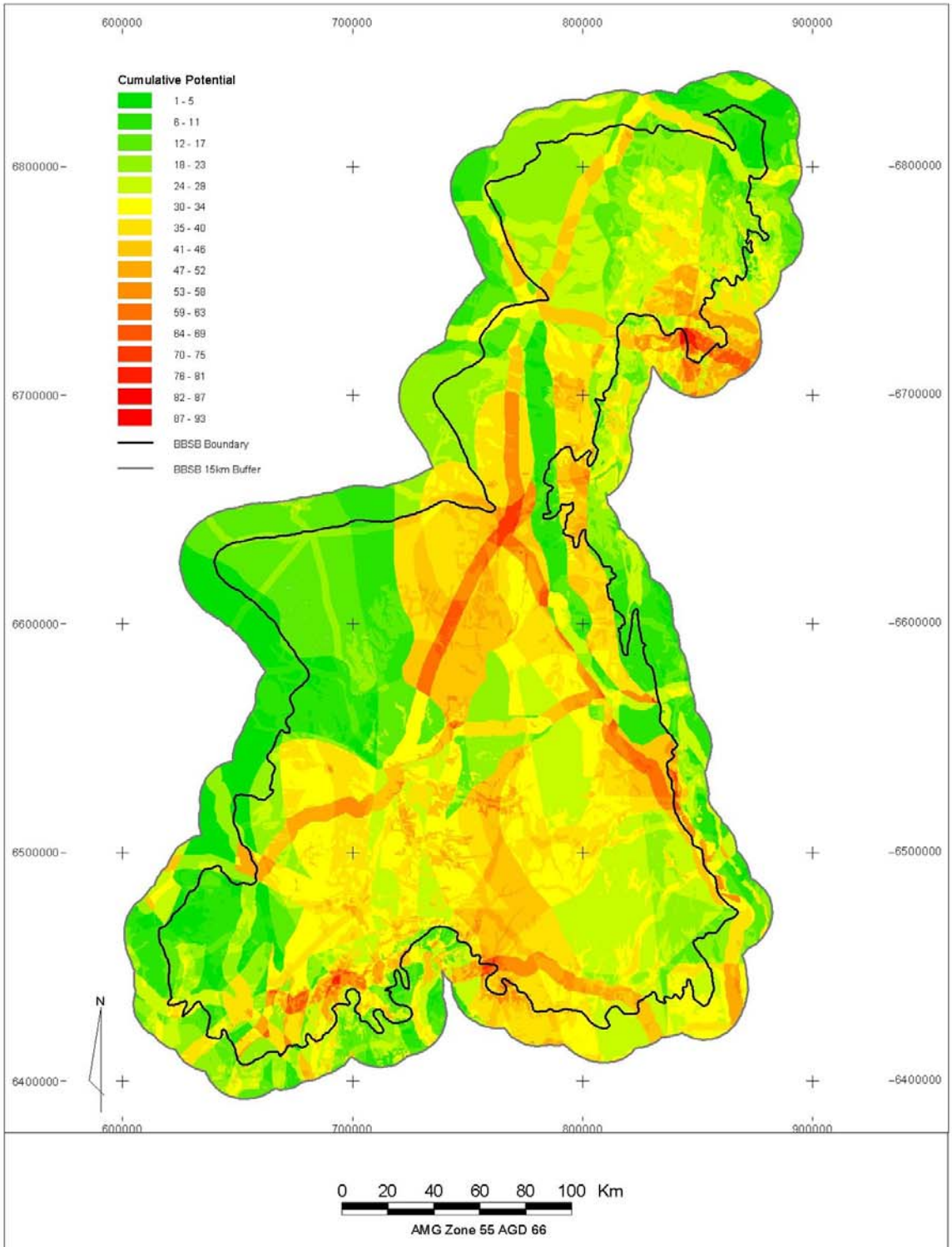

Figure 26. Cumulative Mineral and Petroleum Potential
Brigalow Belt South Bioregion

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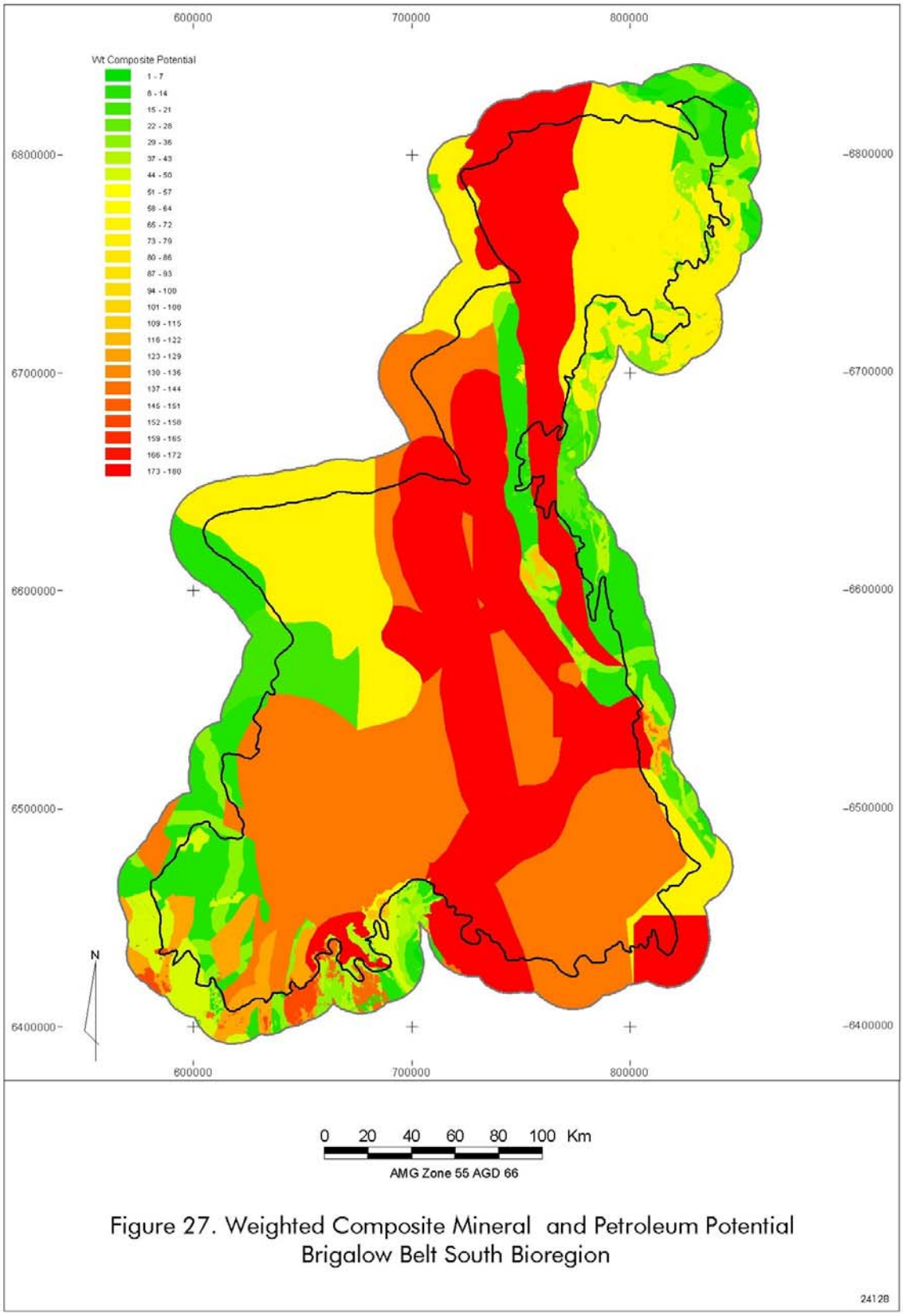

Figure 27. Weighted Composite Mineral and Petroleum Potential
Brigalow Belt South Bioregion

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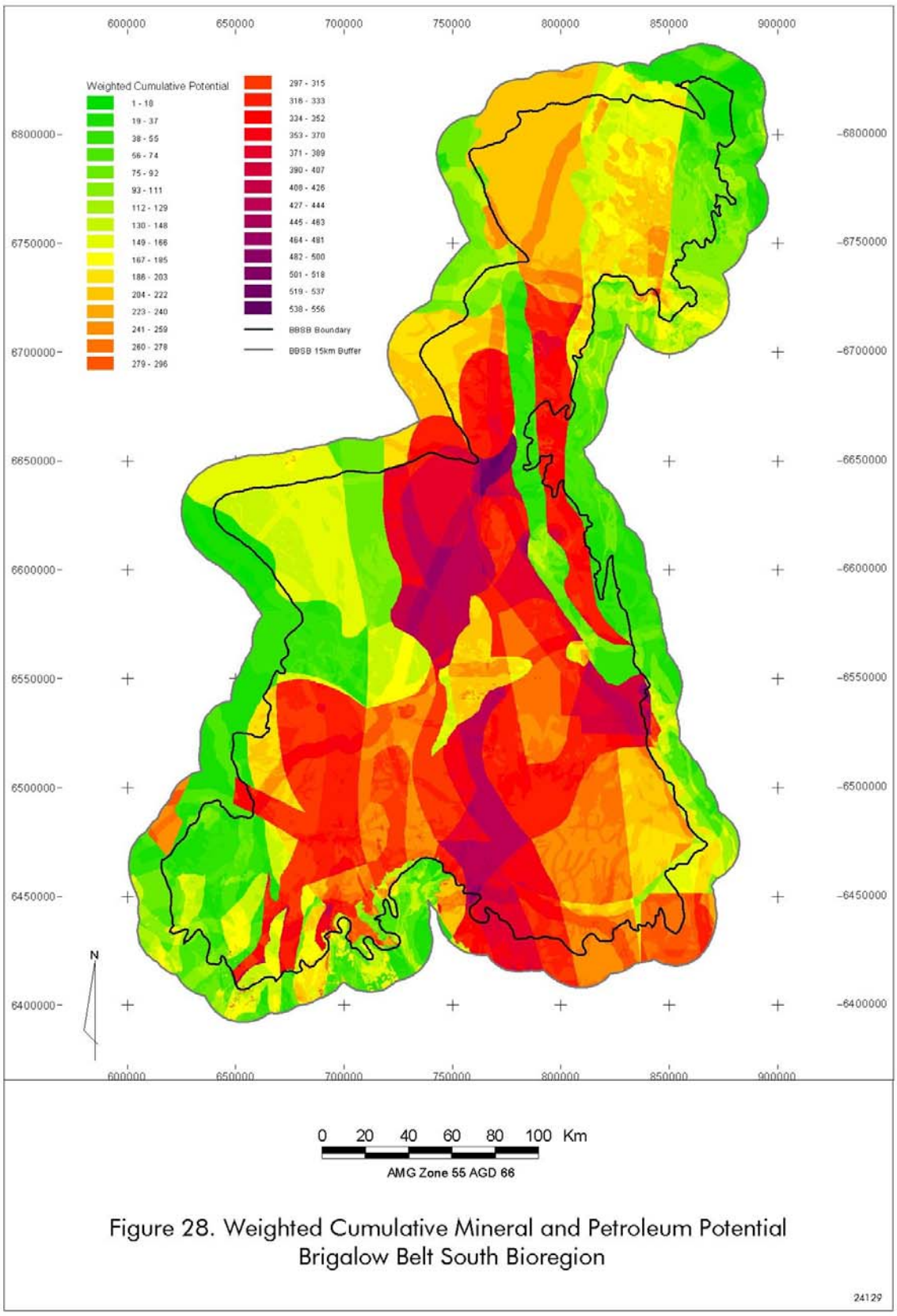

Figure 28. Weighted Cumulative Mineral and Petroleum Potential
Brigalow Belt South Bioregion

24129

high potential (18), moderate – high (12), moderate (6), low – moderate (2), low (1). In those areas where tracts overlap, the scores are added and this cumulative score is assigned to the overlapping areas. The cumulative mineral and petroleum potential takes account of both the diversity of deposit types that may occur in each area, as well as the level of potential of each of these deposit types.

Figure 27 shows the weighted composite mineral and petroleum potential for the region. The weighted composite potential makes some allowance for the relative economic significance between different types of deposits. Deposits have been indexed using the indices listed in table 13. The weighted composite score is calculated by multiplying the deposit index by the standard potential score. Where there are overlapping tracts, with different weighted scores, the highest of these scores is assigned to the area of overlap. Tracts with higher weighted potential include coal, coal seam methane, petroleum and porphyry copper-gold.

Figure 28 shows the weighted cumulative mineral and petroleum potential for the region. It is similar to the weighted composite mineral and petroleum potential in that the score for each tract is calculated by multiplying the deposit index by the potential score. Where there is overlap of tracts, the scores of the overlapping tracts are summed and this total score is assigned to the overlap area. The relative importance of deposit types is taken into account before adding individual potential scores. The weighted cumulative map is similar to the cumulative map but the zones of elevated scores are enhanced.

8. MINERAL, CONSTRUCTION MATERIAL AND PETROLEUM PROSPECTIVITY

Descriptive metallic and industrial mineral, and construction material models for qualitative broad scale assessments of the BBSB are described in Appendix 2. Descriptive models for coal, coal seam methane, and petroleum are described in the text to chapters 7 and 8. The favourable geological tracts for these types of deposits are indicated on figures 25 to 44 and figures 58 to 60.

8.1 METALLIC MINERALS

8.1.1 Porphyry Copper-Gold (Figure 29)

Although there are only a few known porphyry copper-gold occurrences associated with Lachlan Fold Belt rocks in the BBSB, southern extensions of these rocks host world-class porphyry copper-gold deposits such as Goonumbla, Ridgeway and Cadia Hill.

The known and interpreted porphyry copper-gold prospects within or close to the southern margins of the BBSB include the Wongoni Prospect, and numerous prospects in the Comobella area. The latter area is considered highly prospective for this deposit style, satisfying a number of known geological criteria. The prospective rocks also extend beneath shallow basin cover to the north.

Tract CuAu a/H/C-D
The tract includes outcropping and subcropping Late Ordovician volcanics, volcaniclastics, intrusives and sedimentary units of the Molong and Narromine Volcanic Belts (for example, Cabonne Group, Oakdale Formation, and the Cotton Formation). Potential of the tract is assessed to be high with a certainty level of C-D.

Tract CuAu b/M-H/B-C
This tract includes inferred extensions of the Molong and Narromine Volcanic Belts under cover, to an inferred depth of 300 m. Potential of the tract is assessed to be moderate to high with a certainty level of B-C.

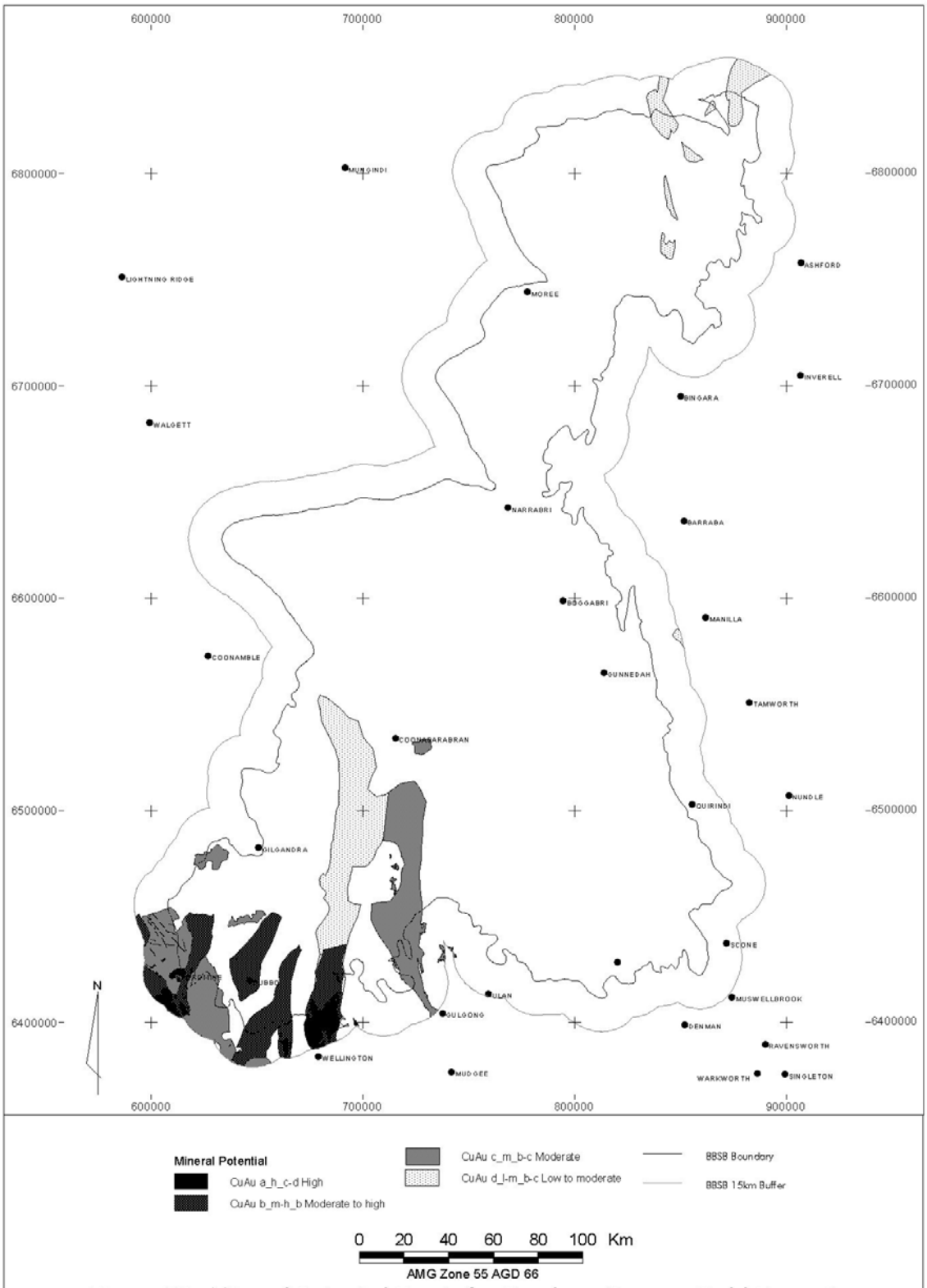

Figure 29. Mineral Potential Tracts for Porphyry Copper-Gold Deposits Brigalow Belt South Bioregion

Tract CuAu c/M/B-C
This tract includes outcropping and inferred subsurface extensions of the Early Devonian Yeoval Complex, a fractionated, I-type, felsic, and oxidised intrusive complex; and Late Ordovician Rockley-

Gulgong Volcanic Belt volcaniclastics, intrusives and sedimentary units and their inferred subsurface northern extensions which intersect with the Hunter River Transverse Zone (HRTZ, see Glen et al, 1998). The HRTZ is a major northwest trending lineament feature which has been suggested to influence the prospectivity of porphyry Cu-Au style deposits in the southern parts of the BBSB. Northern extensions of this belt have also been included along the inferred shallow basement of the Rocky Glen Ridge. The Middle Carboniferous Wuuluman Granite has not been included in this tract because the plutons of this multiphase intrusion are generally described as unfractionated and of intermediate type. Potential of the tract is assessed to be moderate with a certainty level of B-C.

Tract CuAu d/L-M/B-C
The tract includes Late Ordovician volcanics, volcaniclastics, intrusives and sedimentary units of the Rockley-Gulgong Volcanic Belt west of the inferred basement high of the Rocky Glen Ridge, and inferred extensions of the Molong and Narromine Volcanic Belts under basin cover which have been inferred to be deeper than 300 m. It also includes inferred Late Permian to Early Triassic subsurface intrusives of the Moonbi Suite in the New England Fold Belt. The Moonbi Plutonic Suite intrusives are fractionated, I-type, oxidised granites which have been recognised to have porphyry copper-gold potential. A prospect at Bald Hill on the eastern portion of the BBSB has identified Late Permian monzonite intrusives with anomalous gold and copper, possibly belonging to the Moonbi Suite. Potential of the tract is assessed to be low to moderate with a certainty level of B-C.

8.1.2 Epithermal Gold-Silver (Figure 30)

The Mount Terrible deposit, located just east of the BBSB, was discovered in the early 1990s hosted by the Late Permian Warrigundi Igneous Complex. It has an inferred resource of 132,000 t at 7.8 ppm Au. Although the ore zone crops out, Mount Terrible had no previous mining history. The White King deposit is a significant epithermal prospect located just outside the BBSB in Queensland, hosted within Lower Permian Volcanics. Recent exploration has delineated a low-moderate sized resource. Similar volcanic units could also be present beneath shallow basin cover within the northern parts of the BBSB. The recent discovery of the Klondyke Prospect at Cracow in Queensland, with an inferred resource of 1.1 Mt at 11 ppm Au, 9 ppm Ag, is buried beneath shallow basin cover and similar prospects could be discovered in the BBSB.

There are several prospects in the Gunnedah area hosted by Permo-Carboniferous volcanics of the Tamworth Belt close to the margins of the BBSB which could be epithermal Au-Ag in style. They include the Hill 398 Prospect. Areas of subaerial, felsic-intermediate Silurian, Devonian, and Late Permian volcanics and their subsurface extensions in the southern parts of the BBSB are also prospective for epithermal style deposits. The Bowdens Gift deposit is hosted by Late Permian Rylestone Volcanics to the south of the BBSB, situated adjacent to basin cover with an indicated and inferred resource of 59 Mt at 43.8 g/t Ag, 0.22% Pb, 0.31% Zn (2001).

Tract Epi a/H/C
The tract includes outcropping and subcropping subaerial volcanics and associated volcaniclastic rocks (rhyolitic ignimbrites, tuffs and agglomerates and basaltic flows) with known epithermal prospects including the Rylstone Volcanics, and the Warrigundi Igneous Complex. These rocks host the Mount Terrible and Bowden's Gift prospects, which occur outside the BBSB, but the host rocks are known to extend into the BBSB. The volcanics and the volcaniclastics show sericitic and propylitic alterations. Potential of the tract is assessed to be high with a certainty level of C.

Tract Epi b/M-H/B-C
The tract includes outcropping and subcropping rocks which are reported to host possible epithermal occurrences, but are not dominantly subaerial. They include the Boggabri Volcanics, which probably host the Hill 398 prospect. The tract also includes rocks within 2 kilometres of rocks that form Tract Epi a/H/C, because these rocks have the potential to be included in epithermal systems created by and around subaerial volcanic complexes included in the Tract Epi a/H/C. The tract is assessed to have moderate to high potential for epithermal gold-silver deposits with a certainty level of B-C. A lower level of certainty (B) applies to areas within 2 km buffer of rocks that form Tract Epi a/H/C.

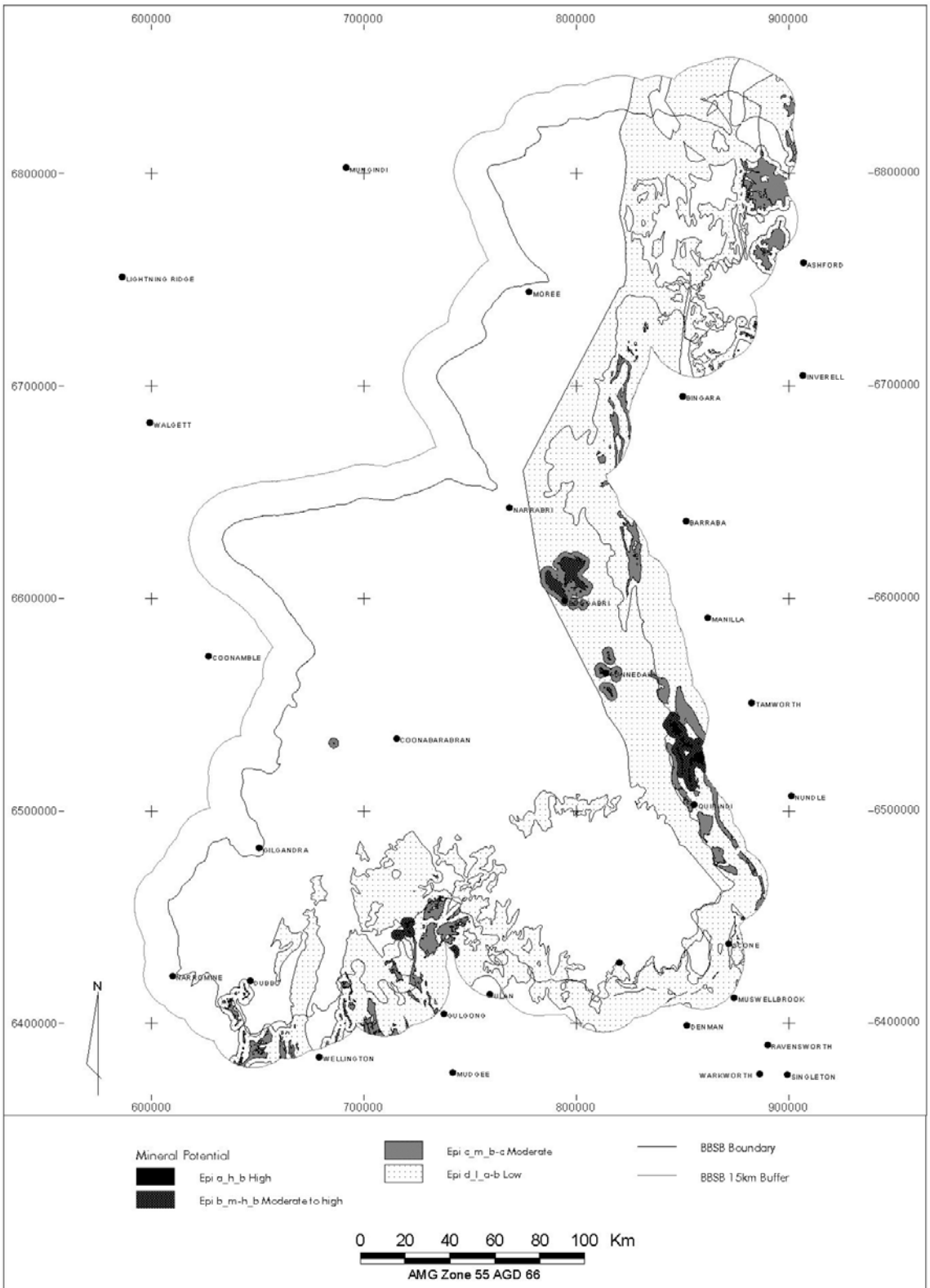

Figure 30. Mineral Potential Tracts for Epithermal Gold-Silver Deposits Brigalow Belt South Bioregion

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Tract Epi c/M/B-C
The tract includes other outcropping and subcropping felsic to intermediate volcanics and volcaniclastics that have formed at least partially in subaerial conditions. In the New England Fold Belt these include: the Silver Gully Formation, Barneys Spring Andesite member, Ermelo Dacite tuff, Plagyan Rhyodacite Tuff Member, Clifden Formation, the Texas Beds, and the Currabubula Formation and its equivalents.

In the Lachlan Fold Belt this includes the Tannabutta Group (Dungaree Volcanics, Toolomanang Formation, and Millsville Formation), Canowindra Volcanics, Turondale Formation, Curga Burga Volcanics, and all the Hyandra Creek Group. Although no occurrences of epithermal gold-silver are known to be associated with these units, some of these rocks have been reported to show alterations typical of epithermal systems. Potential of the tract is assessed to be moderate with a certainty level of B-C. The tract also includes rocks which are within 2 km of tract Epi b/M-H/B-C. A lower level of certainty (B) applies to these areas.

Tract Epi d/L/B-C
The tract consists of rocks within 2 kilometres of tract Epi c/M/B-C. It is possible that these rocks are affected by epithermal systems generated by and around volcanics that form the tract Epi c/M/B-C. Also included are all remaining outcropping Carboniferous units in the New England Fold Belt, and interpreted extensions under shallow basin cover of tracts a, b, and c. Potential of the tract is assessed to be low with a certainty level of B-C.

8.1.3 Kuroko Volcanic Hosted Massive Sulphide (VHMS) (Figure 31)

Volcanic hosted massive sulphide (VHMS) base metal deposits have been a major historical producer of base and precious metals in NSW. Several Kuroko-type deposits are known to occur just south of the BBSB around Belara. These deposits occur in units which extend northwards beneath shallow basin cover into the BBSB.

Tract Kur a/H/C
The tract consists of outcropping and subcropping shallow to deep marine Middle to Late Silurian acid to intermediate volcanic/sedimentary rock packages within the Lachlan Fold Belt which host known Kuroko VHMS occurrences. These include the Piambong Formation and the Gleneski Formation. Potential of the tract is assessed to be high with a certainty level of C.

Tract Kur b/M/B-C
The tract includes inferred extensions under basin cover of the Piambong and Gleneski Formations. It also includes other outcropping and subcropping shallow to deep marine acid to intermediate volcanic/sedimentary rock packages within the Lachlan Fold Belt where there are no known Kuroko VHMS occurrences. This includes outcropping and subcropping Toongi Group units. Potential of this tract is assessed to be moderate with a certainty level of B-C. The higher level of certainty C, applies to outcropping and subcropping Toongi Group units.

Tract Kur c/L/C
The tract consists of all other outcropping and subcropping marine or partly marine acid to intermediate volcanic/sedimentary rock packages of any age in which local deeper marine environments conducive to VHMS deposit formation could occur. It includes the Dungaree Volcanics, the Mostyn Vale Formation (ie rhyodacitic to basaltic lava extruded in a deep marine setting), and all other units of the Tannabutta Group, the Chesleigh Group, the Mumbil Group, and the Cudal Group within the Lachlan Fold Belt not included in the above tracts Kur a, and Kur b. Potential of this tract is assessed to be low with a certainty level of C.

8.1.4 Orogenic Gold (Figure 32)

There are several historically productive orogenic-type gold fields located immediately adjacent to BBSB margins in both the Wellington and Bingara areas. Some of the more significant historical mines in these areas include the Mitchell's Creek Mine near Wellington, and the All Nations Mine near Bingara. Rock units and associated structures which host these deposits extend beneath basin cover into the BBSB. In addition, there are several major structures which may contain buried orogenic gold deposits in the eastern parts of the BBSB.

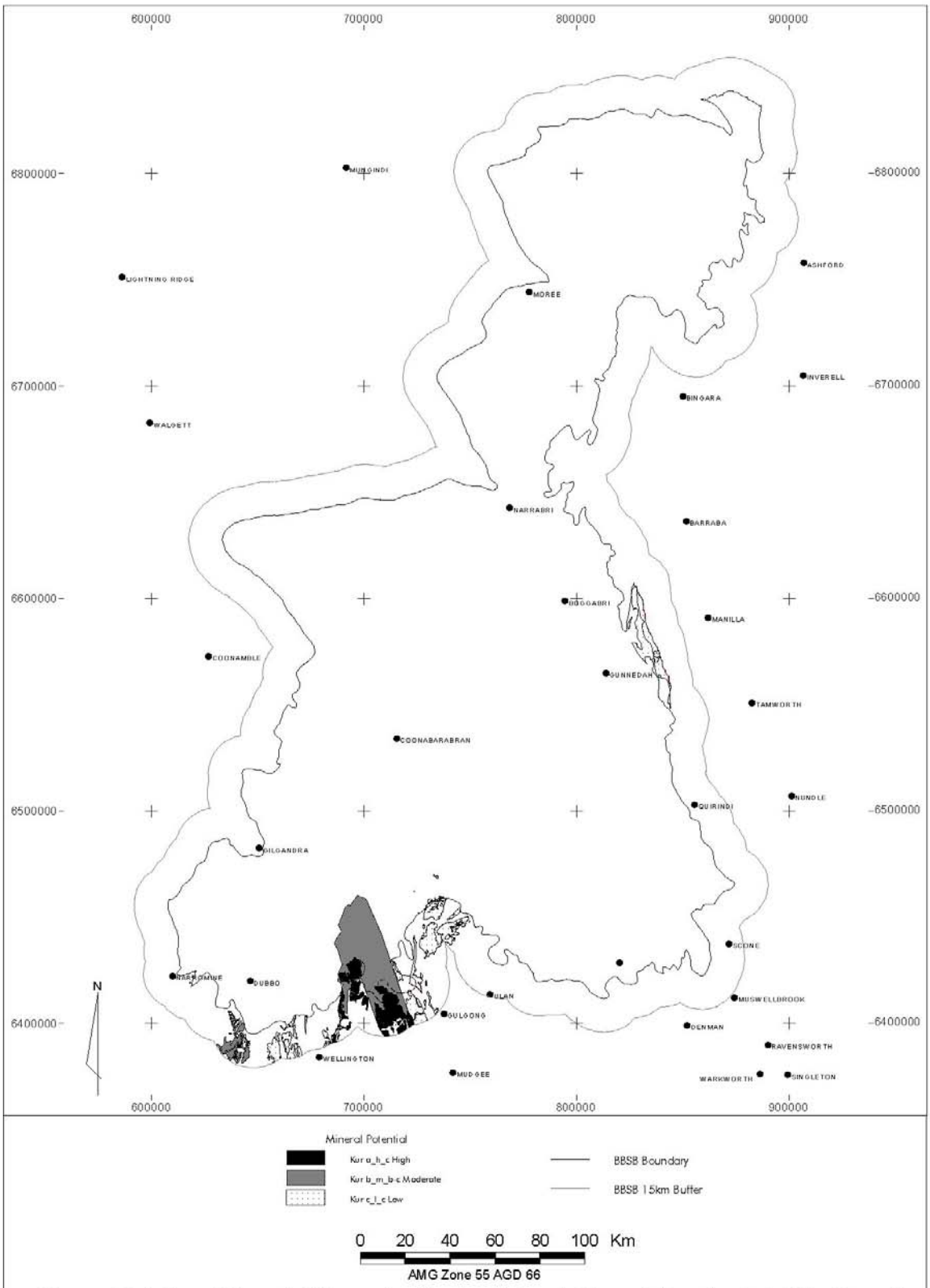

Figure 31. Mineral Potential Tracts for Kuroko Volcanic Hosted Massive Sulphide Deposits Brigalow Belt South Bioregion

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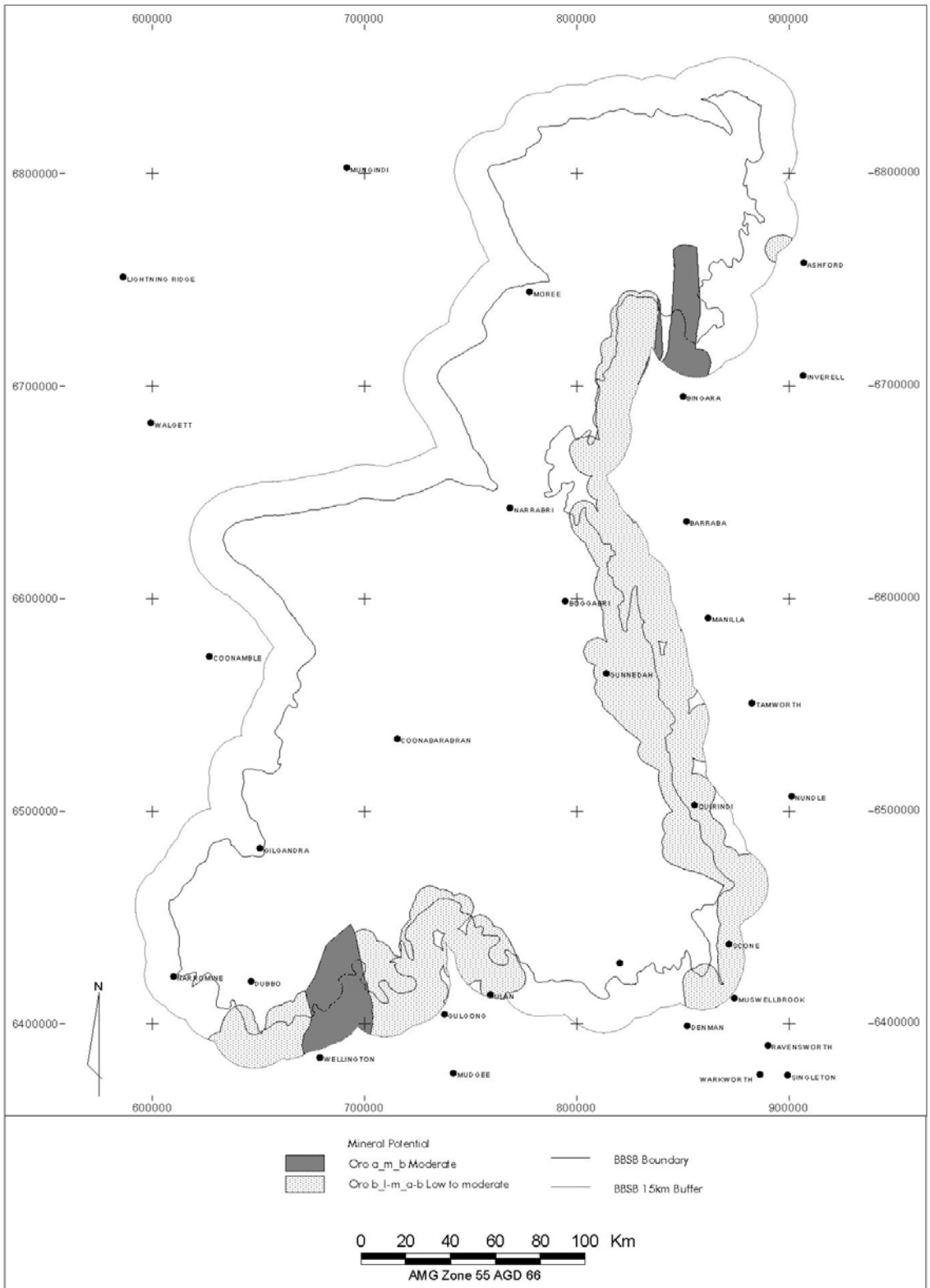

Figure 32. Mineral Potential Tracts for Orogenic Gold Deposits
Brigalow Belt South Bioregion

Tract Oro a/M/B-C
The tract includes all rocks that are within 12 km of 2 major fault zones in the BBSB and their subsurface extensions to an inferred depth of about 200 m. These two faults host the largest orogenic gold deposits adjacent to the BBSB. Potential is assessed to be moderate with a certainty level of B-C.

Tract Oro b/L-M/B-C
The tract includes all rocks that are within 6 kilometres of all 'minor' fault zones and their inferred subsurface extensions to an inferred depth of about 200 m. These faults are not considered as important as the 2 major fault zones in tract Oro above. Potential of the tract is assessed to be low to moderate with a certainty level of B-C.

8.1.5 Zinc-Lead Skarn (Figure 33)

There are a number of scattered, poorly documented old workings in the Glengarry, Bong Bong, and Mount Laut areas within and close to the margins of the BBSB, which may be of the zinc-lead skarn type. A number of probable zinc-lead skarn and related deposits occur at Leadville, just to the south of this area. The host Dungaree Volcanics are also present within the BBSB, and the likely source of the mineralisation-the Early Carboniferous Old Leake Quartz Monzonite or its equivalents-may also occur in the subsurface within the BBSB. It is also possible that mineralisation at Leadville is related to Early Permian volcanism (Downes, 1998).

Tract Skarn a/H/C
The tract consists of outcropping and subcropping calcareous-bearing rocks of the Dungaree Volcanics, situated within about 5 km of the oxidised, highly magnetic Old Leake Quartz Monzonite (I-type, felsic and fractionated) and its inferred subsurface equivalents. These rocks host the Leadville probable 'Zn-Pb Skarns'. Potential of the tract is assessed to be high with a certainty level of C.

Tract Skarn b/M/B-C
The tract consists of outcropping and subcropping calcareous and calcareous-bearing rocks within 5 km of reduced outcropping and subropping granitoids (eg Wuuluman Granite- I-type, mafic, and unfractionated, and its inferred extensions), and within 5 kilometres of outcropping and subcropping oxidised, fractionated, felsic granitoids, and their magnetic extensions without known zinc-lead skarn occurrences. (Eg the Yeoval Complex-I type, oxidised, felsic, and fractionated). Potential of this tract is assessed as moderate with a certainty level of B-C.

Tract Skarn c/L/B
The tract includes inferred buried Carboniferous, Devonian and Late Permian-Early Triassic intrusions buffered to 5 km under shallower basin cover, except where intrusions and calcareous rocks are already included in tracts Skarn a and Skarn b above. The inferred Late Permian-Early Triassic Moonbi Suite under cover is also included, as granites of this suite are characterised as relatively oxidised but vary in their relative oxidation states. Inferred intrusions in the northwest of the BBSB are not included, due to the known prohibitive depths of the basin cover. Potential of this tract is assessed to be low with a certainty level of B.

8.1.6 Besshi-Cyprus Volcanic Hosted Massive Sulphide (VHMS) (Figure 34)

Several deposits interpreted to be of the Besshi and/or Cyprus type occur close to the margins of the BBSB in the Warialda area. These deposits occur in units which extend northwards beneath shallow basin cover into the BBSB.

Tract BesCyp a/H/C
The tract consists of outcropping and subcropping marine intermediate to mafic volcanic/sedimentary rock packages of the New England Fold Belt. These units host all of the occurrences interpreted to be of probable Besshi and/or Cyprus type in the region. It consists of the Woolomin Group, and Cambrian to Ordovician age serpentinites and deep marine mafic to intermediate volcanics and cherts of the Woodsreef Melange of the Great Serpentinite Belt. Potential of the tract is assessed to be high with a certainty level of C.

Tract BesCyp b/M-H/B
The tract consists of inferred extensions of the Woolomin Group and Woodsreef Melange under basin cover. Potential of the tract is assessed to be moderate to high with a certainty level of B.

