Northern Territory Government

Geology and mineral resources of the Northern Territory

Ahmad M and Munson TJ (compilers)

Northern Territory Geological Survey
Special Publication 5

Chapter 36: Bonaparte Basin

BIBLIOGRAPHIC REFERENCE: Ahmad M and Munson TJ, 2013. Chapter 36: Bonaparte Basin: in Ahmad M and Munson TJ (compilers). *'Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey, Special Publicatio*n 5.

Current as of November 2012

Chapter 36: BONAPARTE BASIN

M Ahmad and TJ Munson

INTRODUCTION

The Bonaparte Basin (previously referred to as Bonaparte Gulf Basin, **Figure 36.1**) is a large, predominantly offshore, composite polyphase sedimentary basin, extending from onshore coastal areas along the NT–Western Australia border northward into the Timor Sea across Australia's continental margin. The basin covers an area of approximately 270 000 km^2, with the onshore portion being about 20 000 km^2. It contains up to 15 km of Phanerozoic,

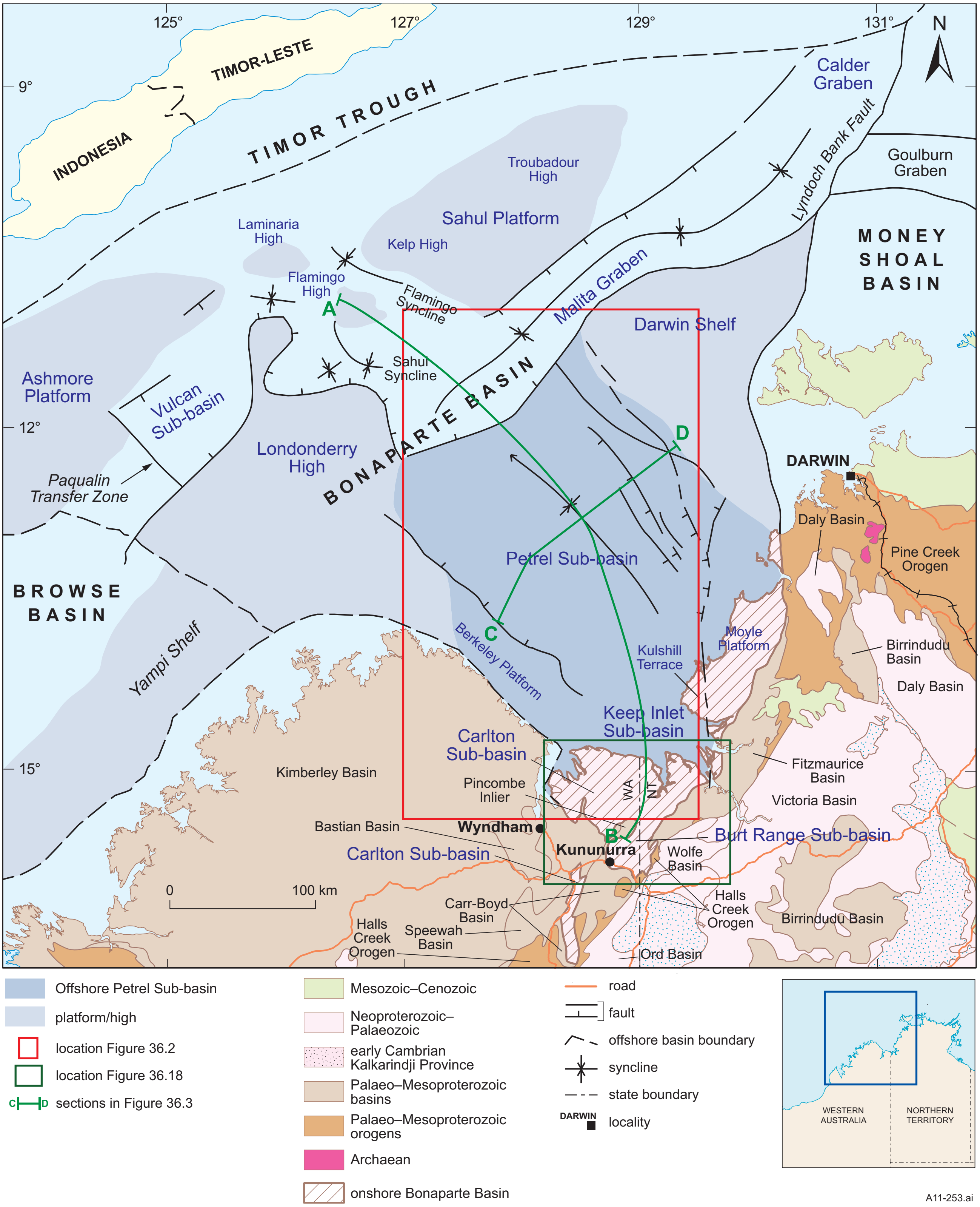

Figure 36.1. Regional setting of Bonaparte Basin showing major structural elements. NT geological regions from NTGS 1:2.5M GIS database. WA geological regions simplified and slightly modified from Tyler and Hocking (2001); some small outliers/inliers omitted.

marine and fluvial, siliciclastic and carbonate sedimentary rocks. Along with the Browse, Roebuck and Carnarvon basins in Western Australia, the Bonaparte Basin forms part of the Late Paleozoic to Cenozoic Westralian Superbasin (Bradshaw *et al* 1988), which extends along the northwestern continental margin of Australia from the Arafura Sea in the north to the Exmouth Plateau in the south.

The boundaries of the Bonaparte Basin are not well defined. Onshore areas in the south are faulted against the Pine Creek Orogen, and Victoria and Kimberley basins. To the northwest, the basin extends across the Timor Sea to the Timor Trough, where water depths exceed 3000 m. To the east the basin is bounded by the Lynedoch Bank Fault System, which separates it from the Money Shoal Basin, and to the southwest, it adjoins the offshore Browse Basin (**Figure 36.1**). Elements of the stratigraphic succession are continuous with those of adjacent offshore basins.