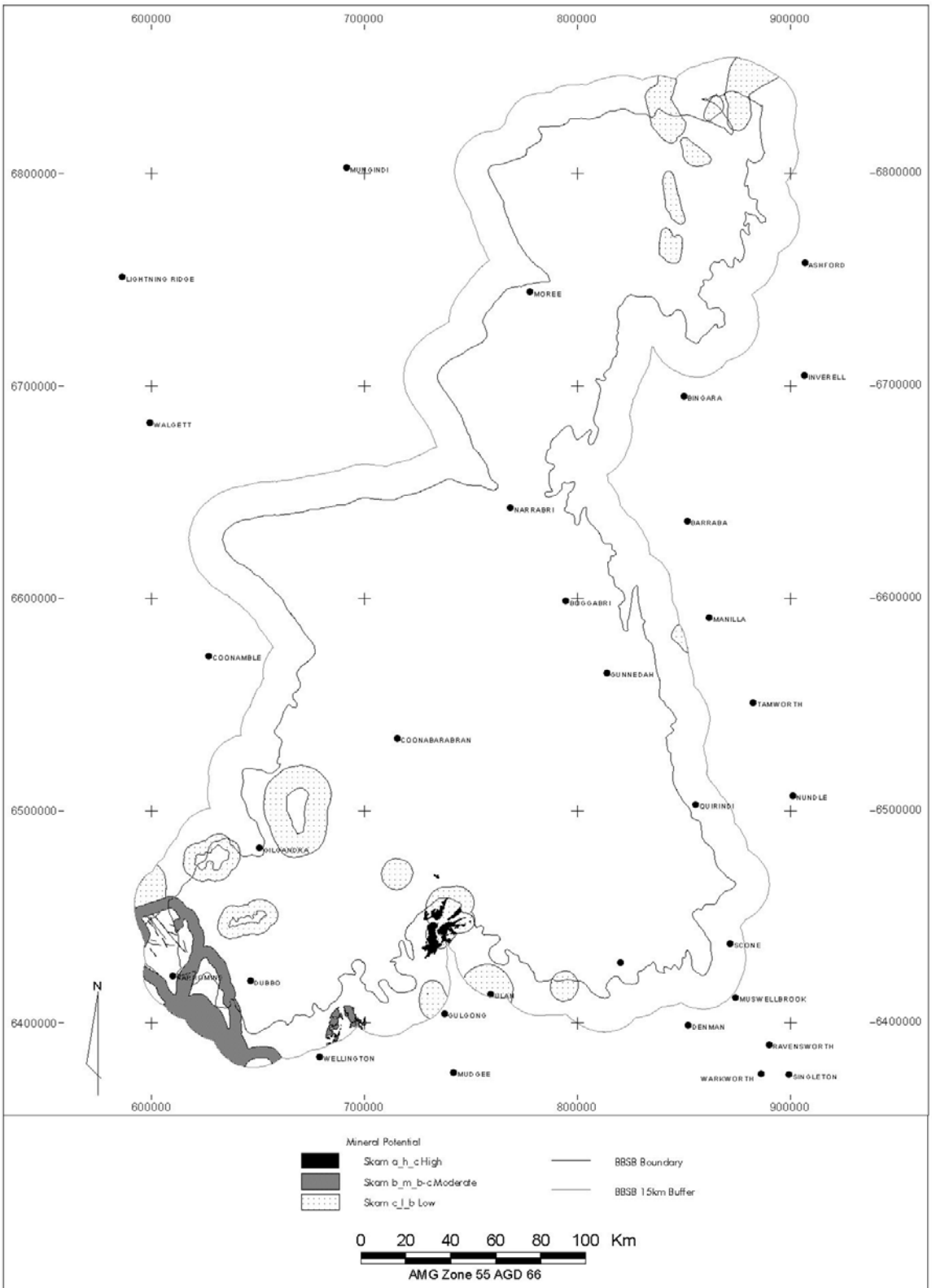

Figure 33. Mineral Potential Tracts for Zinc-Lead Skarn Deposits
Brigalow Belt South Bioregion

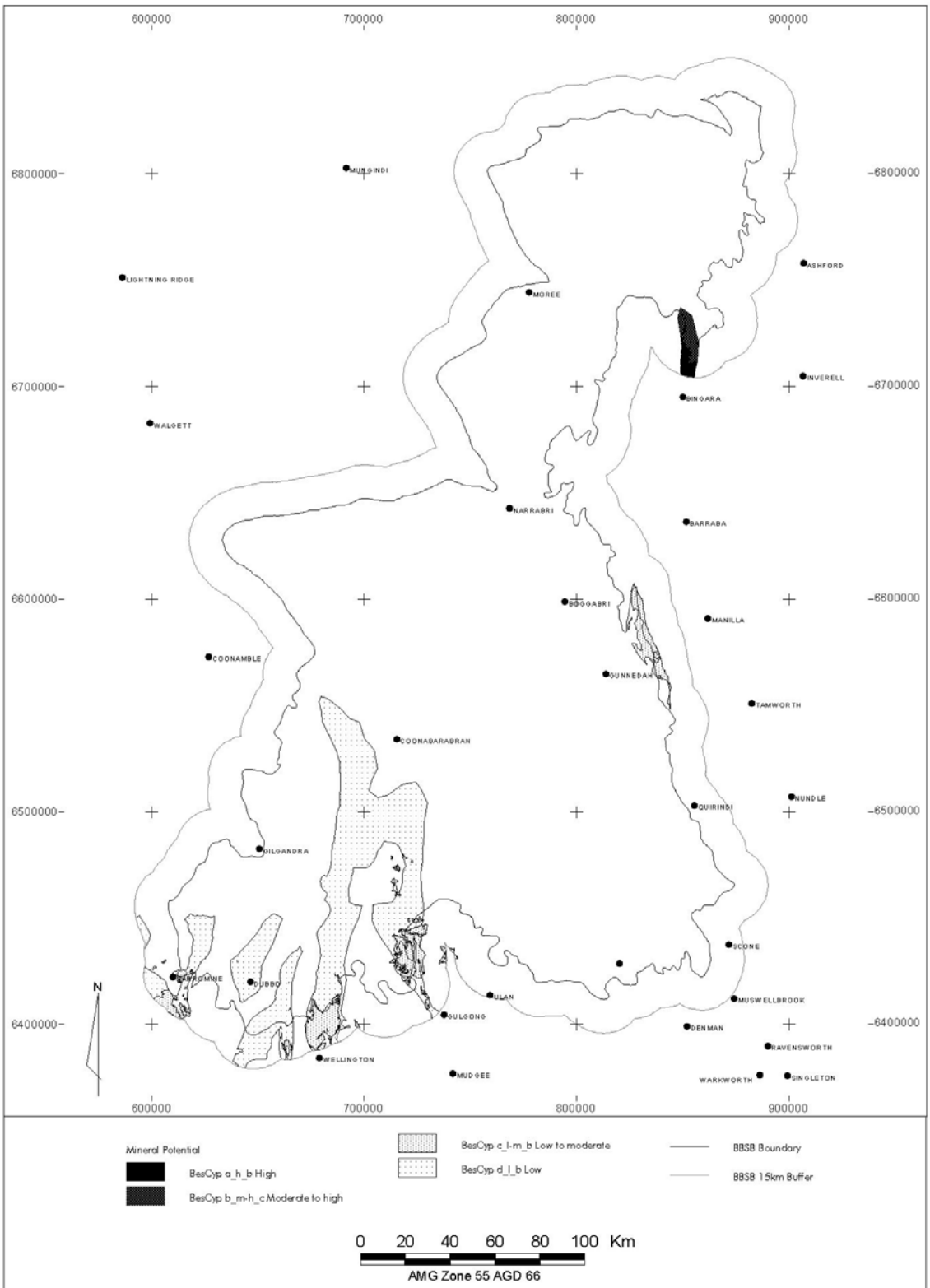

Figure 34. Mineral Potential Tracts for Besshi-Cyprus Volcanic Hosted Massive Sulphide Deposits Brigalow Belt South Bioregion

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Tract BesCyp c/L-M/C
The tract consists of outcropping and subcropping marine mafic to intermediate Ordovician volcanic rocks of the Lachlan Fold Belt, including all of the Cabonne Group, and the Narromine Volcanic Belt. It also includes the Mostyn Vale Formation of the New England Fold Belt. **P**otential of the tract is assessed to be low to moderate with a certainty level of C.

Tract BesCyp d/L/B
The tract consists of inferred extensions under basin cover of the Cabonne Group, inferred extensions of Ordovician marine units within the Rockley-Gulgong Volcanic Belt, and inferred extensions of Ordovician rocks of the Narromine Volcanic Belt. Potential of the tract is assessed to be low with a certainty level of B.

8.1.7 Tin (Greisen and Vein) (Figure 35)

A few tin vein and tin greisen occurrences occur close to the margins of the BBSB in the Warialda area. They are spatially and genetically associated with the Late Permian to Early Triassic Dumboy Gragin Granite. Tin mineralisation in this area is reported to be in the form of cassiterite-bearing veins, and tin-bearing greisen. These occurrences have not been investigated in any detail.

Tract Sn1 a/H/C
This tract is defined by outcropping and subcropping (I-type) Dumboy Gragin Granite. This is an extremely fractionated and reduced granite body. A large number of Sn deposits are associated with similar bodies elsewhere in the New England Fold Belt. Potential of the tract is assessed to be high with a certainty level of C.

Tract Sn1 b/M-H/B-C
The tract is defined by a 10 km buffer around the Dumboy Gragin Granite. Potential of the tract is assessed to be moderate to high with a certainty level of B-C.

Tract Sn1 c/L-M/C
The tract is defined by outcropping and subcropping relatively reduced, moderately fractionated granitoids of the Bundarra suite. The Bundarra (S-type) suite contains rare, small Sn occurrences. The low degree of fractionation as well as the relatively oxidised nature of these granitoids means that the potential of the tract is assessed to be low to moderate with a certainty level of C.

Tract Sn1 b/M-H/B-C
The tract is defined by a 10 km buffer around the Dumboy Gragin Granite. Potential of the tract is assessed to be moderate to high with a certainty level of B-C.

Tract Sn1 c/L-M/C
The tract is defined by outcropping and subcropping relatively reduced, moderately fractionated granitoids of the Bundarra suite. The Bundarra (S-type) suite contains rare, small Sn occurrences. The low degree of fractionation as well as the relatively oxidised nature of these granitoids means that the potential of the tract is assessed to be low to moderate with a certainty level of C.

Tract Sn1 d/L/B-C
The tract is defined by the presence of a 10km buffer around the Bundarra suite. Potential of the tract is assessed to be low with a certainty level of B-C.

8.1.8 Alluvial Tin (Figure 36)

Only a few minor deposits of alluvial tin occur close the margins of the BBSB in the Warialda area, however it is possible that more significant placer deposits occur beneath adjacent basalt, as is common in other parts of the New England Fold Belt. In the Copeton Group of deep leads east of the BBSB, two main levels of intrabasaltic alluvials containing cassiterite and diamonds were worked. The economic layers were overlain by a subeconomic, fine-grained sandy layer. In the Tingha-Gilgai area deep leads range in depth from several metres to fifty metres. Most of these deep leads are capped by thick strongly weathered to fresh basalt, shallow to deep basaltic soil and in many places by surficial concretionary laterite/bauxite (Brown and Stroud, 1997). Modern technology may make some of these areas viable in

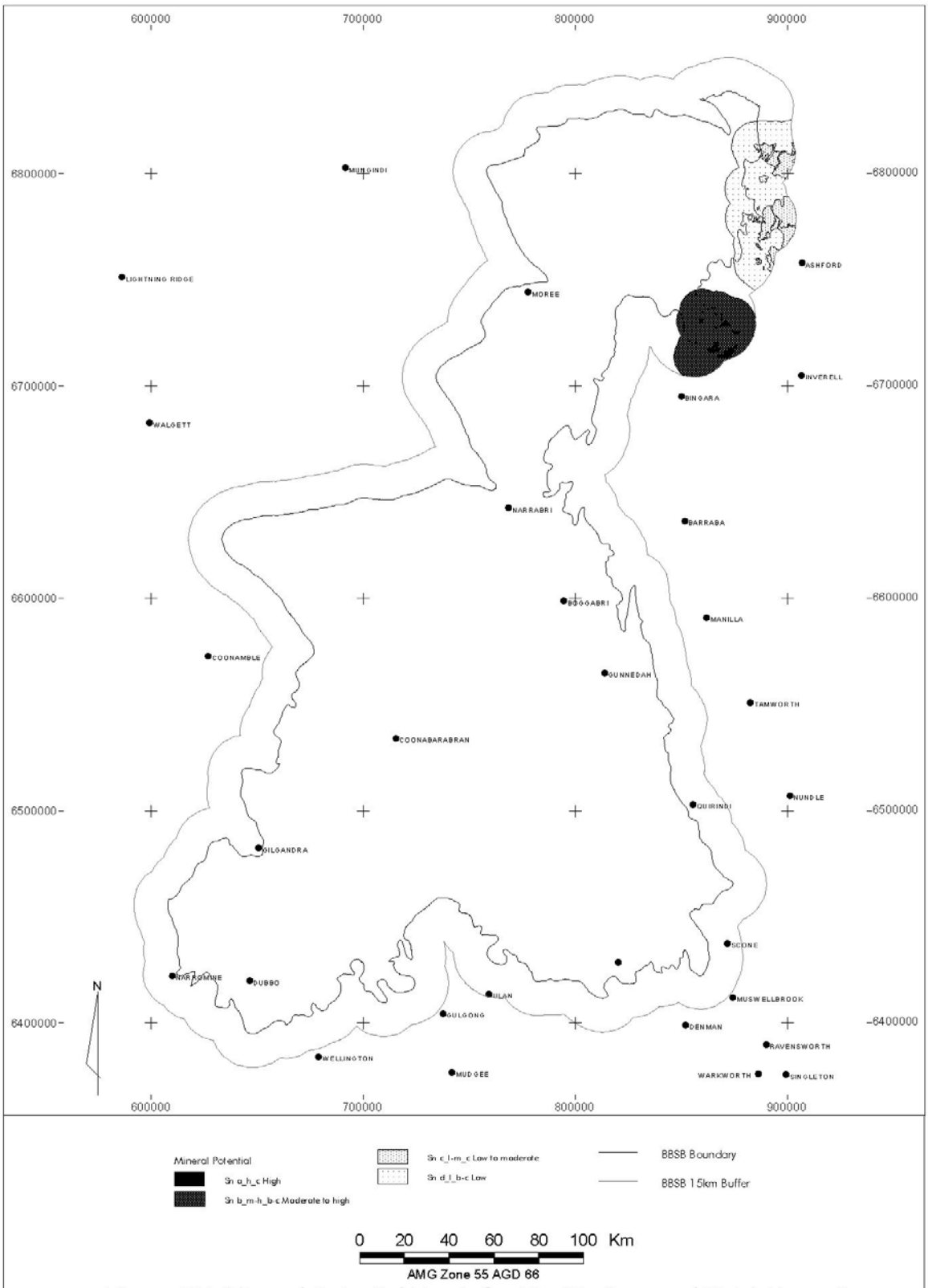


Figure 35. Mineral Potential Tracts for Tin (Greisen and Vein) Deposits
Brigalow Belt South Bioregion

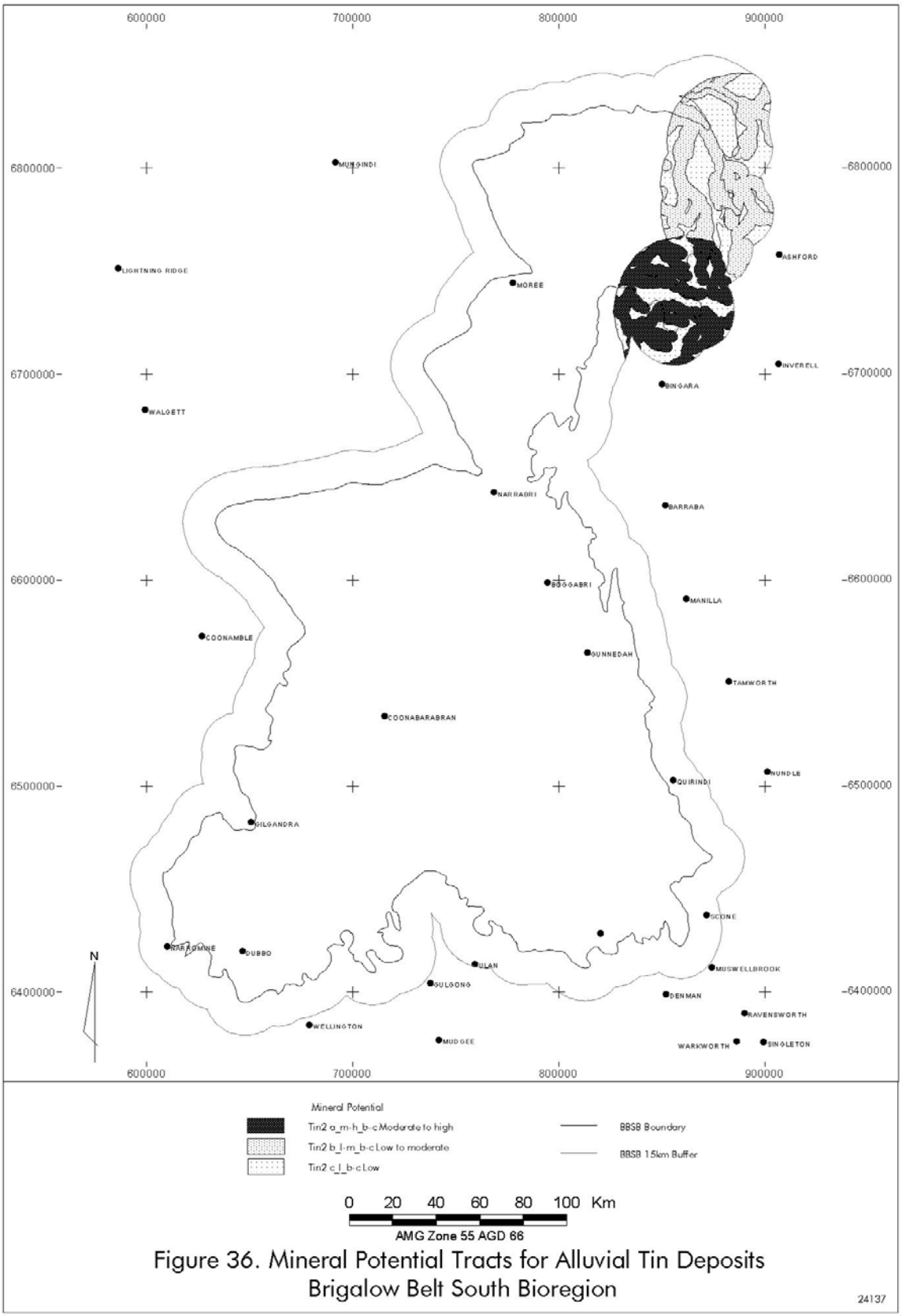


Figure 36. Mineral Potential Tracts for Alluvial Tin Deposits
Brigalow Belt South Bioregion

future and allow access to deep lead deposits not previously mined, which could also occur within the BBSB. Alluvial tin has also been recovered east of Dubbo, however production was small and the occurrence is not considered likely to be economically significant.

Tract Sn2 a/M-H/B-C
This tract includes all major drainages buffered to 5 km within 30 km of outcropping Dumboy Gragin Granite. Potential is assessed to be moderate to high with a certainty level of B-C.

Tract Sn2 b/L-M/B-C
This tract includes all major drainages buffered to 5 km within 30 km of outcropping Bundarra Granite. Potential is assessed to be low to moderate to with a certainty level of B-C.

Tract Sn2 c/L/C
This tract includes all other areas within 30km of outcropping Bundarra and Dumboy Gragin granite. Potential is considered low with a certainty of B-C.

8.1.9 Other Metallic Mineral Deposit Styles

The following deposit style has not been assessed because its occurrence is not considered likely to be economically significant.

Low Temperature Copper Mineralisation
A number of minor copper-gold occurrences occur in the Wellington area within or close to the margins of the BBSB. It is suggested that many of these occurrences formed during deformation and associated low-grade regional metamorphism, possibly during the mid-Devonian (Downes, 1998). The mineralisation has been channelled through porous units and along faults and precipitated by wallrock reactions. They are not considered likely to be economically significant.

8.2 INDUSTRIAL MINERALS

8.2.1 Rare Earth Elements (Figure 37)

A large resource of rare earth elements (REE) has been delineated close to the margins of the BBSB, about 25km south of Dubbo at Toongi. This project (the Dubbo Zirconia Project) is currently at an advanced stage of assessment. An indicated and inferred resource of 83 Mt at 1.91% ZrO_2, 0.041% HfO_2, 0.448% Nb_2O5, 0.027% Ta_2,O_5, 0.138% Y_2O_3, 0.720% REO, has been delineated, which is a world class resource (Australian Zirconia Ltd 2001).

Factors controlling the presence and distribution of elevated background rare earth elements (REE), such as occurs within the fractionated trachyte at Toongi are not well understood. However, some general inferred controls have been used for tract delineation, such as mapped and inferred intrusive rocks of similar age, tectonic setting, geochemistry, magnetic and radiometric signature to the host trachyte at Toongi. Subsurface extensions of prospective units have not been included do to lack of data and lower economic viability.

Tract REE a/H/C
This tract consists of outcropping Mesozoic age intrusive stocks within the Lachlan Fold Belt. Potential of the tract is assessed to be high with a certainty level of B-C.

Tract REE b/M/B-C
This tract contains inferred subcropping Mesozoic age intrusives of the Lachlan Fold Belt, and identified Bulga Complex units of the Garrawilla Volcanic Event. Potential of the tract is assessed to be moderate with a certainty level of B-C.

Tract REE c/L/B-C
This tract includes all outcropping rocks of the Glenrowan and Garrawilla Volcanics within the BBSB. These units have a wide range of geochemical affinities. Subsurface extensions of these rocks have not been included, due to lack of available data. Potential of the tract is assessed to be low with a certainty level of B-C.

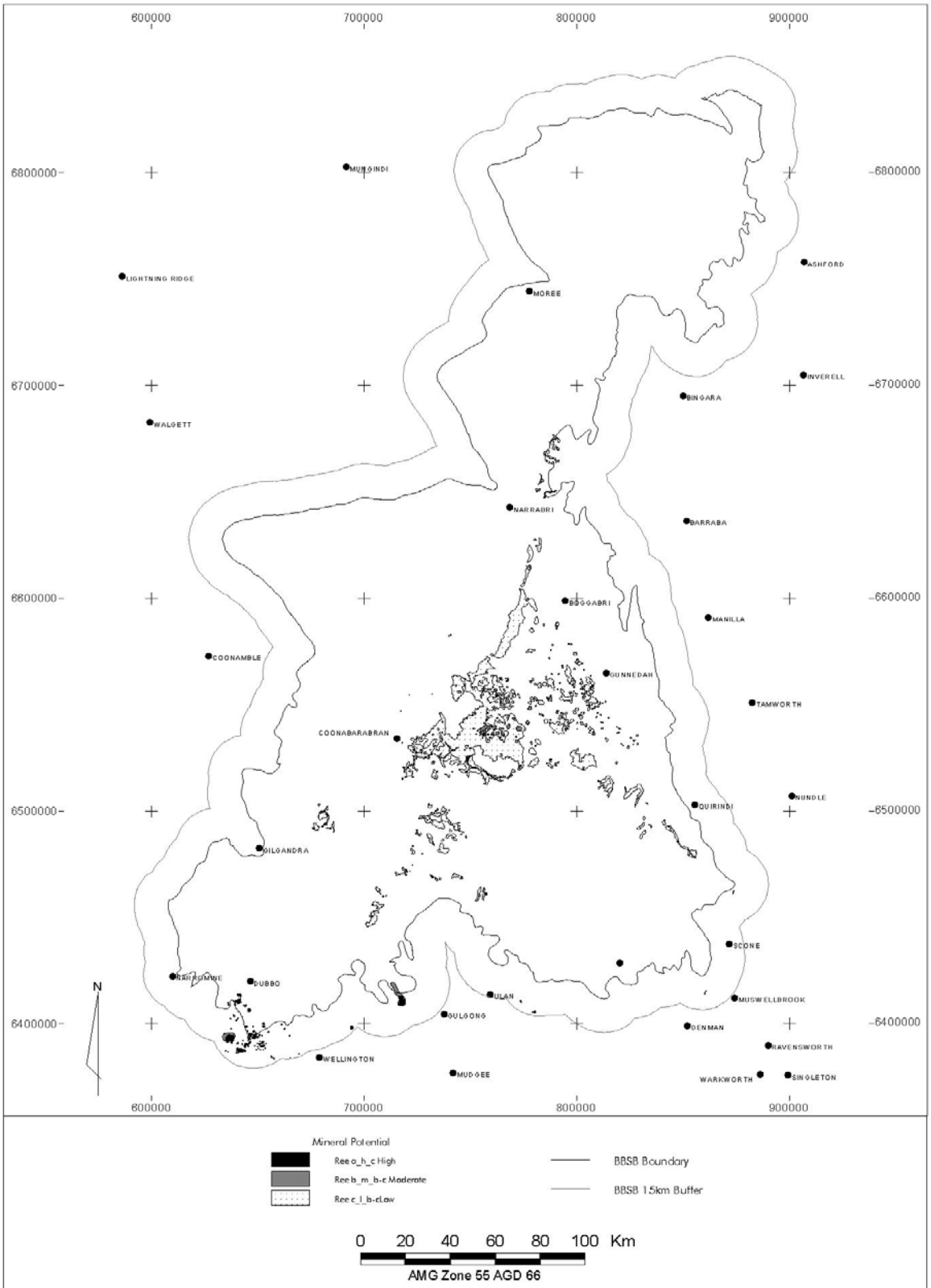


Figure 37. Mineral Potential Tracts for Rare Earth Elements
Brigalow Belt South Bioregion

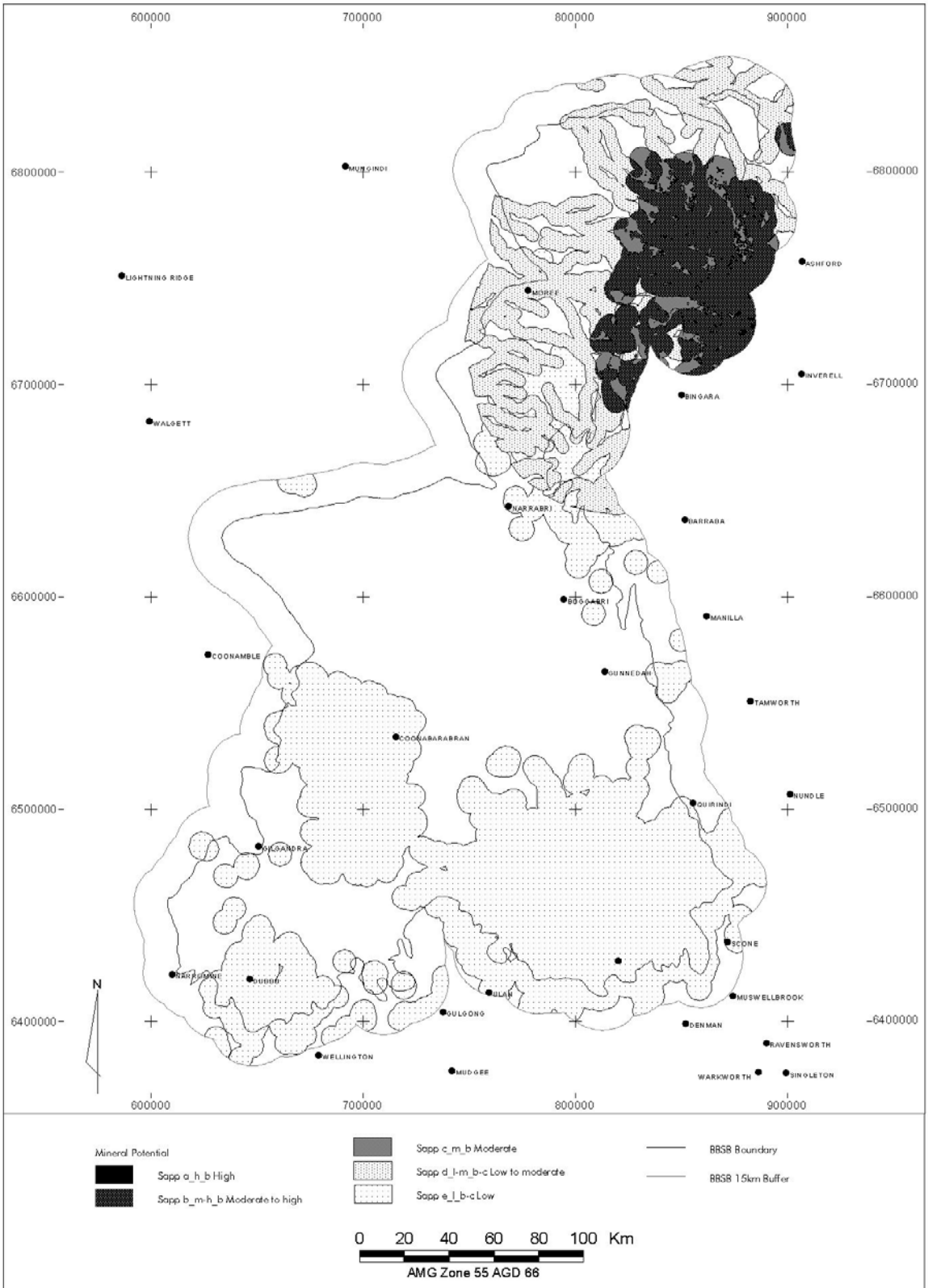


Figure 38. Mineral Potential Tracts for Alluvial Sapphire Deposits
Brigalow Belt South Bioregion

24139

8.2.2 Alluvial Sapphire (Figure 38)

Few alluvial sapphires are known to have been recovered within the BBSB. However large reserves of alluvial sapphire have been mined from reworked Tertiary volcaniclastic rocks in the Kings Plains area about 100 km east of the BBSB. Units of this volcanic province (the Central Volcanic Province, in particular the Maybole Volcano) extends westwards into the northern parts of the BBSB. Similar volcaniclastic units to those which source the Kings Plains deposits (Brown and Stroud, 1997) are also known to occur close to the margins of the BBSB, albeit in limited extent. However, the level and rate of erosion in the Warialda-Yallaroi area is somewhat less than has occurred in the Kings Plains area, and it is probable that some of the extensive basalt flows in this area conceal buried sapphire-bearing volcaniclastic rocks. These volcaniclastic rocks could have been reworked and concentrated in stream palaeochannels, as occurs at the very rich Kings Plains deposits.

A large ruby and sapphire resource has been delineated southeast of the BBSB near Scone, which previously had little prior gemstone production. This discovery highlights the potential for previously unknown alluvial gemstone fields in Tertiary to Quaternary sediments within the BBSB. Tertiary age volcaniclastic units in the Liverpool Range area have also recently been identified as a potential source of gemstones. These have not been previously assessed for gemstone occurrences.

Tract Sapp a/H/B
This tract consists of all outcropping volcaniclastic units of the Central Volcanic Province and its extensions. Potential is assessed to be high with a certainty level of B.

Tract Sapp b/M-H/B
This tract consists of all major drainage networks buffered to 5km draining units of the Central Volcanic Province, to a distance of 5km. Potential is assessed to be moderate to high with a certainty level of B.

Tract Sapp c/M/B
This tract consists of all remaining outcropping Central Volcanic Province units buffered to 5 km. Potential is assessed to be moderate with a certainty level of B.

Tract Sapp d/L-M/B-C
This tract consists of major drainages of the Central Volcanic Province buffered to 5km to a distance of 60km downstream, outside of the areas covered in tracts Sapp a, b, c above. Potential is assessed to be low to moderate with a certainty level of B-C.

Tract Sapp e/L/B-C
This tract consists of all other outcropping Tertiary units in the BBSB, buffered to 5km. Potential of this tract is assessed to be low with a certainty level of B-C.

8.2.3 Weathered Profile-Hosted Opal (Figure 39)

No weathered profile-hosted opal occurrences in the BBSB have been recorded. The Lightning Ridge Opal Field occurs to the west of the BBSB hosted by the Early Cretaceous Rolling Downs Group, which also occurs in the northern parts of the BBSB. Conditions favourable for the formation of weathered profile-hosted precious opal could have occurred within Early Cretaceous Rolling rocks in the BBSB, at present mostly concealed beneath alluvial and colluvial cover.

Geological factors which control the formation of weathered profile-hosted precious opal deposits are not well understood. It is generally thought that arid climatic conditions (similar to those at the Lightning Ridge Field), long exposure, deep weathering, structural control, and low erosion rates are required for the formation of these deposits (Senior, 1998). Many or all of these factors are present in some parts of the northern BBSB. There may also be an important biogenic component in the formation of weathered profile-hosted precious opal deposits. A complicating factor in the assessment of prospectivity for weathered profile-hosted opal in this area is the depth and age of the alluvial and colluvial cover. Volcanic opal is known from the Tooraweenah area and the Nandewar Ranges, but is not considered economically significant.

Tract Opal a/M-H/B
This tract consists of known outcropping and subcropping Rolling Downs Group. Potential of this tract is assessed to be moderate to high with a certainty level of B.

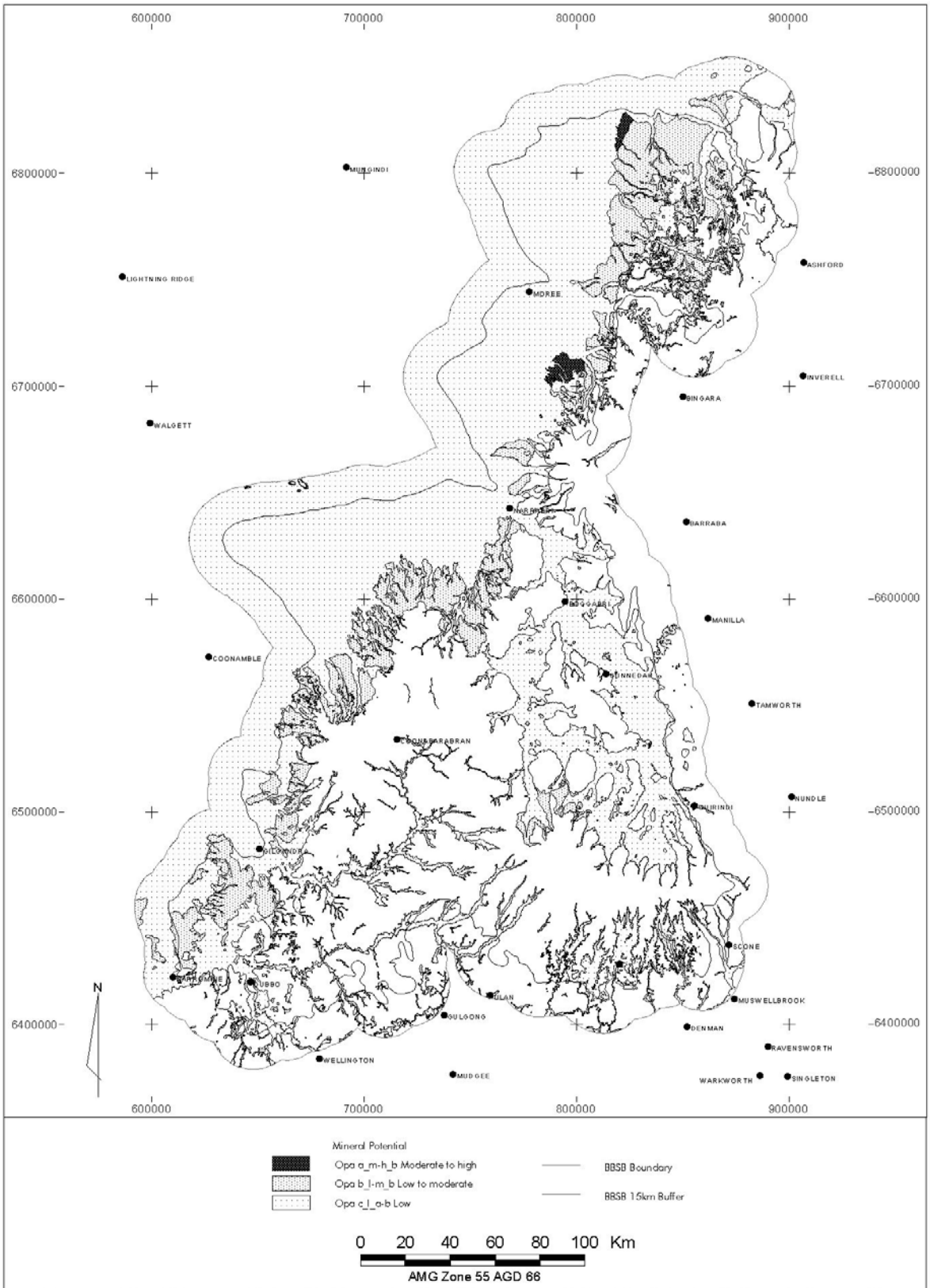


Figure 39. Mineral Potential Tracts for Weathered Profile Hosted Opal Deposits Brigalow Belt South Bioregion

24140

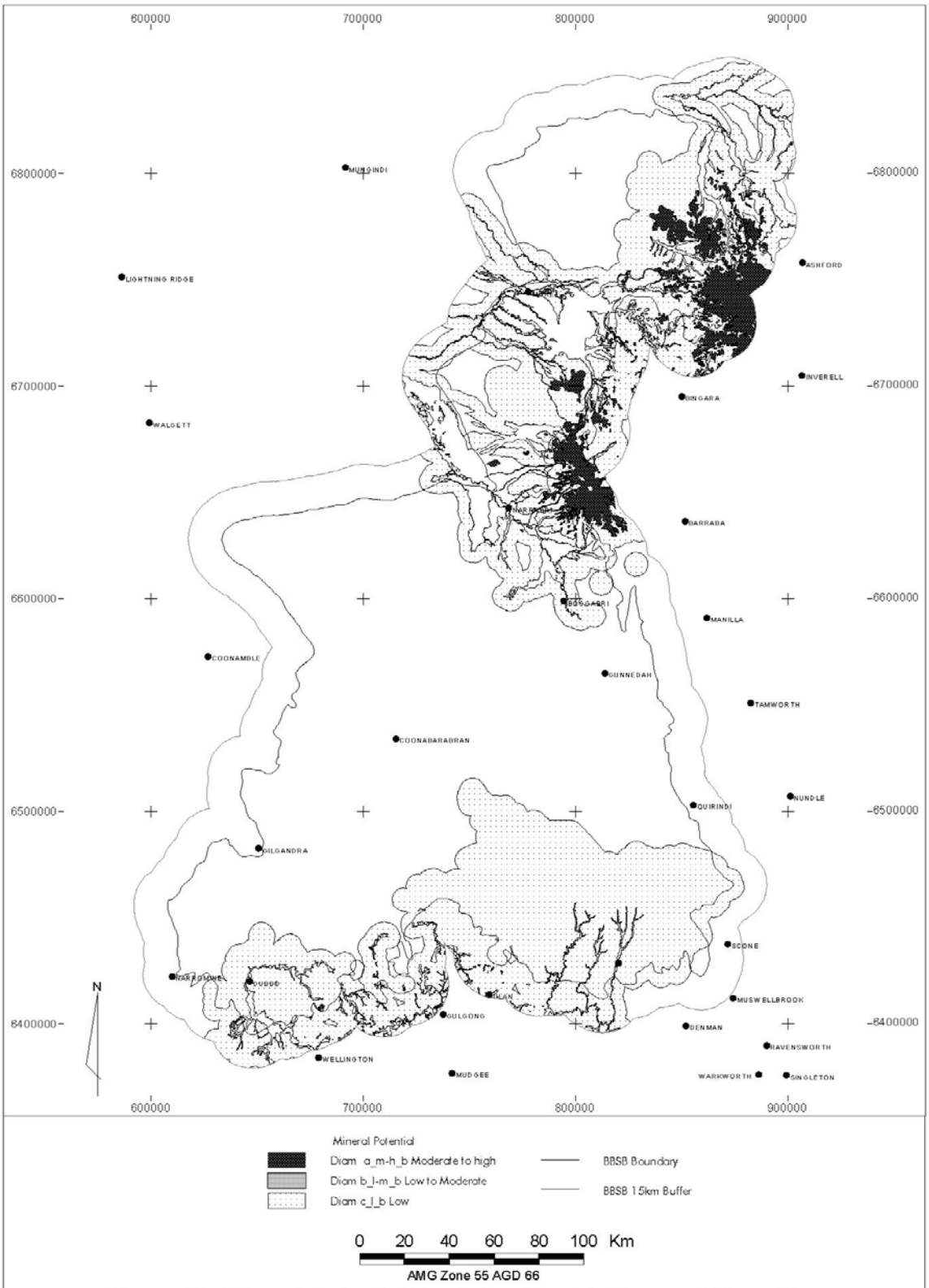


Figure 40. Mineral Potential Tracts for Alluvial Diamond Deposits
Brigalow Belt South Bioregion

Tract Opal b/L-M/B
This tract consists of the known outcropping and subcropping Keelindi beds. Potential of this tract is assessed to be low to moderate with a certainty level of B.

Tract Opal c/L/A-B
This tract consists of all Quaternary and Tertiary cover (only beneath 400m elevation), which could conceal Early Cretaceous opal-bearing strata. Cover occurring above the 400m elevation contour is not suspected to overly Cretaceous strata within the BBSB. Potential of this tract is assessed to be low with a certainty level of A-B.

8.2.4 Alluvial Diamond (Figure 40)

Within a distance of 40 km of the margins of the BBSB are 3 areas of significant alluvial diamond production, the Bingara, Copeton and Cudgegong Diamond Fields. Historical production of diamonds from these fields and their extensions is in excess of 236,000 carats (MacNevin, 1977; and Brown and Stroud, 1997). Alluvial diamonds have been recovered within the BBSB itself east of Narrabri at several localities, although production in these areas was not significant. A small operating alluvial diamond mine is present at Monte Christo in the Bingara area, about 25km east of the BBSB, with production since 1998 of the order of several thousand carats. These areas also contain an unknown potential for diamond pipe deposits, which have not been assessed due to lack of available information on their distribution.

Tract Dia a/M-H/B
This tract consists of outcropping Tertiary volcanics and sediments within a 30 km radius of known diamond occurrences. The 30 km radius is somewhat arbitrary, as the diamonds could have been sourced from greater distances, and indeed from multiple sources. However several geological characteristics of the Bingara and Cudgegong Diamond Fields including the lack of abrasion of the diamonds, and lithological analyses of the wash, suggest that the primary source of the diamonds may be within kilometres to tens of kilometres from the alluvial mines (Brown and Stroud, 1997).

No consensus has been reached concerning likely palaeocurrent directions of diamond-bearing wash in the fields, although most researchers favour a southerly source for both the Bingara and Copteon fields, and a westerly source for the Cudgegong Field. It should be noted here also, that lithological analyses of diamond-bearing wash in the Bingara field suggests a source or sources west of the Peel Fault (Brown and Stroud, 1997). Potential is assessed to be moderate to high with a certainty level of B.

Tract Dia b/L-M/B
This tract consists of all Quaternary cover within a 30 km radius of known diamond occurrences, including downstream alluvial units of these areas. Potential is assessed to be low to moderate with a certainty level of B.

Tract Dia c/L/B
This tract includes all Tertiary and Quaternary cover sequences between 30 and 60 km of known diamond occurrences, buffered to 5 km, including tract Dia b buffered to 5 km. Potential is assessed to be low with a certainty level of B.

8.2.5 Zeolite (Figure 41)

Large resources of zeolite are known to occur close to the eastern margins of the BBSB, hosted by Tamworth Belt Permo-Carboniferous volcanic rocks. An operating mine occurs near Werris Creek, (the Escott Mine), located just outside the BBSB boundary. Several zeolite prospects occur close to the margins of the BBSB and include The Gap, Wingen Mountain, and Z4. The Currabubula Formation, and its equivalents the Lark Hill, Rocky Creek Conglomerate, Clifden Formation, Ermelo Dacite Tuff, and Spion Kop Conglomerate, are perceived to contain the highest prospectivity for zeolite deposits. Subsurface extensions of prospective rocks have not been included, due to their lower economic viability.

Tract Zeo a/H/C
This tract contains outcropping and subcropping Currabubula Formation and its equivalents (Ermello Formation, Clifden Formation, Spion Kop Formation, Rocky Creek Conglomerate, Lark Hill Formation). Potential is assessed to be high with a certainty level of C.

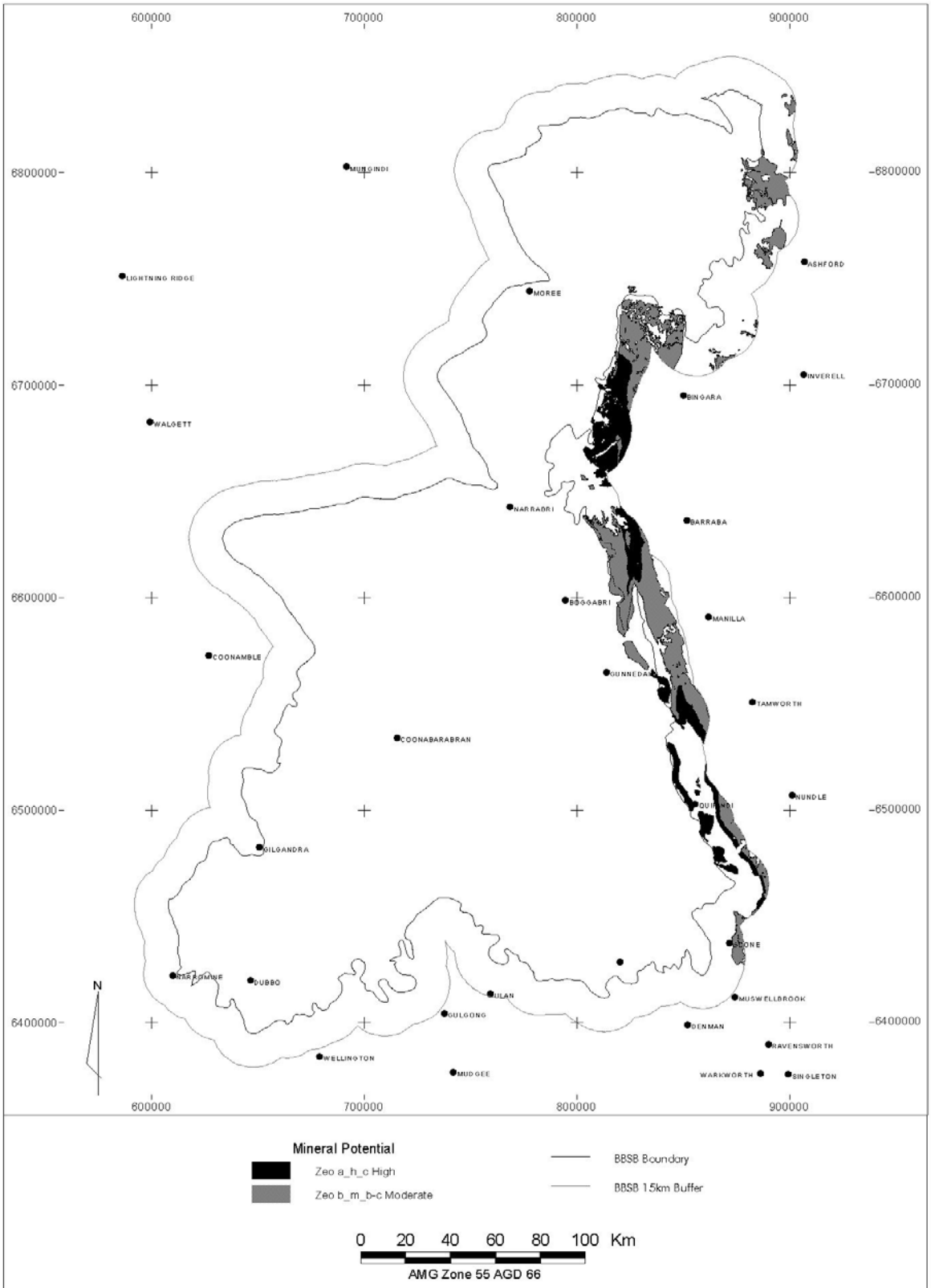


Figure 41. Mineral Potential Tracts for Zeolite Deposits
Brigalow Belt South Bioregion

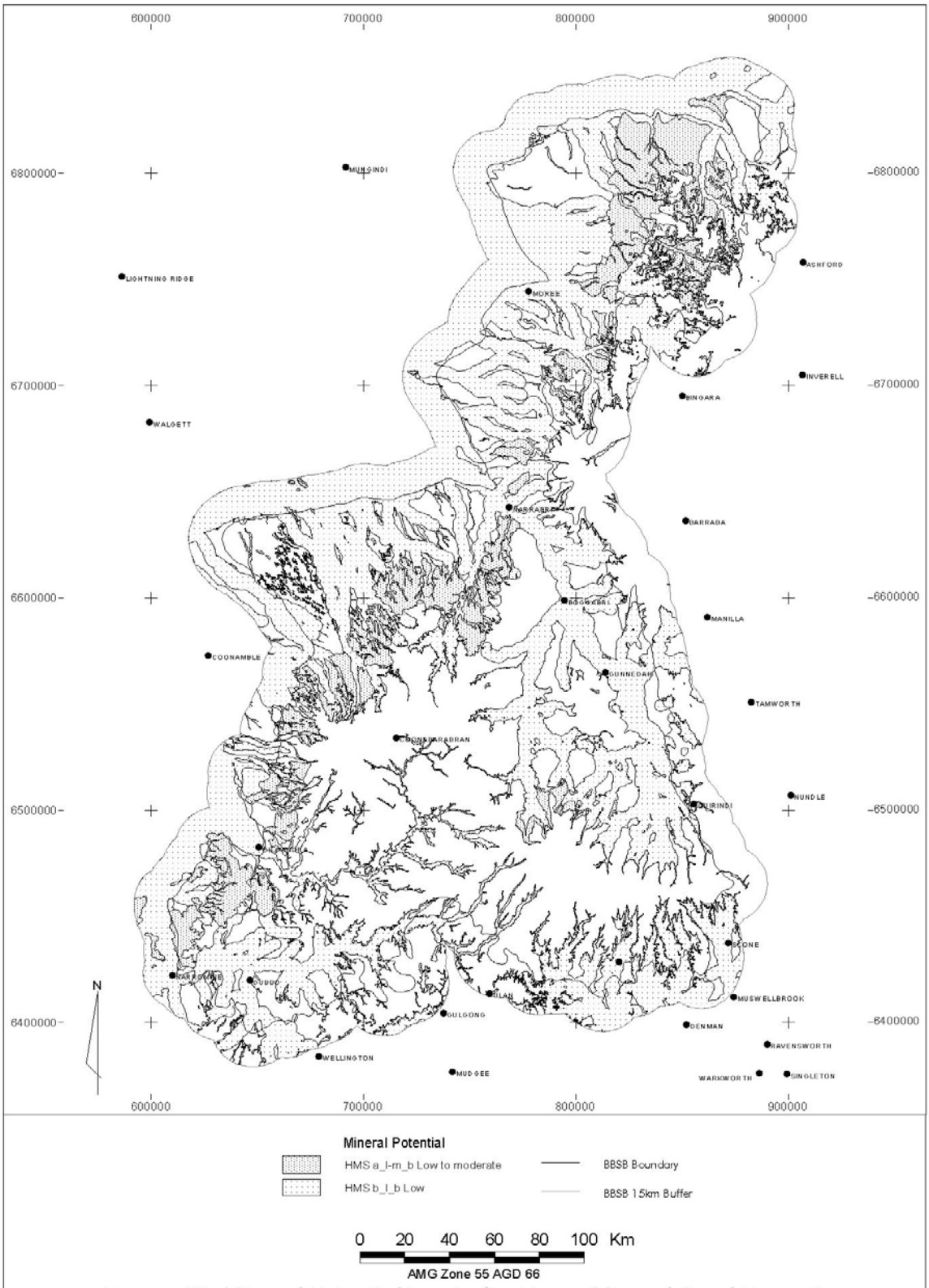


Figure 42. Mineral Potential Tracts for Heavy Mineral Sand Deposits Brigalow Belt South Bioregion

24143

Tract Zeo b/M/C
This tract contains all other outcropping and subcropping formations considered prospective for zeolite. This includes all other Carboniferous volcano-sedimentary units in the New England Fold Belt. Potential is assessed to be moderate with a certainty level of C.

8.2.6 Heavy Mineral Sand (Fluvial and Beach Placer) (Figure 42)

Models used for this tract include both the fluvial and beach placer types. It should be noted that these two deposit types have different levels of economic viability, which have been incorporated into mineral potential scores.

Relatively high concentrations of heavy mineral sands (HMS) have been intersected in reconnaissance drilling in Quaternary alluvium in the BBSB, particularly in the Bohena Creek area. These sands are thought to be sourced mostly from the Early Cretaceous Keelindi beds. However, these HMS accumulations are irregular, lensoidal and fluviatile in origin, and are perceived to be less likely to be present in continuity compared to those which have formed under shoreline (coastal) conditions, and thus less likely to be economically viable. Little exploration has been carried out in the Keelindi beds themselves.

Potential exists for economic concentrations of HMS in beach placers deposited during marine incursions in the Surat Basin, such as occurred in the Early to Late Early Cretaceous Bungil Formation within the Keelindi beds. However it is also noted that probable consolidation of these sediments would present difficulties in the extractive process. Titanomagnetite has also been noted in sandstone in the Caroda Formation close to the margins of the BBSB, but has not been evaluated in any detail.

Tract HMS a/L-M/B
This tract consists of outcropping and subcropping Late Jurassic to Early Cretaceous Keelindi beds and the Early Cretaceous Drildool Beds. Although these units contain varying prospectivity for HMS, they have been grouped together due to incomplete coverage. Potential of this tract is assessed to be low to moderate with a certainty level of B.

Tract HMS b/L/B
This tract consists of all Quaternary alluvium outside of buffered major drainages, and major drainages buffered to 5 km, below the 400 m contour. Analysis has indicated that units above the 400 m elevation contour are not suspected of overlying or draining Cretaceous sediments. This tract includes the all the known high concentrations of fluvial HMS occurrences. Even though the potential is considered higher, the lower economic viability of these fluvial-type deposits has downgraded this unit to low potential. The certainty level is B.

8.2.7 Kaolin (Figure 43)

Kaolin (flint clay) has been mined in the Merrygoen area intermittently since about 1950. The clays of economic interest so far exploited in the area are confined to the Jurassic sequence in the vicinity of Merrygoen and Dunedoo (Markham and Basden, 1974). Flint clay also occurs within the Permian and Triassic sequences, which are perceived to be of lower prospectivity (Loughnon and Higgins, 1973). Flint clay has also been mined near Gunnedah from within the Early Permian Leard Formation (Pratt, 1998).

Tertiary sediments in the BBSB could host transported kaolin, derived from granite, as occurs in the Gulgong area to the south of the BBSB. The Gulgong area also contains a number of residual kaolin deposits hosted within the Ulan Quartz Monzonite, and similar residual deposits could occur in other granites within the BBSB. High quality kaolin occurring as clay cement within friable sandstone also occurs within the Grose Sandstone at Lithgow, however this type of kaolin resource has not been assessed in the BBSB due to lack of available data.

Tract Kao a/M-H/B
This tract consists of outcropping Purlewaugh Formation including the prospective Ukebung member, (Loughnon and Higgins, 1973). Because it has not been possible to map and differentiate the more prospective Ukebung Member, the potential of the tract as a whole is assessed to be moderate to high, rather than high. The certainty level is B.

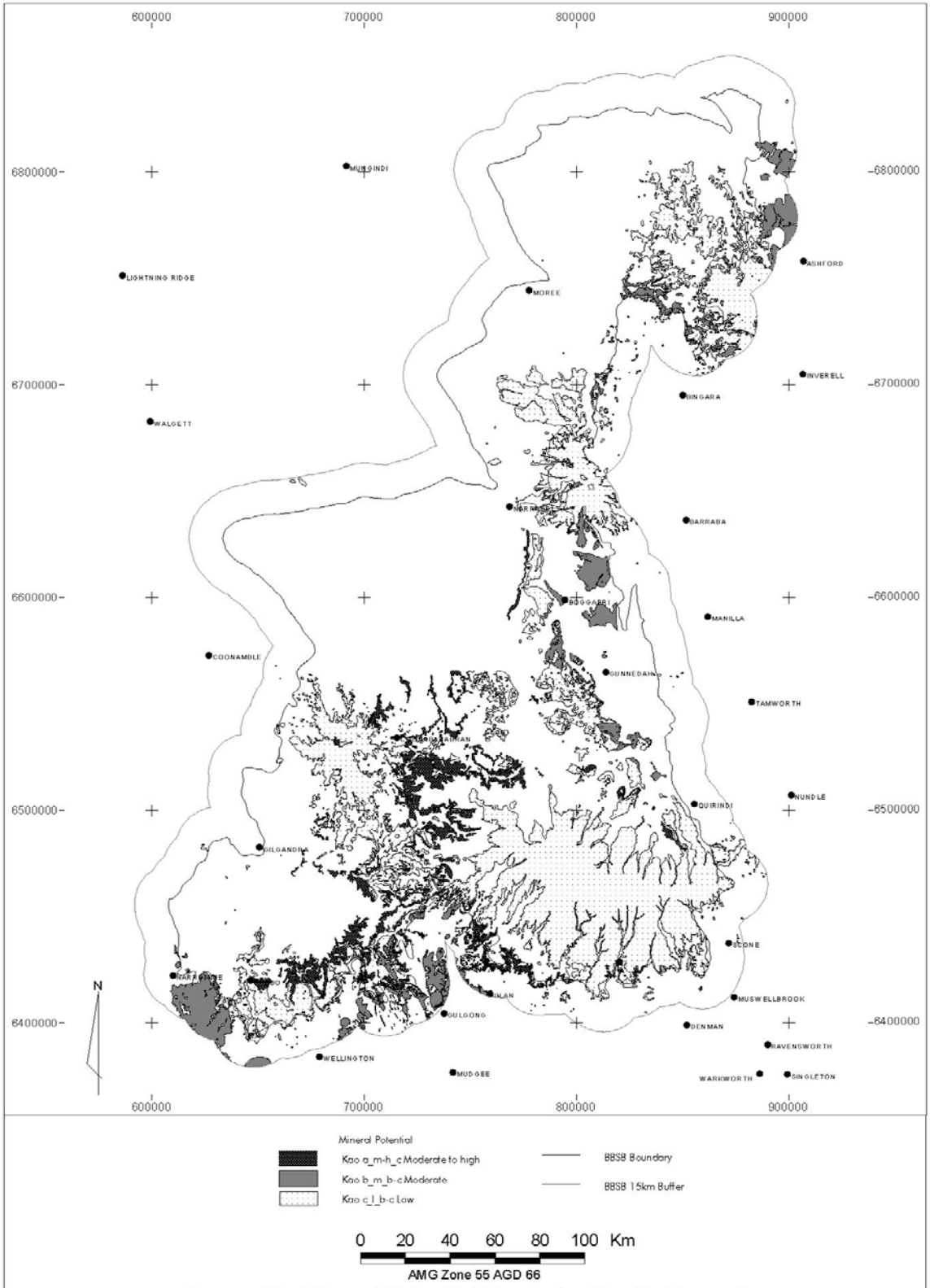


Figure 43. Mineral Potential Tracts for Kaolin Deposits
Brigalow Belt South Bioregion

Tract Kao b/M/B-C
This tract consists of the Blackjack Group, the Leard Formation, Walloon Coal Measures, and the Bellata Group. It also includes all other outcropping granite which could host residual kaolin, as occurs in the Ulan Quartz Monzonite. Potential is assessed to be moderate with a certainty level of B-C.

Tract Kao c/L/B-C
This tract consists of Napperby Formation, the Digby Formation, and all Tertiary sediments. Tertiary sediments could host transported/residual kaolin material, derived from weathered granite. Potential is assessed to be low with a certainty level of B-C.

8.2.8 Other Industrial Mineral Deposit Styles

Diamond Pipe
A few diatremes geochemically favourable for diamonds have been discovered close to the margins of the BBSB in the Upper Bingara and Ulan areas, however no diamonds have been reliably recorded from these pipes. High sodium garnets, considered a favourable indicator mineral for diamonds, have been recorded in the Nandewar Range area just east of the BBSB boundary.

Not far outside the BBSB are several areas of significant historical alluvial diamond production at Bingara, Copeton, and Cudgegong. Analyses of likely sources of the alluvial diamonds in New South Wales, in conjunction with rare examples of rare hard-rock diamonds, suggest that traditional models for diamond formation may not be applicable for Eastern Australia. A relatively new model of diamond formation has been proposed for Eastern Australia, which advocates a subduction related origin (Barron et al, 1996).

A viable model for hard-rock diamonds in the BBSB is precluded at the present time. The difficulties include the low level of historical production in the BBSB itself, the paucity of detailed mapping in key areas, general difficulties with model formulation and parameters for Eastern Australia, and the relatively unexplored and traditionally poor understanding of diamond paragenesis in Eastern Australia.

Diatomite
Deposits of diatomite have been mined intermittently in the vicinity of Chalk Mountain near Bugaldie, and are currently mined just east of the BBSB near Barraba. Diatomite also occurs near Tooraweenah and Mount Kaputar.

Sediment-hosted magnesite
Several occurrences of sediment-hosted magnesite have been recorded close to the margins of the BBSB in the Warialda area. These occurrences have not been investigated in any detail, but are not considered likely to be economically significant.

Sodium Bicarbonate in Groundwater (Brines)
Anomalously high concentrations of sodium bicarbonate in subsurface aquifers have been investigated for commercial soda ash production near Dubbo and Narrabri. Sodium bicarbonate (soda ash) also occurs within the Pilliga State Forest as a natural precipitate from groundwater. These occurrences have not been investigated in any detail, although surface deposits have been quarried locally in the past.

Insufficient information is available to assess the potential of extraction of bicarbonate from groundwaters, although such a process may emerge as viable and sustainable in the future.

Oil Shale
Oil shale of varying quality is recorded in several places either within or near to the margins of the BBSB, including near Quirindi, east of Coonabarabran, north of Barraba, and near Ulan.

8.3 CONSTRUCTION MATERIALS

8.3.1 Construction Materials and Dimension Stone (Figure 44)

Quarrying operations in the BBSB are spatially associated with transport routes and main population centres. It is considered that the most prospective rock types in the study area are those close to major transport routes and close to significant population centres. Roads are important for construction materials as they provide transport routes to population centres where most construction materials are

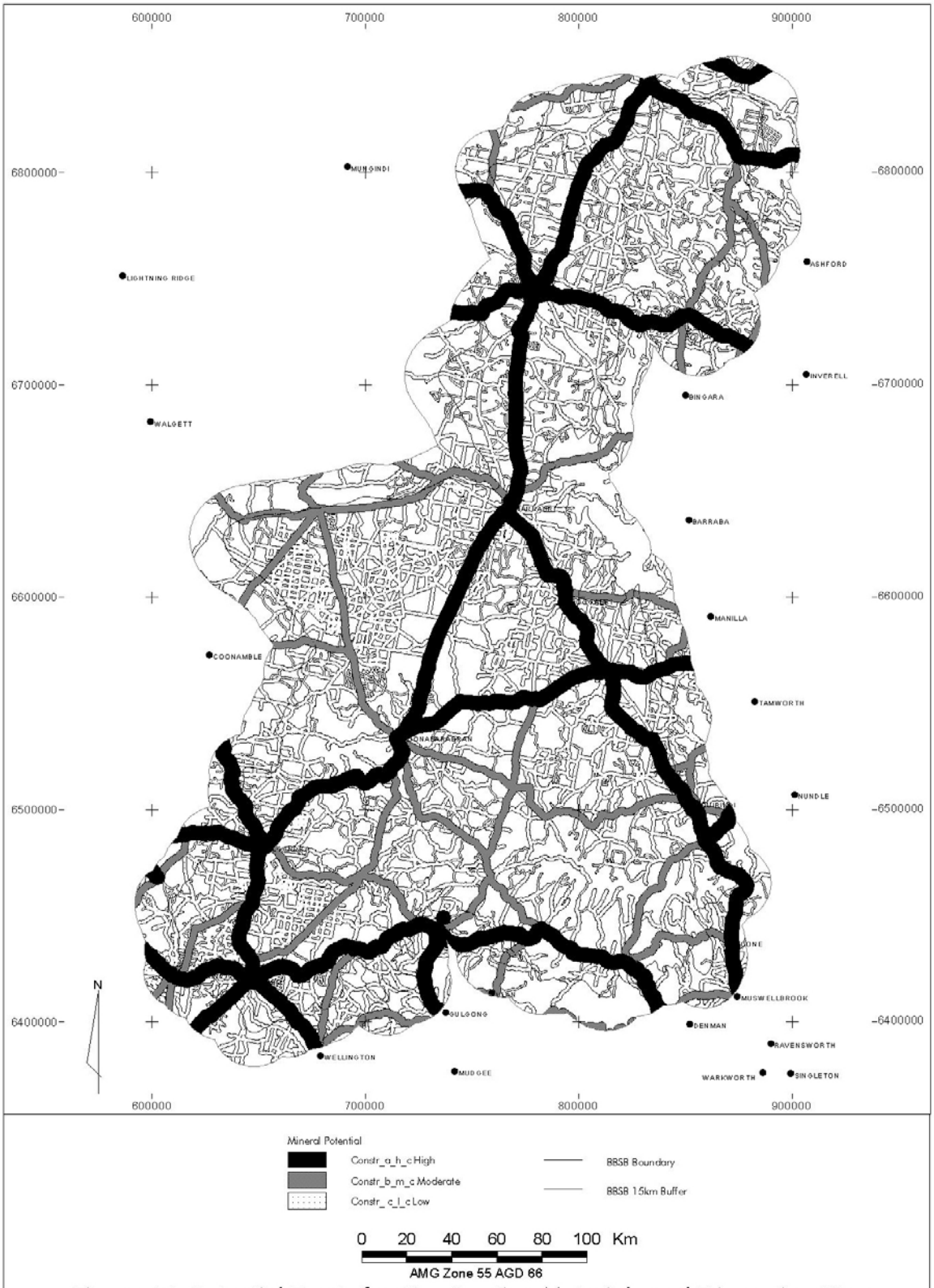


Figure 44. Potential Tracts for Construction Materials and Dimension Stone
Brigalow Belt South Bioregion

24145

consumed, and they are themselves major consumers of materials. Road density in a given area also reflects the population density.

The AUSLIG Geodata road data set has been used for modelling. This road data has been classified and buffered as shown in Table 14.

Table 14. AUSLIG GEODATA ROAD DATA SET, AND BUFFERED DISTANCES USED IN MODELLING FOR THE BBSB

Class	Description	Explanation	Buffered distance each side of road (metres)
1	Dual carriageway	Freeway, tollway or other major road with lanes in different directions separated	N/a
2	Principal road	Highway, regional and through road	3200
3	Secondary road	Connector and distributor road	1600
4	Minor road	Access, residential, local road	800
5	Track	Public or private roadway of minimum or no construction, not necessarily maintained	400

Note: there are no Class 1 roads in the BBSB.

Tract Const a/H/C

The tract includes areas within 3200 m from major roads 2, specified above. There are no class 1 roads in the BBSB. Potential is assessed to be high with a certainty level of C.

Tract Const b/M/C

The tract includes areas within 1600 m from minor roads in class 3 above. Potential is assessed to be moderate with a certainty level of C.

Tract Const c/L/C

The tract includes areas within 800m from minor roads in class 4, and areas within 400m of class 5. Potential of the tract is assessed to be low with a certainty level of C.

8.4 MISCELLANEOUS OCCURRENCES

8.4.1 Other Metallic and Industrial Mineral Commodities in the BBSB

The following commodities occur but have not been assessed:

Small or less economically significant occurrences of alluvial gold (eg Merrygoen, Pilliga State Forest), bauxite (Dubbo), clay/shale (Coolah), loam (Narrabri), nepheline syenite (eg Dubbo), ochre and other mineral pigments (eg Merrygoen, Boggabri), bentonite and fullers earth (eg Boggabri, Dubbo), emery (eg Quirindi), volcanic opal (eg Tooraweenah), zircon (eg Bugaldie), and 'travertine' (eg Narrabri) have also been recorded, and in some cases mined on a small scale within the BBSB.

8.4.2 Other Metallic and Industrial Mineral Commodities in the BBSB Buffer Zone

The following commodities occur in the 15 km buffer zone but have not been assessed:

Limestone (eg Leadville, Geurie), antimony (eg Warialda area), silica gems (eg Narrabri area), tungsten-molybdenum (eg Dubbo area), garnet (eg Dubbo area), tourmaline gems (eg Dubbo area), manganese (eg Warialda area), sulphur (eg Leadville), ruby (eg Gulgong), arsenic (eg Manilla area), magnetite (eg

Manilla area) bismuth (eg Gragin), silcrete (Delungra) and phosphate-guano (eg Ashford Caves), have also been recorded, and in some cases mined on a small scale within the BBSB buffer zone.

8.4.3 Miscellaneous

An organic-derived, phosphate-rich tarry substance is reported to ooze from sandstone in the Tambar Springs and Coonabarabran areas (Rolls 1981), and a 'paraffin' substance is reported from a coal borehole located near the Kerringle State Forest (Harper, 1907). An oil seep is reported from several sources about 27 km north-east of Coonabarabran (Rolls 1981, local residents pers comm 2001). 'Cannel coal' outcrops east of Coonabarabran, which has been used for heating by local farmers (local residents pers comm 2001). Soda ash within the Pilliga State Forest has been quarried in the past by locals for cleaning purposes (Rolls 1981). Petrified wood, hydrothermal zeolite, fossil fish and other mineral and fossil curiosities and semi-precious stone is sold locally in several places.

8.5 COAL

8.5.1 Gunnedah-Bowen Basin

Borehole evidence indicates that the Late Permian Kianga Formation (Black Jack Group equivalents) is restricted to the far northeast of the BBSB at depths greater than 600 M. The Reids Dome Beds (Goonbri and Maules Creek Formation equivalents) are restricted to the Boomi Trough and the Trough east of the Gil Gil Ridge (Bowen Basin eastern Flank). The units contain thick coals but are at depths greater than 600 m.

8.5.2 The Maules Creek Sub-basin

Most of the Maules Creek Sub-basin is currently under coal exploration or mining titles. Sediments thicken eastward to greater than 1000 m with coal seams contained within the Maules Creek Formation. Two large-scale, multi-seam project proposals are currently planned and there is one current mining operation within the sub-basin. These are the Boggabri and Maules Creek Projects and the Whitehaven mine.

There are up to 21 economic coal seams in the Boggabri Project. Seam thicknesses range from 0.9 to 5 m but split and thin towards the southeast. Coal from this area will provide a premium grade energy coal suitable for steaming, gasification and PCI markets. The Maules Creek Project is bounded to the north by the Boggabri Project southern boundary. The area is structurally more complex but numerous seams of good quality coal making both open cut and underground mining viable.

8.5.3 Mullaley Sub-basin

The Mullaley Sub-basin extends the length of the Gunnedah basin from Moree in the north to the Liverpool Ranges in the south. The Rocky Glen Ridge defines the western limit of the Mullaley Sub-basin.

The only known coal seams of any economic significance occur in the Black Jack Group. Coal depth increases to the west away from the Boggabri Ridge, then decreases onto the flank of the Rocky Glen Ridge. Quality in general deteriorates in a westerly direction away from the Boggabri Ridge as the coal bearing sequence thickens and seams split and thin. Figure 9 is a schematic east-west section graphically depicting that the greatest potential exists along the margins of the Boggabri Ridge and along the eastern margin of the Rocky Glen Ridge. Coal quality along the Boggabri Ridge is good with thick seams, fewer splits and shallow seams. Figure 10 is a schematic long section extending from the north to the southeast of the Mullaley Sub-basin. It demonstrates a thickening sediment wedge and coal bearing Black Jack Group to the southeast.

As a result of coal seams being thickest and shallowest along the Boggabri Ridge, most exploration and mining has concentrated in this zone of shallow better quality coal, particularly in the Hoskissons seam which is generally thick and with a good quality basal working section. The Hoskissons coal and to a lesser extent the Melvilles Seam show potential in both the northern and southern sections of the Mullaley Sub-basin, whereas, stratigraphically higher seams only have economic potential in the southern parts of the sub-basin.

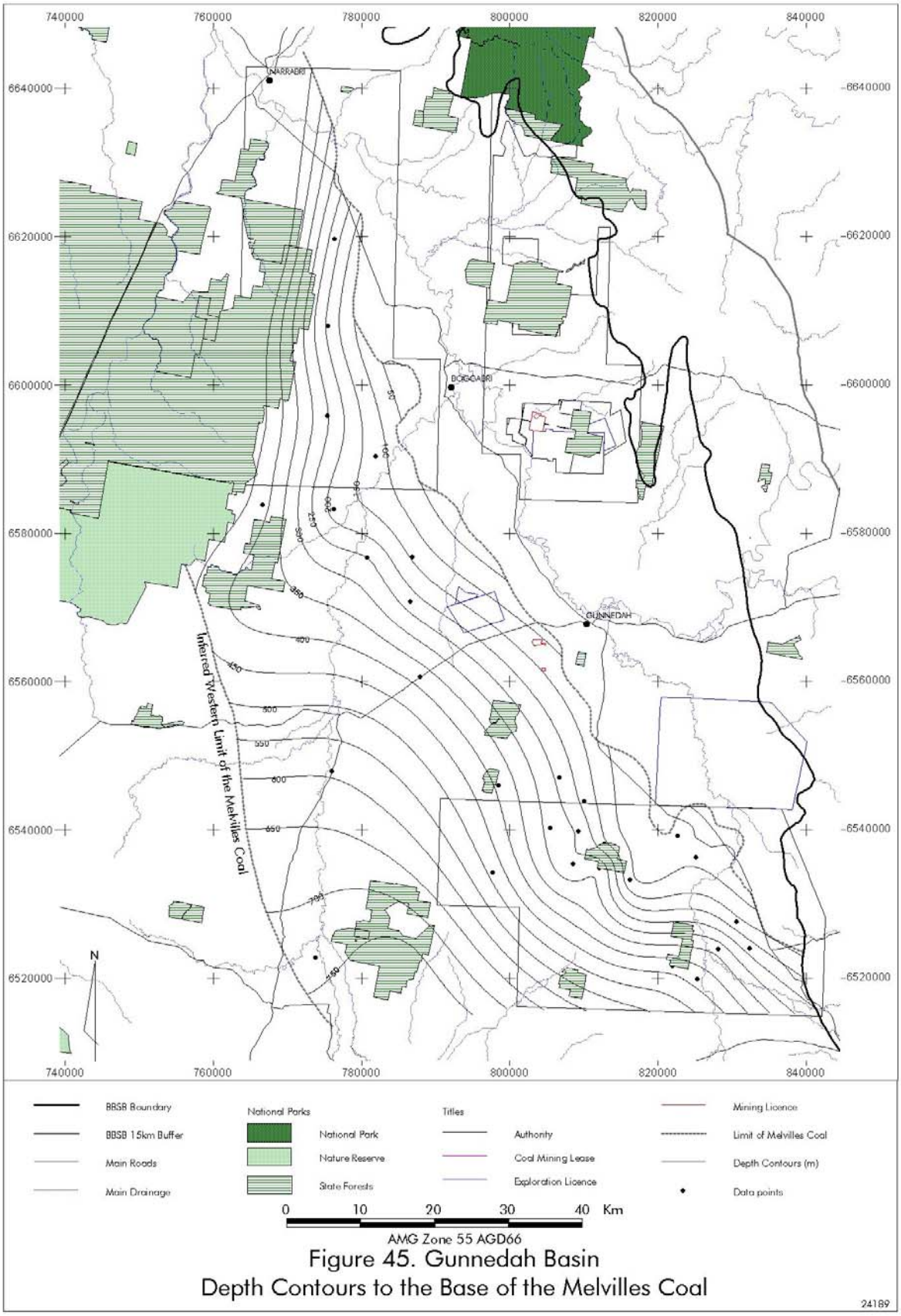
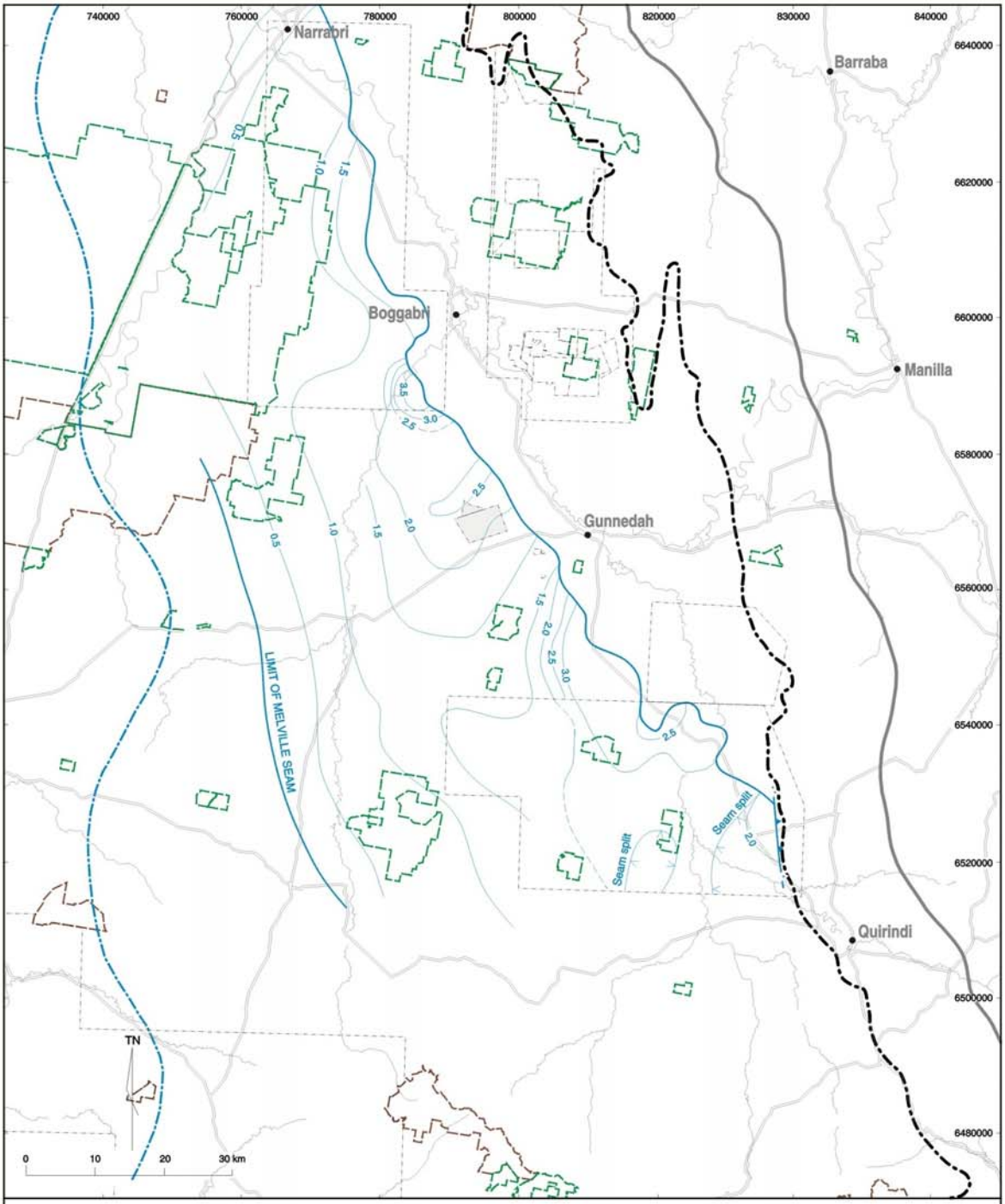


Figure 45. Gunnedah Basin
Depth Contours to the Base of the Melvilles Coal



Brigalow Belt South Bioregion
15 km buffer
State Forests
National Parks
Main Roads
Main Drainage
Exploration Licences
Mining Leases
2.5 Isopachs (m)

Figure 46 Gunnedah Basin Potential Working Section

Isopachs, Melvilles Coal

Adapted from Tadros 91 and Bamberry, Moloney and Hawley 92 and Wiles 96

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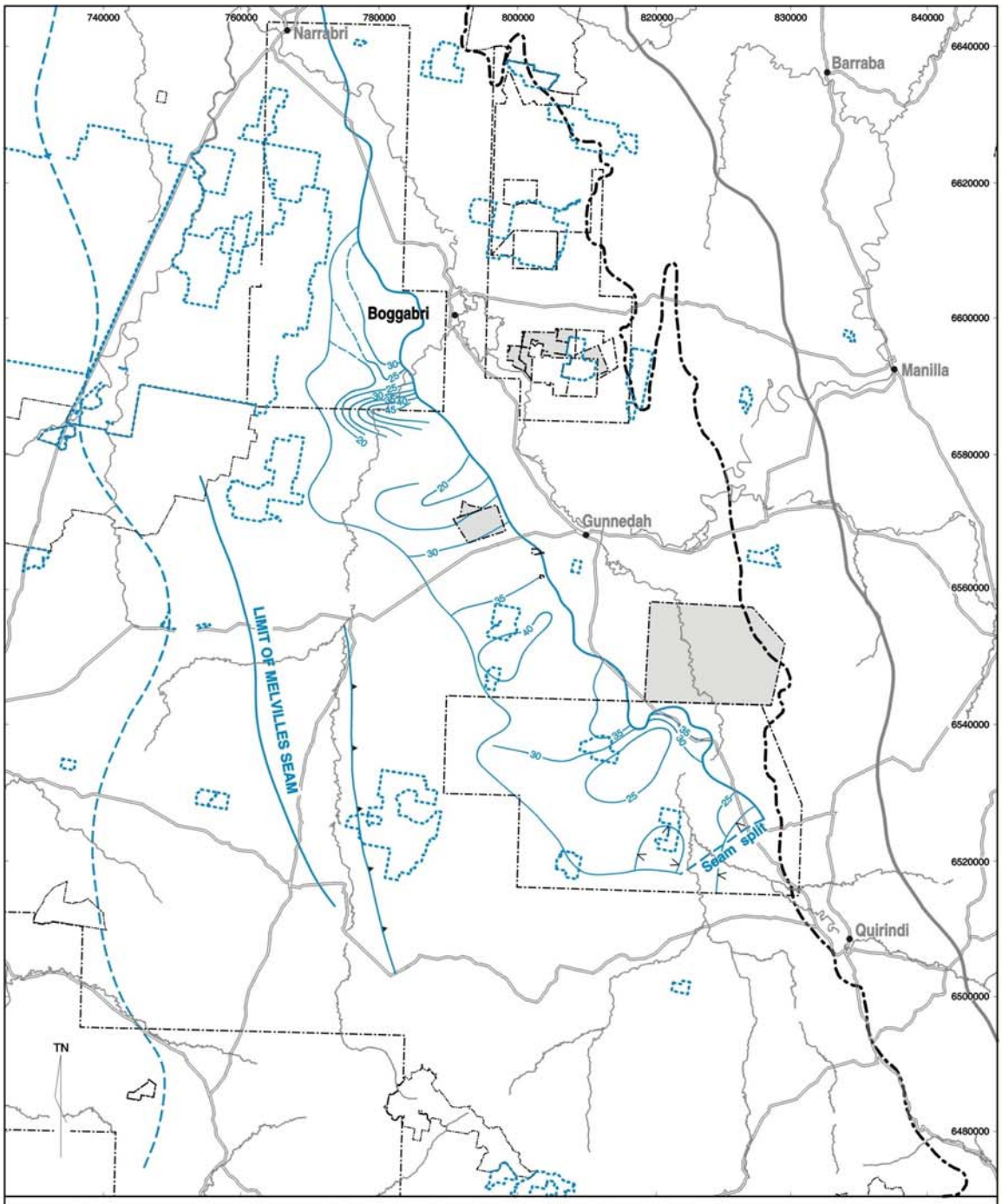

Fifgure 47 Basin Raw Coal Isoash
Melvilles Coal

Adapted from TadroS 91, Bambery, Moloney and Hawley 92, & Wiles 96

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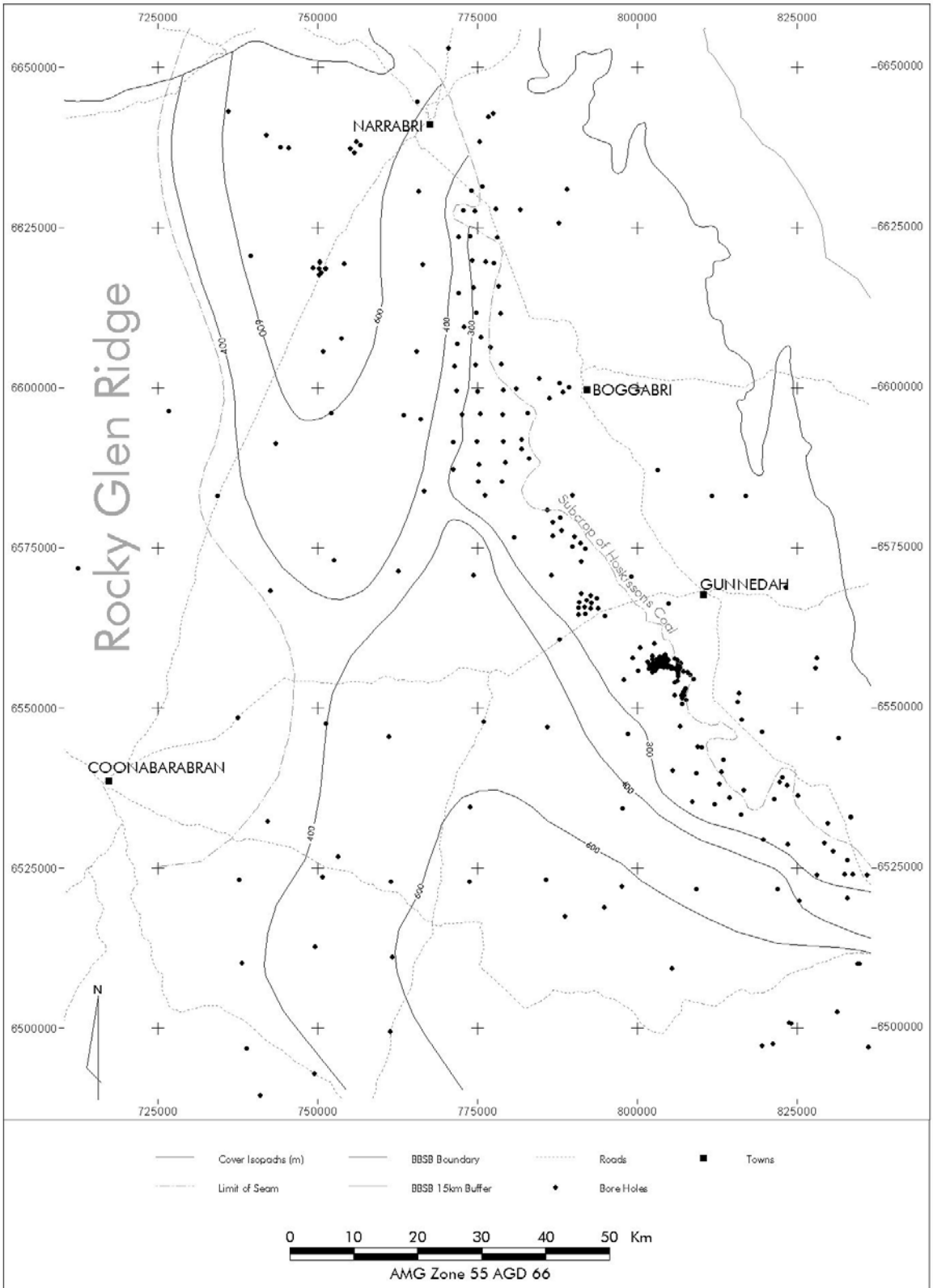

Figure 48. Gunnedah Basin
Cover Isopachs to the Top of the Hoskissons Coal

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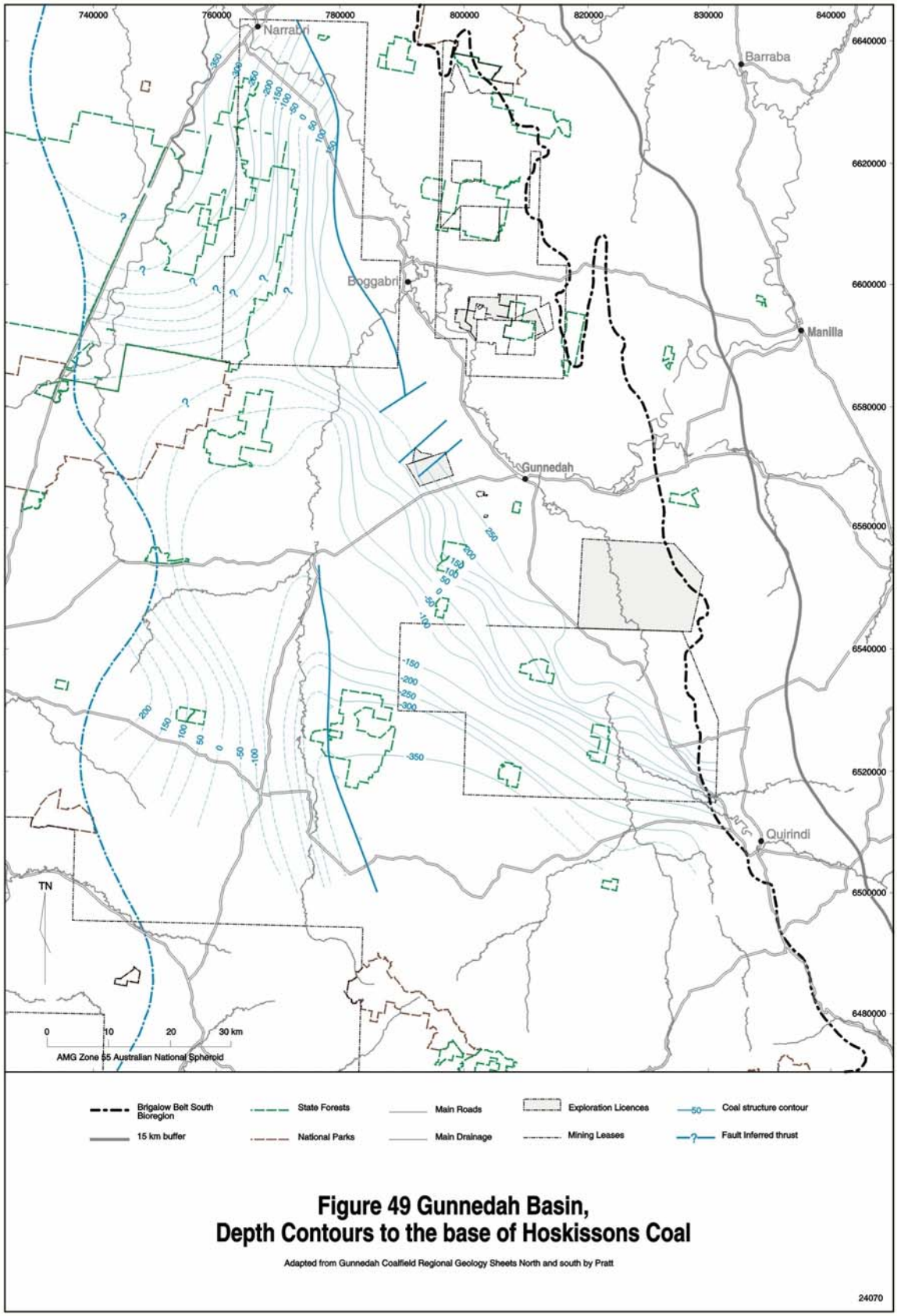

Figure 49 Gunnedah Basin, Depth Contours to the base of Hoskissons Coal

Adapted from Gunnedah Coalfield Regional Geology Sheets North and south by Pratt

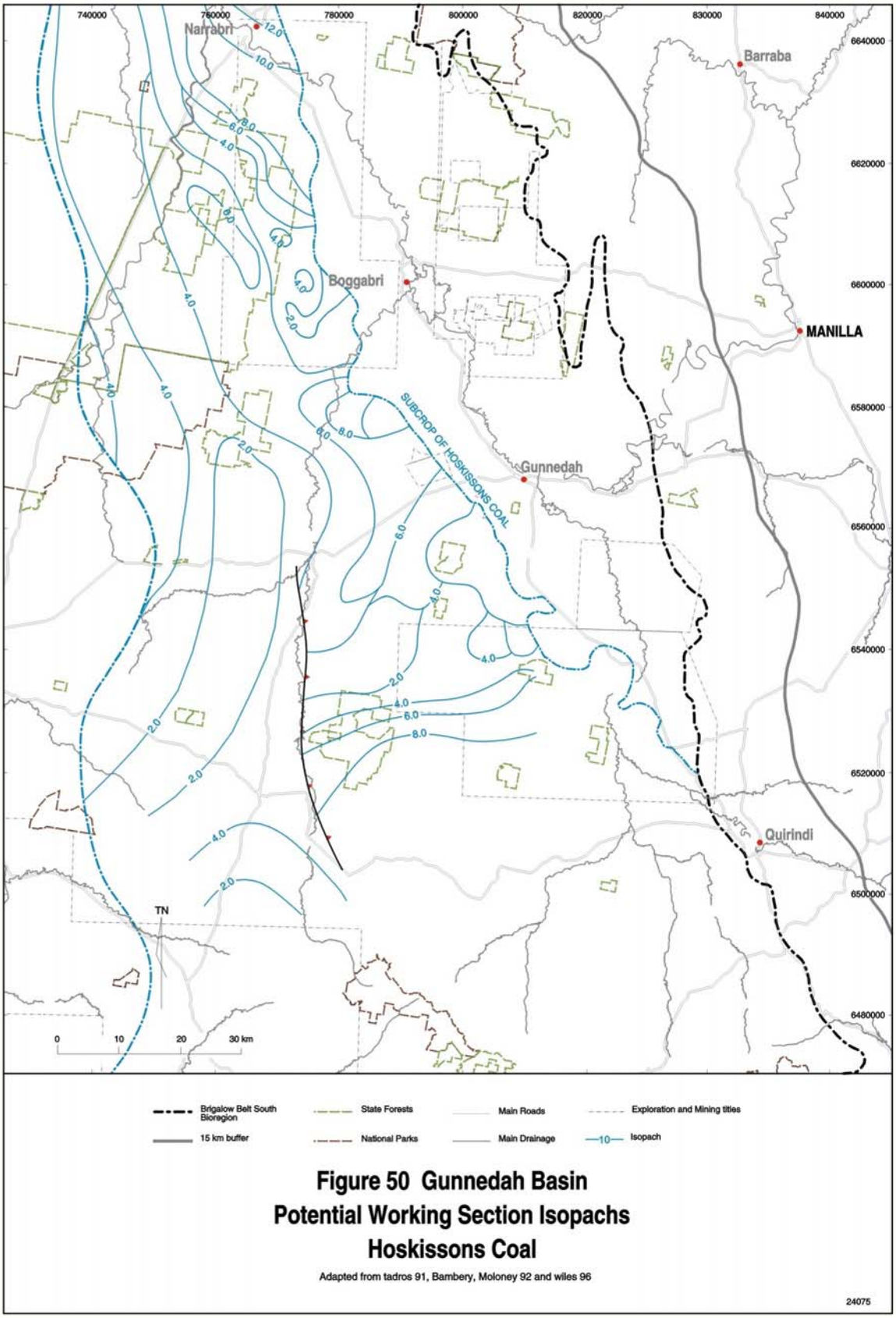

Figure 50 Gunnedah Basin
Potential Working Section Isopachs
Hoskissons Coal

Adapted from tadros 91, Bambery, Moloney 92 and wiles 96

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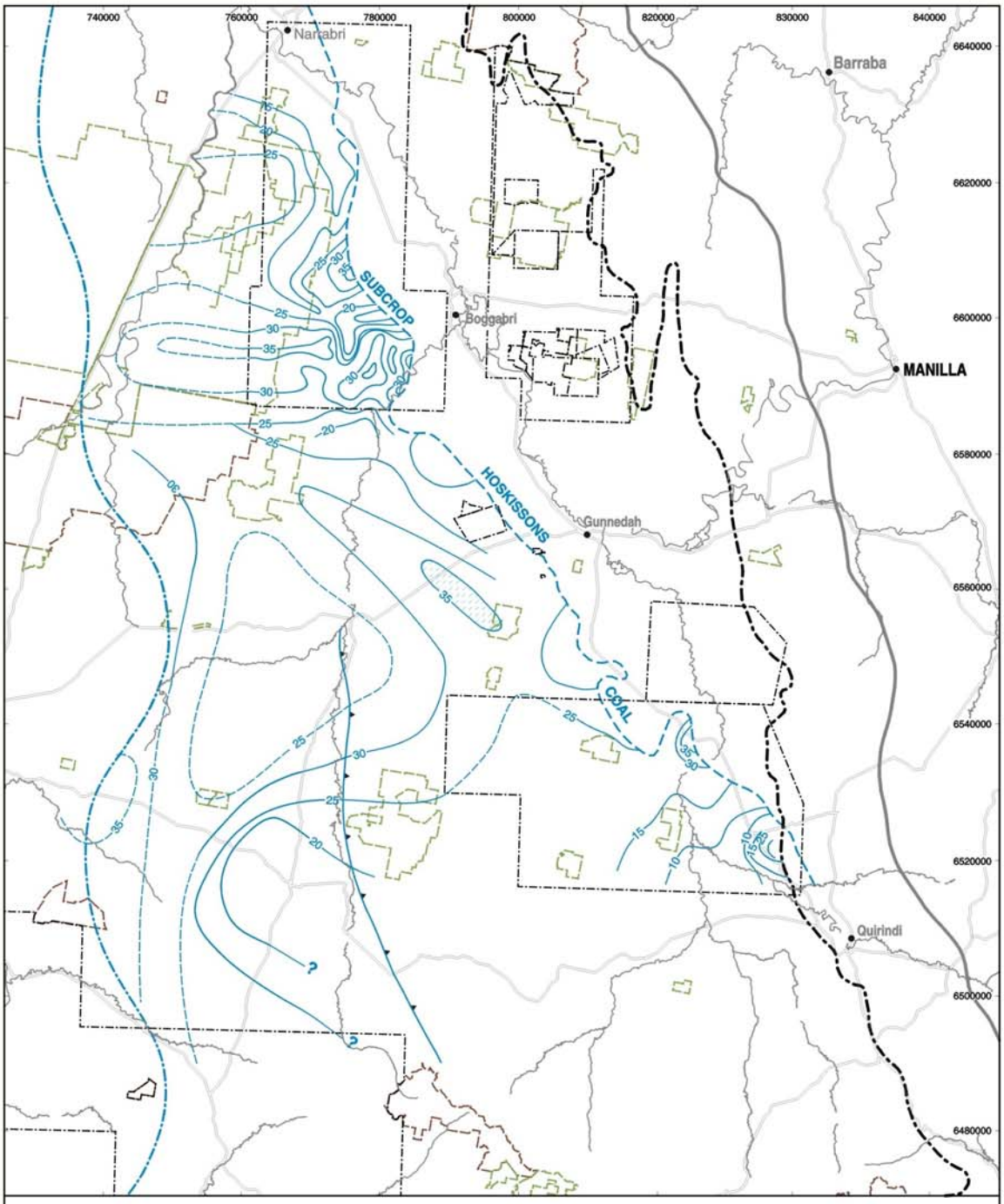

Figure 51 Gunnedah Basin, Raw Coal Isoash Hoskissons Coal

Adapted from Tadros 91, Bambery, Moloney and Hawley 92 and Wiles 96

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The upper seams of the Mullaley Sub-basin from the Caroona seam up, cover a large area of the southern Mullaley Sub-basin. Exploration to date has only shown potential in these upper seams in the Caroona area. Figures 46, 47, 50 and 51 show isopach and isoash maps for the Mullaley Sub-basin for the Hoskissons and Melvilles seams. Figure 49 shows depth contours to the base of the Hoskissons Coal.