The Bonaparte Basin is structurally complex and consists of a number of Palaeozoic and Mesozoic platform areas and sub-basins (Mory 1991, **Figures 36.1**, **36.2**). The *Vulcan Sub-basin* is a major northeast-trending Late Jurassic rift depocentre in the western part of the Bonaparte Basin. It is separated from the Ashmore Platform to the west and the Londonderry High to the east by two en-echelon fault systems. The *Ashmore Platform* is a large elevated block located to the west of the Vulcan sub-basin. It contains a relatively thin succession of flat-lying Cretaceous strata overlying Permian–Triassic rocks which were faulted and eroded during the Jurassic. The *Londonderry High* comprises elevated Permian–Triassic rocks with thin Late Jurassic and Cretaceous cover. The *Sahul Platform* is also an elevated basement area overlain by less than 5000 m of Late Permian to Cenozoic rocks. It was uplifted to form a structural high during Jurassic extension of the adjacent Malita and Calder grabens. The *Malita Graben* is a northeast-trending trough between the Sahul Platform and Darwin Shelf. Its eastward extension is known as the *Calder Graben*. Both grabens contain a thick succession of late Palaeozoic, Triassic, Jurassic and Early Cretaceous sedimentary rocks. They were developed during the Middle Jurassic as a result of rifting prior to the break-up of Gondwana. The northwest-trending *Sahul* and *Flamingo* synclines are depocentres that link and offset the northeast-trending Vulcan Sub-basin, and Malita and Calder grabens. They are separated by the *Laminaria* and *Flamingo* highs. The *Petrel Sub-basin* **Figure 36.2**) is a broad northwest-trending Palaeozoic rift in the southeastern Bonaparte Basin that extends into onshore areas of the NT and Western Australia. It contains a thick Palaeozoic succession overlain by thinner Mesozoic sedimentary rocks. Offshore, the Petrel Sub-basin experienced Late Palaeozoic and Mesozoic rifting that has resulted in a northeast-trending structural overprint. The *Darwin Shelf*, to the northeast of the Petrel Sub-basin, represents a thin succession of Jurassic to Cenozoic sedimentary rocks. The *Keep Inlet Sub-basin* refers to a poorly developed depocentre to the east and southeast of the Turtle-Barnett High, which extends onshore to the north of drillhole Keep River-1 in northeast AUVERGNE[1] and possibly to the east as part of the Kulshill Terrace. The middle Cambrian to Early Carboniferous *Carlton Sub-basin* occurs to the south of an east–west fault zone in onshore areas of the basin, mostly in Western Australia. The Proterozoic *Pincombe Inlier* separates the Carlton Sub-basin to the west from a northerly plunging syncline to the east that forms the Late Devonian–Carboniferous *Burt Range Sub-basin* (Sweet 1977). The Pincombe Inlier was a probable emergent palaeohigh through the Late Devonian to Early Carboniferous (Jorgensen *et al* 1990).