Melvilles Coal Member

The Melvilles Coal Member is identified over large parts of the Mullaley Sub-basin. It is generally a high ash coal with variable thickness throughout the area. The seam has limited potential as a source of medium to high-ash, high volatile thermal coal.

In the south of the Sub-basin in the Caroona area, the Melvilles Seam has a maximum thickness of 3 m, however, the seam diverges into up to 4 splits, often less than 1.5 m in thickness, over large parts of the area. The seam is characterised by a series of cyclical bright and bright banded plies grading up into banded dull coal. Thin beds of tuff and carbonaceous claystone separate these units. The Melvilles Seam subcrops in the east of the area under Quaternary alluvial sediments and gently dips to the south-southwest to depths greater than 600 m (figure 45). In this part of the Sub-basin the Melvilles Seam is not considered to have any underground development potential due to its thickness and quality, however, there may be some potential for open-cut extraction when considered with the more attractive Hoskissons Seam.

In the north of the Mullaley Sub-Basin, the Melvilles Seam has economic potential in a small area southwest of Boggabri. Typically the seam is dull and bright interbanded with sporadic tuff and carbonaceous claystone bands. The Melvilles Seam ranges in thickness from 1.5 to 3.8 m and averages 2.0 m with depth of cover to the top of the seam ranging from 70 to 210 m. The eastern section, where the seam is not split and the basal section is better developed has underground development potential. The seam is typically medium to high ash thermal coal.

Hoskissons Coal

The Hoskissons Coal has the greatest resource potential of all seams in the Gunnedah Basin (figure 52). It is predominantly a source of low to medium ash, high-volatile thermal coal. Isopachs of the Hoskissons Seam show the thickness of this seam can be greater than 10 m but has an average thickness of 6 m. The thickest sections are developed over the northern and southern parts of the Sub-basin along the Boggabri Ridge in the Narrabri and Caroona areas. These are also areas of low to medium ash content.

The seam is principally composed of thick coal plies with minor sandstone, siltstone, claystone and tuff bands. Typically it is structured with an upper and lower section divided by a tuff or claystone layer that is generally about 0.1 m thick. The lower section is generally considered to be of most economic significance with a higher proportion of bright coal and a low mineral matter content. The upper section in contrast is high in mineral matter and is composed mainly of dull coal. A significant proportion of ash occurs as stone layers (rock bands) that may be separated from the coal by washing.

In the south of the Mullaley Sub-basin, the Hoskissons Seam subcrops under Quaternary alluvial sediments in the east and generally dips to the south-southwest at less than 3 degrees to obtain depth of cover greater than 600 m. To the west, as the seam approaches the Rocky Glen Ridge, depth of cover to the Hoskissons Seam decreases to less than 400 m (figure 48).

In the Caroona area the Hoskissons Seam is the primary underground resource. The seam averages 8 m thick but where it converges with the overlying Caroona Seam it obtains a maximum thickness of 15 m. A consistent 3 to 4.5 m dull to bright banded working section is present across the area. The seam is primarily suitable for underground extraction, however, there is limited open-cut extraction potential along the subcrop in the east of the area. The Hoskissons Seam will produce a low to medium ash thermal coal suitable for the export market.

In the northeast of the Mullaley Sub-basin the Hoskissons Seam contains important coal resources. To the south of Narrabri, the Triassic Digby Formation erodes the upper Black Jack Formation in an easterly direction until the Digby Formation sits unconformably on top of the Hoskissons Seam. Depth of cover

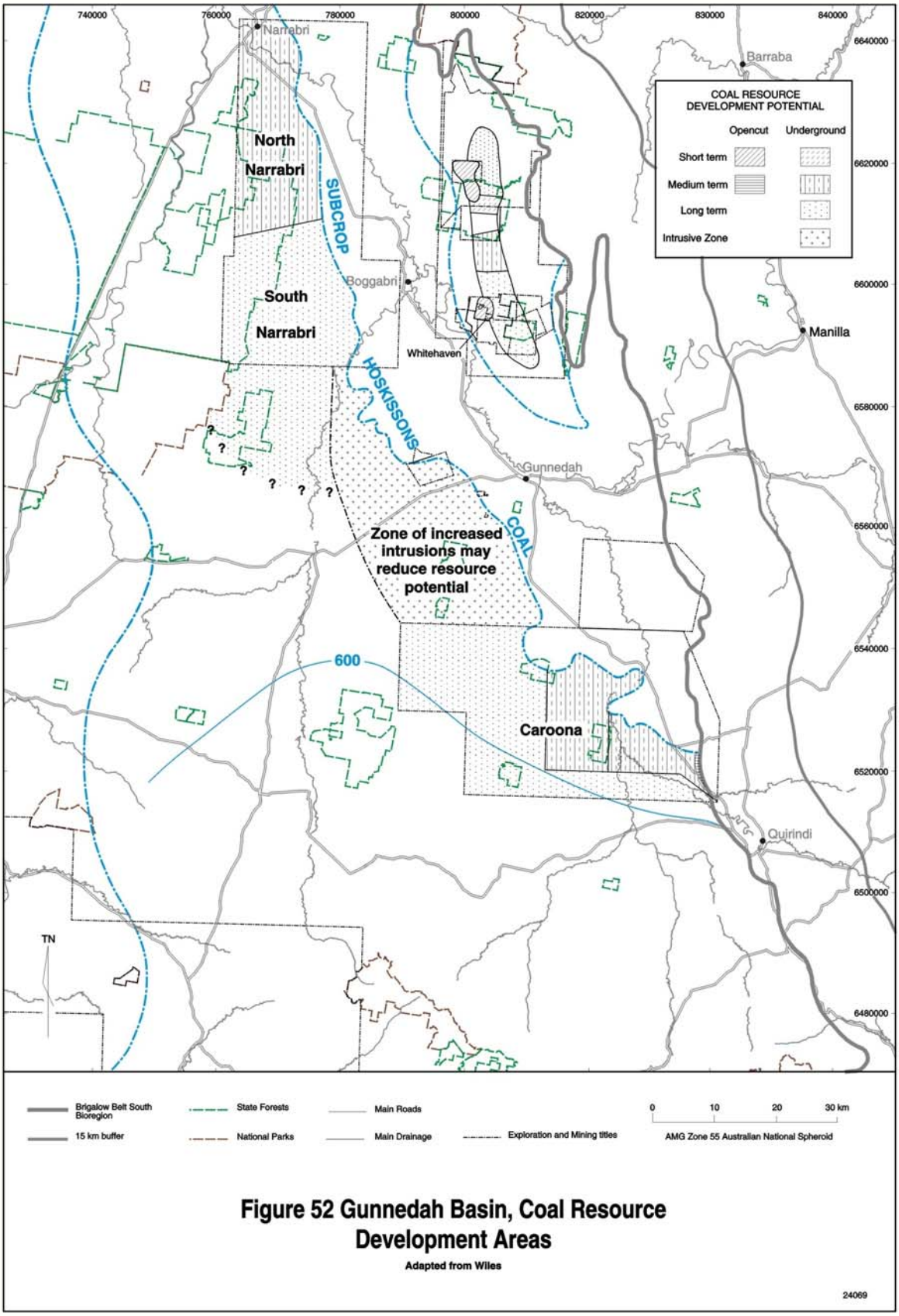

Figure 52 Gunnedah Basin, Coal Resource Development Areas

Adapted from Wiles

to the Hoskissons Seam in this area ranges from approximately 100 m in the east to over 600 m in the west. Generally the seam dips to the west at less than 3 degrees.

Approximately 80% of resources from the Hoskissons Seam in the northern Mullaley Sub-basin contain coal with less than 20% raw coal ash. The coal resource occurs in a potential working section greater than 3 m in thickness. The seam averages 10 m thick and consists of an upper and lower section, separated by a persistent tuff band averaging 0.1 m in thickness. The lower section consists of two major plies, the bottom ply being interbanded dull and bright coal averaging 2.2 m and the top ply consisting of dull coal with minor bright bands and sporadic thin carbonaceous claystone and tuff bands averaging 3.0 m in thickness. The Hoskissons Seam in the northern Mullaley Sub-basin will produce a low to medium ash export thermal coal and a medium to high ash domestic thermal coal.

To the southwest of Narrabri, covering the centre and north of the Bohena Trough, the Hoskissons seam is deeper than 600 m. There is little borehole control in this area but existing data indicates that the seam is up to 6 m in thickness and has raw coal ash values in the range of 20 to 35 %. To the south and west of this area, covering the southern and western flanks of the Bohena Trough, the seam lies at depths between 400 and 600 m. The potential working section of the seam is between 3.5 and 7 m and raw coal ash values vary between 15 and 20 % in the east and 20 and 30 % in the west.

To the southwest of Gunnedah, in the middle of the Sub-basin, there is a large area where the Hoskissons seam does not have economic potential, either because the seam is less that 1.8 m thick or because the raw coal ash is over 35%. To the west of this area, on the eastern flank of the Rocky Glen Ridge (Weetaliba Shelf), the seam shallows, thickens and improves in quality. It lies at depths between 300 and 600 m, averages 25% in raw coal ash and averages 4 m in thickness.

To the south of the area with poor seam development, there is a broad area covering most of the Yarraman High, the Bundella High and the northern Wollar Shelf. The Hoskissons seam is generally at depths between 400 m and 600 m, and the coal is potentially mineable by underground methods. The potentially mineable section/s of the Hoskissons seam is 2.5 to 7.1 m thick, averaging 4.0 m. Raw coal ash for the seam ranges from 13.7% to 30 % with a large part of the resource between 25% and 30% ash.

Caroona Seam

The Caroona seam has significant development potential. The seam is confined to the south-eastern corner of the Mullaley Sub-basin at depths from subcrop to over 600 m and thicknesses up to 5 m, with an average thickness of 3 m. It is generally about 35 m above the Hoskissons seam. Open cut potential exists in the seam subcrop but generally the seam is amenable to underground mining. The economic potential of the seam section is disrupted by splitting. In the southeast, the upper and lower splits thicken to workable thicknesses. This seam has potential as a soft coking coal with CSN values commonly ranging from 3 to 6.

Howes Hill Seam

The Howes Hill Seam contains predominantly high-ash coal, which may be suitable for domestic electricity generation but also includes a component that may be washed to an export quality thermal product. The seam is mainly amenable to underground mining methods with an average thickness of 2.5 m and is confined to the south of the Mullaley Sub-basin. In this area the seam subcrops under Quaternary alluvials in the east and reaches depths of greater than 600 m to the south and southwest.

Breeza Seam

The Breeza Seam is widely developed in the southern part of the Mullaley Sub-basin where it ranges from 1.53 to 4.84 m thick. The seam contains banded dull coal and several tuff layers to 0.35 metres thick. A prominent tuff band occurs in the middle of the Breeza Seam, subdividing it into upper and lower sections. It subcrops under Quaternary alluvials in the east of the area and obtains depths of greater than 600 m in the south and southwest. The ash content of the seam is generally high to very high due to the presence of numerous stone bands, therefore the seam is considered to have limited underground development potential.

Clift Seam

The Clift Seam is well developed in the southern Mullaley Sub-basin in the area of the Doona State Forest. The seam ranges in thickness from 3 to 4.5 metres at depths of approximately 150 to 400 metres. The seam is characterised by predominantly dull banded coal with sparse very thin tuffaceous or

carbonaceous claystone bands. This seam, suitable for underground extraction, is particularly attractive as it may produce a low to medium ash soft coking coal

Springfield and Doona Seams
The upper seams in the Black Jack Group, the Springfield and Doona Seams are well developed over the southern Mullaley Sub-basin. They range in thickness from less than 1 metre to approximately 2.5 metres and are characterised by interbanded stony coal and tuff units. These seams split and are very high in ash and are considered to have limited to no development potential.

8.5.4 Gilgandra Sub-Basin
The Gilgandra Sub-Basin is the least known part of the BBSB with one cored borehole in the Pilliga trough and three cored boreholes in the central and eastern part of the Tooraweena Trough. The completion of DM Goonoo DDH2, in June 2002, demonstrated for the first time that the Rocky Glen Ridge south of the Baradine High has not been uplifted in the Late Permian to any significant extent. It is now likely that the entire Black Jack Group extends across the ridge from the Mullaley Sub-basin to the Tooraweenah Trough.

Coal resources within the Tooraweenah Trough have been identified in two units. The Hoskissons Coal, and the unnamed Early Permian coals within the Maules Creek Formation (figure 53). The Hoskissons Coal subcrops in the Cobbora area, reaches a depth of 563 in the trough centre in DM Pibbon DDH 1, and is at 470 m in DM Goonoo DDH2 to the east. The Coal is not present in DM Goonoo DDH1 in the southwest. It is up to 5 m thick in the Cobbora area, is split into two 2.5 m thick seams in DM Pibbon DDH 1, is 2.5 m thick in DM Mirrie DDH 1 and is 5 m thick in DM Goonoo DDH2.

Coal quality data for the Hoskissons Coal is restricted to the Cobbora area and to DMs Pibbon DDH1 and Mirrie DDH 1. Raw coal ash values vary from 20 to 30% and the Coal contains a large potential underground resource of domestic and export thermal coal. This coal will only be mined when other resources closer to markets have been exhausted. It is therefore the State's last strategic resource of coal.

Early Permian Coals have been intersected in DM Goonoo DDH1, DM Mirrie DDH1 and in the Cobbora and Yarindury grabens. In DM Mirrie DDH1 a thin coal seam was intersected at 375.90m. Two coal seams were encountered in DM Goonoo DDH1 at depths of 388.7 and 391.75. The seams are 4.32 and 1.92 m in thickness. Raw coal ash values are 11.9% and 6.5% respectively. These coals are extremely clean and are high quality export thermal quality.

The extent of this high quality thermal coal is unknown. Gunn (2002) has predicted that Early Permian grabens extend to the north towards the trough centre. Further assessment is required to clearly define the resource.

8.5.5 Werrie Basin
Coal and oil shale deposits have been recorded in the Werrie Basin since the 1860s. Oil shale occurrences are mainly confined to that part of the Werrie Basin southeast of the New England Highway whereas the coal deposits are mostly confined to that part of the basin northwest of the highway.

Coal deposits in the Werrie Basin had been known since the 1890's when coal beds were intersected in the Temi Formation in water bores between Werris Creek and Quirindi. An extensive exploration program extending from the New England Highway to Werris Creek was undertaken by CRA in 1996-97. This exploration failed to find any seams with economic potential in the Temi Formation.

The coal seams of the Willow Tree Formation at Werris Creek were explored in 1924 and underground mining commenced as a small operation in 1925. Mining ceased in 1963 due to cancellation of railway contracts for coal.

The Werris Creek deposit occurs in a synclinal deposit on the top of a hill. The deposit has a limited extent and steep dips (up to 25 degrees) and faulting caused extraction difficulties. Run of mine coal from the Tunnel seam is reported with a raw ash of 5.2%, moisture of 5.7 %, total sulphur of 0.5 % and calorific value of 29.4 mj/kg.

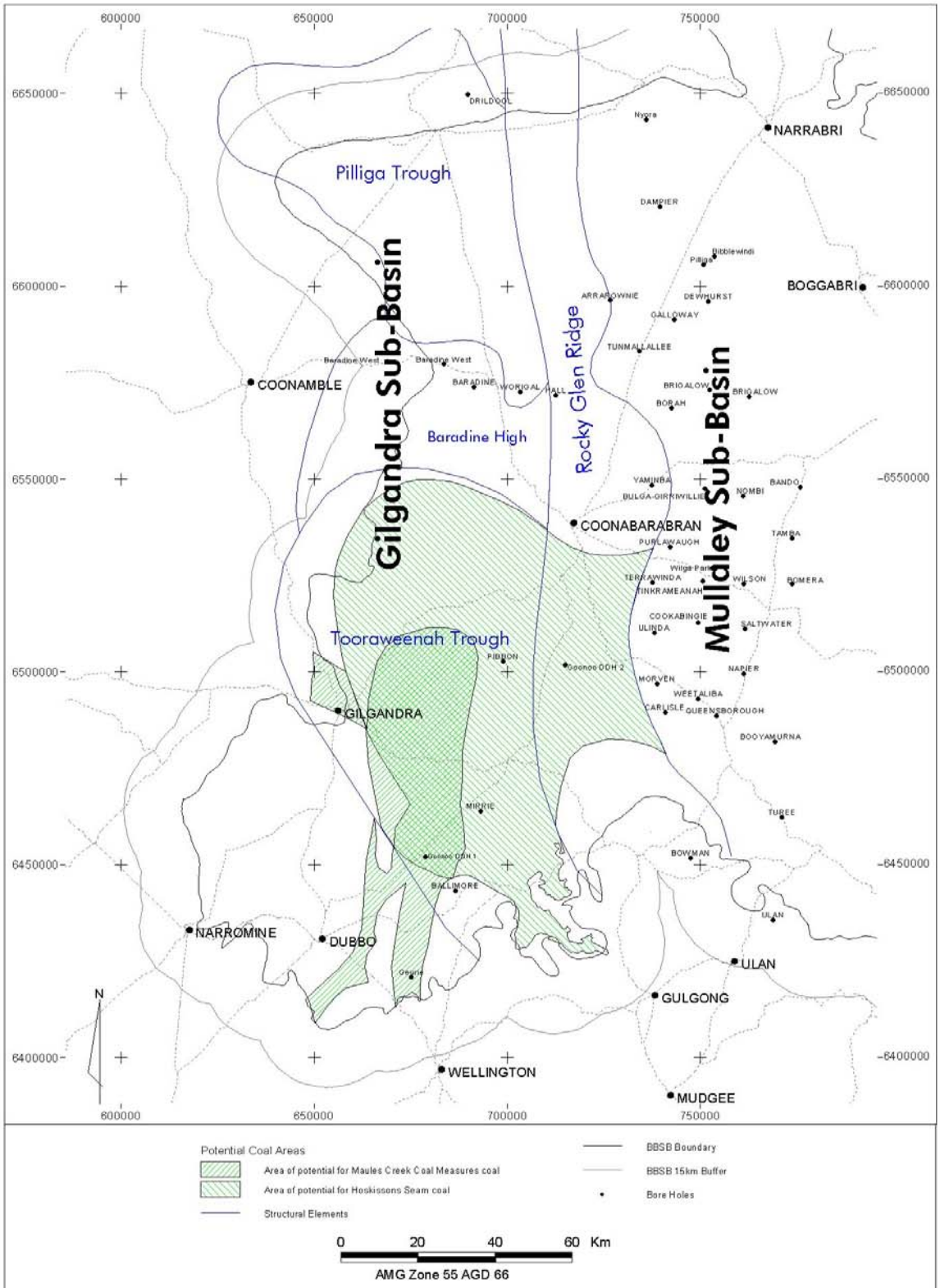

Figure 53. Gilgandra Sub Basin
Potential Coal Resources and Bore Hole Locations

While the mine is now closed, there is a small in situ remnant resource of approximately 3.9 Mt of which 1.4 Mt are contained in the tunnel seam pillars of the Werris Creek Colliery workings which were almost entirely first workings only. A small amount of coal, presumably from the 'Black seam' was also won by open cut mining. The site has now been rehabilitated.

At Willow Tree a coal seam in the Willow Tree Formation was discovered in 1937 during excavation of a water well. The very steep dip and strike beneath the alluvials of Borambil Creek precludes extraction by current mining methods and environmental constraints. In summary, the only known coal resources in the Werrie Basin occur in the vicinity of the Werris Creek Colliery.

8.5.6 Northern Hunter Coalfield – north of Scone

Coal has been mined in the Northern Hunter Coalfield at the Bickham Colliery in the Greta seam equivalents of the Koogah Formation on Bickham Station near the Pages River. The area is currently within Exploration Licence 5306 and the title holders are reassessing the coal resources contained in seven of the seams identified in the sequence.

Seam correlations in this coalfield are difficult, particularly due to the lack of reliable marker beds. The seams lack lateral continuity of thickness and quality and the raw ash and moisture are high. Intrusions are frequent with only 2 boreholes out of 16 between Scone and Wingen not intruded. The area appears to be subject to significant structural disturbance. It also appears that the seams identified as having underground potential and occurring at depths in excess of 200 m do not subcrop in the area. Consequently there is almost no open cut and little underground coal resource potential in the area.

Since 1978-79 the DMR has drilled 14 boreholes in its DM Scone series. This assessment concluded that there is no coal mining potential east of Kingdon Ponds and no viable areas of open cut resources or shallow coal were identified. Seams with underground mining potential were identified but there is insufficient data to effectively evaluate these resources as the coal exploration was targeted at shallow coal resources. Intrusions are again frequent in this area with only 1 out of 15 boreholes west of Kingdon Ponds and to 6 km south of Scone not intruded. Again significant structural disturbance which would constrain the extent of underground mining was indicated in this area.

8.5.7 Northern Hunter Coalfield – south of Scone

In the area south of Scone, the Watts Sandstone, a distinctive marker horizon the base of which currently defines the interface of the Wollombi and Wittingham Coal Measures, is present as are other important marker horizons which both make seam correlations more reliable. There is significantly less structural disturbance away from the Hunter Thrust Fault. As the Hunter Thrust swings eastwards and the separation between the Hunter Thrust and the Triassic escarpment becomes wider an increasingly larger area of relatively flat lying and undisturbed coal-bearing strata becomes exposed.

In the area west of Muswellbrook and to the west of the Hunter River, the Foybrook Formation is exposed and as the dip is gently westwards the Jerrys Plains Sub-group is also exposed. This configuration has promoted the development of the Bengalla and Mount Pleasant open cut mines and, to the north, the Dartbrook Underground Mine. Further up dip, to the southwest, lies the Anvil Hill Project with upper Wollombi Coal Measure resources, while the Rosehill and Castlerock Exploration Licences lie between the existing mines and the Triassic escarpment.

In the Dartbrook Mine Lease the major seams are the Warkworth, Mt Arthur, Kayuga, Piercefield, Vaux, Broonie, Bayswater and Upper Wynn A seams. The mine has In Situ Resources of 661 Mt at Measured status and Marketable Reserves of 81.8 Mt. The mine has an annual production capacity of 3.4 Mt of raw coal.

In the Mount Pleasant Proposal the major seams present are the Bowfield, Warkworth, Mt Arthur, Piercefield, Vaux, Broonie, Bayswater, Wynn, Edderton, Clanricard, Bengalla, Eddinglassie and Ramrod Creek seams. The mine has In Situ Resources of 1300 Mt at Measured status and Recoverable Open Cut Reserves of 440 Mt. The Proposal has a proposed annual production capacity of 10.5 Mt of raw coal.

In the Bengalla Lease the major seams present are the Warkworth, Mt Arthur, Piercefield, Vaux, Broonie, Bayswater, Wynn, and Edderton seams. The mine has In Situ Resources of 361 Mt at Measured status. The mine has an annual production of 4.04 Mt of raw coal.

Exploration Licences 5431 Rosehill, and 5600 Castlerock, are held by Muswellbrook Coal Company Pty Ltd. Although the primary exploration target is open cut resources in the upper part of the Wittingham Coal Measures, intersections of attractive seams in the Wollombi Coal Measures or deeper seams in the Wittingham Coal Measures would also be evaluated. Exploration Licence 5552 Anvil Hill is held by Powercoal and the primary exploration target is open cut resources in the upper part of the Wollombi Coal Measures.

The area held under title (A102) by the DMR between the Bengalla Mine and EL 5600 is transected by two north-north-west trending major faults, the Lyndale and Mirrabooka Faults in the east and west respectively. Drilling in and around this Lyndale–Mirrabooka area indicates that the major coal development being exploited in the Bengalla Mine extends westwards into the area as a potential underground resource. The Lyndale and Mirrabooka Faults may place constraints on underground development and it is noted that the intensive drilling conducted in association with the development of Bengalla Mine identified structures affecting mining that were not apparent in the early drilling stages.

The gently west-northwesterly dipping coal sequence between Denman and Scone can be expected to exist at depth to the west, beneath the plateau formed by the Triassic Narrabeen Group and overlying Tertiary Liverpool Range Volcanic Complex units. The same applies to the potentially economic seams occurring near the top of the Wollombi Coal Measures, as identified in Powercoal's Anvil Hill Project or the DMR Ridgelands Project. These seams, however, present a potential underground resource if they could be accessed from the base of the escarpment or from valley floors within the plateau.

In the area between the western boundary of EL 5552 (Anvil Hill) and Merriwa, there is only one borehole, DM Doyles Creek DDH 10, located adjacent to the western boundary of EL 5552. In this area the strata is believed to strike in a direction parallelling a line between DM Doyles Creek DDH 10 and Merriwa, 35 km to the north-west, where two further boreholes (Amoco's East Dunlop 1 and Doolans Creek 1) are located. Some scout drilling is required to determine if potential underground resources exist, and if they could be accessed from the valley floor.

8.5.8 Northern Western Coalfield

Drill hole coverage in the Northern Western Coalfield area is widely variable. High-density data is available in the southwestern third of the area, within and around Ulan Mine and in the Wilpinjong-Moolarben area. In the north and east of the area, data is sparse and very widely separated.

The majority of the coal resources in the Northern Western Coalfield are held under title to the NSW Department of Mineral Resources. In the buffer zone in the south, Ulan Mines Limited holds a significant coal resource within its colliery holding and exploration titles. Only the Ulan seam is currently being mined in the Northern Western Coalfield. This seam is best developed at Ulan Colliery where it is mined by open cut and underground methods. The total section of the seam is being mined at Ulan Open cut mine but with a very high raw coal ash and the coal is mostly supplied to the Eraring Power Station. The raw coal ash for the underground working section at Ulan is low and the coal is produced for the export market.

In the unallocated areas to the north and east of the Ulan mine, the Ulan seam has been identified in almost all of the area. Raw coal ash is generally medium to moderately high and the coal is suitable for domestic thermal purposes. Where the raw coal ash is low, the coal would also be suitable for export thermal purposes or for PCI.

Raw coal ash of other seams in the Illawarra Coal Measures is medium to very high and the coal is only suitable for domestic thermal purposes or in the manufacture of cement. Potentially mineable Moolarben seam coal occurs under less than 40 m of cover in the Moolarben area between Ulan Colliery and the village of Wollar. Raw coal ash of the seam is generally medium to high. However, a small tonnage may be recoverable by opencut methods. Potentially mineable resources in the "Coolah seam" and "Turill seam" occur in the northern part of the coalfield area. The seams have variable but moderate to high raw coal ash. There are widespread intersections of other seams in the northern part of the coalfield area but there is insufficient data to correlate them or to accurately categorise the coal quality.

Ulan Coal

The Ulan Coal is a 14 m thick coal seam in the Ulan–Wilpinjong area. The seam is divided into upper and lower sections by a 0.3 m thick tuffaceous claystone (C-marker)(figure 57). The tuffaceous layer maintains its constant thickness to Wilpinjong from where it has been reworked and thickens eastwards. While the lower section persists basinward, the upper plies split over an interval up to 50 m forming the Long Swamp Formation. The uppermost ply has been correlated with the Irondale Coal (Yoo 1993).

In the Ulan area, the lower section of the Ulan Coal, the D Working Section (DWS) is mined by longwall and highwall methods, and the lower and upper sections of the Ulan Coal are mined by opencut methods. The DWS ply averages 3 m in thickness and contains a raw coal ash averaging 11% to 13%, while the upper section of the seam averages approximately 7 m, is heavily banded, and is typically up to 45% raw coal ash. Fifures 55 and 56 show isopach and isoash maps for the Ulan Coal. Figure 54 shows depth contours to the top of the Ulan Coal.

In the Wilpinjong area, the upper section of the Ulan Coal has a combined thickness ranging from 1.35 m to 3.5 m (B and C plies in that area). Raw coal ash of the combined section ranges from 14.5% to 30.7%. Washability tests in DM Wilpinjong DDH1 indicate that a yield of 87.8% for a thermal product with an ash of 18.6% is indicated for this section. The lower section of the Ulan Coal incorporates the plies between C-lower and EA (from 3.5 m to 5.6 m thick). Raw ash of this section ranges from 23.6% to 35% (ad). Washability tests of the D ply (3.2 m thick and 18 % raw ash) of the Ulan Coal in DM Wilpinjong DDH1 indicate that a product yield of 96% with an ash of 16.3% at CF 1.60 RD could be achieved.

In the Turill–Uarbry area, the lower section of the Ulan Coal has a potential working section ranging from 1.8 m to 3.8 m (D top to EA plies in this area). Raw ash of the section ranges from 16% to 29% (ad). The C-marker has been reworked and loses its tuffaceous characteristics, and the upper section splits and disappears. DM Curryall DDH6, further north, indicates an improving trend of the lower section to approximately 22% raw coal ash (Bayly 1997). From the available 11 boreholes, washability testing at CF 1.60 RD indicates that the coal could be beneficiated to a product at yields in excess of 80%, at an ash range of 13.2% to 24.2% (ad). Beneficiation of the coal could produce a medium-ash fraction suitable for the domestic thermal market and an export thermal product.

Irondale Coal

Exploration conducted by Energy Recycling Corporation, north of the Wilpinjong–Moolarben area (A449) before the declaration of the Goulburn River National Park indicates an improved Irondale seam up to 2.0 m thick (ERC DDH13) with 10.6 % raw coal ash.

Moolarben Coal Member

The Moolarben Coal Member consists of dull coal with minor bright coal layers and a number of carbonaceous/tuffaceous claystone layers. North of Ulan, the Member coalesces with the underlying Bungaba Coal Member where the Watts Sandstone and the Denman Formation wedge out, and the two coal members form a potentially mineable coal section.

The potential working section of the Moolarben Coal Member ranges from 1.76 m to 2.72 m, and a raw coal ash ranging from 27% to 34%. The potentially mineable coal is restricted to the Cockabutta Creek area and a limited area at Moolarben, where the coal may be amenable to opencut extraction (Bayly 1999). At Bylong, the Moolarben Coal Member is up to 4.9 m thick, consisting of carbonaceous claystone, claystone and coal.

Turill Seam

The Turill seam consists of dull coal with common bright coal layers, and numerous thin carbonaceous claystone layers in the lower half. The upper half also consists of dull coal with common bright layers, but with moderately thick carbonaceous claystone and tuffaceous claystone layers. Three scout drillholes indicate a seam ranging from 3.5 m to 4 m in thickness at depths from 210 m to 600 m. Raw ash ranges from 23% to 45%. Washability testing at CF 1.6 RD yields 50% to 90 % products with a 17% to 25% ash.

Coolah Seam

A coal seam, referred to as the “Coolah seam” and correlated with the Irondale Coal, has been recognised in four Department of Mineral Resource drillholes. DM Booyamurna DDH1 and DM Bowman DDH1 intersected the seam with an average thickness of 1.7 m and raw coal ash of about 20% (ad) in an area south west of Coolah.

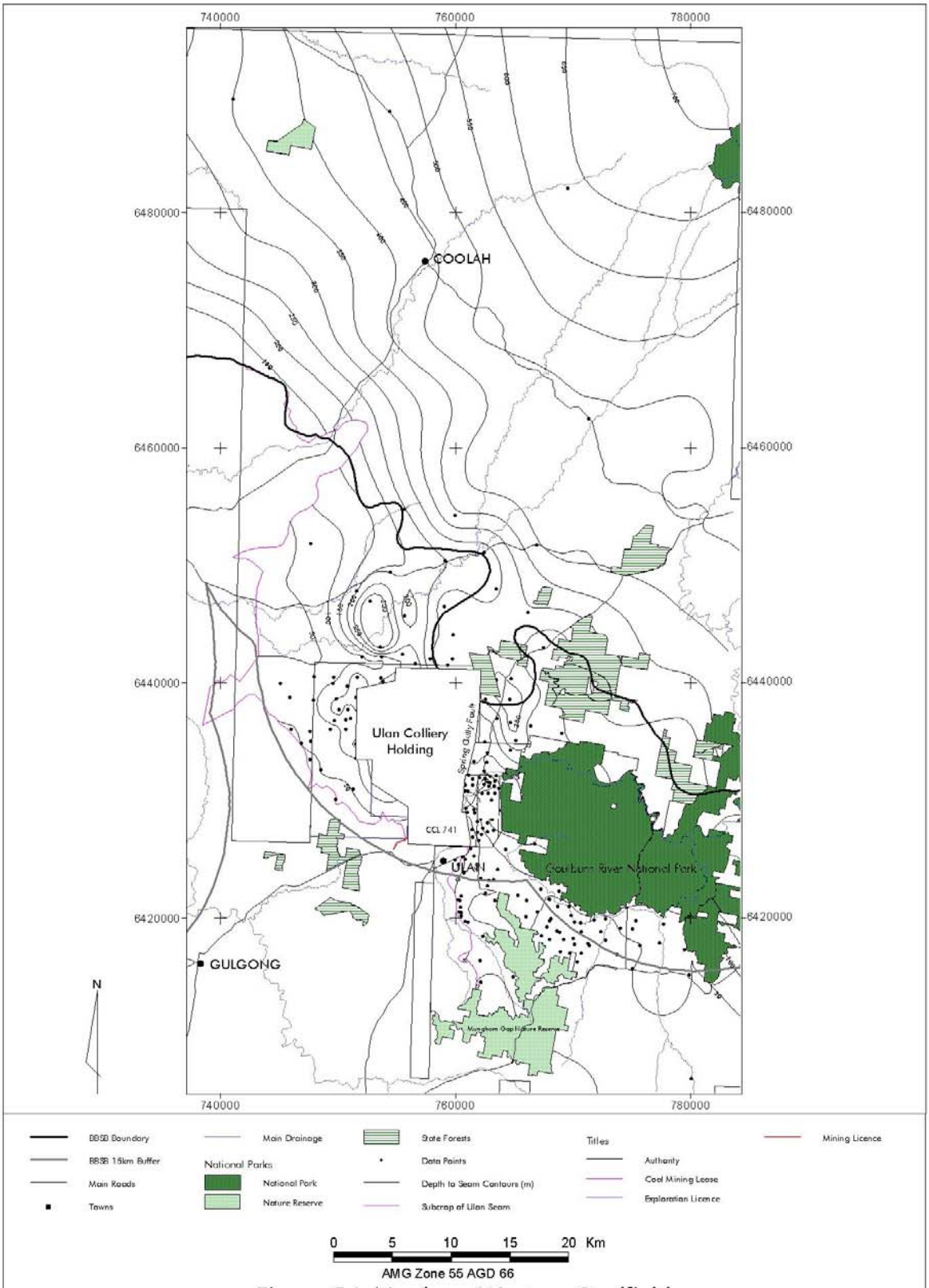

Figure 54. Northern Western Coalfield
Depth Contours to the Top of the Ulan Coal

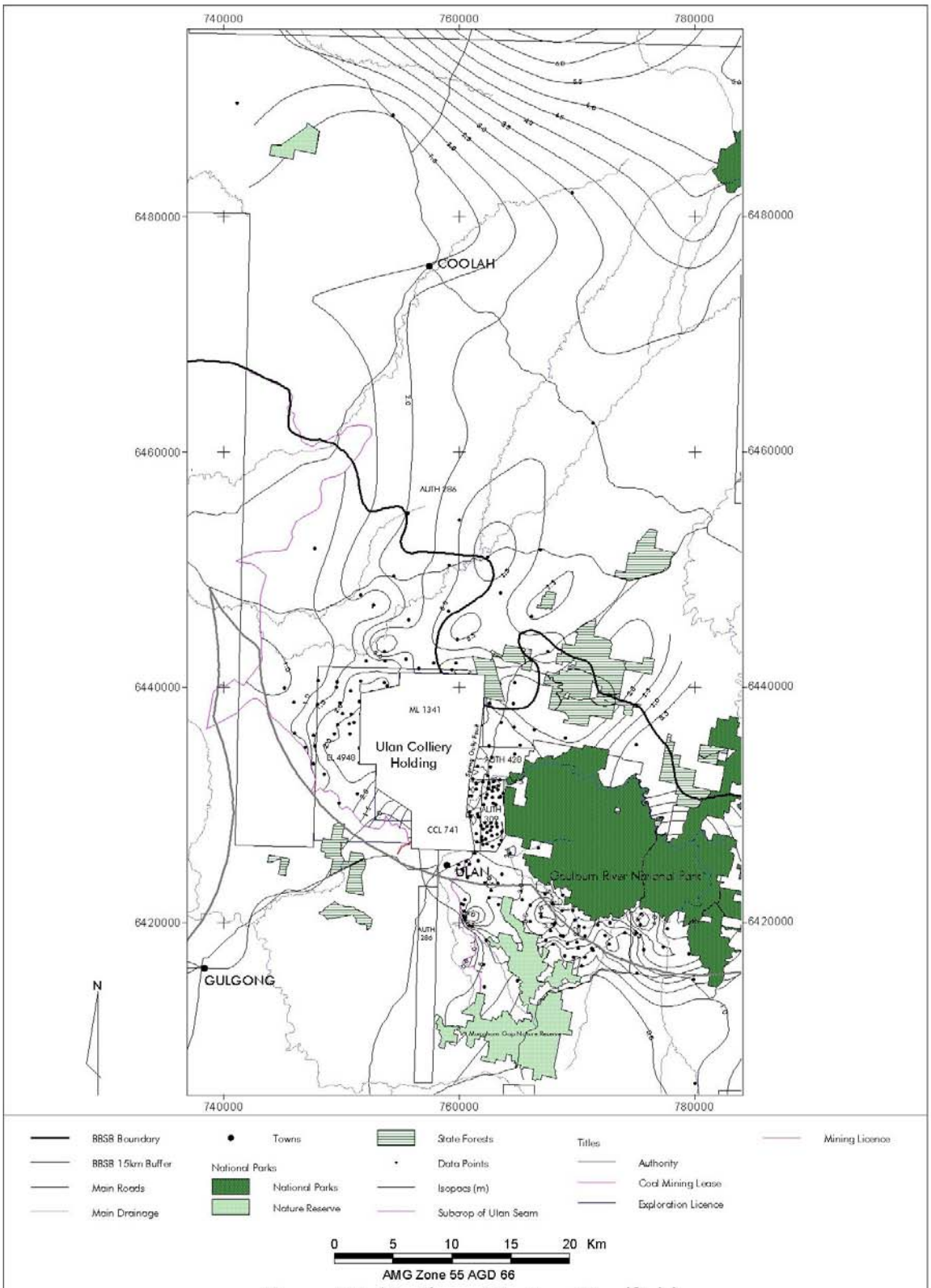

Figure 55. Northern Western Coalfield Isopachs Ulan Coal

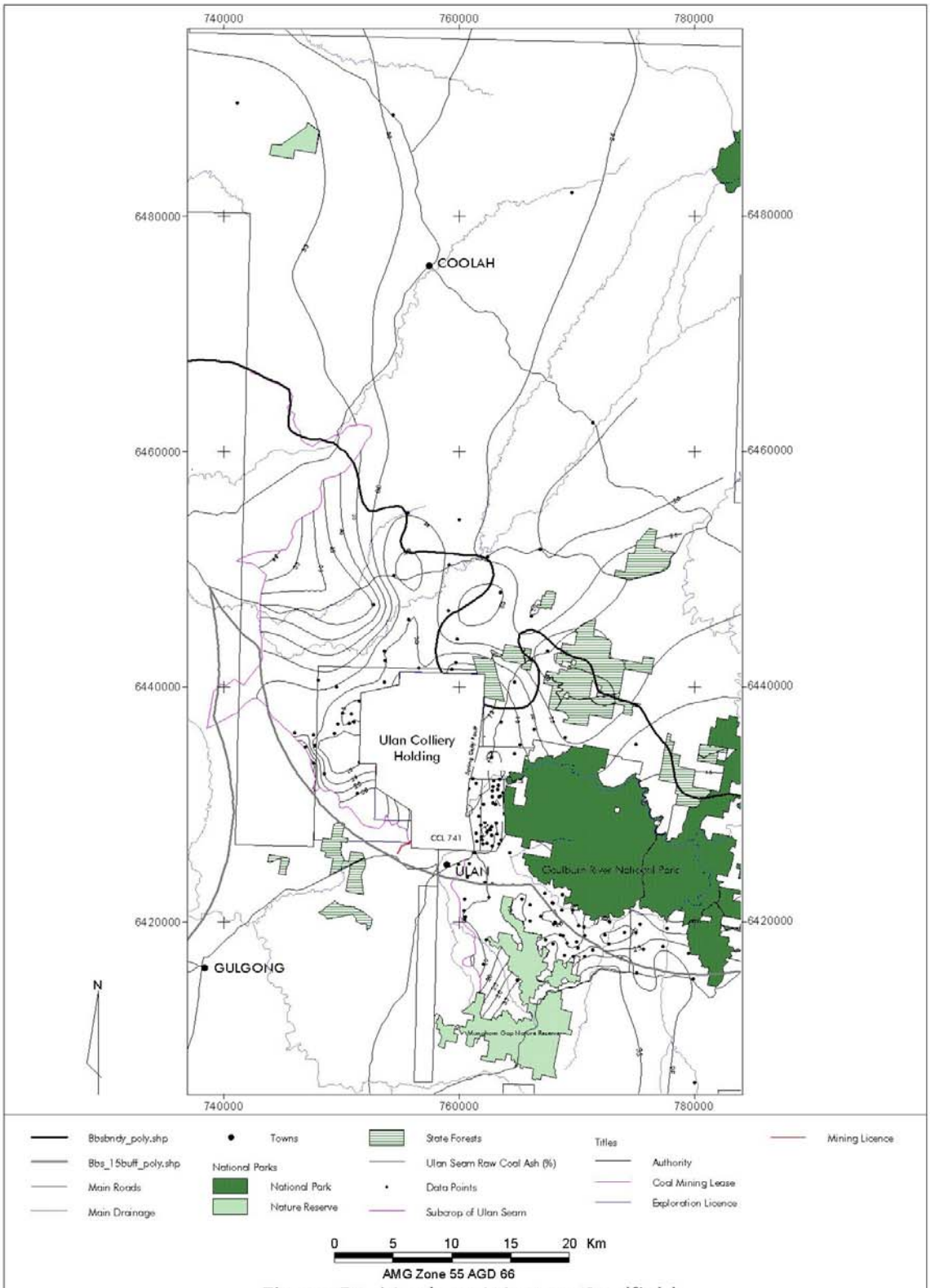

Figure 56. Northern Western Coalfield
Raw Coal Isoash Ulan Coal

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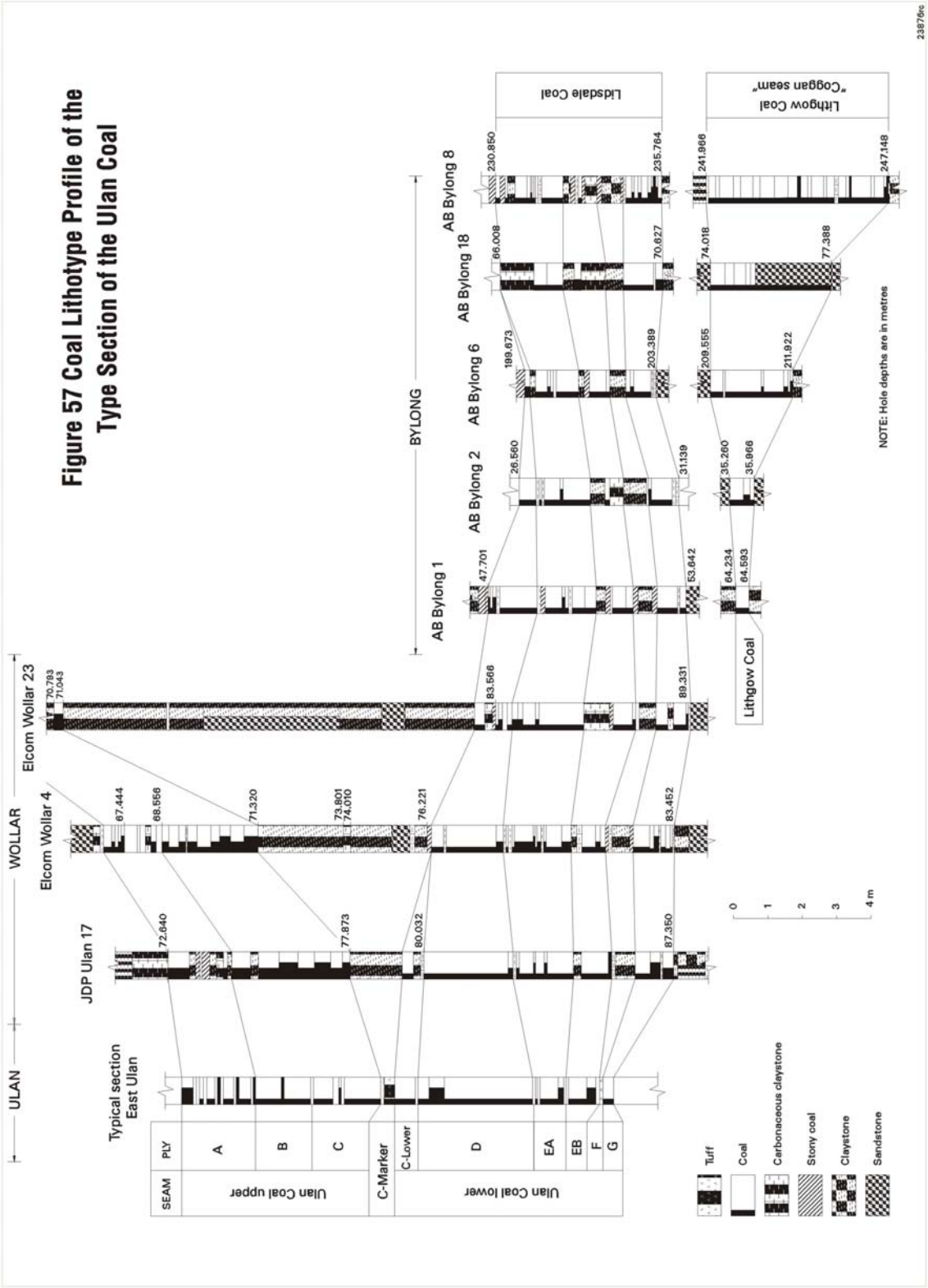
Figure 57 Coal Lithotype Profile of the Type Section of the Ulan Coal
ULAN
WOLLAR
BYLONG
Elcom Wollar 23
Elcom Wollar 4
JDP Ulan 17
Typical section East Ulan
SEAM
PLY
Ulan Coal upper
C-Marker
Ulan Coal lower
A
B
C
C-Lower
D
EA
EB
F
G
AB Bylong 1
AB Bylong 2
AB Bylong 6
AB Bylong 18
AB Bylong 8
Lithgow Coal
Lithgow Coal "Coggan seam"
Lidsdale Coal
NOTE: Hole depths are in metres
Tuff
Coal
Carbonaceous claystone
Stony coal
Claystone
Sandstone
0
1
2
3
4 m
23876ec

Gundangaroo Seam

One borehole, drilled 20 km south east of Coolah, in the deeper part of the Northern Western Coalfield, intersected a seam referred to as the "Gundangaroo seam". In this single intersection the seam had a raw ash content of less than 10%.

Allocated Coal Resources

Only Ulan Mines have allocated resources in the Northern Western Coalfield. The coal resources within the Ulan Colliery Holdings (mine lease areas, Authorisations and Exploration Licences) are listed in Table 15. The in-situ coal resources within company areas total 325 Mt. Of this amount 226 Mt is recoverable reserves.

TABLE 15. COAL RESOURCES AND RESERVES WITHIN THE COMPANY TITLES IN THE ULAN AREA (2000-2001)

Ulan Colliery	In-situ Resources (Mt)	Recoverable Reserves (Mt)	Marketable Reserves (Mt)	Mining Method
Ulan LW+O/C	325	226	195	
A287 & A342	163	106		U/G*
Total	488	332		

LW = *Longwall mine* **O/C =** *Opencut mine* *U/G = *Proposed underground*
Source: Tadros & Armstrong (2002).

Unallocated Coal Resources

Resource information on the unallocated areas is available in several internal reports of the New South Wales Department of Mineral Resources. The estimates given below are indicative only.
The Northern Western Coalfield is very large, measuring nearly 90 km long and 42 km wide and covering approximately 3740 sq kms. Approximately 53% of the area is underlain by potentially mineable Ulan seam. However, seam characteristics and resource criteria are variable over such a large area and can only be assessed in smaller blocks of more homogeneous character. At present, areas of highest mining potential for the Ulan seam are in the southeast within the buffer zone (Wilpinjong – Moolarben resource area). Total in-situ unallocated coal resources of the Ulan seam in the area are estimated to be around 8.6 billion tonnes and are summarised in Table 16.

TABLE 16. ULAN SEAM UNALLOCATED RESOURCES NORTHERN WESTERN COALFIELD

(A) INDICATED/MEASURED RESOURCES (million tonnes)

Resource Category	Block No.	Depth Range m	Thickness Range m	Average m	Ash Range %	Resource Million Tonnes
Indicated	A	< 300	2.5 - 3.5	3.0	10 - 20	391
Indicated	B	300 - 450	3.0 - 4.0	3.5	25 - 30	542
Indicated	C	< 300	2.0 - 3.0	2.8	20 - 25	269
Indicated/Measured	(I)	< 300	0.5 - 5.5	3.0	<20 - 35	624
	Total					**1825**

(I) See East Ulan - Moolarben - Wilpinjong Resources

(B) INFERRED INSITU COAL AND RESOURCES (million tonnes)

Resource Category	Block No.	Depth Range m	Thickness Range m	Average m	Ash Range %	Resource Million Tonnes
Inferred	D	300 - 550	2.0 - 3.0	2.8	20 - 25	933
Inferred	E	300 - 400	1.5 - 3.5	2.2	25 - 35	381
Inferred	F	300 - 400	2.5 - 3.8	3.0	15 - 25	416
Insitu Inferred	G	350 - 600	2.0 - 3.5	3.0	20 - 25	2895
Insitu Inferred	H	> 600	3.5 - 6.0	4.5	20 - 25	2093
Inferred (Moolarben seam)	9	< 300	0.3 - 3.0	2.8	Dec-20	51
	Total					**6770**
Grand Total (A) + (B) 0 - > 600 m						**8595**

8.5.9 Purlawaugh Formation/Walloon Coal Measures and equivalents in the BBSB

The Surat Basin sedimentary rocks dip towards the north and the northwest. Assessment of the Purlawaugh Formation/Walloon Coal Measures in the BBSB can be divided into two areas, north and south of Narrabri. North from Narrabri, cover on the coal measures increases rapidly from about 200 m to over 1000 m and exploration has essentially been for petroleum. South and southwest of Narrabri, where cover is generally in the range of 100 to 250 m, exploration has been principally for coal in the Permian Black Jack Coal Measures.

As well as coal and petroleum holes scattered irregularly across the area, there are numerous water wells. These holes are of only limited assistance because of the very basic geological descriptions, presumably recorded by the driller. Many of the water bores were geophysically logged as part of a program conducted in the Great Australian Basin from 1969 to 1975, to supplement data then available from petroleum wells. Because water wells are cased over their entire length only neutron logs were run in the early stages, and gamma only later after no benefit was gained from the neutron logging. On their own, gamma logs are not good indicators of coal. At best, water wells only record the presence or absence of coal in the Purlawaugh Formation, but this can only be inferred from descriptions such as “rock with black streaks”. Geophysical logging of petroleum wells was conducted on a routine basis, but within the limitations of the logging, there did not appear to be any significant coals.

In general, the Purlawaugh Formation is composed of interbedded claystones, mudstones and minor fine to medium grained sandstones. Coal, when present, is in thin bands within the claystone units and has no commercial value as a coal mining prospect. Coal has been mined in very limited quantities in the south west of the area near Dubbo where a banded seam 1.2 m thick with an ex bands ash content of 25.5% was intersected in the shaft. The prospect of finding Jurassic coal as good or better elsewhere is not encouraging.

South of Narrabri, the presence of coal was recorded in only about half of the holes examined. Of the holes recording coal, the maximum recorded thicknesses are 0.88 m, about 35 km north east of Dubbo, and 0.7 m, 40 km west of Boggabri. All other recorded thicknesses are less than 0.5 m. There has been one analysis conducted, on a 0.33 m coal intersection in a hole between Gilgandra and Dubbo. This coal contained 24% raw coal ash content and had a specific energy of 24.4 Mj/kg. In general the coal intersections have been too poor to warrant analysis.

North of Narrabri the Walloons dip rapidly beneath thick Cretaceous sediments and within 50 km are at depths of over 500 m, increasing to a maximum depth of 1350 m at the north western boundary of the region. Between Narrabri and Moree most holes whether drilled for coal, water or petroleum, recorded no occurrence of coal in the Jurassic, however significant gas was reported in one hole. Depth of cover in this region ranges from about 220 m at Narrabri to about 800 m at Moree.

Analysis in general was not available and only one rank determination was found. This was conducted in a hole about 40 km north of Narrabri at a depth of about 600 m. The Ro max was determined on a sample from a vitrain parting and was found to be low, in the bituminous range at 0.38 to 0.59%. The Purlawaugh Formation appears to have very low potential as a coal mining prospect.

In the Warialda-Goondiwindi area numerous water bores and several stratigraphic holes have intersected generally minor coal intervals within the Walloon Coal Measures, and also in the overlying Cretaceous sediments. Minor coal is also reported from the Gunnee Formation within the Warialda Trough. The most significant intersection recorded in this area is a 3m section of 'black coal' reported from water bore WRC No. 4866, presumably within the Walloon Coal Measures, 10 km north-east of Warialda at about 91m depth. However the available analyses, whilst very limited, suggest that the prospects of significant Jurassic coal deposits within the Walloon Coal Measures in this area is relatively low. However it must be noted, that most water bores have the overlying Pilliga Sandstone as their target, and because the underlying Walloon Coal Measures seldom crop out, it is clear that the Walloon Coal Measures in this area remain largely unexplored (Hawke and Cramsie, 1984). There are also several coal mines within Walloon Coal Measure sediments over the state border in Queensland.

8.5.10 Coal Tracts (Figure 58)

Tract Coal a/H/B-C

Maules Creek Sub-basin
This tract contains important high quality coal resources that will be mined in the future.

Cobbora Area
This tract has potential resources of open cut coal in the Hoskissons Coal. Limited analysis data is available, but raw coal ash for the potential working section in the range of 25 to 30%.

Mullaley Sub-basin Eastern Flank
This tract covers the eastern flank of the Mullaley Sub-basin immediately to the west of the Boggabri Ridge. The tract contains significant coal resources in the Hoskissons, Melvilles, Caroona, Howes Hill and Breeza seams. The Narrabri North and Caroona areas have Short-term development potential. They contain large quantities of low raw coal ash (less than 20%) coal with the Hoskissons seam working section greater than 4m. The Narrabri South area has medium term potential containing large quantities of medium raw coal ash (20-30%) coal with a working section of 2-4m. The remainder of the tract including the Benelabri, Hill 60/Breeza and Mill Ridge areas contains long term potential resources with medium to high raw coal ash (+30%), working sections of variable thickness, areas where intrusions have locally effected the development potential, or greater depths (to a maximum of 600 m).

Hunter Coalfield from Scone south
This tract covers the Hunter Coalfield from Scone south to Muswellbrook, Denman and Sandy Hollow. The tract includes some of the largest coalmines in New South Wales. It has the highest potential for coal mining.

Ulan-Wilpinjong area
This tract covers the southwestern part of the Northern Western Coalfield and contains all of the coal resources in the Ulan seam at depths less than 300 m. The tract has the highest potential for future coal mining.

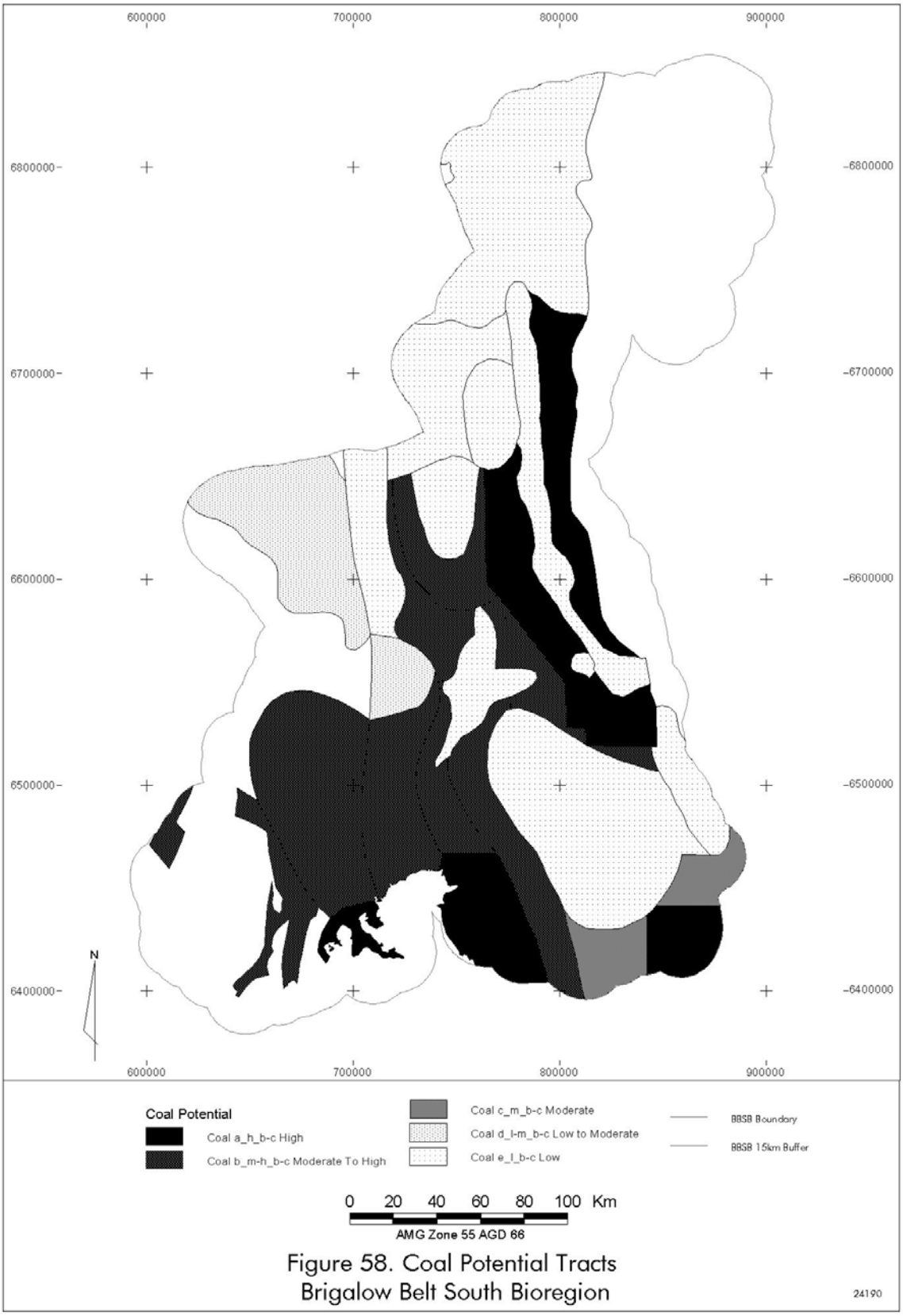

Figure 58. Coal Potential Tracts
Brigalow Belt South Bioregion

Tract Coal b/M-H/B-C

Bohena Trough Flanks
This tract lies to the southwest of Narrabri on the eastern, southern and western flanks of the Bohena Trough. It contains Hoskissons seam resources generally at depths between 400 m and 600 m, and the coal is potentially mineable by underground methods. The working section of the Hoskissons seam is 3.5 to greater than 7 m thick, averaging 4.5 m. Raw coal ash ranges from 15% to 20 % in the eastern areas and 20% to 30% in the west. Borehole coverage in this area is sparse and the resource poorly understood.

Bando trough Eastern Flank
This tract contains Hoskissons seam resources generally at depths between 400 m and 600 m, and the coal is potentially mineable by underground methods. The working section of the Hoskissons seam is 2.5 to 7 m thick, averaging 4.0 m. Raw coal ash for the seam ranges from 15 to 30 % with a large part of the resource between 25% and 30%.

Eastern and Central Tooraweenah Trough
This tract contains Hoskissons Coal resources at depths between 200 and 600 m. The Coal averages 2.5 m in thickness and its raw coal ash is between 20 and 30%. There is also a potential resource in the Maules Creek Formation for low ash thermal coal.

Southern Rocky Glen Ridge
DM Goonoo DDH 2 has proved that the Blackjack Group is continuous between the Mullaley Sub-basin and the Tooraweenah Trough. The Hoskissons Coal lies at depths between 300 and 600 metres and was 5 m thick in DM Goonoo DDH2. Coal quality is likely to be similar to that to the west and to the east, with raw coal ash values in the range 20 to 35%.

Northeastern Wollar Shelf

This tract contains Hoskissons seam resources at depths between 400 m and 600 m. The coal is potentially mineable by underground methods. The working section of the seam is 2 to 7 m thick averaging 4 m. Raw coal ash for the seam ranges from 13% to 30 % with a large part of the resource between 25% and 30%.

Weetaliba Self and Yarraman High
This tract covers the eastern flank of the southern Rocky Glen Ridge. Depth to the Hoskissons seam is generally less than 400 m. The working section of the Hoskissons seam is 2.2 to 6 m thick, averaging 3 m. Raw coal ash is relatively consistent, mainly in the range 25% to 30% with a large part of the resource between 28% and 30%.

Central part of the Northern Western Coalfield
This contains all of the coal resources in the Ulan seam at depths between 300 m and 600 m. The tract has the moderate to high potential for future coal mining.

Tract Coal c/M/B-C

Northern Hunter Coalfield – north of Scone
This tract contains underground resources of coal but there is a high level of structural disturbance and insufficient data to fully evaluate the resources. This tract has a moderate potential for long term coal development.

Tract Coal d/L-M/B-C

Pilliga Trough
Only one borehole has been drilled in this tract. A thin sequence of Late Permian coal measure sediments were intersected. The results of Seismic surveys in the north have indicated that the Trough is less extensive than originally believed. However, the Black Jack Group and the Maules Creek Formation coals may exist in the centre, as they are believed to do in the Tooraweenah Trough. An additional drill hole in the centre of the Trough is urgently required.

Tract Coal e/L/B-C

Gunnedah-Bowen Basin
The coal measures are too deep to be considered for mining in the foreseeable future.

Bellata Trough-Wee Waa Shelf
The Blackjack Group have been removed by erosion north of Narrabri and the Maules Creek Formation while present is below 600 m.

Bohena Trough Centre and North
This tract lies to the west of Narrabri and covers the central and northern part of the Bohena Trough. The Hoskissons Coal is deeper than 600 m. The tract has low potential for economic resources.

Northern Rocky Glen Ridge
This tract covers the Rocky Glen Ridge north of the Baradine High. The Black Jack Group has been eroded from parts of this block when it was uplifted in the Late Permian. The tract has low potential for economic resources.

Central and Western Bando Trough
This tract has low potential because of seam deterioration through very high raw coal ash or a reduced seam thickness. In a zone trending E-W in the middle of the Trough, raw coal ash is very high and in the western end of this zone, channel deposits have replaced the seam. Along a zone trending N-SW, the seam is less than 2 m thick with raw coal ash in the 25% - 30% range. The coal resource in the tract has no foreseeable potential for mining.

Murrurundi Trough
This tract covers the Murrurundi Trough south to the Liverpool ranges. The coal lies at depths greater than 600 m. The coal resource in the tract has no foreseeable potential for mining.

Curlewis
This tract covers an area southwest of Gunnedah and adjacent to the Boggabri Ridge where the coal has been affected by igneous intrusions. This area has a low potential for future development.

Werrie Basin
This area has low potential for economic coal resources.

Hunter Coalfield from Scone south
This tract covers the deepest part of the Murrurundi Trough beneath the Liverpool Ranges and to the south towards Merriwa. The top of the Late Permian Coal Measures is deeper than 600 M. The tract has low potential for the economic development of the coal.

Northeastern part of the Northern Western Coalfield
This tract covers the northeastern part of the Northern Western Coalfield and contains all of the coal resources in the Ulan seam at depths greater than 600 m. The tract has low potential for future coal mining.

Purlawaugh Formation/Walloon Coal Measures and equivalents
This tract covers the Jurassic Purlawaugh Formation/Walloon Coal Measures and equivalents.
The formation contains discontinuous coal seams that are usually less than 0.5 m in thickness. The tract has low potential for coal mining.

8.6 COAL SEAM METHANE

8.6.1 General Discussion

In Australia most interest has focused on the Bowen - Gunnedah - Sydney basin system. It has been estimated that in the Bowen Basin (Queensland), the coal seam methane resources could be of the order of 3.5 trillion m^3 or 124, 000 PJ of energy (Oldroyd referenced in Brown et al., 1996). Weber and Bocking (1995) noted that the Sydney Basin might contain 130, 000 PJ of energy in coal seam methane. Brown et al. (1996) indicated that the methane resources of the Australian coalfields might be of the order of 10 trillion cubic metres. In 1996, values this would be worth about AUD$200 billion, at the then current gas price, assuming a recovery factor of 20% (Brown et al., 1996).

Between March 1998 and February 1999, the PEL 238 joint venture expended some $30 million on the drilling of 15 wells, the acquisition of 484 km of seismic data, two cavity completions and 7 hydraulic fracture stimulations (Morton, 2000). In 2000, wells at Bohena and Wilga Park, produced quantities of gas to the surface. Significant exploration activity has occurred elsewhere within the BBSB targeting equivalent, or similar, geological units.

As a measure of the potential economic benefits that might flow from this exploration and development, one estimate of the natural gas resources for Petroleum Exploration Licence 238 (covering approximately 9,500 km^2) has been put at over 35 trillion cubic feet (TCF) (Morton, 2000). Although this is not yet at a status of producible reserves, just 1TFC of gas reserves would supply, at current consumption levels, the entire Newcastle-Sydney-Wollongong gas market for approximately 10 years.

Gas reserve forecasts for csm are developed by the same analytical process as conventional reserves, with input from all critical data into a reservoir simulator that forecasts gas rates and reserves, over time. Utilising the measured reservoir parameters in the Bohena Project area the "Comet II" reservoir simulation forecast reserves of 5-12 BCF/well on a 240 acre (1 square kilometre) well spacing. Reserve variability reflects variations in coal thickness, permeability and completion effectiveness. Future programs will include drilling additional wells in the Bohena Project area and also focusing on the 15 anticlines identified on the recently acquired seismic data as sites for conventional oil and gas exploration. These newly identified anticlines will not only be preferred targets for conventional gas resources but also may locate coal seams with increased permeability.

The value of a CSM project is determined by both the size of the gas in place and the potential reserves (Mavor and Nelson, 1997). The Late Permian Black Jack Formation coal sequence and the Early Permian Maules Creek Coal Measures contain sizeable coal reserves. The size of the resource BBSB is potentially enormous. However, caution needs to be exercised because at this stage of exploration and production assessment it is not yet possible to quantify what percentage of the ultimate resource is recoverable.

Bohena Trough

Recoverable reserves of methane are controlled by many factors and it is first necessary to quantify the critical coal reservoir properties; coal thickness, gas contents, permeability and reservoir pressure. In the Bohena Sub-basin the Maules Creek coals are thick, very gassy, highly fractured with little or no mineralisation, highly permeable and over-pressured. Reservoir testing of Maules Creek coal seams indicates gas reserves of 5-12 BCF/well at depths less than 1,000 metres (Morton, 2000). Reservoir characterisation projects are being undertaken at both Bohena and Wilga Park areas.

Forcenergy (1999) reported that the Bohena Project area contains an average 16.2 to 21.6 m of coal over a stratigraphic interval ranging between 36.6 to 45.7 m in thickness. A basal seam varies between 4.6-12.2 m thick. Thirty three gas content measurements have been performed on Maules Creek coals. Gas content measurements are high with an average of 474 SCF/ton on a clean coal basis and 540 SCF/ton on a Dry-Ash Free basis (Morton, 2000). Bohena Project area gas-in-place calculated using these gas content measurements is 29 to 40 BCF/sq mile (2.56 sq km). Maules Creek coals were isolated for drillstem testing ("DST") during the recent drilling program. DST analysis calculated permeability of 18 md in Bohena-2 at a depth of 920 metres and 36 md in Bohena-3 at a depth of 887 metres. The high measured permeability is consistent with the highly fractured nature of coals that were recovered by coring and the high fracture intensity mapped with borehole images. Both wells were over-pressured with a pressure gradient of 0.48 psi/ft.

Five widely spaced wells were drilled and stimulated using different stimulation technologies. Two wells were completed open hole and treated using the dynamic cavitation method. Two wells were stimulated using a nitrogen foam hydraulic stimulation and two wells were hydraulically stimulated using a borate cross-linked gel. Post stimulation production varied between 200MCF/D and 100BWPD to 1.2MMCF/D and 350BWPD (Morton, 2000). Wells have been undergoing production testing and applications for the drilling of additional production wells are currently before the Department for approval.

Wilga Park wells encountered clean coal in the Maules Creek Coal measures ranging in thickness from 20.9-30.7 metres. Gas content measurements of Black Jack Group coal yielded 292 SCF/ton on a clean coal basis and 341 SCF/ton on a Dry-Ash free basis. There is no gas content data available for the Maules Creek Formation (Morton, 2000). Wilga Park Project area gas in place estimates quoted by Morton (2000) range between 12-19 BCF/square mile. Four CSM wells have been drilled at Wilga Park and two of these wells have been hydraulically stimulated using water and one well with nitrogen foam. The wells are currently undergoing production testing.

Csm gas occurrences and pilot testing at Coonarah, Bohena and Wilga Park establish the Permian coal seams of the Pilliga region of the Gunnedah Basin as having the potential to be a significant gas resource.

Similarities of the geology and burial depths and minor occurrences of gas in coal bores imply that the neighbouring, but the less well explored, Bando, Pilliga, Tooraweenah and Murrurundi Troughs are also likely to be sites for generation of csm.

With the current state of knowledge, the least prospective areas for both conventional oil and gas and csm is coincident with the structural axis of the Baradine High, which lies immediately to the south of the Pilliga Nature Reserve and West Pilliga Forest.

Although it is too early to quantify actual recovery rates and quantities, the csm gas accumulations may have the potential to provide the Newcastle-Sydney-Wollongong market for many years and so be of comparative size to the Cooper Basin reserves. Industry assessment is on going and although the commercial viability will depend ultimately upon the outcome of future production tests, there is a reasonable expectation that the exploration in the BBSB could yield significant economic benefits.

In the southern part of the BBSB the Late Permian coals reach maximum development in the Murrurundi and Bando Troughs where the principal targets are the Hoskissons Seam, Breeza Seam and Clift Seam, with the Caroona, Springfield and Melvilles seams considered sub-ordinate targets. The Maules Creek and Goonbri Formations are best developed in the deeper parts of the troughs.

Late Permian in the Bando Trough

The initial tests in this area have not been encouraging but are at a very early stage. Gas contents in the 9.7 m thick Hoskissons Seam range from 5 m^3/t in the higher ash upper four metres to almost 8m^3/t in the lower ash basal five metres, with methane levels peaking at 99%. Sorption isotherm tests indicate that the seam is undersaturated in gas by around 40%. High horizontal stress and very low permeability were experienced in the test hole.

Breeza Shelf and northern Yarraman – Bundella High

ACM Calala No 1 was drilled in November-December 1998 at a location approximately 9 kilometres south of Curlewis, with the aim of appraising the coal seam methane potential of Early Permian coal of the Maules Creek Formation. This site lies on the Breeza Shelf, an area of clastic sediment bypass in the Early Permian and with coal development in the order of 8 to 10 m occurring within a minimal depth interval. Aggregate Early Permian coal thickness of 9.9 metres in ACM Calala 1 is similar to adjacent holes. However, significant seam splitting has occurred even over the relatively short distance of 600 metres. Desorption testing was undertaken on drill chips (Black Jack Formation coals) and core (Maules Creek Formation coal). Black Jack coals were intersected at relatively shallow depths (less than 200 metres) and, as expected, were shown to be largely degassed. Maules Creek coals contained gas from 5.7 to 7.0 m3/t (dry ash free basis).

Although no sorption isotherms have been run on these coals, the low figures indicate a large degree of undersaturation. Methane content was indicated in the range 82 to 96%. Well testing was undertaken on one coal interval (497.3 to 499.6 metres) that indicated a relatively low seam permeability of 0.92 millidarcies. Early Permian coal was shown to have vitrinite reflectance values in the range 0.78 to 0.83%. Whilst the results from ACM Calala No. 1 do not enhance the potential for economic extraction of coal seam methane in this part of the Breeza Shelf area, such potential is in no way written off. At this stage however, additional drilling in the Breeza Shelf area has been postponed pending further assessment of results and additional interpretation of the regional geology.

Eastern and Southeastern flanks of the Murrurundi Trough

A region of enhanced permeability is suggested on the eastern and southeastern portions of PEL 1, which was partially evaluated by ACM West Quirindi-1, drilled to a depth of 652 metres. ACM West Quirindi-1 encountered thick Hoskissons seam, totalling 11.51 m, as well as thick Springfield (20.935m) and Clift (7.9 m) seams. Maturities range from 0.71% to 0.81% vitrinite reflectance with one anomalously higher value (1.47%) attributed to proximity of intrusive material.

Observed permeability in the Springfield interval was low, less than 1 md, whilst the Clift and Hoskissons seams were high to very high, 4 and 46 md respectively. A total of 47 coal samples were tested by gas desorption. Curiously the results suggested a progressive down-hole decrease in desorbable gas to zero for the Hoskissons seam. The Springfield Seam produced 1.5 - 3.5 m^3/t the Clift Seam 0.50 to 0.95 m^3/t and the Hoskissons - zero. This well raised the potential for the existence of an inverse relationship between gas content and seam permeability.

The well appeared to down-grade the csm potential of the southern part of the Mullaley Sub-Basin, although in subsequent reports "gas migration" or down-dip flushing by ground-water have been proposed as possible reasons for the absence of gas in the deeper, more permeable seams. Hence, these might be considered "conventional" reservoirs and have important ramifications for down-dip accumulations in this area of the Basin.

West Quirindi-1 well illustrates the potential for permeable Hoskissons Seam and possibility for migration or flushing of gas perhaps into dip-related structures under the influence of buoyancy, akin to conventional petroleum migration and observations in the Black Warrior Basin. However, it also highlights the exploration risk of having to locate gas-bearing coals in this region.

Western Flank of the Murrurundi Trough

Two wells, ACM Goodgerwirri 1 and Pine Ridge 1, were drilled to investigate the csm potential of the western flank of the Murrurundi Trough, where extrapolation from outcrops in the Caroona area through the West Quirindi well were predicted to provide for optimal coal development. ACM Pine Ridge-1 was sited between Goodgerwirri-1 and West Quirindi-1 on the northern extension of the New Windy Anticline. It penetrated almost 57 metres of coal, including nearly 20 m of Hoskissons seam, the thickest recorded in the Gunnedah Basin. Again, gas contents are low but permeabilities high. Mean gas contents of 1.6 m^3/t to 3.6 m^3/t, and permeability of 3 md at 750m were recorded. The Breeza Seam, comprising more than 9m of coal over three splits at a depth of around 633m, had a permeability of 1 md and gas content of 3.5 m^3/t.

In the Caroona area, the Department has been assessing future coal potential as part of a DMR/NEDO consortium. A total of 7 holes were evaluated as part of a collaborative agreement reached between this consortium and the ACM-PP joint venture. Seven holes were evaluated during 1996 and 1997, but gas contents were generally found to be low, between 2 and 3 m^3/t. However, two holes yielded very high permeabilities of 89 and 781 md for the Hoskissons and Breeza seams, respectively.

Southwestern Flank of the Murrurundi Trough

During 1995, Amoco Australia Limited drilled five wells to test the csm potential of the western Hunter Valley and the Denman-Sandy Hollow-Merriwa area. The wells intersected the Late Permian Coal Measure sequence at depth, but permeabilities were low, the seams were undersaturated, and there were high levels of CO2. The area covered by this drilling is very large and further work is required before a meaningful assessment of the csm resource can be made. The area is made more difficult by the thick basalts of the Liverpool ranges and by the high co2 contents that are sometimes associated with intruded coal.

8.6.2 Coal Seam Methane Tracts (Figure 59)

Tract CSM a/H/B-C

Bohena Trough-Narrabri High

This tract covers the Bohena and Wilga Park areas and has high potential in the thick coal measure sequences with good permeability.

Tract CSM b/M-H/B-C

Bellata Trough

The Late Permian Blackjack Group has been removed from most of the trough by erosion. The thick section of Maules Creek and Goonbri Formation sediments has a moderate to high potential for csm.

Murrurundi trough flanks

The testing by Amoco Australia Pty Ltd south of the Liverpool Ranges was not totally favourable. Csm assessment is at such an early stage that it is not possible to downgrade potential resources. Further exploration is being conducted to define areas with high gas contents and good permeabilities. This tract has a moderate to high potential. Areas of Black Jack Group deeper than 1000m in the central parts of the Murrurundi Trough have a lower potential, but these have not been defined.

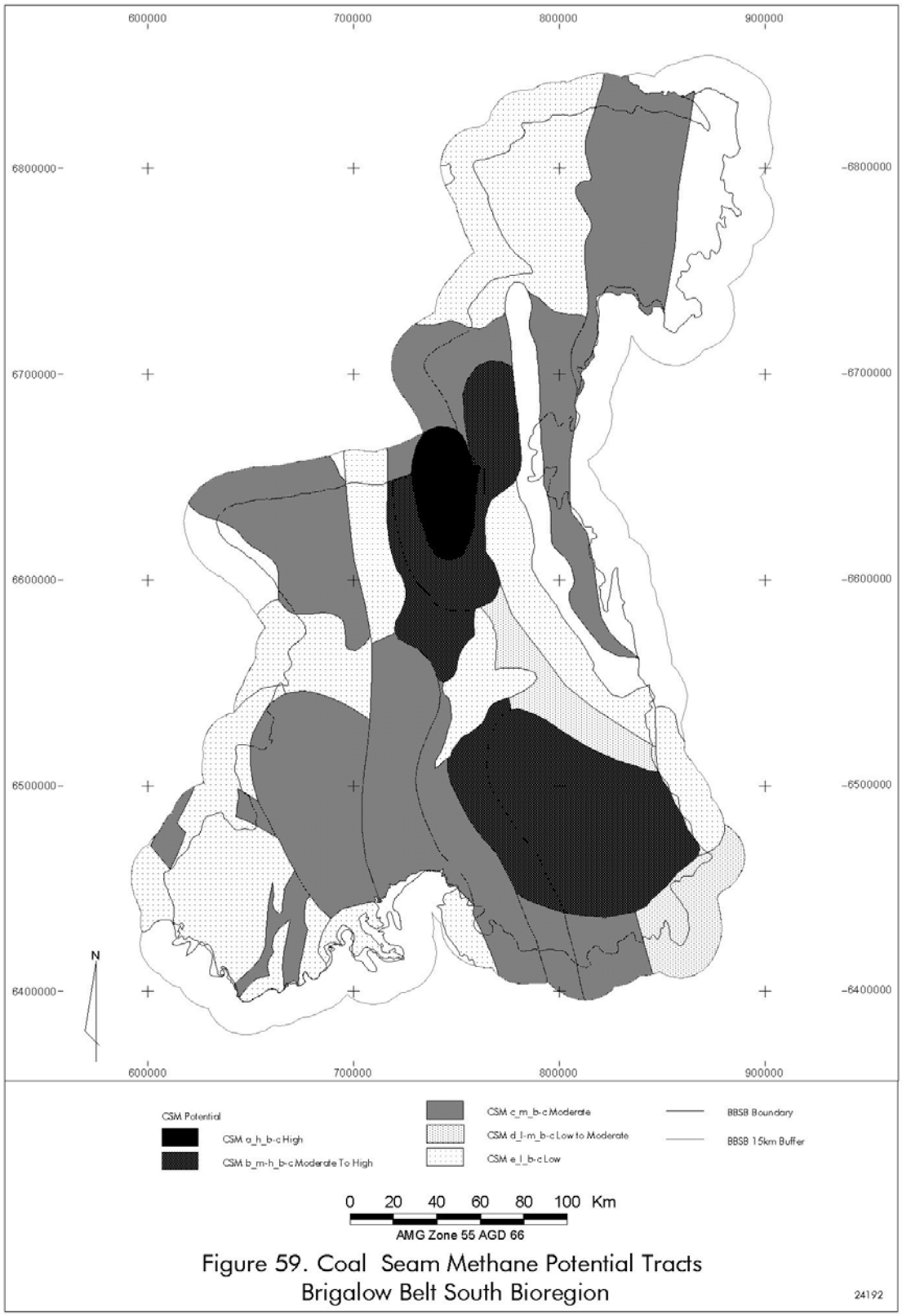

Figure 59. Coal Seam Methane Potential Tracts
Brigalow Belt South Bioregion

Tract CSM c/M/B-C

Maules Creek Sub-basin

The Maules Creek Sub-basin has moderate potential for csm close to the Hunter-Mooki Fault System.

Pilliga Trough

There is no data on the sequence in the deepest part of the Pilliga Trough. If both Early Permian and Late Permian coal measures exist then there is a moderate potential for csm.

Bando trough

This tract includes the Early and Late Permian coal measures at depths greater than 500 m and has a moderate potential for csm.

Tooraweenah trough

There is moderate potential for csm in the Maules Creek Formation and the Blackjack Group in the deepest part of the trough.

Rawdon Ridge

The Rawdon Ridge has moderate potential for csm.

Tract CSM d/L-M/B-C

Yarraman and Bundella High

The Maules Creek Formation does not occur over most of the tract. The Blackjack Group contains less coal than in the east and the seams are at depths of 200 to 500 m. The tract has a low to moderate potential for csm.

Tract CSM e/L/B-C

Gunnedah-Bowen Basin

This tract includes the Boomi Trough and the Bowen Basin east flank where the coal measure sequences are generally deeper than 1000 m and therefore have limited potential for csm.

8.7 PETROLEUM

8.7.1 General Discussion

The following assessment of the petroleum resource potential of the BBSB follows Upstream Petroleum Consulting Services (2002a, 2002b, and 2002c), and Vanibe (2000). Sedimentary sequences of the Sydney-Bowen and Surat Basins cover most of the Brigalow Belt South Bioregion area. Petroleum has been discovered within these basins in Queensland, to the north of the BBSB boundary, and within the BBSB itself, at Coonarah and Wilga Park. Numerous gas and one oil show have been reported in other wells drilled in the area and a surface seep has been reported north of Coonabarabran (Rolls, 1981).

Exploration in Queensland has identified significant hydrocarbon accumulations in reservoirs ranging in age from Permian to Early Jurassic. The largest of these deposits, and the first commercial oil field discovered in Australia is the Moonie Oil Field, which was discovered in 1961 and contained original recoverable reserves of 0.3 x 10^6 kL (Elliot and Brown, 1988).

The major producing horizons identified in the Surat and Bowen Basins are:

- Early Jurassic Evergreen Formation sandstones.
- Early Jurassic Precipice Sandstone.
- Middle Triassic Showgrounds Sandstone.
- Middle Triassic Moolayember Formation sandstones.

Permian sandstones also host gas where the sandstones have sufficient reservoir quality, such as in the Cabawin Gas-Condensate Field and Wallumbilla South Gas Field (Thomas et al., 1982).
Excellent reservoir potential exists in the Hutton Sandstone, although only one commercial discovery from the base of this unit has been made in Queensland.

In the Pilliga area within the Bioregion, a DST of sands within the Late Permian Porcupine Formation at Wilga Park-1 flowed gas at a rate of 1.0 MMCFD (Morton, 1995). The gas is dry and this may reflect local conditions of the main gas reservoir having been intruded by a 6m thick diorite sill. Conventional gas was discovered within Early Triassic clastics of the Digby Formation at a depth of 473 m by the Coonarah-1 and 1A wells. A minimum 37 m gas column was intersected with no gas-water contact encountered. Seismic mapping indicates a maximum vertical closure of 47 metres. Coonarah-2, located 1.8 km northeast of Coonarah-1 and 1A, intersected a gas filled but tight Digby Formation and recovered a small amount of gas from the underlying Late Permian Black Jack Group. Post-Coonarah-2 reserve estimates indicate potential for sufficient gas in both the Black Jack and Digby formations to be economic (Forcenergy, 1999). High helium and nitrogen contents are also of commercial interest.

These hydrocarbon occurrences demonstrate that the sedimentary basins in the BBSB are active petroleum systems with a number of potential producing horizons. It should be emphasised that the relatively low level of knowledge about the Basins and the small number of discoveries reflects the low historical levels of exploration rather than the intrinsic prospectivity.

8.7.2 Gunnedah-Bowen and Surat Basins

To the north of Moree, petroleum exploration has concentrated on locating and testing the known producing reservoir horizons found in Queensland. These are also present within NSW although the Jurassic sequence thins to the south with basal onlapping and pinching out restricting the extent of the reservoirs.

The Early to Middle Permian Back Creek Group sediments generally have poor reservoir potential with low porosities (less than 10 percent) and low permeabilities (1 millidarcy) due to the lithic and argillaceous composition of sandstones. Reservoir quality sandstones, which host gas fields in the northern part of the Bowen Basin, are found in fluvial-deltaic sediments of the Aldebaran Sandstone and surrounding formations (Morton et al., 1993). Late Permian Back Creek Formation sandstones intersected in Limebon-1 and Goondiwindi-1 have excellent reservoir potential, and have been compared to these Aldebaran Sandstones.

Although these sandstones have been recognised as such by previous operators they have not previously been specifically targeted. These sandstones were derived from Late Carboniferous Early Permian felsic volcanic rocks of the New England High and although they have a high gamma ray signature, they have good reservoir characteristics (Moreton, 1995). The sandstones form part of a large northwesterly prograding deltaic sequence and comprise both marine and non-marine sediments which contain 200m of sand encased within marine shale and siltstones at the Limebon-1 location (Sherwood et al., 1995). They may have been deposited along an easterly margin of the basin, and east of the Gil Gil Ridge.

The Triassic Showgrounds Sandstone is productive less than 80 km north of the NSW- Queensland border and has been targeted by exploration, especially during the 1980's. Generally, however, good quality sands were not encountered within this unit. In Queensland drilling experience indicated that depositional patterns show strong facies and paleo-topographic control. The formation is known to have a westerly provenance and therefore reservoir quality sandstones were deposited mainly in the western portions of the basin. The distribution of Showgrounds Sandstone in the NSW part of the basin is poorly understood due to the paucity of subsurface control.

Low reservoir potential is encountered in the Triassic Rewan Group and the Moolayember Formation in NSW. Extensive silicification accompanied by alteration of clays has lowered original porosities and permeabilities. Both units act as regional seals and strongly influence the distribution of hydrocarbons in the basin.

The Precipice Sandstone and Evergreen Formation thin from Queensland into NSW, eventually onlapping to the south. Good to excellent porosities are found in the former, ranging from 15-30% (Stewart and Alder, 1995). The Evergreen Formation becomes very sandy in a southerly direction,

eventually merging with the Precipice Sandstone. Both formations are excellent reservoirs although as an exploration target their distribution is limited to the very northern part of the basin in NSW. Stewart and Alder (1995) noted good to excellent porosities ranging from 15% to 20% are found in the Precipice Sandstone. Sandstones in the Evergreen Formation encountered in Macintyre-1, Goondiwindi-1 and Limebon-1 range in thicknesses up to 18 m for individual beds.

The Hutton Sandstone, which is a major hydrocarbon-producing reservoir in the Eromanga Basin in SW Queensland, is a major exploration target in NSW. Very few structures have been mapped at the top of the Hutton Sandstone level and therefore petroleum traps are difficult to locate. However, The unit laps onto and is pinched out against the highs to the south and it forms potentially large structural/stratigraphic traps with direct access to mature source rocks within the more deeply buried parts of the basin to the north.

The Late Jurassic Pilliga Sandstone is a widespread, excellent quality, quartz sandstone reservoir although lack of a top seal limits its exploration potential. The highest level of porosity for the sedimentary sequence is the Hooray/Mooga Sandstone interval and its equivalents. These units are the major aquifers for water production within the basin and they are known to be excellent quality reservoirs from water bore control. They are also major exploration targets.

Available Total Organic Carbon analyses indicate that the most organic rich facies are the Cretaceous Bungil formation, Jurassic Orallo and Evergreen Formations, Triassic Wandoan Formation and Permian Back Creek/Maules Creek formations. Other organic rich stratigraphic intervals, such as the Walloon Coal Measures are also present. Vitrinite reflectance data indicates that the Jurassic succession is immature with mean reflectance of less than 0.50%. The Triassic section is however marginally mature, and the Permian is marginally mature to mature. Igneous bodies intruding Permian and Triassic rocks have locally heated source rocks past their regional levels.

Maturation modelling indicates that the early to Middle Jurassic success would enter the main phase of hydrocarbon generation at about 2000m depth of burial. The Jurassic succession only acquires such thicknesses in Queensland. Basal units, such as the Evergreen Formation, only reach “early oil maturity” in the central part of the Surat Basin in Queensland (Thomas et al, 1982).

The work of Thomas et al. (1982) and Boreham (1995) identified Permian rocks as the source for both liquid petroleum and natural gas. The observed oil window for the Permian sediments is between 0.7% Ro and 1.3% Ro with peak generation at 0.9-1.0% R_o. According to Sherwood et al. (1995), there is considerable potential to generate liquid petroleum and this is supported by the general abundance of vitrinite and liptinite in the Late Permian sediments. Nevertheless, the Early Permian sediments contain predominately vitrinite to inertinite maceral types indicating that this sedimentary section is more likely to generate gas.

Triassic and Jurassic sediments tend to be more liptinite-rich than the Permian sediments and would probably yield oil and gas, although pyrolysis results are not always favorable. Liptinite rich source rocks occur in the lower part of the Moolayember Formation and particularly in the Snake Creek Mudstone. Liptinite-rich organic matter also occurs in the Evergreen Formation and Walloon Coal Measures that are good oil source rocks although, in the New South Wales, these sediments are at low levels of maturity.

Seals exist for most of the potential reservoir intervals. Early Permian Back Creek Group reservoirs are interbedded within marine shale seal. The Triassic Showground Sandstones is overlain by the Snake Creek Mudstone and the Moolayember Formation, which forms a regional seal. In Queensland, the Evergreen Formation forms a seal for hydrocarbons in the Precipice Sandstone. However, towards the limits of the Precipice Sandstone in New South Wales, the Evergreen Formation is sandy and forms a questionable seal.

The Hutton Sandstone is effectively sealed by the Walloon Coal Measures. The Pilliga Sandstone is sealed by the Orallo Formation, however, increased sandstone content in the Orallo Formation towards its depositional limits reduce the integrity of this seal. The Mooga Sandstone is sealed by shales of the Bungil Formation.

The Moonie Oil Field in Queensland is formed by an anticlinal structure within the Jurassic sedimentary section. Subsequent exploration has shown that the Moonie structure is unique and it is unlikely that similar large-scale structures will be found in Queensland or NSW.

The main features of traps in the Surat and Bowen Basins consist of one or more of the following components:

- Compactional draping of sediments over basement highs.
- Wrench faulting.
- Reversal of pre-existing normal faults.
- Stratigraphic pinch-outs on gently sloping flanks of basement to the west of the Bowen Basin.

Structural traps host the major plays discovered so far in the Surat Basin. Exploration is now directed to finding stratigraphic/structural and stratigraphic traps as little remains to be discovered from conventional structural plays, at least in the Queensland part of the basin. Many of the wells drilled in New South Wales may have been drilled off structure since they were based on early vintage seismic data. This has become apparent through more recent compilations of the earlier drilling and seismic data. As such, many structures remain untested in the New South Wales portion of the Surat Basin.

Shaw (1995) recently defined an underthrust play in southern Bowen Basin (NSW) whereby impervious basement rocks are juxtaposed against Back Creek Group reservoirs. Xylex-1, in Queensland, intersected oil in the Hutton Sandstone east of the Moonie-Leichhardt Fault indicating that underthrust plays may not just be confined to Permian sequences. Morton et al., (1993) suggested that folding has occurred between the Gil Gil Ridge and the Goondiwindi-Moonie Fault during compressive events associated with the faulting. According to these authors, the Gil Gil Ridge formed an incompressible barrier during the Late Permian to Middle Triassic east-west compression.

Basement in the western part of the Surat Basin exhibits considerable relief. Linear north-south basement trends are anticipated in this area and compactional drape of sediments over these highs has potential to form trapping structures. Onlap of Jurassic reservoirs onto basement highs may also provide stratigraphic traps, although the potential for hydrocarbons is made reduced by the restricted access of these reservoirs to exposed migrating hydrocarbons.

Sherwood et al. (1995) identified the following petroleum systems:

- Back Creek Formation reservoirs, sourced by petroleum from laterally equivalent marine shales and siltstones, sealed by overlying Back Creek Formation lacustrine shales and trapped in anticlines formed by either Late Permian or Middle to Late Triassic folding and faulting.
- Showgrounds Sandstone reservoirs, sourced by petroleum from underlying Back Creek Formation marine shales/siltstones and /or Late Permian Coal Measures and the directly overlying Snake Creek Mudstone, sealed by the overlying Snake Creek Mudstone, the main trap type is anticlines and faults formed by Middle to late Triassic compressional deformation.
- Precipice Sandstone reservoirs with petroleum sourced from underlying Permian/Triassic sediments or overlying Evergreen Formation sediments; traps are of two main types, formed either structurally, or late Early Jurassic and /or late Cretaceous-Early Tertiary compressional faulting and folding or, stratigraphically by onalp along the southern margin of the basin.
- Hutton Sandstone reservoirs with petroleum sourced from underlying Permian, Triassic and Jurassic sediments, traps are of two main types formed either structurally, by Late Cretaceous – Early Tertiary compressional faulting and folding, or stratigraphically, by onlap along the southern margin of the basin, north of the Moree High.
- Mooga/Hooray Sandstone or its equivalents, sealed by the Wallumbilla Formation shales and sourced by underlying Permian sediments located in graben remnants or from thermally mature Jurassic or older sediments by long range migration from deeper parts of the basin in the north; traps are anticlines and faulted caused by Late Cretaceous-Early Tertiary compressional deformation.

8.7.3 Sydney-Gunnedah and Southern Surat Basins

Significant gas occurrences have been discovered at Bohena, Wilga Park and Coonarah within the Bohena Trough. All of the troughs within the Sydney-Gunnedah Basin contain similar thick sections of Permian sediment with Early and Late Permian coal measure sequences. They also share many of these geological elements considered pre-requisite for hydrocarbon occurrences.

One of the key factors that has emerged for conventional oil and gas exploration in the Sydney-Gunnedah Basin is recognition of the importance of sediment provenance in controlling reservoir potential. Previous drilling established that sediments derived from the east, sourced from the New England Fold Belt, tend to be clay rich, resulting in poor reservoir potential. In contrast, sediments shed from the Lachhlan Fold Belt tend to be quartz rich and generally display good reservoir quality (Stewart and Alder, 1995, Morton, 1995, and Pratt, 1998). Sandstones within the Late Permian Brigalow and Clare Formations and the early Triassic Wollar Sandstone Member of the Digby Formation are considered the most prospective (Pratt, 1998). Reservoir potential of easterly-derived sandstones is usually associated with reworked sediments that have been cleaned in a marine environment such as the upper Watermark Formation and the lower Black Jack Group (Pratt, 1998).

The Brigalow Formation was found to have typical porosities of 15-20% and good permeabilities, up to 5.1 Darcies. The unit occurs across the western part of the Basin with the sandstones up to 20m thick (Hamilton, 1987). The Clare Formation is more extensively deposited across the Tooraweenah Trough and the Mullalley Sub-basin, thickening into the Murrirundi Trough and its eastern margin. Net sandstone thicknesses average between 10 and 14 m. The upper Watermark and lower Black Jack Formations have porosities of 15% and 16-18% with permeabilities of 4.6-9.6 md and 5.9-31.3 md. Individual sands may be up to 12m thick and Hamilton (1987) showed that net thicknesses increase in the southeast along the faulted eastern edge of the Basin.

The Triassic Wollar Sandstone Member displays excellent reservoir properties. Porosity values range from 13.3% and permeabilities range between 14-719 md. Permiability is best developed in the west and decreases in the southeast due to mixing with easterly-derived volcano-lithic detritus. Conventional gas was discovered within the Digby Formation at a depth of 473 m by the Coonarah-1 and 1A wells. A gas saturated sandstone has also been intersected within the Jurassic Purlawaugh Formation in the north near Bellata. In the Southern part of the area, however, the Purlawaugh Formation is more likely to function as a seal because the lithologies change largely to siltstones and claystones.

Assuming a 300,000 SCF/Acre-FT recovery factor for conventional gas and adopting a 20ft thick net pay interval (within the combined Porcupine, Black Jack and Digby units) this equates to a 4,000,000 SCF per acre of net pay. This equates to 1.5 BCF of gas per sq km of trap. For oil, using standard parameters, a conservative recovery of 150 barrels equivalent per acre ft is anticipated. Assuming a 20ft net pay interval this equates to 3000 barrels per acre of trap, or 750,000 barrels per sq km. Individual volumetrics will obviously vary depending upon specific reservoir parameters. For example at Coonarah a thicker pay is indicated and reserves have been estimated at between 15 and 40 BCF (Mullard, 1999).

All potential reservoir horizons are considered to have an adequate top seal. Deltaic deposits in the lower part of the Black Jack Formation comprise relatively thick (up to 15m) and laterally extensive claystone and siltstone sequences. These sequences provide adequate intra-formational seals for potential reservoirs in the underlying distributary mouth bar and barrier beach sandstones of the upper Watermark Formation.

The Hoskissons Coal overlies the Brigalow Formation over most of the Basin. The shales and coal represent a good regional seal for potential reservoirs within the sandstones. The coals and tuffs of the Trinkey Formation form a good regional seal over the Clare Formation sandstones. The Digby Formation reservoirs are overlain by the basal part of the Napperby Formation, a regionally extensive lacustrine shale up to 40 m thick.

The source potential of sediments within the Basin sequence has been assessed by Hamilton et al (1988), and more recently by Boreham et al (1995). Oil generation occurrs within a window where vitrinitie reflectance ranges between 0.7% and 1.3%, with the main source rocks being Permian terrestrial sediments with minor contributions from marine-influenced source rocks. Generally the Triassic is too immature to contribute to source potential. The best potential source rocks are floodplain, lacustrine, and shallow marine facies of the Purlawaugh, Napperby, Watermark, Maules Creek, Blackjack and Goonbri Formations. However, only the Permian sequences are likely to be sufficiently mature.

There have been a number of extensive studies of the rank of coals within the Gunnedah Basin, including Gurba and Ward (1998 and 1999), and Gurber and Weber (1999). These studies were based mainly on borehole data from the Mullaley Sub-basin. Vitrinite reflectance levels of the Permian coals range between 0.6 to 1.0% with coal rank increasing in the southwestern part of the area, a trend which is

somewhat counter to present depth and burial thickness trends of the coal-bearing Permian strata. The origin for this is not known but may be related to deeper burial and subsequent uplift associated with deposition and erosion of the overlying Surat Basin, or it may be a result of variations in geothermal gradient, perhaps generated by basement features, including the presence of granites recently identified by Gunn (2002a).

Whilst the measured vitrinite reflectance indicates maturities consistent with oil generation some anomalous trends with depth have been observed. The main causes of such vitrinite anomalies are, variations in organic and mineral matrix, marine influence on coal seams, and igneous activity and local variations in heatflow.

The Bioregion has been subject to not only elevated heatflow at the time of the initial Early Permian crustal thinning and graben formation, but also the subsequent high heat flows during the implacement of the Jurassic Garawilla and Tertiary volcanics. This is significant because local heating may well have played a critical role in providing gas generation within the Coonarah Field area. The Permian coals within the depocentres may be within the oil and gas window of maturation, notwithstanding their nominally relatively shallow depths of burial.

A number of structures have been identified which may provide adequate trapping potential to accumulate hydrocarbons, providing they have access to migrating hydrocarbons, suitable seal and reservoir. A number of fold axes have been mapped on the eastern side of the Mullaley Sub-basin. These include the south to southwest plunging New Windy, Caroona, Tribella, Watermark and Curlewis anticlines and associated synclines. In the Gilgandra Sub-basin, the Early Permian grabens containing thick flood plain sequences are an obvious target.

8.7.4 Conventional Petroleum Potential Tracts (Figure 60)

Tract a/H/B

Eastern Flank of Bowen Basin

This tract represents one of the most prospective in the region. Lying between the Gil Gil Ridge and the thrusted margin of the Moonee-Goondiwindi Fault, this tract is believed to contain mature source rocks. Hydrocarbons generated within the Reids Dome Beds and the lower Back Creek units may have migrated up-dip to the west, where there are a number of compressional anticlines identified, trending north-northwest. Additionally, hydrocarbons may have migrated across the eastern flank of the Gil Gil Ridge where a number of anticlinal leads had been identified. These anticlines often have vertical relief much larger than the current targets sought in southeast Queensland. Additionally, they existed prior to hydrocarbon generation. The anticlines may contain thick good quality sandstone reservoirs. Prospects could be of the order of several hundred BCF.

Boomi Trough

This is the deepest area of the Bowen Basin developed in NSW. One well, Macintyre-1 established that the Reid Dome Beds are mature source rocks. The lacustrine source rocks of the Goonbri Formation may not be extensively developed (Totterdell and Krassay, 1995). Seismic mapping indicates that Early Permian rocks lap onto the rapidly shallowing basement to the south, and deposition is probably confined to the area north of latitude 29°S. Basement in this region is thought to comprise the Boggabri Volcanics and its equivalents.

There is little seismic control, but a number of fault-related tilted basement blocks, with overlying drape compactional closure, are anticipated. Gunn (2002a) interpreted a northwest structural trend which may also have associated structural closures. Additionally, stratigraphic pinchout closures may be anticipated within units of the Reids Dome Beds, the Maules Creek Formation, and the Back Creek Formation to the south. The best potential in this area are marine reworked sandstones, equivalent to the Watermark and Porcupine Formations, or quartz sandstones derived from the west, such as the Brigalow Formation.

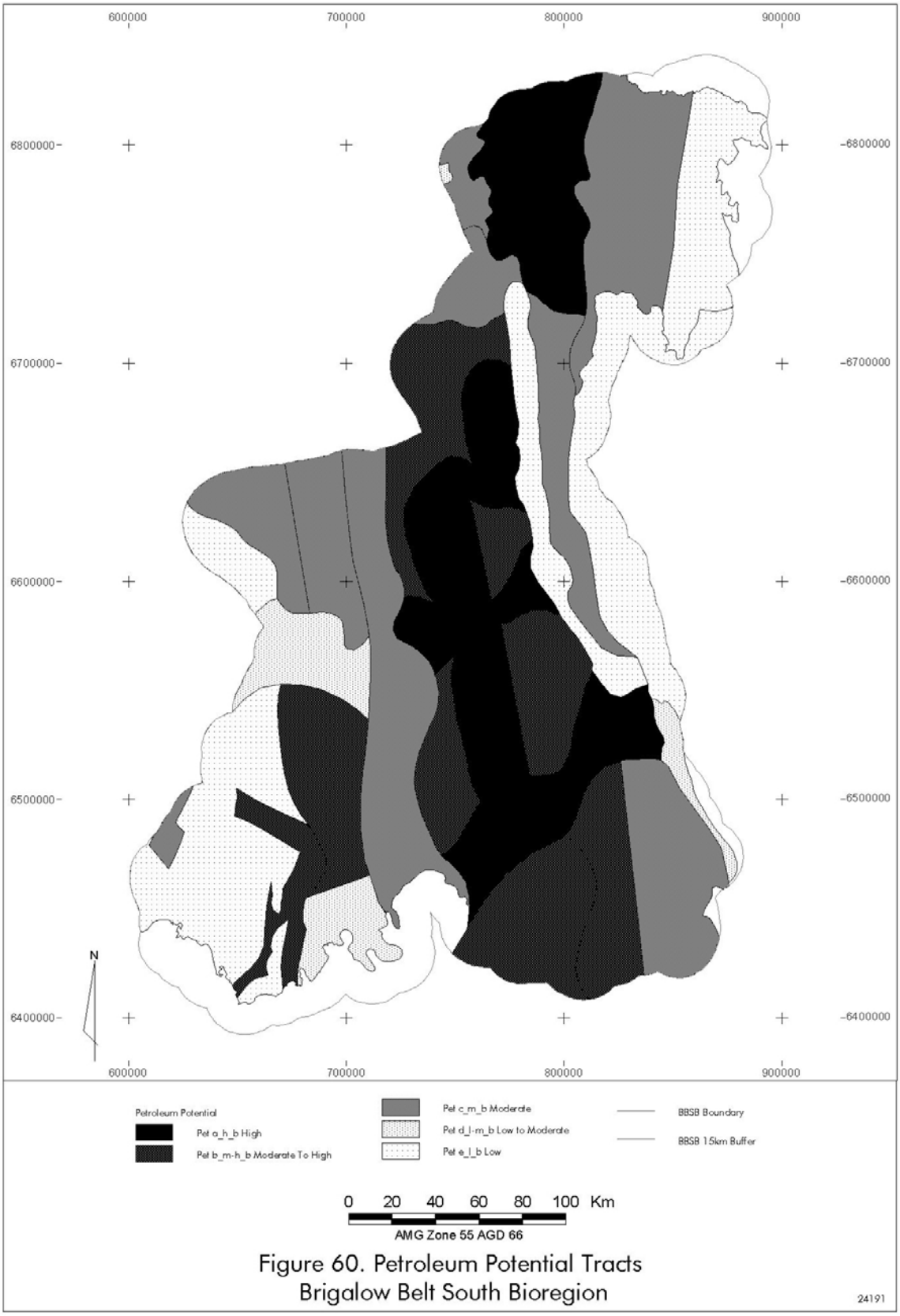

Figure 60. Petroleum Potential Tracts
Brigalow Belt South Bioregion

Possible Evergreen and Precipice reservoirs exist, however these require access by breaching of the underlying regional seals (Rewan Group, Snake Creek Mudstone, and Moolayember Formation) in order to allow vertical migration of hydrocarbons up from the Permian source rocks.

Bellata Trough East Flank

This tract encompasses the eastern flank of the Bellata Trough and the western side of the Boggabri Ridge (locally referred to as the Moema High). East of the synclinal axis, hydrocarbons generated within this Trough would migrate under the influence of buoyancy into westerly plunging noses and tilted basement fault blocks on the shallowing basement to the east. Southerly migrating hydrocarbons may also charge structures on the eastern portion of the Narrabri High. Portions of this tract may be adversely impacted by shallow intrusives.

Bellata Trough West Flank

This tract encompasses the western flank of the Bellata Trough and the eastern flank of the Wee Waa Shelf. Regional geological cross-sections confirm that the Maules Creek Formation and Back Jack Group thin towards the west onto the shelf. Westerly derived quartz rich sandstones within the Brigalow Formation, Clare Sandstone and Upper Digby Formation are anticipated to provide the principal reservoir targets.

Narrabri High

This tract covers the Narrabri High separating the Bellata and Bohena Troughs and is the location of the Wilga Park and Coonarah hydrocarbon discoveries. The occurrence of gas at these localities attests to the presence of an active petroleum system within the Bohena Trough.

Bohena Trough West Flank

This tract encompasses the western flank of the Bohena Trough and the eastern flank of the Rocky Glen Ridge. Regional geological cross-sections confirm that the Maules Creek Formation and Back Jack Group thin towards the west onto the Rocky Glen Ridge. Easterly plunging structural noses, and fault related tilted basement blocks are known to provide valid traps in the easterly portion of the tract. Westerly derived quartz rich sandstones within the Brigalow Formation, Clare Sandstone and Upper Digby Formation are anticipated to provide the principal reservoir targets.

Bando Trough West Flank

This tract encompasses the western flank of the Bando Trough and includes the eastern projection of the Baradine High and the Weetaliba Shelf. The prospectivity is predicated on the presence of an active petroleum system within the Bando Trough. West of the synclinal axis generated hydrocarbons would migrate up-dip to the west under the influence of buoyancy. Onlap of sands across shallowing basement, together with faulted basement blocks and drape over easterly plunging structural noses constitute the main trapping targets in this area. Objectives would be sought within the Porcupine, Black Jack and Digby units, especially those quartz rich units derived from the west.

Walla Walla Ridge

This Tract is a northeast trending basement high with significant hydrocarbon potential because it can receive hydrocarbons from the adjacent Bohena and Bando Troughs. This high is interpreted to have faulted margins that would assist vertical migration up into otherwise relatively immature portions of the section. Crestal anticlinal traps associated with folding, especially towards the eastern margin are likely to be structural targets for future exploration. This tract is similar to the Narrabri High, the location of the Coonarah Gas Field.

Bundella and Yarranan Highs

This Tract is a northeast trending basement high zone considered to have significant hydrocarbon potential because it can receive hydrocarbons from the adjacent Bando and Murrurundi Troughs. Across the eastern part, a 50m thick upper Watermark Formation has been mapped. In the central part, the upper Black Jack Group net sand thicknesses exceed 70m

This high is interpreted to have faulted margins that would assist vertical migration up into otherwise relatively immature portions of the section. Crestal anticlinal traps associated with folding, especially towards the eastern margin are likely to be structural targets for future exploration. A number of these have already been identified, mainly from coal mapping at Nea, Clift, Sprinhurst and Watermark. Cross-strike structural partitioning of this trend is anticipated on the basis of northwest trending lineations interpreted by Gunn (2002b). This tract is similar to the Narrabri High, the location of the Coonarah Gas Field.

Tract b/M-H/B

Wee Waa Shelf

This tract covers part of the Wee Waa Shelf and the northern extension of the Rocky Glen Ridge. The prospectivity is predicated on the presence of an active petroleum system within the Bellata Trough. West of the synclinal axis, generated hydrocarbons would migrate up-dip to the west under the influence of buoyancy. Onlap of sandstones across shallowing basement, together with faulted basement blocks constitute the main trapping targets in this area. Objectives are the Black Jack and Digby units, especially those quartz rich units derived from the west.

Bohena Trough East Flank

This Tract encompasses the eastern flank of the Bohena Trough and western side of the Boggabri Ridge. Hydrocarbons may have migrated to the east out of the Bohena Trough, under the influence of buoyancy. Onlap of sands across shallowing basement, together with faulted basement blocks and drape over westerly plunging structural noses constitute the main trapping targets in this area. Objectives would be sought within the Porcupine, Black Jack and Digby sequences, especially those quartz rich units derived from the west.

Bando Trough East Flank

This tract encompasses the eastern flank of the Bando Trough and includes the southwestern flank of the Boggabri Ridge. The prospectivity here is predicated on the presence of an active petroleum system within the Bando Trough. East of the synclinal axis, generated hydrocarbons would migrate up-dip to the east under the influence of buoyancy. Gravity data suggests a relatively steep margin with the likelihood of strong dip controlled migration up the flanks of the Yarranan and Bundella Highs. Onlap of sands across shallowing basement, faulted basement blocks, and drape over southwesterly and southeasterly plunging structural noses would constitute the main trapping targets in this area.

There area number of basin-deep folds to the south, including the Curlewis Anticline and anticlines near Howes-1 and Calala-1. They appear to be systematically developed between northwest trending thrust fault segments projecting across the basin, from the thrust faulted eastern margin. This association is similar to the Wandoan Oil and Gas Field of the Surat and Bowen Basins in southern Queensland where similar structuring occurs off the northern extension of the Mooki Fault. Reservoir objectives are the Porcupine, Black Jack and Digby Formations. Net sand thicknesses of the Clare Sandstone Member in this area are between 30 and 60 m, whereas reworked marine sandstones of the upper Watermark Formation range between 10 and 30 m thick across most of the area.

Eastern and Central Tooraweenah Trough

This tract encompasses the northern and eastern flank of the Tooraweenah Trough together with the southern flank of the Baradine High. Prospectivity is predicated on the presence of an active petroleum system within the Tooraweenah Trough. North of the synclinal axis, generated hydrocarbons would migrate up-dip northwards under the influence of buoyancy into the surrounding highs. Traps are envisaged to involve southern plunging noses, and drape over undulations along the flank of the Baradine High. A stratigraphic component, with pinchouts onto shallowing basement, is envisaged. Target reservoirs are anticipated within the Black Jack and Digby units.

Murrurundi Trough West Flank

This tract encompasses the western flank of the Murrurundi Trough and adjacent Wollar Shelf. Much of the deeper portions of the trough are masked beneath significant thickness of basalts, making future exploration difficult. However, the basalts are a source of elevated heatflow. Across the eastern portions,

the Clare Sandstone Member is up to 30m in thickness This unit also being mapped as subcropping onto shallowing basement across the Dunedoo High. Although not mapped specifically across the Wollar Shelf, a similar fluvial system may have developed associated with granite outwash off the adjacent hinterland now forming the Capertee High. In the absence of any detailed control, gravity trends suggest this flank would be strongly controlled by dip-related migration out of the adjacent Trough. A number of northeast trending structural noses are implied in the gravity anomaly trends. These would form potential targets for locating closed structural highs on the plunging edges of these noses.

Tract c/M/B

Moonee-Goondiwindi Fault Margin

A very large trap has been identified on the downthrust side of the Mooni-Goondiwindi Fault where the Back Creek Sandstone reservoirs may be sealed to the east against Basement of the New England Fold Belt. Structural closure is predicted with rollovers to the west, south and north. It is similar to other possible traps further to the south, adjacent to the Maules Creek Sub-basin. Other possible traps could be heavily fault dependent, involving tightly folded imbricate sheets along westerly and northwesterly trends. This could lead to a considerable enhancement of total thickness of the Maules Creek and older section below the Moonee-Goondiwindi Fault System due to duplication of the section. Fracturing in the crests of hanging wall anticlines may have developed leading to the enhancement of porosity and permeability of the rocks (Beckett et al., 1995).

Vertical migration up the thrust faults may also provide access into overlying Surat Basin reservoirs, although the trapping potential of the Surat sequence in this setting has yet to be ascertained. Reworked marine sediments of the equivalent Porcupine and Watermark formations are anticipated to provide the best primary reservoir potential.

Western Margin of the Bowen Basin, (Western Shelf, Yarradine High and Boomi Nose)

Hydrocarbons are anticipated to have migrated from the adjacent Boomi Trough, to the pinchout edge of Permian sediments and into the overlying, shallower and better quality Triassic and Jurassic sedimentary rock cover. The region is probably underlain by granites and as such is considered to be too shallow to have generated hydrocarbons. However, local generation could be associated with hot spots arising from intrusions as is possible at Coonarah and Bellata.

The Showgrounds Sandstone is in direct communication with the Kianga Formation due to the absence of the impermeable Rewan Group sediments (OCA, 1985). Secondary objectives in the Showgrounds Sandstone may be encountered beyond the limits of the Kianga Formation, towards the zero edge of the Showgrounds Sandstone where stratigraphic traps may occur.

During the 1980s, wells such as Pearl-1 Boomi-1, Glencoe-1 were drilled to test structural closures resulting from the drape of younger sediments across basement topographic highs, with reservoir objectives in the Showgrounds Sandstone and Hutton Sandstone. The Showgrounds Sandstone has been a main reservoir target. Testing has been unsuccessful for three reasons:
Lack of four-way closures at the Showgrounds level.
Lack of reservoir. Either the Showgrounds sandstone was absent or, alternatively, it was poorly developed, thin and tight. Effect of igneous intrusions. Many wells have been sited on low relief closures, possibly with critical closure created by Tertiary aged igneous intrusions. These probably post-date hydrocarbon generation and migration.

The Evergreen Formation and Precipice Sandstone contain good to excellent quality reservoirs. These may also have been sourced from the Permian in the adjacent Boomi Trough via fault conduits or updip migration. The increased sand content of the Evergreen Formation towards its depositional limits reduces the potential for intraformational seals. However, migration of hydrocarbons into the Hutton Sandstone may be possible. Late Early Jurassic and/or Late Cretaceous-Early Tertiary compressional faulting and folding may have created stratigraphic traps towards the depositional limits. Although good quality reservoirs have been found in a number of wells at the Hutton Sandstone level, the potential reservoirs were water-wet and without hydrocarbon indications. However there are a number of potential traps which have not been tested.

Moree High

This tract is a major focal point for up-dip migrating hydrocarbons out of the adjacent Boomi Trough. Critical to the prospectivity of this area may be the presence of Rewan Formation seal and the position of the pinchout edge of the Rewan relative to its bounding margin faults.
Exploration in the area has targeted the shallower and younger Hutton Sandstone, (eg Moree-1 to 3, Camurra 1) although drilling results indicated that the Hutton Sandstone is water saturated. However, the gas show in Bellata-1 in a stratigraphic equivalent of the Hutton Sandstone indicates that this play concept should not be disregarded. There is very little seismic in this region and only one well, Camara-1 was located on a loose seismic grid. Nevertheless, there is potential for sourcing from the south from within the Bellata Trough, where mature Permian source rocks have been identified.

Maules Creek Sub-basin

The Maules Creek Sub-basin contains up to 1000 m of Maules Creek Formation. The sub-basin continues to the east under the overthrust New England Fold Belt and there may be traps developed where permeable sandstones within the sequence are sealed against the fault. The Goonbry and Maules Creek Coals provide source rocks which may have been subject to higher heat flows close to the thrust.

Rocky Glen Ridge

To the north of the Barradine High, the Permian sediments have been uplifted and eroded. The quartz sandstones of the Digby Formation form an excellent reservoir for hydrocarbons migrating from the Pilliga Trough or the Bohena Trough with possible traps involving drape over undulations along the flank of the High. South of the Baradine High, the full Permian sequence is preserved, with potential traps in the Watermark and Porcupine Formations, the Brigalow and Clare Formations and in the Wollar Sandstone member of the Digby Formation.

Murrurundi Trough East Flank

This tract encompasses the eastern flank of the Murrurundi Trough, east of the axis of the Meandarra Gravity Ridge. Its eastern boundary is the thrust faulted margin with the adjacent Werrie Basin. Much of the area lies under extensive basaltic cover. Although this inhibits exploration it does provide both regional seal, especially for the shallower Pilliga Sandstone, and a potential source of elevated heatflow for Late Permian source rocks. Substantial structuring is anticipated across the eastern side of the region, adjacent to the thrust margin. Imbricated blocks, as well as compressionally induced folds and fault compartments are expected to be developed, along northwest trends, across the eastern portion of the trough.

Tract d/L-M/B

Lightning Ridge Shelf

This tract is located on the northwestern boundary of the BBSB and has been subject to limited exploration. Excellent reservoir potential exists in the Pilliga Sandstone and Mooga Sandstones. Grabens containing Early Permian sedimentary rocks may be present within the underlying basement. This could provide a mature source for hydrocarbon development.

Pilliga Trough

This Tract encompasses the Pilliga Trough and the western flank of the Rocky Glen Ridge, west of the north-south trending structural axis. Regional geological cross-sections based on existing drilling, confirm that Permian sediments thin onto the flank of this Ridge and as such provide regional stratigraphic traps within sands of the Black Jack and Digby units. This play type is predicated upon a petroleum system located within the Pilliga Trough. This tract is anticipated to have the greatest proportion of quartz-rich sandstone facies capable of providing potential reservoir sequences, particularly within equivalents of the Digby Formation.

Cobbora Area

In total, there are four possible grabens identified in this area. Gunn (2002a) notes that the northernmost graben has a sinuous magnetic high along its central axis. This high is interpreted as a meandering river system filled with Tertiary basalt. It is possible that the meandering river system was flowing along the

axis of the graben. This area is relatively free of interpreted intrusive plugs. Early Permian coals could provide hydrocarbon source rock potential with numerous interbedded sands and shales providing intraformational reservoirs and seals. Intersecting north-northwest and northeast trending faults, controlling graben formation, are

Goonoo Graben Complex

Gunn (2002a) identified a number of slightly arcuate, but essentially north-south trending linear magnetic zones. Goonoo-1 has established that one of the zones coincides with a graben that may contain thick Early Permian coal measures. Early Permian Maules Creek or older rocks are predicted as probable conventional and CSM source rocks with intraformation reservoirs and seals. Hoskisson Seam and other Black Jack source rocks may provide subordinate source potential, especially around those areas subjected to elevated heat flow during the volcanic events. In this regard, the north and central areas are anticipated to have elevated maturity levels compared to those of the south. Digby Formation reservoirs may provide objective targets higher in the section and outside the bounding graben complexes, where they are likely to be sealed by the Napperby Formation. Within the graben numerous structural traps are anticipated on the basis that the margins were probably subject to multiple phases of transpressional reactivation inducing pop-up and redel type structures.

Werrie Basin

Prospectivity within this basin is somewhat restricted because of the extensive erosional truncation of much of the section. Nevertheless, mapping has highlighted a significant number of structures, including anticlines. It is believed that the Murrurundi Trough continues beneath the Werrie Basin under the thrust fault system. Traps are likely to be heavily fault dependent, involving tightly folded imbricate sheets along westerly and northwesterly trends. Given the large component of easterly-derived sediments, reworked marine sediments of the Porcupine and Watermark formations provide the best reservoir potential.

APPENDIX 1. OPERATING AND INTERMITTENTLY OPERATING INDUSTRIAL MINERAL AND CONSTRUCTION MATERIAL QUARRIES IN THE BBSB (EXCLUDING THE BUFFER ZONE).

QUARRY NAME	MAIN COMMODITY	HOST ROCK	STATUS	SIZE
Hobsons Clay Pit	clay, clay/shale - structural	shale, sandstone	intermittent	unknown
Wilga Park Clay Pit	clay, clay/shale - structural	laminite, shale	intermittent	unknown
Merrygoen, BHP	kaolin - flint clay	claystone	intermittent	unknown
Willow Tree, Pollocks Lane	unprocessed construction materials	basalt & conglomerate	continuous	large
Runnymede near Pallamallawa	coarse aggregate - hard rock	basalt, sandstone	intermittent	medium
Warialda Pit	sand - construction	alluvium	intermittent	unknown
Cains Crossing, Bohena Creek	sand - construction	alluvium	intermittent	unknown
Gunnembene Lane, Carroll	sand - construction	alluvium	intermittent	unknown
Chinook, 14 km east of Moree	sand - construction	alluvium	intermittent	unknown
Coolatai Road, Warialda	unprocessed construction materials	alluvium		unknown
Terramungamine Via Dubbo	sand - construction	alluvium	continuous	unknown
Ardglen SRA Quarry	coarse aggregate - hard rock	basalt	continuous	very large
Wave Hill Quarry	coarse aggregate - hard rock	basalt	continuous	unknown
Talbragar Quarry Brocklehurst	coarse aggregate - hard rock	basalt	continuous	large
Oxley Hwy Coonabarabran	coarse aggregate - hard rock	basalt	continuous	medium
Eulomogo Quarry Dubbo	coarse aggregate - hard rock	basalt	intermittent	large
Dubbo, Sheraton Road	coarse aggregate - hard rock	basalt	continuous	very large
Galager's-R2C	unprocessed construction materials	alluvium	intermittent	unknown
Pilliga Rubish Tip-R2A	unprocessed construction materials	alluvium	intermittent	unknown
Balmer's-R2	unprocessed construction materials	alluvium	intermittent	unknown
Blue Pole-S2	unprocessed construction materials	alluvium	intermittent	unknown
Bugilbone-P2	unprocessed construction materials	alluvium	intermittent	unknown
Cubbo Forest-W7	unprocessed construction materials	alluvium	intermittent	unknown
Cubbo-V7	unprocessed construction materials	alluvium	intermittent	unknown
Pickaxe Road-W8	unprocessed construction materials	alluvium	intermittent	unknown
Kings Road-W12	unprocessed construction materials	sandstone	intermittent	unknown
Squires Lane-V5	unprocessed construction materials	alluvium	intermittent	unknown
Euliga Creek-W6	sand/gravel - undifferentiated	alluvium	intermittent	unknown

Merimborough-T7	unprocessed construction materials	alluvium	intermittent	unknown
Bullen's-Q7	unprocessed construction materials	alluvium	intermittent	unknown
Kyber-P8	unprocessed construction materials	alluvium	intermittent	unknown
Cruckshank's-P9	unprocessed construction materials	alluvium	intermittent	unknown
Karinga-Q10	unprocessed construction materials	alluvium	intermittent	unknown
Tharlane-P10B	unprocessed construction materials	alluvium	intermittent	unknown
Brigalow Cr-P10A	unprocessed construction materials	alluvium	intermittent	unknown
Bilary-P13	unprocessed construction materials	alluvium	intermittent	unknown
Copps-N13	unprocessed construction materials	alluvium	intermittent	unknown
Maxwell's-O13	unprocessed construction materials	alluvium	intermittent	unknown
Lowanna-R5	unprocessed construction materials	alluvium	intermittent	unknown
Tambar Springs North	unprocessed construction materials	basalt	intermittent	unknown
Unnamed	unprocessed construction materials	sandstone	intermittent	unknown
Linden	unprocessed construction materials	sandstone	intermittent	unknown
Plantation Pit	unprocessed construction materials	sandstone	intermittent	unknown
Trinkey State Forest - Jungle Rd	unprocessed construction materials	mudstone	intermittent	unknown
Trinkey S F - Jungle & Belmont Rds	unprocessed construction materials	sandstone	intermittent	unknown
Lucky Flat-U14	sand/gravel - undifferentiated	alluvium	intermittent	unknown
Blairmore-X22	unprocessed construction materials		intermittent	unknown
Mayfield	unprocessed construction materials		intermittent	unknown
Ackland's-T23	unprocessed construction materials		intermittent	unknown
Tullamullen-U23	unprocessed construction materials		intermittent	unknown
Bowhills-S23	unprocessed construction materials	colluvium	intermittent	unknown
Green Hill-R23	unprocessed construction materials	alluvium	intermittent	unknown
Burgess'-T24B	unprocessed construction materials	volcanics	intermittent	unknown
Eather's-V24	unprocessed construction materials		intermittent	unknown
Culgoora State Forest-N14	unprocessed construction materials	alluvium	intermittent	unknown
Knellar's-R15	unprocessed construction materials	alluvium	intermittent	unknown
Newson's-O15	unprocessed construction materials	alluvium	intermittent	unknown
Carberry's-N15	unprocessed	sandstone	intermittent	unknown

	construction materials			
Drysdale's-P17	unprocessed construction materials	alluvium	intermittent	unknown
Bohena Creek-R17	unprocessed construction materials	alluvium	intermittent	unknown
Review-Q17	unprocessed construction materials	alluvium	intermittent	unknown
Oaklands-O17	unprocessed construction materials	alluvium	intermittent	unknown
Wesport-S18	unprocessed construction materials	sandstone	intermittent	unknown
Corglen-O18	unprocessed construction materials	alluvium	intermittent	unknown
Wine Shop/5 Mile-M18A	sand/gravel - undifferentiated	alluvium	intermittent	unknown
Smart's-J18	sand/gravel - undifferentiated	alluvium	intermittent	unknown
5 Mile Reserve-N18	sand/gravel - undifferentiated	alluvium	intermittent	unknown
Gunclub-P20A	unprocessed construction materials	sandstone	intermittent	unknown
Gillham's-P20B	unprocessed construction materials	alluvium	intermittent	unknown
Rifle Club-M20A	unprocessed construction materials	sandstone	intermittent	unknown
Aerodrome-N20A	unprocessed construction materials	sandstone	intermittent	unknown
Pistol Club-N20B	unprocessed construction materials	sandstone	intermittent	unknown
Rosevale-R21	unprocessed construction materials	sandstone	intermittent	unknown
Rees'-Q21	unprocessed construction materials	sandstone	intermittent	unknown
Killarney Forest-L20	unprocessed construction materials	sandstone	intermittent	unknown
Egan's-O21	unprocessed construction materials	sandstone	intermittent	unknown
12 Mile Hill-K22B	unprocessed construction materials	sandstone	intermittent	unknown
Murrumbilla-K22A	unprocessed construction materials	sandstone	intermittent	unknown
Tulla Mullen Ck North	unprocessed construction materials	sandstone	intermittent	unknown
Wairoa-O22	sand/gravel - undifferentiated	alluvium	intermittent	unknown
Tulla Mullen Ck East	unprocessed construction materials		intermittent	unknown
Orman's-O23	sand/gravel - undifferentiated	alluvium	intermittent	unknown
Park's-N23	unprocessed construction materials		intermittent	unknown
Currawidgen-Q24	sand/gravel - undifferentiated	alluvium	intermittent	unknown
Koiwon-D15	unprocessed construction materials		intermittent	unknown
Wilga-D16	unprocessed construction materials		intermittent	unknown
Old Dobiken-E18	unprocessed construction materials		intermittent	unknown

Rockdale-D18	unprocessed construction materials		intermittent	unknown
Cemetery-E19	unprocessed construction materials		intermittent	unknown
Donnaghue's Pit	unprocessed construction materials	basalt	intermittent	unknown
Coomoo Coomoo	unprocessed construction materials	basalt	intermittent	unknown
Daymer Pit	unprocessed construction materials	basalt	intermittent	unknown
Duddy's Pit	unprocessed construction materials	basalt	intermittent	unknown
Merrilong	unprocessed construction materials	basalt	intermittent	unknown
West Warrah Pit	unprocessed construction materials	basalt	intermittent	unknown
Hendersons Pit	unprocessed construction materials	basalt	intermittent	unknown
Graces Pit	unprocessed construction materials	basalt	intermittent	very small
Parraweena	unprocessed construction materials	basalt	intermittent	unknown
Yarrimanbar Creek	sand/gravel - undifferentiated	alluvium	intermittent	unknown
McKenzies Pit	unprocessed construction materials	conglomerate	intermittent	unknown
Paddys Point	unprocessed construction materials	basalt	intermittent	unknown
Pine Ridge West Sandstone Pit	unprocessed construction materials	sandstone	intermittent	unknown
Pine Ridge East Pit	unprocessed construction materials	basalt	intermittent	unknown
Round Island Hill Pit	unprocessed construction materials	sandstone	intermittent	unknown
Moore's Pit	unprocessed construction materials	sandstone	intermittent	unknown
Lavender's Pit	unprocessed construction materials	sandstone	intermittent	unknown
Goran State Forest	unprocessed construction materials	sandstone	intermittent	unknown
Wandoba Rd	unprocessed construction materials	sandstone	intermittent	unknown
Stevensons Rd	unprocessed construction materials	conglomerate	intermittent	unknown
Chevy Chase Pit	unprocessed construction materials	sandstone	intermittent	unknown
Kilkenny	unprocessed construction materials	sandstone	intermittent	unknown
Springe Ridge State Forest	unprocessed construction materials	conglomerate	intermittent	unknown
Balgowrie	unprocessed construction materials	sandstone	intermittent	unknown
Macathlan Downs	unprocessed construction materials		intermittent	unknown
Breeza State Forest	unprocessed construction materials	sandstone	intermittent	unknown
Linavardi	unprocessed construction materials	sandstone	intermittent	unknown

APPENDIX 2: METALLIC AND INDUSTRIAL MINERAL, AND CONSTRUCTION MATERIAL RESOURCE ASSESSMENT AND DEPOSIT MODELS

CuAu: PORPHYRY COPPER-GOLD
(Model 20c of Cox and Singer 1986).

Model Description
Description of the model after Cox in Cox and Singer (1986), Cook et al (1998), and Corbett and Leach (1998).

Description
Stockwork veinlets of chalcopyrite, bornite, and magnetite in porphyritic intrusions and coeval volcanic rocks. Ratio of Au (ppm) to Mo (percent) is greater than 30.

General References
Sillitoe (1979,1989), Cook et al (1998).

Geological Environment
Rock Types:
Tonalite to monzogranite; dacite, andesite flows and tuffs coeval with intrusive rocks. Also syenite, monzonite, and coeval high-K, low-Ti volcanic rocks (shoshonites). In LFB shoshonitic geochemistry a major control (Downes 1998).

Textures:
Intrusive rocks are porphyritic with fine-to medium-grained aplitic groundmass.

Age Range:
Mainly Palaeozoic to Quaternary, but can be any age.

Depositional Environment:
In porphyritic stocks and dykes intruding coeval volcanic rocks. Large-scale breccias common. Evidence for volcanic centre; 1-2 km depth of emplacement.

Tectonic Setting(s):
Subduction related, eg Island-arc volcanic setting, especially waning stage of volcanic cycle; active continental margin. Also continental margin rift-related volcanism.

Associated Deposit Types:
Porphyry Cu-Mo; Gold-porphyry; epithermal Au-Ag, copper skarn, mesothermal gold (spatial association in LFB), gold placers.

Deposit Description
Mineralogy:
Chalcopyrite ± bornite; traces of native gold, electrum, sylvanite, and hessite. Quartz + K-feldspar + anticipated to provide adequate fault related trapping potential both within and adjacent to the major graben.

Texture/Structure:
Veinlets and disseminations.

Alteration:
Quartz ± magnetite ± biotite (chlorite) ± K-feldspar ± actinolite, ± anhydrite in interior of system. Outer propylitic zone. Late quartz + pyrite + white mica ± clay may overprint early feldspar-stable alteration.

Ore controls:
Veinlets and fractures of quartz, sulphides, K-feldspar magnetite, biotite, or chlorite are closely spaced. Ore zone has a bell shape centred on the volcanic-intrusive centre. Highest grade ore is commonly at the level at which the stock divides into branches.

Weathering:

Surface iron staining may be weak or absent if pyrite content is low in protore. Copper silicates and carbonates. Residual soils contain anomalous amounts of rutile.

Geochemical signature:
Anomalous Cu, Au, Mo, Ag, Zn, Pb, As, Sb, Hg, Te, Sn, S (Cook et al 1998). Central Cu, Au, Ag; peripheral Mo. Peripheral Pb, Zn, Mn anomalies may be present if late sericite pyrite alteration is strong. Au (ppm): Mo (percent) >30 in ore zone. Au enriched in residual soil over ore body. System may have magnetic high over intrusion surrounded by magnetic low over pyrite halo.

Examples

Goonumbla, NSW	Heithersay et al (1990)
Panguna, PPNG	Clark (1990)
Ok Tedi, PPNG	Rush and Seegers (1990)
Dos Pobres, USAZ	Langton and Williams (1982)
Copper Mountain, CNBC	Fahrni et al. (1976)
Cadia, NSW	Wood and Holliday (1995)

Known deposits and prospects in the BBSB and adjacent areas.
There are several known and interpreted porphyry Cu-Au prospects within or close to the southern margins of the BBSB. These include the general area of the Wongoni Prospect, and numerous prospects in the Comobella area. The Comobella area and its northerly extensions are considered highly prospective, satisfying a number of known geological criteria for porphyry Cu-Au deposits. These prospective rocks also extend beneath shallow basin cover within the BBSB to the north.

Late Ordovician shoshonitic rocks of the Molong Volcanic Belt on the western parts of the Dubbo 250:000 sheet appear to become more prospective northwards and into the BBSB beneath shallow cover, for the following reasons:
1) coherent and proximal nature of the volcanics to an inferred eruptive centre
2) rocks become more fractionated and shoshonitic
3) outcropping and subcropping shoshonitic intrusives have been identified, which are also inferred to be favourably situated close to their prospective roof zones.

Late Ordovician rocks of the Rockley-Gulgong Volcanic Belt on the Dubbo 250:000 sheet which extend beneath shallow basin cover into the BBSB do *not* appear to be as prospective for porphyry Cu-Au style mineralisation as the Molong Volcanic Belt, for the following reasons:
1) Lack of identified eruptive centres and distal nature of the volcanics
2) Calc alkaline rather than shoshonitic geochemistry (diorites versus monzonites) approaching the BBSB
3) Shoshonitic units are present (eg Burranah Formation) but in general further to the south.

General Assessment Criteria
1. Distribution of Late Ordovician shoshonitic rocks and their inferred subsurface extensions, eg units within the Molong Volcanic Belt, and the Narromine Volcanic Belt.
2. Distributions of Late Ordovician rocks of calc-alkaline affinity and their subsurface extensions (eg units within the Rockley-Gulgong Volcanic Belt).
3. Distribution of I-type and/or magnetite series granitoids (oxidation state of granites) of any age and their subsurface extensions. **NOTE**: Bald Hill, Late Permian -Early Triassic Cu-Au prospect in monzonite. Also the Yeoval Complex.
4. Presence of localised magnetic lows within zones of high magnetic Late Ordovician signatures.
5. Presence of mineral prospects having features similar to porphyry copper deposits.
6. Distribution of inferred eruptive centres.

Economic Significance
Generally these deposits are important sources of copper and gold. The grade/tonnage model (Cox and Singer 1986) for porphyry copper gold deposits indicate that 90% of these deposit contain at least 25 Mt of ores, 50% contain at least 100 Mt and 10% contain at least 400 Mt. In 90% of these deposits ores contain at least 0.35 wt % copper and 0.2 ppm gold, in 50 % of the deposits ores have at least 0.5 wt % copper and 0.38 ppm gold and in 10% of the deposits the ores contain at least 0.72 wt % copper and 0.72 ppm gold.

Pre-mining resource of the Cadia Hill porphyry Cu-Au mine in central New South Wales was 202Mt at 0.73ppm Au, 0.17% Cu (proved and probable, 1998); and the Cadia Ridgeway Mine was 54Mt at 2.5ppm Au, 0.77% Cu (measured, indicated and inferred, 2000; Downes 1998). This amounts to greater than $5 billion ($AUD2002) in situ metal value.

Epi: EPITHERMAL GOLD-SILVER
(Model 25b of Cox and Singer 1986)

Model Description
Description of the model after Cox and Singer (1986).

Approximate Synonym
Epithermal gold (quartz-adularia) alkali-chloride-type, polymetallic veins.

Description
Galena, sphalerite, chalcopyrite, sulfosalts, + tellurides + gold in quartz-carbonate veins hosted by felsic to intermediate volcanics. Older basin evaporites or rocks with trapped seawater are associated with these deposits.

General References
Buchanan (1980), White and Hedenquist (1990), Henley et al. (1984), Berger and Bethke (1985)

Geological Environment
Rock types:
Host rocks are andesite, dacite, quartz latite, rhyodacite, rhyolite, and associated sedimentary rocks. Mineralisation related to calc-alkaline or bimodal volcanism.

Textures:
Porphyritic.

Age range:
Mainly Tertiary (most are 29-4 Ma, on a world wide basis), but can be any age. For the LFB major mineralising events identified in the Devonian and Late Permian. In the New England Fold Belt Late Permian.

Depositional environment:
Bimodal and calc-alkaline volcanism. Deposits related to sources of saline fluids in prevolcanic basement such as evaporites or rocks with entrapped seawater.

Tectonic setting(s):
Through-going fractures systems; major normal faults, fractures related to doming, ring fracture zones, joints associated with calderas. Underlying or nearby older rocks of continental shelf with evaporite basins, or island arcs that are rapidly uplifted.

Associated deposit types:
Placer gold, epithermal quartz alunite Au, polymetallic replacement, Porphyry Cu-Au

Deposit Description
Mineralogy:
Galena + sphalerite + chalcopyrite + copper sulfosalts + silver sulfosalts ± gold ± tellurides ± bornite ± arsenopyrite. Gangue minerals are quartz + chlorite ± calcite + pyrite + rhodochrosite + barite ± fluorite ± siderite ± ankerite ± sericite ± adularia ± kaolinite. Specular haematite and alunite may be present.

Texture/structure:
Banded veins, open space filling, lamellar quartz, stockworks, colloform textures.

Alteration:
Top to bottom: quartz ± kaolinite + montmorillonite ± zeolites ± barite ± calcite; quartz + illite; quartz + adularia ± illite; quartz + chlorite; presence of adularia is variable.

Ore controls:
Through-going or anastomosing fracture systems. High-grade shoots where vein changes strike or dip and at intersections of veins. Hanging-wall fractures are particularly favourable.

Weathering:
Bleached country rock, goethite, jarosite, alunite--supergene processes often important factor in increasing grade of deposit.

Geochemical signature:
Higher in system Au + As + Sb + Hg; Au + Ag + Pb + Zn + Cu; Ag + Pb + Zn, Cu + Pb + Zn. Base metals generally higher grade in deposits with silver. W + Bi may be present.

Examples

Pajingo, Queensland	Bobis et al (1996)
Creede, USA	Steven and Eaton (1975); Barton et al (1977)
Pachuca, Mexico	Geyne et al (1963)
Toyoha, Japan	Yajima and Ohta (1979)

Known deposits and prospects in the BBSB and adjacent areas.
There are several prospects within the Permo-Carboniferous volcanics of the Tamworth Belt within or close to the margins of the BBSB in the Gunnedah area which are thought to be epithermal Au-Ag in style, including the Hill 398 prospect. The Mount Terrible deposit, located just east of the BBSB, was discovered in the early 1990s in the Late Permian Warrigundi Igneous Complex. It has an inferred resource of 132,000t at 7.8ppm Au. Although the ore zone outcrops, Mount Terrible had no previous mining history, which is unusual for major mineral deposits in the New England and Lachlan Fold Belts in NSW. Difficult access was probably a contributing factor.

The White King deposit is another significant epithermal prospect located just outside the BBSB, in Queensland just over the border with NSW, hosted within Permian Volcanics. Recent exploration has delineated a low-moderate sized resource. Similar volcanic units could also be present beneath shallow basin cover within the northern parts of the BBSB.

Another recent discovery in Queensland occurs at Cracow, with an inferred resource of 1.1Mt at 11g/t Au, 9g/t Ag, buried beneath shallow basin cover, similar to the style and setting of some prospects situated in the eastern parts of the BBSB.

Areas of subaerial, felsic-intermediate Silurian, Devonian, and Late Permian volcanics and their subsurface extensions in the southern parts of the BBSB are also prospective for epithermal style deposits. The Mount Aubrey Mine is an epithermal style deposit hosted by Middle Devonian volcanics which occurs to the southwest of the BBSB near Peak Hill, with 120,000t at 3.3g/t Au mined by open cut in 1990-1991. The Bowdens Gift deposit is another epithermal style deposit hosted by Late Permian Rylestone Volcanics to the south of the BBSB, situated adjacent to basin cover with an indicated and inferred resource of 59Mt at 43.8 g/t Ag, 0.22% Pb, 0.31% Zn (2001).

Economic Significance

Epithermal gold-silver deposits are important sources for gold and silver. Grade/tonnage model for deposits of this type (Cox and Singer, 1986) indicates that 90% of deposits contain more than 0.065 Mt of ore, 50% more than 0.77 Mt and 10% contain more that 9.1 Mt. In 90% of these deposits ores have at least 2.0 grams per tonnes gold and 10 grams per tonne silver. The ores in 50% of these deposits have at least 7.5 grams per tonne gold and 110 grams per tone silver. In 10% of these deposits the ores have at least 27 grams per tonne gold and 1300 grams per tonne silver.

Kur: KUROKO VOLCANIC HOSTED MASSIVE SULPHIDE (VHMS)
(Model 28A of Cox and Singer 1986)

Model Description
Description of the model after Singer in Cox and Singer (1986), and Gemmel et al (1998).

Approximate Synonym
Noranda type, volcanogenic massive sulphide, felsic to intermediate volcanic type.

Description: lead-zinc-copper bearing massive sulphide deposits in marine volcanic rocks of intermediate to felsic composition.

General References
Ishihara (1974), Franklin et al. (1981), Hutchinson et al. (1982), Ohmoto and Skinner (1983), Large (1992); Allen and Barr (1990), Gemmel et al (1998).

Geological Environment
Rock types:
Submarine rhyolite, dacite, and subordinate basalt and associated sediments, principally organic-rich mudstone or shale. Pyritic, siliceous shale. Some basalt.

Textures:
Flows, tuffs, pyroclastics, breccias, bedded sediment, and in some cases felsic domes.

Age range: Archaean through Cainozoic.

Depositional environment:
Hot springs related to submarine volcanism, probably with anoxic marine conditions. Lead-rich deposits associated with abundant fine-grained volcanogenic sediments.

Tectonic setting(s):
Island arc. Local extensional tectonic activity, faults, or fractures. Archaean greenstone belts.

Associated deposit types:
Epithermal quartz-adularia veins in Japan are regionally associated but younger than Kuroko massive sulphide deposits. Volcanogenic Mn, Algoma Fe, disseminated Henty-style gold (Lachlan Fold Belt).

Deposit Description
Mineralogy:
Upper stratiform massive zone (black ore)--pyrite + sphalerite + chalcopyrite ± pyrrhotite ± galena ± barite ± tetrahedrite - tennantite ± bornite; lower stratiform massive zone (yellow ore)--pyrite + chalcopyrite ± sphalerite ± pyrrhotite ± magnetite; stringer (stockwork) zone--pyrite + chalcopyrite (gold and silver). Gahnite in metamorphosed deposits. Gypsum/anhydrite present in some deposits.

Texture/structure:
Massive (>60 percent sulphides); in some cases, an underlying zone of ore stockwork, stringers or disseminated sulphides or sulphide-matrix breccia. Also slumped and redeposited ore with graded bedding.

Alteration:
Adjacent to and blanketing massive sulphide in some deposits--zeolites, montmorillonite (and chlorite?); stringer (stockwork) zone--silica, chlorite, and sericite; below stringer--chlorite and albite. Cordierite and anthophyllite in footwall of metamorphosed deposits, graphitic schist in hanging wall.

Ore controls:
Toward the more felsic top of volcanic or volcanic-sedimentary sequence. Near centre of felsic volcanism. May be locally brecciated or have felsic dome nearby. Pyritic siliceous rock (exhalite) may mark horizon at which deposits occur. Proximity to deposits may be indicated by sulphide clasts in volcanic breccias. Some deposits may be gravity-transported and deposited in palaeo depressions on the seafloor. In Japan, best deposits have mudstone in hanging wall.

Weathering:
Yellow, red, and brown gossans. Gahnite in stream sediments near some deposits.

Geochemical signature:
Gossan may be high in Pb and typically Au is present. Adjacent to deposit-enriched in Mg and Zn, depleted in Na. Within deposits--Cu, Zn, Pb, Ba, As, Ag, Au, Se, Sn, Bi, Fe.

Geophysical signatures:
Magnetic surveys may detect associated magnetite and/or pyrrhotite within orebody or magnetite within wallrocks. Induced polarisation techniques may detect pyritic schists. Electromagnetic techniques may detect massive sulphide mineralisation. Radiometrics may show K-depletion in alteration envelope.

Examples

Kuroko:

Benambra, Australia	Allen and Barr (1990)
Mt. Lyell, Australia	Hills (1990)
Rosebery, Australia	Lees et al (1990)
Furutobe, Japan	Kuroda (1983)
Woodlawn, New South Wales	McKay and Davies (1990)

Known deposits and prospects in the BBSB and adjacent areas.
There are no known VHMS type occurrences within the BBSB. However there are several known Kuroko type VHMS prospects close to the margins of the BBSB in the Comobella area, including the Belara and Native Bee prospects. Rock units which host these deposits continue beneath basin cover into the BBSB. The Belara Prospect has an inferred resource of 700,000 t at 55g/t Ag, 0.85% Cu, 2.3% Pb, and 5.9% Zn.

Economic Significance
Kuroko volcanic-hosted massive sulphide deposits are significant sources for copper, lead and zinc. Some of these deposits can also have up to a few tens of ppm of gold and few hundreds of ppm of silver. Global grade/tonnage models for this type of deposits indicate that 90% of these deposits have more than 0.12 Mt of ore, 50% have more that 1.5 Mt and 10% have more than 18 Mt. Similarly 90% of these deposits the ores have more than 0.45% copper, 50 % have more than 1.3% copper and 2.0% zinc and 10% have more than 3.5% copper , 8.7% zinc and 1.9% lead.

Oro: OROGENIC GOLD
(Model 36A of Cox and Singer 1986)

Model Description
Description of the model after Berger and Bethke (1985), and Philips and Hughes (1998).

Approximate Synonyms
Slate belt gold veins, mesothermal quartz veins, mother lode veins, turbidite-hosted gold veins, low sulphide gold-quartz veins, metahydrothermal gold, structurally controlled gold, Victorian gold deposits.

Description
Gold in quartz veins and silicified lode structures, mainly in regionally metamorphosed rocks.

General References
Philips and Hughes (1998).

Geological Environment
Rock types:
Greenstone belts; oceanic metasediments: regionally metamorphosed volcanic rocks, greywacke, chert, shale, and quartzite, especially turbidite-deposited sequences. Alpine gabbro and serpentine. Late stage granitic batholiths.

Age range:
Archaean to Tertiary.

Depositional environment:
Continental margin mobile belts, accreted margins. Vein age is pre to post-metamorphic and locally cut granitic rocks.

Tectonic setting(s):
Fault and joint systems produced by regional compression; high strain zones.

Associated deposit types:
Placer Au-PGE, Homestake gold. Fosterville-Nagambie style gold (stockworks), alluvial gold.

Deposit Description
Mineralogy:
Quartz ± carbonates ± native gold ± arsenopyrite ± pyrite ± galena ± sphalerite ± chalcopyrite ± pyrrhotite ± sericite ± rutile. Locally tellurides ± scheelite ± bismuth ± tetrahedrite ± stibnite ± molybdenite ± fluorite. Gold-bearing quartz is greyish or bluish in many instances because of fine-grained sulphides. Carbonates of Ca, Mg, and Fe abundant.

Texture/structure:
Saddle reefs, ribbon quartz, breccias, open-space filling textures commonly destroyed by vein deformation.

Alteration:
Quartz + siderite and (or) ankerite ± albite in veins with possible halo of carbonate alteration. Chromian mica ± dolomite ± talc ± siderite in areas of ultramafic rocks. Sericite ± disseminated arsenopyrite ± rutile in granitic rocks.

Ore controls:
Veins occur along regional high-angle faults, joint sets. Best deposits overall in areas with greenstone. High-grade ore shoots locally at metasediment-serpentine contacts. Disseminated ore bodies where veins cut granitic rocks. Carbonaceous shales and may be important. Competency contrasts, e.g. shale/sandstone contacts and intrusive contacts may be important. Fold hinge zones also locally important.

Weathering:
Abundant quartz chips in soil. Red limonitic soil zones. Gold may be recovered from soil by panning.

Geochemical signature:
Gold best pathfinder in general; As, Ag, Pb, Zn, Cu may be useful.

Geophysical signature:
Poorly defined generally, but magnetics may define important structures.

Examples

Bendigo Goldfield, Victoria	Sharpe and MacGeehan, (1990)
Ballarat East Gold Deposits, Victoria	d'Auvergne, (1990)
Mother Lode, USA	Knopf, (1929)
Goldfields of Nova Scotia, Canada	Malcolm, (1929)
Hargraves, NSW	Markham and Basden (1974)

Known deposits and prospects in the BBSB and adjacent areas.
There are few, if any, orogenic style gold deposits within the BBSB. However several major orogenic gold deposits occur just outside the BBSB margins near Wellington and Bingara. The host rock units and associated major structures in both these areas extend beneath basin cover into the BBSB.

Most orogenic gold deposits are spatially related to well-defined major fault zones. Major faults are large penetrating structural zones which potentially provide greater access to mineralising fluids from deeper in the earths crust.

Economic Significance
Orogenic gold deposits are one of the largest types of gold deposit and are an important source of gold and silver. According to the grade /tonnage models for the low-sulphide gold -quartz veins (Cox and Singer, 1986) 90% of these deposits contain at least 0.001 Mt of ore; 50% contain at least 0.03 Mt and 10% contain at least 0.91 Mt. In 90% of these deposits ores contain at least 6 g/t gold; 50% contain at least 15 g/t gold and 10% contain 43 g/t gold.

Skarn: ZINC-LEAD SKARN
(Model 18C of Cox and Singer 1986)

Model Description
Modified by David and Jaireth (AGSO), Cox and Singer (1986)

Description
Sphalerite and galena in calc-silicate rocks.

General References
Einaudi and Burt (1982); Einaudi et al. (1981).

Geological Environment
Rock Types:
Granodiorite to granite, diorite to syenite. Calc-alkaline felsic to intermediate batholiths, stocks, dykes and sills, ranging in composition from high-silica leucogranite and topaz granite, syenite plutons and diorite. Small quartz monzonite stocks most common. Both S-type and I-type granitoids. Carbonate rocks, calcareous clastic rocks.

Textures:
Granitic to porphyritic; granoblastic to hornfelsic.

Age Range:
Can be any age.

Depositional Environment:
Basin sequences intruded by generally small bodies of igneous rock.

Tectonic Setting (s):
Continental margin, late-orogenic magmatism.

Associated Deposit Types:
Copper skarn.

Deposit Description
Mineralogy:
Sphalerite + galena ± pyrrhotite ± pyrite ± magnetite ± chalcopyrite ± bornite ± arsenopyrite ± scheelite ± bismuthinite ± stannite ± fluorite. Gold and silver do not form minerals. Mn- and Fe-rich calcsilicate minerals. High pyroxene to garnet ratios. Sulphide association with pyroxene.

Zoning:
Proximal skarns rich in Cu and W and distal skarns, mantos, and veins rich in Mn, Ag, and Pb.

Texture/Structure:
Granoblastic, sulfides massive to interstitial.

Alteration:
Mn-hedenbergite ± andradite ± grossular ± spessartine ± bustamite ± rhodonite. Late stage Mn-actinolite ± ilvaite ± chlorite ± dannemorite ± rhodochrosite.

Ore Controls:
Carbonate rocks especially at shale-limestone contacts. Deposit may be hundreds of meters from intrusive along structural and lithological contacts. Fluid depletion in Mg, Al, and Cu and enrichment in Mn, Fe, Zn, and Pb with increasing distance from intrusive.

Weathering:
Gossan with strong Mn oxide stains.

Geochemical Signature:
Zn, Pb, Mn, Cu, Co, Au, Ag, As, W, Sn, F, possibly Be.
Magnetic anomalies.

Examples

Ban Ban, AUQU	Ashley (1980)
Hanover-Fierro district, USNM	Hernon and Jones (1968)

Known deposits and prospects in the BBSB and adjacent areas.
There are a number of scattered, poorly documented old workings in the Glengarry, Bong Bong, and Mount Laut areas within and close to the margins of the BBSB, which could be of the zinc-lead skarn type. A number of probable zinc-lead skarn-type and related deposits occur at Leadville, just to the south of this area. The host Dungaree Volcanics are also present within the BBSB, and the likely source-the Early Carboniferous Old Leake Quartz Monzonite or its equivalents-may also occur in the subsurface within the BBSB, as inferred from geophysical interpretation. It is also possible that mineralisation at Leadville is related to Early Permian volcanism (Downes, 1998).

General Assessment Criteria.
1. Presence of oxidised/reduced (not highly oxidised) granitoids.
2. Presence of magnetic extensions around oxidised granitoids.
3. Degree of fractionation and felsic character of the above granitoids.
4. Presence of inferred subsurface extent of Old Leake Quartz Monzonite.
5. Presence of inferred subsurface extent of other Carboniferous Intrusions.
6. Presence of calcareous rocks within 5km of inferred Old Leake QMz eg STDL-in Dungaree Volcanics, and other Carboniferous Intrusions.
7. Presence of known occurrences of skarns.

BesCyp: BESSHI-CYPRUS VOLCANIC HOSTED MASSIVE SULPHIDE (VHMS)
(Models 24A, and 24B of Cox and Singer 1986)

Model Description
Description of the model after Donald A.Singer (1986), and L. David (AGSO, pers.comm.1999).

Approximate Synonym
Keislager

Description
Consist of thin, sheet-like bodies of massive to well-laminated pyrite, pyrrhotite, chalcopyrite, and sphalerite within thinly laminated clastic sediments and mafic lavas and tuffs.

General References
Ishihara (1974), Franklin et al. (1981), Hutchinson et al. (1982), Ohmoto and Skinner (1983), Large (1992); Allen and Barr (1990), Gemmel et al (1998).

Geological Environment
Rock Types: occur in interbedded clastic marine sedimentary rocks and tholeiitic to andesitic tuff and breccia (or their metamorphosed equivalents such as schist and amphibolite). Some areas contain ultramafic units such as peridotites (often serpentinized) and locally, black shale, oxide-facies iron formation, red chert, and exhalative carbonate material. The amount of mafic rock can vary. In the type area rocks are metamorphosed to blue schist facies.

Textures: Diabase dykes, pillow basalts, and in some cases thinly laminated clastic rocks, quartzose and mafic schist. All known examples are in strongly deformed metamorphic terrain.

Age range: Archaean through Cainozoic.

Depositional environment: generated by submarine hot springs along axial grabens in oceanic or back-arc spreading ridges or related to submarine volcanoes producing seamounts. Besshi/Cyprus ores may be localized within permeable sediments and fractured volcanic rocks in anoxic marine basins in an epicontinental rifting environment.

Tectonic setting(s): associated with mid-oceanic spreading ridge/centres but within a narrow oceanic arm adjacent to emerged lands, which serve as the source of abundant sediments swamping the basaltic volcanism.

Associated deposit types:
Mn and Fe-rich cherts regionally. Cyprus type. Podiform chromite. Cu-Ni-Co-Fe-sulphides. Exhalative Sn (-W) deposits.

Deposit Description
Mineralogy:
Pyrite + pyrrhotite + chalcopyrite + sphalerite + marcasite ± magnetite ± valleriite ± galena ± bornite ± tetrahedrite ± cobaltite ± cubanite ± stannite ± molybdenite.
Quartz, carbonate, albite, white mica, chlorite, amphibole, and tourmaline.

Texture/structure: generally of tabular shape, or cigar-shaped when deformed, and contain fine-grained, massive to laminated ore (with colloform and framboidal pyrite), breccia or stringer ore and cross-cutting veins containing chalcopyrite, pyrite, calcite or galena, sphalerite, calcite.

Alteration:
Besshi/Cyprus deposit alteration is difficult to recognise because of metamorphism but chloritisation of adjacent rocks is noted in some deposits.

Ore controls:
Mineralisation is stratigraphically controlled at the margin of mafic-volcanic rich unit and overlying argillite-rich unit. Lenticular bodies occur in hinge zones of isoclinal folds. Mineralisation is predominantly hosted by clastic sediments (argillite, chert) or their metamorphic equivalents.

Weathering:
Massive limonite gossans. Gold in stream sediments.

Geochemical signature:
Cu, Zn, Co, Ag, Ni, Cr, Co/Ni >1.0, Au up to 4 ppm, Ag up to 60 ppm.

Geophysical signatures:
Magnetic surveys may detect associated magnetite and/or pyrrhotite within orebody or magnetite within wallrocks. IP techniques may detect pyritic schists. EM techniques may detect massive sulphide mineralisation. Radiometrics may show K-depletion in alteration envelope.

Examples

Besshi/Cyprus:

Besshi, Japan	Kanehira and Tatsumi (1970)
Motoyasu, Japan	Yui (1983)
Kieslager, ASTR	Derkman and Klemm (1977)
Girilambone, Australia	Suppel (1975)

Known deposits and prospects in the BBSB and adjacent areas.
There are no known VHMS type occurrences within the BBSB. However there are several known Besshi type VHMS prospects near the BBSB margin in the Warialda area and rock units which host these deposits continue beneath basin cover into the BBSB. Prospects include the Rileys Copper Prospect and O'Neills Copper Mine, near Warialda.

Economic Significance
Besshi volcanic-hosted massive sulphide deposits are a significant source for copper, silver and zinc. Some of these deposits can have a few tens of ppm of silver and at least a ppm of gold. Global grade/tonnage models for this type of deposit indicates that 90% of these deposits have more than 0.012 million tonnes of ores, 50% have more that 0.22 million tonnes and 10% have more than 3.8 million tonnes. Similarly 90% of these deposits the ores have more than 0.56% copper, 50% have more than 1.5% copper and 2.0% zinc and 10% have more than 3.3% copper.

Sn1: TIN (GREISEN AND VEINS)
(Models 15c and 15b of Cox and Singer 1986)

a) Tin Veins (15c of Cox and Singer 1986)

Model Description
Description of the model after Reed (1982)

Approximate Synonym: Cornish type lodes.

Description: Simple to complex quartz-cassiterite ± wolframite and base-metal sulphide fissure fillings or replacement lodes in ore near felsic plutonic rocks.

General References: Solomon and Groves (1994), Hosking (1974), Taylor (1979**)**.

Geological Environment

Rock Types: Close spatial relation to multiphase granitoids; specialised biotite and(or) muscovite leucogranite common; pelitic sediments generally present.

Textures: Common plutonic textures.

Age Range: Palaeozoic and Mesozoic most common; may be any age.

Depositional Environment: Mesozonal to hypabyssal plutons; extrusive rocks generally absent; dykes and dyke swarms common.

Tectonic Setting(s*)*: Fold belts and accreted margins with late orogenic to postorogenic granitoids which may, in part, be anatectic; regional fractures common.

Associated Deposit Types: Sn greisen, Sn skarn, and replacement Sn deposits.

Deposit Description

Mineralogy: Extremely varied; cassiterite ± wolframite, arsenopyrite, molybdenite, hematite, scheelite, beryl, galena, chalcopyrite, sphalerite, stannite, bismuthinite; although variations and overlaps are ubiquitous, many deposits show an inner zone of cassiterite ± wolframite fringed with Pb, Zn, Cu, and Ag sulphide minerals.

Texture/Structure: Variable; brecciated bands, filled fissures, replacement, open cavities.

Alteration: Sericitisation (greisen development) ± tourmalisation common adjacent to veins and granite contacts; silicification, chloritisation, hematisation. An idealised zonal relation might consist of quartz-tourmaline-topaz, quartz-tourmaline-sericite, quartz-sericite-chlorite, quartz-chlorite, chlorite.

Ore Controls: Economic concentrations of tin tend to occur within or above the apices of granitic cusps and ridges; localised controls include variations in vein structure, lithologic and structural changes, vein intersections, dykes, and cross-faults.

Weathering: Cassiterite in stream gravels, placer tin deposits.

Geochemical Signature: Sn, As, W, B are good pathfinder elements; elements characteristic of specialised granites (F, Rb, Be, Nb, Cs, U, Mo, REE).

Examples

Cornwall, GRBR	Hosking (1969)
Herberton, AUQL	Blake (1972)

Known deposits and prospects in the BBSB and adjacent areas.
Only a few small tin vein occurrences occur close to the margins of the BBSB, in the Warialda area. They are spatially and genetically associated with the Late Permian to Early Triassic Dumboy Gragin Granite. Mineralisation is reported to be in the form of cassiterite bearing veins. These occurrences have not been investigated in any detail.

General Assessment Criteria

1. Distribution of S-type or I-type fractionated and reduced granites.
2. Distribution of granitic intrusions at shallow depth inferred from geophysical information, Sn- and base metal vein occurrences.

Economic Significance
According to grade/tonnage models for tin vein deposits, 90% of deposits contain at least 0.012 Mt of ore, 50% at least 0.24 Mt and 10% at least 4.5 Mt. In these types of deposits, 90% contain at least 0.7% Sn, 50% at least 1.3% Sn and 10% at least 2.3% Sn (Cox and Singer 1986).

b) Tin Greisen (Model 15b of Cox and Singer 1986)
Model Description
Description of the model after Reed (1982)

Description: Disseminated cassiterite, and cassiterite-bearing veinlets, stockworks, lenses, pipes, and breccia in greisenised granite.

General References: Reed (1982), Solomon and Groves (1994)

Geological Environment

Rock Types: Specialised biotite and(or) muscovite leucogranite (S-type) granite; distinctive accessory minerals include topaz, fluorite, tourmaline, and beryl. Tin greisens are generally post-magmatic and associated with late fractionated melt.

Textures: Common plutonic rock textures, miarolitic cavities may be common; generally nonfoliated; equigranular textures may be more evolved (Hudson and Arth 1983); aplitic and porphyritic textures common.

Age Range: May be any age; tin mineralisation temporally related to later stages of granitoid emplacement.

Depositional Environment: Mesozonal plutonic to deep volcanic environment.

Tectonic Setting(s*)*: Fold belts of thick sediments ± volcanic rocks deposited on stable cratonic shield; accreted margins; granitoids generally postdate major folding.

Associated Deposit Types: Quartz-cassiterite sulphide lodes, quartz-cassiterite ± molybdenite stockworks, late complex tin-silver-sulphide veins.

Deposit Description

Mineralogy: Cassiterite, molybdenite, arsenopyrite, beryl, wolframite, bismuthinite, Cu-Pb-Zn sulphide minerals and sulphostannates. Gangue mineralogy includes quartz, ± fluorite, calcite, tourmaline, muscovite and topaz.

Texture/Structure: Exceedingly varied, the most common being disseminated cassiterite in greisens, and quartz veinlets and stockworks (in cupolas or in overlying wallrocks); less common are pipes, lenses, and tectonic breccia.

Alteration: Incipient greisen (granite): muscovite ± chlorite, tourmaline, and fluorite. Greisenised granite: quartz-muscovite-topaz-fluorite, ± tourmaline (original texture of granites retained). Greisen: quartz-muscovite-topaz ± fluorite ± tourmaline ± sulphides (typically no original texture preserved). Tourmaline can be ubiquitous as disseminations, concentrated or diffuse clots, or late fracture fillings. Greisen may form in any wallrock environment, typical assemblages developed in aluminosilicates.

Ore Controls: Greisen lodes located in or near cupolas and ridges developed on the roof or along margins of granitoids; faults and fractures may be important ore controls.

Weathering: Granite may be "reddened" close to greisen veins. Although massive greisen may not be economic as lodes, rich placer deposits form by weathering and erosion.

Geochemical Signature: Cassiterite, topaz, and tourmaline in streams that drain exposed tin-rich greisens. Specialised granites may have high contents of SiO2 (>73 percent) and K2O (>4 percent), and are depleted in CaO, TiO2, MgO, and total FeO. They are enriched in Sn, F, Rb, Li, Be, W, Mo, Pb, B, Nb, Cs, U, Th, Hf, Ta, and most REE, and impoverished in Ni, Cu, Cr, Co, V, Sc, Sr, La, and Ba.

Examples

Lost River, USA	Dobson (1982); Sainsbury (1964)
Anchor Mine, AUTS	Solomon and Groves (1984)
Erzgebirge, CZCL	Janecka and Stemprok (1967)

Known deposits and prospects in the BBSB and adjacent areas.
Tin-bearing greisen occurs close to the margins of the BBSB in the Late Permian to Early Triassic Dumboy Gragin Granite. These occurrences have not been investigated in any detail.

General Assessment Criteria
1. Distribution of S-type or I-type, fractionated, felsic and reduced granites.
2. Magnetic lows on the aeromagnetics.
3. Presence of mineral occurrences of tin greisens.
4. Presence of mineral occurrences and/ or deposits of tin veins
5. Proximity of known occurrences of alluvial tin.

Economic Significance
According to grade/tonnage models for tin greisen deposits, 90% of deposits contain at least 0.8 Mt of ore, 50% at least 7.2 Mt and 10% at least 65 Mt. In these types of deposits, 90% contain at least 0.17% Sn, 50% at least 0.28% Sn and 10% at least 0.47% Sn (Cox and Singer 1986).

Sn2: ALLUVIAL TIN
(Model 39e of Cox and Singer 1986)

Model Description
Description of the model after Reed (1982).

Description: Cassiterite and associated heavy minerals in silt- to cobble-size nuggets concentrated by the hydraulics of running water in modern and fossil streambeds.

General References: Hosking (1974), Taylor (1979), Sainsbury and Reed (1973).

Geological Environment

Rock Types: Alluvial sand, gravel, and conglomerate indicative of rock types that host lode tin deposits.

Textures: Fine to very coarse clastic.

Age Range: Commonly Tertiary to Holocene, but may be any age.

Depositional Environment: Generally moderate to high-level alluvial, where stream gradients lie within the critical range for deposition of cassiterite (for instance, where stream velocity is sufficient to result in good gravity separation but not enough so the channel is swept clean). Stream placers may occur as offshore placers where they occupy submerged valleys or strandlines.

Tectonic Setting(s*)*: Alluvial deposits derived from Palaeozoic to Cainozoic accreted terranes or stable cratonic fold belts that contain highly evolved granitoid plutons or their extrusive equivalents. Tectonic stability during deposition and preservation of alluvial deposits.

Associated Deposit Types: Alluvial gravels may contain by-product ilmenite, zircon, monazite, and, where derived from cassiterite-bearing pegmatites, columbite-tantalite. Economic placers are generally within a few (<8) kilometres of the primary sources. Any type of cassiterite-bearing tin deposit may be a source. The size and grade of the exposed source frequently has little relation to that of the adjacent alluvial deposit.

Deposit Description

Mineralogy: Cassiterite; varying amounts of magnetite, ilmenite, zircon, monazite, allanite, xenotime, tourmaline, columbite-tantalite, garnet, rutile, gold, sapphire, and topaz may be common heavy resistates.

Texture/Structure: Cassiterite becomes progressively coarser as the source is approached; euhedral crystals indicate close proximity to primary source. Where a marine shoreline intersects or transgresses a stream valley containing alluvial cassiterite the shoreline placers normally have a large length-to-width ratio.

Ore Controls: Cassiterite tends to concentrate at the base of stream gravels and in traps such as natural riffles, potholes, and bedrock structures transverse to the direction of water flow. The richest placers lie virtually over the primary source. Streams that flow parallel to the margin of a tin-bearing granite are particularly favourable for placer tin accumulation.

Geochemical Signature: Anomalously high amounts of Sn, As, B, F, W, Be, W, Cu, Pb, Zn. Panned concentrate samples are the most reliable method for detection of alluvial cassiterite.

Examples

South East Asian tin fields	Hosking (1974), Newell (1971), Simatupang et al. (1974), Westerveld (1937).

Known deposits and prospects in the BBSB and adjacent areas.
Only a few minor deposits of alluvial tin occur close the margins of the BBSB in the Warialda area, however it is plausible that more significant placer deposits could occur beneath adjacent basalt, as is common in other parts of the NEFB.

In the Copeton Group of deep leads east of the BBSB, two main levels of intrabasaltic alluvials containing cassiterite and diamonds were worked. The economic layers were overlain by a subeconomic, fine-grained sandy layer. In the Tingha-Gilgai area deep leads range in depth from several metres to fifty metres. Most deep leads are capped by thick strongly weathered to fresh basalt, shallow to deep basaltic soil and in many places by surficial concretionary laterite/bauxite (Brown and Stroud 1997).

Alluvial tin has also been recovered east of Dubbo, however production was small and the occurrence is not considered likely to be economically significant.

General Assessment Criteria
1. Presence of rocks, containing or with a potential for, tin
2. Distribution of tin vein and greisen deposits.
3. Distribution of alluvial tin prospects and deposits.
4. Distribution of Tertiary sediments deposited by ancient streams, rivers, lakes and swamps, in the vicinity of 1,2,3.
5. Distribution of Tertiary basalts in the vicinity of 1,2,3.
6. Distribution of Quaternary sediments deposited by ancient streams, rivers, lakes and swamps in the vicinity of 1,2,3.

Industrial Mineral Deposit Models

REE: RARE EARTH ELEMENTS

General Discussion.
Factors controlling the presence and distribution of elevated background rare earth elements (REE), such as occurs within the fractionated trachyte at Toongi are not well understood, which precludes a detailed description of model parametres. However, some general inferred controls have been used for tract delineation, such as mapped and inferred intrusive stocks and units of similar age, tectonic setting, geochemistry, magnetic and radiometric signature to the host trachyte at Toongi. There may be an association of the Toongi deposit to the tectonic setting and style of elevated REE in carbonitites.

The trachyte at Toongi is dated at 184+–19Ma (fission track dating F.L.Sutherland pers comm to P. Downes, 1998). It is highly fractionated, and has undergone significant carbonate, chloritic, potassic, and argillic alteration. It has probably been emplaced as part of the extensive Eastern Australian Alkaline Volcanic Event, to which the Garrawilla Volcanics (Pratt 1998) also belong.

Mesozoic intrusives are widespread in the BBSB, ranging in age from at least the Late Triassic (eg Twelve Mile Hill) to the Early Cretaceous (eg Mount Binalong, Pratt 1998), and occur over a wide range of depths in the subsurface (Pratt 1998, Slater and McEvilly 2001). They also exhibit a wide range of geochemical affinities and ages (Pratt, 1998, Scheibner and Basden, 1998). Tertiary intrusives are also widespread, both aerially and in the subsurface, especially in the vicinity of the Liverpool Ranges, the Warrumbungle Igneous Complex, and the Nandewar Volcanic Complex (Slater and McEvilly 2001). These rocks also exhibit a wide range of geochemical affinities and ages (Pratt, 1998). However with regards to inferred Mesozoic and/or Tertiary intrusives with no surface expression, these have generally not been included in the REE tract, due to the known wide range in Mesozoic and/or Tertiary intrusive geochemisty, varying depths beneath the surface, lack of understanding of controls with regards to elevated background level of REEs, and the wide range of ages of these intrusive bodies. Furthermore, at present it is in most cases not possible to delineate Mesozoic from Tertiary age intrusives in the subsurface. On the surface, rocks of Mesozoic and Tertiary age can be delineated through age dating, field and petrological associations, and radiometric signature.

For the purpose of this study, it is considered that intrusive rocks related to the East Australian Alkaline Event in the Mesozoic which do not outcrop have limited exploration and mining potential for REEs, and have not been included in the tract. The sole exception to this is subcropping Mesozoic intrusive rocks in the immediate area of known high background REE intrusive bodies in the area around Toongi in the far south western BBSB.

Outcropping Tertiary intrusives have also not been included in the tract, however it is possible that magmatic, tectonic or other processes which led to high background levels of REE in the Jurassic Toongi Trachyte, could also occur in Tertiary age intrusive stocks.

It is noteworthy that Scheibner and Basden (1998) mention that the metallogenic significance of intraplate igneous activity of the Jurassic-Cretaceous in Eastern Australia has not been properly assessed. Layered cumulates and other mineral deposit styles which could be associated with these types of rocks have thus not been included for this study.

General References
Australian Zirconia Ltd (2001), Scheibner and Basden (1998), Veevers (2000).

Known deposits and prospects in the BBSB and adjacent areas.
A large resource of rare earth elements (REE) has been delineated close to the margins of the BBSB, about 25km south of Dubbo at Toongi. This project (the Dubbo Zirconia Project) is currently at an advanced stage of assessment. An indicated and inferred resource of 83 Mt at 1.91% ZrO_2, 0.041% HfO_2, 0.448% Nb_2O5, 0.027% Ta_2,O_5, 0.138% Y_2O_3, 0.720% REO has been identified, which represents a world class resource of REE (Australian Zirconia Ltd 2001). The Toongi REE deposit has comparable tonnages and REE grades to major deposits of REE in carbonitites elsewhere in the world (Cox and Singer 1986).

Examples
Toongi, NSW (Australian Zirconia Ltd, 2001).

Sapp: ALLUVIAL SAPPHIRE
(partially based on model 39d of Cox and Singer 1986)

Model Description
Description of the model after Cox in Cox and Singer (1986).

Approximate Synonym
sapphire placers, placer gemstones.

Description

Sapphires and other gemstones in alluvial sediments.

General References
Pecover (1992), Coenraads et al (1990), Pecover (1988).

Geological Environment
Rock types
Sand and gravel alluvial deposits. Conglomerate beds may contain palaeoplacers.
Textures
Coarse clastic
Age range:
Commonly Tertiary to Quaternary, but may be any age.
Depositional environment:
Streams draining areas of mantle derived igneous intrusives with associated sapphire bearing pyroclastic rocks.
Tectonic setting(s):
Accreted fold belts
Associated deposit types:
placer gold, placer tin, placer PGE.

Deposit Description
Mineralogy:
Sapphire of inky blue to green and yellow parti-coloured associated with zircon and other heavy minerals. Diamonds may also be present in New England Fold Belt.
Texture/structure:
Sapphire and zircon as subhedral to euhedral crystals often with glossy crystal faces in Tertiary alluvial sediments but more abraided in Quaternary sediments.
Ore controls:
Sapphire is concentrated in low energy parts of stream systems with other heavy minerals. Sapphires decrease in size and increase in quality with distance from source.
Weathering
N/a
Geochemical signature:
N/a

Examples

Kings Plains, NSW	Brown and Pecover 1986, Johnson, 1996

Known deposits and prospects in the BBSB and adjacent areas.
Few alluvial sapphires have been recovered within the BBSB. However large resources of alluvial sapphire have been mined from reworked Tertiary volcaniclastic units in the Kings Plains area about 100 km east of the BBSB, and this same volcanic province (the Central Volcanic Province) extends westwards into the northern parts of the BBSB in the Warialda-Yallaroi area. Similar volcaniclastic units to those which source the Kings Plains deposits are also known to occur close to the margins of the BBSB, albeit in limited extent. However, the level and rate of erosion in the Warialda-Yallaroi area is less than has occurred in the Kings Plains area, and it is plausible that the extensive basalt flows in the northern part of the BBSB could conceal buried sapphire-bearing tuffs and alluvial palaeochannels.

Of note is the recent recognition of Tertiary age volcaniclastic units in the Liverpool Range area. These have not been previously assessed for gemstone occurrences. Furthermore, a large ruby and sapphire resource has been delineated south-east of the BBSB near Scone, which previously had little prior gemstone production. This discovery highlights the potential for previously unknown alluvial gemstone fields in Tertiary to Quaternary sediments within the BBSB.

Opal: WEATHERED PROFILE-HOSTED OPAL

Model Description
Description of the model after Senior (1998), and Watkins (1985).

Approximate Synonym

N/a
Description
Opaline silica deposited within a weathered profile which is dominantly kaolinitic with silicified and ferruginous components.
General References
Bird and Chivas (1993), Senior (1979), Darragh et al (1966), Watkins (1985), Pecover (1999).

Geological Environment
Deep chemical weathering in kaolinitic weathered profiles, with influence from local and regional structures (Senior 1998). In GAB (Great Australian Basin) opal within 20m of current land surface. Coastal plain to shallow marine setting.

Textures:
Infilling of cavities (nobbies) and replacement (fossils). Nobbies often show concentric zoning.

Age range: In GAB Late Cretaceous to Early Cainozoic weathering developed on Cretaceous rocks within the Eromanga and Surat (Sub) Basins.

Depositional environment:
In GAB opaline silica which has accumulated in host rocks of Cretaceous age within open spaces associated with vertical and lateral permeability barriers (Senior 1998). Bedding discontinuities may also be important (Pecover, 1999). Source of silica debated: presence of sandstone as a source of colloidal silica, with vertically enhanced permeability, and suitable depositional sites (Watkins 1985). A biogenic origin for the silica has also been proposed (Watkins pers. comm. 2001).

Tectonic setting(s):
Stable deeply weathered environments.

Associated deposit types:
Kaolin, silcrete.

Deposit Description
Mineralogy:
opaline silica+-gypsum+-alunite+-hollandite.

Texture/structure:
A meniscus, flow structures and colour layering shown by some specimens indicate a sequential process of infilling followed by dehydration of a silica gel, which hardened into opal.

Alteration:
Intense kaolinisation, minor ferruginisation, zonation of Fe, Si02, and Al oxides frequently present, upper portion of profile usually stongly indurated. Ferruginisation may increase toward the basal one third of the profile, particularly in the Queensland (Winton Formation) deposits.

Ore controls:
Deposits occur in or near faults or joints, or in cracks induced through swelling of former smectite clays. Opal entrapment sites lie close to former groundwater permeability barriers (Senior 1998). A biogenic component has also been proposed (Watkins pers.comm. 2001). In GAB, rocks are Cretaceous age.

Weathering:
See alteration

Geochemical signature:
n/a

Examples
Lightning Ridge, NSW (Watkins, 1985)

Known deposits and prospects in the BBSB and adjacent areas.

No weathered profile-hosted precious opal occurrences in the BBSB have been recorded. The Lightning Ridge Opal Field occurs to the west of the BBSB hosted by the Early Cretaceous Rolling Downs Group, which is also believed to underlie alluvial cover in the northern parts of the BBSB. Conditions favourable for the formation of weathered profile-hosted precious opal occurrences could have occurred within Cretaceous Rolling Downs Group rocks in the BBSB, at present mostly concealed beneath alluvial cover.

Volcanic opal is known to occur within and near to the margins of the BBSB near Mount Kaputar and Toorooweenah, although these occurrences are not considered economically significant.

General Assessment Criteria

1. Presence of exposed Early Cretaceous age sedimentary rocks.
2. Inferred Early Cretaceous under cover.
3. Presence of inferred Early Cretaceous bedrock, (especially possible equivalents of the Wallangulla Sandstone Member), above a Finch Clay facies ie an impermeable bed within a sandstone unit (not assessed for tracts).
4. Presence of local structures and photolineaments, especially intersections of photolineaments (not assessed for tracts).
5. Absence of silcrete, (prevents prospecting), however the presence of silcrete also enhances prospectivity (not assessed for tracts).
6. Depth of alluvium less than 5m. (prevents prospecting). Also, thicker alluvium is likely to be present in topographic lows, which are also areas likely to be less silicified, or to have escaped silicification processes, which are also considered to be important for the formation of opal at Lightning Ridge in the Early Tertiary (Watkins 1985). (Not assessed for tracts).
7. Vegetation trends (particularly box trees), and discernible lines of trees parallel to lineaments (not assessed for tracts).
8. Biogenic component (not assessed for tracts).

Dia: ALLUVIAL DIAMOND
(Model 39d of Cox and Singer 1986)

Model Description
After Cox in Cox and Singer (1986).

Description: Diamonds in alluvial units, beach sediments, sandstone and conglomerate.

General References: Barron et al. (1996), Pecover (1988), Sutherland (1982).

Geological Environment

Rock types: Sand and gravel in alluvial and beach deposits. Conglomerate units may contain palaeoplacers.

Textures: Coarse clastic.

Age Range: Tertiary and Quaternary.

Depositional Environment: Streams draining areas of lamproite pipes or other mantle derived igneous intrusives or diamond concentrations in sedimentary or metamorphic rocks. Alluvial diamond deposits may be 1,000 km from source. Some diamonds may have been derived from Palaeozoic or older fold belts associated with subduction.

Tectonic Setting(s*)*: Stable craton, accreted fold belts.

Associated Deposit Types: Primary diamond pipe deposits, alluvial gold, alluvial tin, alluvial gemstones

Deposit Description

Mineralogy: Diamond, bort or carbonado (polycrystalline, generally dark coloured), ballas (spherulitic, polycrystalline and amorphous carbonado).

Texture/Structure: Diamonds derived from ancient placers in sedimentary rock commonly retain sand grains cemented to grooves or indentations in the crystal.

Ore Controls: Diamonds are concentrated in low-energy parts of stream systems with other heavy minerals. Diamonds decrease in size and increase in quality (fewer polycrystalline types) with distance from their source.

Geochemical Signature: Diamond: Cr, Ti, Mn, Ni, Co, PGE, Ba. Anomalous Ni and Nb together with the heavy minerals pyrope, Mg-ilmenite, and phlogopite indicate nearby kimberlite pipes.

Examples

African deposits	Sutherland 1982
Venezuelan deposits	Fairbairn 1971, Reid and Bisque 1975
Bow River Alluvials, Australia	Fazakerley 1990

Known deposits and prospects in the BBSB and adjacent areas.
Within a distance of 40 kilometres of the margins of the BBSB are 3 areas of significant alluvial diamond production; namely the Bingara, Copeton and Cudgegong Diamond Fields. Historical production of diamonds from these fields and their extensions is in excess of 236,000 carats (MacNevin 1977; and Brown and Stroud 1997). Alluvial diamonds have been recovered within the BBSB itself east of Narrabri at several localities, although production was not significant. A small operating alluvial diamond mine is present at Monte Christo in the Bingara area, about 25km east of the BBSB, with production since 1998 of the order of several thousand carats.

The Bingara Diamond Field lies about 25km east of the BBSB with recorded production of at least 34,000 carats between 1872-1904 (Brown and Stroud 1997). Alluvial gold was also present in payable quantities in places, notably in reworked Holocene alluvial flats and stream beds derived from the Tertiary leads. The host for the diamonds include Tertiary deep leads, unroofed Tertiary gravels and minor volumes of redistributed alluvials. Average size of the diamonds is small (0.20 carat), with gem proportion high. Corundum, zircon, and tourmaline are also present in varying concentrations in the Tertiary leads (Brown and Stroud 1997). Clast compositions indicate that the Central Block was the provenance of the Bingara diamond-bearing gravels. The original diamond source is believed to be located west of the Peel Fault, possibly within kilometres of the Bingara Diamond Field itself (Brown and Stroud 1997).

The Ruby Hill volcanic pipe near Bingara, located about 40km the east of the BBSB, contains eclogite rock fragments (MacNevin 1977) indicating deep crustal to mantle derivation where diamonds are thought to form. However no diamonds have been reliably recorded from within the pipe.

The Copeton Diamond Field lies roughly 35km from the closest margin of the BBSB where rich (3.3 to 12 carats/cubic metre of gravel, Brown and Stroud 1997) diamond deposits were discovered in 1872 and mined in association with tin from 1884-1922. Recorded diamond production was over 200,000 carats but mining in general was not very profitable. A high proportion (90% approx) of the diamonds is of gem quality but they are relatively small. They are found in Tertiary boulder beds, gravels and sands, and Quaternary river/creek gravels within and bordering the Copeton Dam (Brown and Stroud 1997).

Small scale open cut mining of remaining resources at old mine sites at Copeton such as Streak of Luck, Doctors Workings and Round Mount and Mount Ross on the east side of the Copeton Dam commenced in 1996. Airborne electromagnetic geophysical anomalies in the area suggest the presence of possible volcanic centres hidden beneath basalt lavas.

MacNevin (1975) suggests the deep leads at Copeton form part of a once continuous Tertiary stream system with primary diamond sourced from concealed or eroded diatremes originating from deep seated magma sources. Brown and Stroud (1997) and MacNevin (1977) refer to dolerite dykes and “plugs” in the deep leads of the Copeton field as possible primary diamond sources.

The Cudgegong Diamond Field is mostly located in the buffer zone about 10km south of the BBSB and was discovered in 1867 during the course of gold mining operations, with Tertiary deep leads and minor redistributed Holocene sediments worked mostly between 1869-1870 (MacNevin 1977). Total recorded production of the field is of the order of 2000 carats (MacNevin 1977). Diamonds have historically been

recovered in the area from near the junction of Wyaldra Creek and the Cudgegong River, to a point about 11 kilometres downstream. Diamonds have also been recovered from the Macquarie-Turon River system in this region (MacNevin 1977).

The diamonds in the Cudgegong Diamond Field average 0.23 carats in weight, with historical reports indicating a relatively high proportion as gem quality (Platsearch NL, 1996). The primary source is believed to be ''not far removed'' from the leads themselves due to a number of factors, including clast composition, and the diamonds themselves being little water-worn and seldom fractured (MacNevin 1977). At least 2 mantle-derived diatremes, informally named the Winona and Walker Vents, have been identified to the north-east of the Cudgegong Diamond Field from contemporary exploration, although no diamonds have been recovered from these diatremes (Platsearch NL, 1996). Mantle indicator minerals have also been found in streams in this general area.

Hard-rock diamonds found in Eastern Australia do not appear to fit into traditional models for diamond formation. A relatively new model of diamond formation has been proposed for Eastern Australia, which advocates a subduction related origin (Barron et al. 1996).

Zeo: ZEOLITE

Model Description
Description of the model after Pecover (1987) in Homes and Pecover (1987), and Flood (1993).

Approximate Synonym
Natural zeolites

Description
Naturally occurring crystalline hydrated aluminosilicates containing positively charged metallic ions (cations) of the alkali and alkaline earth elements within three-dimensional crystal frameworks.

General References
Homes and Pecover (1987), Flood (1993).

Geological Environment
Varied. In the New England Fold Belt Late Carboniferous vitric ash fall tuffs deposited within lacustrine, fluvial overbank, and shallow marine environments appear to have the highest zeolite content.

Textures: n/a

Age range: Most are Cainozoic on a world scale, but they can be older. Their physio-chemical instability renders them unlikely to be older than Palaeozoic. In the New England Fold Belt the highest concentration of zeolite-rich rock appears to be in the continental to marine Late Carboniferous sequence, which are amongst the oldest known economically viable zeolite-rich rocks in the world. Zeolitic pyroclastics within the Currububula Formation appear to have highest prospectivity (Flood, 1987).

Depositional environment:
Varied. In the New England Fold Belt Late Carboniferous vitric ash fall tuffs deposited within lacustrine or similar environments appear to have highest zeolite content. Welded and non welded ignimbrite ash-flow units and ash-flow tuffs show evidence of having contained high vitric contents at the time of their deposition. Alteration of these vitric components to zeolite minerals appears to have occurred mainly in the non-welded ash-flow pyroclastic units and in ash-fall tuffs. Factors which have influenced the formation of zeolite include the porosity of the original host and the availability of water during and after emplacement (Flood 1987).

Tectonic setting(s):
Varied. In NEFB active continental margin arc (both fore-arc and back-arc)

Associated deposit types:
Epithermal Au-Ag

Deposit Description

Altered volcanic ash-flow units and tuffs.

Mineralogy:
Zeolite minerals which are most widely used in industry and agriculture are: clinoptilolite, mordenite, chabazite, phillipsite, and erionite.

Escott Mine: Ca-type clinoptilolite (formerly thought to be heulandite)>>modenite+-quartz+-albite+-sanidine (Flood and Taylor 1991).

Texture/structure:
N/a

Alteration:
N/a

Ore controls:
In NEFB high vitric content of original ash-flow units. Style of eruption, porosity of the original host, and the availability of water during and after emplacement (Flood, 1987). Burial and metamorphic history (Homes and Pecover, 1987).

Weathering:
N/a
Geochemical signature:
N/a
Examples
Escott (NSW).

Known deposits and prospects in the BBSB and adjacent areas.
Extensive zeolite deposits occur in a number of localities close to the margins of the BBSB, especially about Quirindi and Boggabri. An operating mine (Escott) is hosted by the Late Carboniferous Currububula Formation within the buffer zone in the Werris Creek area. Other prospects in the BBSB include Wingen, Castle Mountain, The Gap, Z4 (buffer). Prospects have been identified west of Bingara also. Favourable units include the Currubulla Formation, the Lark Hill Formation, the Clifden Formation, the Rocky Creek Conglomerate, and the Ermelo Dacite Tuff.

Zeolite minerals are also known to occur as alteration products in trachyte compositional pyroclastic rocks associated with Tertiary diatomite deposits in the Barraba and Coonabarabran areas. Zeolites also occur within basic tuffs and lavas associated with Triassic, Jurassic, and Tertiary volcanics occurring in the Warrumbungle and Liverpool Ranges (representing possible “hydrothermal alteration-type deposits”) (Homes and Pecover 1987). These types of zeolite deposits are not considered likely to be economically prospective and have not been assessed.

HMS: HEAVY MINERAL SAND (FLUVIAL AND BEACH PLACER)
(partially based on model 39C of Cox and Singer 1986)
Model Description
Description of the model after Whitehouse et al (1999), Roy (1999), and Cox and Singer (1986). Model incorporates both alluvial and beach placers.

Approximate Synonym
Shoreline placer Ti, alluvial placers

Description
Ilmenite, rutile and zircon, concentrated by beach and alluvial processes and altered by weathering.

General References
Whitehouse et al (1999), and Roy (1999).

Geological Environment
Age range:
Commonly Miocene to Holocene, but may be any age.

Depositional environment:
Eroding coastal region receiving sediment from either deeply weathered igneous and metamorphic terranes of sillimanite or higher grade, or eroding fluvio-deltaic or shoreline facies basin sediments. Alluvial placers in point bars and backplains, receiving sediment from similar sources.
Tectonic setting(s):
Margin of craton. Crustal stability during deposition and preservation of deposits. In Murray Basin crustal instability (eg growth faults) an important component.
Associated deposit types: placer gold, placer tin, placer PGE.

Deposit Description
Mineralogy:
Altered (low Fe) ilmenite +- rutile +- zircon. Trace of monazite, magnetite, and pyroxene, amphibole rare or absent. In beach placers feldspar absent.
Texture/structure:
elongate "shoestring" ore bodies parallel coastal dunes and beaches. Lensoidal and discontinuous ore bodies in fluvial placers.

Ore controls:
High grade metamorphic source. Eroding coastline with efficient sorting and winnowing; weathering of beach deposits. In fluvial/alluvial placers eroding fertile bedrock with low admix of alluvium sourced from barren sources.

Weathering:
Leaching of Fe from ilmenite and destruction of labile heavy minerals results in residual enrichment
Geochemical signature:
high Ti, Zr, REE, Th, and U. Gamma radiometric anomalies resulting from monazite content. (Monazite content generally too low in Murray Basin, although monazite content in Cretaceous high enough to be effective (Whitehouse pers. comm. 2001). Aeromagnetic anomalies useful for ilmenite in Murray Basin. Induced polarisation anomalies from ilmenite.

Examples
Murray Basin, NSW, Vic, SA (Whitehouse et al 1999)

Known deposits and prospects in the BBSB and adjacent areas.
Relatively high concentrations of heavy mineral sands (HMS) have been intersected in reconnaissance drilling in Tertiary to Quaternary alluvium in the BBSB, particularly in the Bohena Creek area, sourced from the Early Cretaceous Keelindi beds, and possibly the Early Cretaceous Drildool beds and the Late Jurassic-Early Cretaceous Pilliga Sandstone. However these HMS accumulations are spasmodic, lensoidal and fluviatile in origin, and are perceived to be less likely to be present in continuity compared to those which have formed under shoreline (coastal) conditions, and thus less likely to be economically viable.

Potential exists for economic concentrations of HMS in beach placers deposited during marine incursions in the Great Australian Basin, such as occurred in the Early to Late Early Cretaceous Bungil Formation, Keelindi beds and Warrumbilla Formation. However it is also noted that possible consolidation of these sediments would present difficulties in the extractive process. Heavy mineral sands have also been noted to occur in horizons within rock units of the Tamworth Belt of the New England Fold Belt, close to the margins of the BBSB. These occurrences have not been investigated in any detail.

Economic Significance
HMS are a significant source of rutile, zircon, and ilmenite. In the Murray Basin of SE Australia, the in situ value of HMS has been estimated at up to $14 billion (AUD2000) (Whitehouse et al 1999).

Kao: KAOLIN

Model Description
Model modified after Hora (1992).

Synonyms:
Primary kaolin, residual kaolin, secondary kaolin, ball clay, flint clay, fire clay, halloysite.

General References:
Harben and Bates (1990).

Geological Environment:
Rock types:
Kaolinised feldspathic rocks, ranging in composition from granites to diorites with their volcanic equivalents. Secondary alluvial kaolinitic clays.

Age Range:
Can be any age. In the southern BBSB economic deposits have been identified within the Jurassic sequence, and transported deposits have been mined in the Tertiary sequence to the south of the BBSB, sourced from weathered granite.

Tectonic Setting:
Down-faulted sedimentary basins; stable deeply weathered environments for residual deposits.

Depositional Environment:
Interior basins and flat alluvial plains with basement composed of feldspathic rocks. Alteration of feldspathic rocks by hydrothermal and/or residual weathering. Also feldspathic volcanic rocks may be the host for kaolin deposits, particularly where faults may provide the channels for circulating ground waters. Secondary alluvial clays eroded from primary deposits laid down in river channels and lakes.

Associated deposit types:
Fireclay, bentonite, coal, ceramic and cement shales.

Deposit Description
Mineralogy:
kaolin, quartz, feldspar, with minor biotite and hornblende.

Alteration mineralogy: n/a

Ore controls:
Unconformity and fractured basement rocks.

Examples:
Merrygoen Loughnon and Higgins (1973)

Known deposits and prospects in the BBSB and adjacent areas.
Flint clay has been mined in the Merrygoen area intermittently since about 1950. The clays of economic interest so far exploited in the area are confined to the Jurassic sequence in the vicinity of Merrygoen and Dunedoo (Markham and Basden 1974). Flint clay also occurs within the Permian and Triassic sequences, which are perceived to be of lower prospectivity (Loughnon and Higgins 1973). Flint clay has also been mined near Gunnedah from within the Early Permian Leard Formation (Pratt, 1998).

Tertiary sediments in the BBSB could host transported kaolin, derived from granite, as occurs in the Gulgong area to the south of the BBSB. The Gulgong area also contains a number of residual kaolin deposits hosted within the Ulan Quartz Monzonite, and similar residual deposits could occur in other granites within the BBSB. High quality kaolin as clay cement within friable sandstone also occurs within the Grose Sandstone at Lithgow, however this type of kaolin resource has not been assessed in the BBSB due to lack of available data.

Construction Materials

Const: CONSTRUCTION MATERIALS AND DIMENSION STONE

Model Description
J.W.Brownlow, R.G.Barnes, and G.P.MacRae (pers.comm. 1999), Geological Survey of New South Wales.

Definitions
Construction materials are naturally occurring, low unit value commodities which are generally exploited in bulk and with limited processing for use in civil construction. Transport costs contribute significantly to the delivered cost of construction materials and, therefore, it is important to obtain such materials as close as possible to markets. Increased transport costs associated with the need to use more distant resources result in increased raw material costs which are inevitably passed on to the consumer. Their use in construction, road building and related uses is an integral part of modern urban living and therefore supplies need to be assured for sustained development.

Approximate Synonyms
The term extractive resources is used as a synonym for construction materials, particularly in the sense of resources not covered by mining legislation.

Various terms are used for construction aggregates depending on size and specific use. Such terms include hard rock aggregate, coarse aggregate, crushed and broken stone, rip rap, decorative aggregate, prepared road base, fine aggregate, construction sand, sand and gravel, river stone, shingle. Note that some of these terms describe products (e.g., coarse aggregate, fine aggregate, construction sand) whereas others describe geological units (e.g. gravel and sand) or a combination of geological units and materials (e.g. hard rock aggregate).

Descriptive terms for clays used in construction include clay/shale, structural clay, brick clay, low cost clay, stoneware clay, pipe clay, terra cotta clay.

Dimension stone is also referred to as building stone, ornamental stone or monumental stone depending on its end use.

General References
Carr (1994), Holmes et al (1982).

Deposit Descriptions (in the BBSB)
Hard rock aggregate: In the BBSB, the main types of rock used for hard rock aggregate are Tertiary and Mesozoic basalt.

Construction sand: In the BBSB, the main source of construction sand is in various floodplain deposits.

Clay/shale: The main source in the BBSB is weathered fine grained rock types such as shale or mudstone.

Assessment Criteria
Quarrying operations in the BBSB are spatially associated with transport routes and main population centres. The most prospective rock types in the BBSB are those close to major transport routes and close to significant population centres.

Distance from existing roads is an important criteria in assessing the development potential of any particular site. Transport to markets is generally by truck and therefore requires road linkage from the quarry to markets. Building new access roads is expensive, and may not be economically justified. Generally, larger quarries producing higher value products are more likely to warrant the construction of longer, better quality new roads. These considerations have been incorporated into a land access rating based on distance from existing roads (see Table 1). Gaining legal transport access to a site and appropriate development consent for any needed road development/ upgrading are preconditions to developing suitable access roads to quarries. Thus upgrading of an existing road might be far easier than developing a new one. This reinforces the importance of proximity to existing roads emphasised in Table 14 (chapter 8).

Road networks are important for construction materials as they provide transport routes to population centres where most construction materials are consumed. Road density in a given area reflects the population density and consumption of materials.

The AUSLIG Geodata road data set has been used for modelling. This road data has been classified and buffered as shown in Table 14 (chapter 8).

Economic Significance
The value of mineral production for quarrying and mining for industrial minerals and construction materials in the BBSB is estimated at $15.23 M for the 2000-2001 financial year (Royalty Branch, Department of Mineral Resources). The actual value of production is greater than the amount reported because some operations (particularly construction material quarries) have not provided data to the Department.

Construction material production was made up of crushed and broken stone (coarse aggregate) at $9.78M, construction sand at about $0.348M, clay/shale at about $105,000, loam $10,255, river gravel $403,000, and unprocessed construction materials at $4.574M.

APPENDIX 3 DETAILED RESOURCE ASSESSMENT OF THE NORTHERN WESTERN COALFIELD

The term "resources" is used to refer to all in-situ coal, which has potential for use. Recoverable reserves have been determined, in allocated areas (areas held under title by exploration and mining companies) only, from measured and indicated resources and also from the potentially mineable in-situ tonnages. Marketable reserves are those tonnages that will be available for sale.

The terminology used in this chapter and other chapters dealing with the economic aspects of coal differentiate between the geological unit which carries a formal stratigraphic name e.g. Ulan Coal, Turill Coal Member etc. and the contained potentially economic section or seam.

Coal, generally, is considered to be a resource for underground mining when it contains a potential working section greater than 1.5 m and the raw coal ash is less than 35%. Depending on economics of mining and coal prices, these limits may or may not be considered extremes and, therefore, should only be considered independent of each other.

Industry, in many instances in other coalfields, would consider 1.8 m to be the lower mining limit for a coal seam and would be likely to prefer coal with raw coal ash significantly less than 35% — except in the cement industry or where the coal contains some specifically desired characteristic. For example, Irondale seam coal with raw coal ash of as high as 35% is currently being mined in the Cullen Valley opencut mine and sold to the local electricity generating stations after blending with lower ash coal. In this study, a lower mining limit of 2.0 m has been taken as the most likely thickness for a coal seam for underground mining in the Ulan - Coolah Area.

Generally, the depth to the seam can be a limiting factor in the identification of resources under present and near future economic conditions. In practice, coal at depths in excess of about 600 m is not likely to be mined in the near future anywhere other than in the Southern Coalfield where the higher cost of deep mining is offset by the higher value of the coking coal product. The only part of the Ulan - Coolah Area where resources are at depths greater than 600 m is in the north east.

Coal is considered to be a resource for opencut mining when it contains a potential working section of 0.3 m or greater at a maximum linear overburden to coal ratio of 5:1 and a raw coal ash of less than 35%.

RESOURCE BLOCK A:

Resource Block A contains Ulan seam resources in an area of approximately 93 square kilometres surrounding the Ulan Mine in the north east, north and west. The resource in this block is generally at depths less than 300 m and the coal is potentially mineable by underground methods except along the south western subcrop zone where the Ulan seam is present at depths less than 50 m. The potentially mineable DWS of the Ulan seam is 2.5 to 3.5 m thick, averaging 3.0 m.

Raw coal ash for the DWS ranges from 10% to 20 % with a large part of the resource less than 15% Borehole coverage in this block is adequate to classify the resource as Indicated. It is estimated that the Resource Block A contains up to 390 Mt in the DWS of the Ulan seam of which some 12 Mt are present at depths less than 50 m in the south western subcrop zone and is amenable to open cut extraction. This area also contains approximately 5 Mt in the Moolarben seam at depths less than 50 m. Resources in this area are most probably too small to be mined independently.

RESOURCE BLOCK B:

Resource Block B forms a natural northern extension to Block No. 1 with the exception that the potentially mineable Ulan seam is present at depths generally greater than 300 m but less than 450 m. This Resource Block occupies an area of approximately 100 square kilometres to the north of Ulan Mines. Borehole spacing in this area, although larger than in Block B, is generally adequate to consider the resource under the Indicated Category. The potentially mineable DWS of the Ulan seam is generally 3.4 m thick averaging 3.5 m and raw coal ash is generally high ranging from 25% to 30% but drops down to 20% in the north east. It is estimated that the Resource Block B contains up to 540 Mt in the DWS of the Ulan seam.

RESOURCE BLOCK C:

Resource Block C occupies approximately 66 square kilometres between Block B and the western subcrop zone. The potentially mineable Ulan seam is 2 – 3 m thick, averaging 2.8 m and is present at depths generally less than 300 m. Raw coal ash is at the 20% - 25% range.

It is estimated that the Resource Block C contains up to 270 Mt of Indicated Category in the DWS of the Ulan seam.

RESOURCE BLOCK D:

Resource Block D occupies approximately 230 square kilometres in the central area of the Ulan - Coolah Area. The coal resources in Block D are generally of similar thickness and quality to those in Block C but are present at depths greater than 300 m. The resource is progressively under thicker cover towards the north where it reaches some 550 m.
It is estimated that the Resource Block D contains up to 930 Mt in the DWS of the Ulan seam and is considered as Coal Insitu Category only because of the sparse borehole data available.

RESOURCE BLOCK E:

Resource Block E occupies approximately 112 square kilometres area north east of the Ulan Mine. This resource block contains high ash coal in the Ulan seam, generally ranging from 25% to 35% and from 1.5 m to 3.5 m, averaging only 2.2m in thickness and is present at depths generally between 300 m and 400 m. It is estimated that the Resource Block E contains up to 380 Mt in the DWS of the Ulan seam. The resource in this block is considered as Coal Insitu Category only because of the sparse borehole data available.

RESOURCE BLOCK F:

Located some 10 –20 kms east of the Ulan Mine, Resource Block F covers approximately 99 square kms and is bounded by the Goulburn River National Park in the east, south and south west. Raw coal ash of the potential working section of the Ulan seam in Resource Block F is high, generally ranging from 25% to 35% and thickness from 1.5 m to 3.5 m averaging only 2.2m. The seam is present at depths between 300 m and 400 m. It is estimated that the Resource Block F contains up to 415 Mt in the DWS of the Ulan seam. The resource in this block is considered as Coal Insitu Category because of the sparse borehole data available.

RESOURCE BLOCKS G and H:

Resource Blocks G and H occupy nearly 1000 square kms in the east and norteast of the Ulan - Coolah Area. The Ulan seam in these blocks generally has quality characteristics similar to that in Block D with raw coal ash ranging from 20 % to 25% but is progressively thicker and is present at greater depths (> 600 m) in the north and northeast. It is estimated that the Resource Blocks G and H may contain up to 5 billion tonnes in the potential working section of the Ulan seam. The resource in Blocks G and H is considered only as Coal Insitu Category because of the sparse borehole data available.

RESOURCE BLOCK I:

Resources within Block I have been the subject of extensive exploration since the late 1970's. A number of internal and unpublished reports, kept by the Department, provide detailed assessment of the resources within this Resource Block. Resource Block I is covered by Authorisations A428 and A309 and Ex CCL741, east of the Spring Gully Fault in the northern half (collectively known as East Ulan Area) and A449 (containing the Wilpinjong and Moolarben areas) in the south. The Goulburn River National Park defines the eastern boundary of A428 and A309 and the northern boundary of A449, the southern boundary of which is defined by the Munghorn Gap Nature Reserve. The Wilpinjong area in the eastern half of A449 contains a major resource present at very shallow depths in the Ulan seam amenable to open cut extraction. All other areas within this Block mainly contain deeper resource amenable to underground extraction methods only.

TABLE A3.1: COAL RESOURCES AND RESERVES WITHIN THE COLLIERY HOLDINGS AND COMPANY AUTHORISATIONS IN THE ULAN - COOLAH AREA (2000-2001)

Colliery	In-situ Resources (Mt)	Recoverable Reserves (Mt)	Marketable Reserves (Mt)	Mining Method
Ulan	325	226	195	LW+O/C
A287 & A342	163	106		U/G*
Total	488	332		

LW = *Longwall mine* **O/C =** *Opencut mine* *U/G = *Proposed underground*

Source: Tadros and Armstrong (2002), *New South Wales Coal Industry Profile* (published by Department of Mineral Resources).

The Ulan seam resources in the Bioregion have, therefore, been divided into nine blocks based on a number of criteria such as thickness and quality characteristics of the potentially mineable section, its depth below surface and the level of confidence in continuity of its characteristics over long distances between boreholes.

TABLE A3.2: ULAN SEAM RESOURCES

(A) INDICATED/MEASURED RESOURCES

(million tonnes)

Resource Category	Block No.	Depth Range m	Thickness Range m	Average m	Ash Range %	Resource Million Tonnes
Indicated	A	< 300	2.5 - 3.5	3.0	10 - 20	391
Indicated	B	300 - 450	3.0 - 4.0	3.5	25 - 30	542
Indicated	C	< 300	2.0 - 3.0	2.8	20 - 25	269
Indicated/Measured	(I)	< 300	0.5 - 5.5	3.0	<20 - 35	624
	Total					1825

(I) See East Ulan - Moolarben - Wilpinjong Resources

(B) INFERRED INSITU COAL AND RESOURCES

(million tonnes)

Resource Category	Block No.	Depth Range m	Thickness Range m	Average m	Ash Range %	Resource Million Tonnes
Inferred	D	300 - 550	2.0 - 3.0	2.8	20 - 25	933
Inferred	E	300 - 400	1.5 - 3.5	2.2	25 - 35	381

Inferred	F	300 - 400	2.5 - 3.8	3.0	15 - 25	416
Insitu Inferred	G	350 - 600	2.0 - 3.5	3.0	20 - 25	2895
Insitu Inferred	H	> 600	3.5 - 6.0	4.5	20 - 25	2093
Inferred (Moolarben seam)	9	< 300	0.3 - 3.0	2.8	Dec-20	51
	Total					6770
Grand Total (A) + (B) 0 - > 600 m						8595

The easternmost part of the Wilpinjong area – named the Moolarben East area contains a small resource amenable to extraction by underground methods only.

Wilpinjong Open Cut Area (A449)

Within the Wilpinjong open cut area, three sections of the Ulan seam are potentially mineable, these are ULAWS, UB1C1 and CLEBT. The C-Marker (CMK), which separates the latter two sections, thickens from 0.3 to 2.8m toward the southeast. Accordingly, winning of the coal resources by open cut methods is likely to require the CMK to be separately mined.

The coal resource within the Wilpinjong open cut area has been determined by the 5:1 cumulative linear overburden ratio. A total resource for the upper (ULAWS) section has been calculated at 8.3 Mt. The total resources for the UB1C1 and CLEBT sections have been determined respectively at 42.8mt and 137.2Mt (table 3).

TABLE A3.3: WILPINJONG OPEN CUT RESOURCES

<5:1 CUMULATIVE LINEAR OVERBURDEN RATIO

ULAWS	<20% raw coal ash	(17.4% av)	0.50m av thickness	1.9mt
	20-25%	(22.4% av)	0.51m av. thickness	3.0mt
	25-30%	(27.3% av)	0.53m av. thickness	1.6mt
	30-35%	(31.9% av)	0.67m av. thickness	1.8mt
				8.3mt
UB1C1	<20% raw coal ash	(18.9% av)	2.1m av. thickness	3.9mt
	20-25%	(22.9% av)	2.4m av. thickness	31.4mt
	25-30%	(26.1% av)	2.38m av. thickness	6.8mt
	30-35%	(31.3% av)	2.45m av. thickness	0.7mt
				42.8mt
CLEBT	<20% raw coal ash			–
	20-25%	(24.9% av)	5.48m av. thickness	1.6mt
	25-30%	(28.1% av)	5.11m av. thickness	74.8mt
	30-35%	(32.0% av)	4.54m av. thickness	60.8mt
				137.2mt
	GRAND TOTAL			188.3mt

Moolarben West Area (A449):

The coal resources within the Moolarben West area are potentially mineable mainly by underground mining methods. A small resource potentially mineable by open cut methods, is present in three areas near the subcrop zone in the west.

Ulan Seam

The underground resource in this area is contained mainly in the DWS of the Ulan seam. The resource is estimated at 377.3 million tonnes as shown in table 5.

The available raw coal ash data indicates that the resource could be suitable for domestic power generation as a run of mine product. To produce an export thermal product (<12% ash), some level of beneficiation of the ROM coal would be required. The mix of export and domestic products would depend on the availability of suitable markets and the economics of the mining operation. Slim core washability testing suggests that beneficiation of a 20% ROM product coal could produce an export thermal product (<12%) and a domestic thermal middlings with minimal reject material. The entirety of the ROM coal could be marketed as a domestic thermal product without the requirement of beneficiation.

Moolarben Seam

A potential working section has been identified in the Moolarben seam. An in situ resource satisfying the parameters of less than 35% raw coal ash and greater than 1.5m is located within the Moolarben West area, covering approximately 21 square km. Within this area, the Moolarben Seam working section ranges in thickness from 2 to 3m and from 24 to 35% raw coal ash. The in situ resource has been estimated at 58mt and has been subdivided using appropriate raw coal ash ranges as shown in table 5. The raw coal ash values suggest that this resource would only be a marginal domestic thermal coal even with appropriate beneficiation.

TABLE A3.4: RESOURCES OF THE MOOLARBEN WEST UNDERGROUND AREA

ASH	12-15%	15-20%	20-25%	25-30%	30-35%	TOTAL
SEAM						
Moolarben	_	_	2.2	10.7	45.4	58.3
Ulan -UB1C1	_	_	11.2	128.9	38.3	178.4
Ulan -DWS *	62.4	134.2	2.3	_	_	198.9
TOTAL	62.4	134.2	15.7	139.6	83.7	435.6

** Preferred mining section*

Open Cut Resources:

Within the Moolarben West area, three separate potential open cut areas are present in close proximity to Moolarben Creek and referred to as Moolarben Creek open cuts no's 1 – 3. (tables 5-8). The resources are essentially restricted to sub-sections of the Ulan seam.

TABLE A3.5: RESOURCES OF THE MOOLARBEN CREEK OPEN CUT NO. 1

<5:1 CUMULATIVE LINEAR OVERBURDEN RATIO TO CLEBT

4. ASH	<20%	20-25%	25-30%	30-35%	TOTAL
SEAM					
ULAWS	0.39	0.07	-	-	0.46
UB1C1	-	-	0.58	0.95	1.53
DPEBT	3.38	2.84	-	-	6.22
CLEBT*	-	6.13	1.17	-	
TOTAL (indicated)	3.77	2.91	0.58	0.95	8.21

TABLE A3.6: MOOLARBEN CREEK OPEN CUT NO. 2

<5:1 CUMULATIVE LINEAR OVERBURDEN RATIO TO CLEBT

5. ASH	<20%	20-25%	25-30%	30-35%	TOTAL
SEAM					
UB1C1	-	-	<5		<5
CLEBT	-	-	<10	-	<10
TOTAL (inferred)			<15		<15

TABLE A3.7: MOOLARBEN CREEK OPEN CUT NO. 3

<5:1 CUMULATIVE LINEAR OVERBURDEN RATIO TO CLEBT

ASH	<20%	20-25%	25-30%	30-35%	TOTAL
SEAM					
ULAWS	2.0	-	-		2.0
UB1C1	-	-	5.3	-	5.3
DPEBT	10.8	0.1	-	-	10.9
CLEBT*	-	12.8	-	-	
TOTAL (indicated)	12.8	0.1	5.3	-	18.2

** Alternate section, not included in totals*

TABLE A3.8:COAL RESOURCES OF THE MOOLARBEN SEAM OPEN CUT AREA

<5:1 CUMULATIVE LINEAR RATIO LINE TO MOOLARBEN SEAM

ASH	<20%	20-25%	25-30%	30-35%	TOTAL
SEAM					
Moolarben	-	0.5	0.01	0.9	1.4
TOTAL	-	0.5	-	0.9	11.4

Moolarben East Area

The underground resources in the Moolarben East area are restricted to either the UB1C1 or DWS section. The latter section is regarded as the preferred mining interval.

The DWS section varies in ash from 16 to 25% with thickness of the nominated section ranging from 1.35m to 1.9m. The in situ resource potential for the DWS section has been estimated at 9.8mt and has been subdivided using appropriate raw coal ash ranges (table 9).

TABLE A3.9: COAL RESOURCES OF THE MOOLARBEN EAST UNDERGROUND AREA

DWS	15-20%	17.8% av. ash	1.8m av. thickness	5.8mt
	20-25%	21.5% av. ash	2.07 av. thickness	4.0mt
				9.8mt
UB1C1	Alternative Section	<25% raw coal ash		**12.9mt**

For the alternative UB1C1 section an in situ resource potential has been estimated at 12.9 Mt at less than 25% raw coal ash. The available raw coal ash values suggest that this resource would be suitable for domestic power generation with the possibility of a small tonnage suitable for use as an export thermal coal after beneficiation.

East Ulan Area

The East Ulan Area is covered by Authorisations A309, A428 and the Ex part of CCL741 on the eastern side of the Spring Gully Fault. Only the D section (DWS plus DTP) of the Ulan seam have been considered as potentially mineable in this area, for coal quality, mining and economic reasons. The DWS ranges in thickness from 2.8 to 3.2 m in A309, A428 and EX CCL 741. The DTP averages 0.3 m in thickness. Other seams in the area have no economic significance, being too thin, too variable or too high in raw coal ash. The coal resource is amenable to underground extraction only. The raw coal ash for the DWS is 14% with a maximum of 19%. Sulphur content ranges from 0.35 % to 1.1%.

Resources within A309 and those east of the Spring Gully Fault (Ex. CCL741) are considered within the Measured Category, while the resources in A428 fall into the Inferred Category. Table 10 summarises the coal resources for A 309, A428 and the area east of the Spring Gully Fault (Ex CCL741).

TABLE A3.10: COAL RESOURCES IN A309, A428 & CCL741 EX.
(million tonnes)

Area	Resource Category	Ply/ Seam Section	Thickness Average m	Ash %	6. RESOURCE Million Tonnes
A309	Measured	DTP	0.29	24.1	5
	Measured	DWS	2.99	15.2	45
	Measured	Total			50
A428	Inferred	DTP	0.30	20.1	5.12
	Inferred	DWS	2.89	12.3	46.24
	Inferred	Total			51
EX. CCL741	Measured	DTP	0.30	22.8	1.68
	Measured	DWS	2.99	13.3	15.68
	Measured	Total			17
Grand Total					118

Turill Seam

In 1983 as a part of the Goulburn River - Binnaway drilling program conducted by the Department of Mineral Resources, four boreholes intersected the medium to high ash 'Turill seam'. Two of the holes intersected potentially mineable coal that may be suitable for the domestic thermal market. One intersection showed significant coking properties but at a poor washing yield so the coal could only be marketed as domestic thermal coal. No meaningful estimate of resources is possible at this stage.

Coolah Seam

Four boreholes in the 1983 Goulburn River - Binnaway drilling program intersected a seam referred to as the Coolah seam. In two of the holes south east of Coolah, this seam, with an average thickness of about 1.75 m, had a raw ash content of < 20%. Some of the higher ash coal may only be suitable for the domestic thermal market. Further drilling may prove a mineable resource but at this stage it is not possible to give a meaningful resource estimate.

Gundangaroo Seam

Drilling conducted by the New South Wales Department of Mineral Resources in 1983 in the deeper northern parts intersected a seam 20 km south east of Coolah — referred to as the "Gundangaroo seam". In this single intersection the seam had a raw ash content of <10%. Should this seam be found to extend over sufficient area to prove mineable it could be sold on the export thermal market. No estimate of resources is meaningful at this stage.

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