The regional geology and stratigraphic succession of the Bonaparte Basin has been described by many authors over the last half century. Regional studies of the onshore succession include Traves (1955), Brady *et al* (1966), Veevers and Roberts (1968), Dickins *et al* (1972), Laws (1981), Whitehead and Fahey (1985), Beere and Mory (1986), Mory (1988, 1991), Mory and Beere (1988), Lavering and Ozimic (1989), Petroconsultants (1990), McConachie *et al* (1996) and Dunster *et al* (2000). Significant studies of the offshore successions include Laws and Kraus (1974), Gunn (1988), Lee and Gunn (1988), Gunn and Ly (1989), MacDaniel (1988), Mory (1988, 1991), Botten and Wulff (1990), Petroconsultants (1990), Hocking *et al* (1994), Woods (1994), Gorter (1998), a number of papers in Ellis *et al* (2004), Gorter *et al* (2005, 2008, 2009) and Bourget *et al* 2012. Significant summaries of the basin include Longley *et al* (2002), Cadman and Temple (2004) and Geoscience Australia (2009, 2011).

The Bonaparte Basin contains significant oil and gas accumulations and is an important petroleum producer. Onshore portions of the basin in the NT and WA contain an extensive Mississippi Valley-type base metals province.

This chapter focuses on the onshore sedimentary successions of the Petrel and Keep Inlet sub-basins in the NT. A full discussion of the other components of the Bonaparte Basin is beyond the scope of this volume. However, brief summaries of the middle Cambrian–Early Ordovician Carlton Group, which only outcrops in the Carlton Sub-basin in Western Australia, and of the offshore successions of the Petrel Sub-basin are also included.

Southeastern Bonaparte Basin

The southeastern Bonaparte Basin includes the Petrel, Keep Inlet and Carlton sub-basins. The Petrel Sub-basin is located mostly offshore in the Joseph Bonaparte Gulf, but extends onshore into coastal areas of the NT (**Figure 36.2**). The sub-basin is an northwest-trending Palaeozoic rift (**Figure 36.3**) that contains a succession of thick Palaeozoic and thinner Mesozoic sedimentary rocks. The eastern and western margins of the sub-basin are both faulted and converge to the south. To the east, the onshore Petrel Sub-basin and poorly defined Keep Inlet Sub-basin are bordered by the Proterozoic Pine Creek Orogen, Fitzmaurice Basin and Halls Creek Orogen, whereas to the southwest and south, the Petrel and onshore Carlton and Burt Range sub-basins abut Proterozoic rocks of the Kimberley, Speewah and Carr-Boyd basins. Proterozoic basement rocks form extensive shelves around the eastern, western and southern margins of the southeastern Bonaparte Basin (**Figure 36.2**) and these are overlain by a relatively thin cover of Phanerozoic sedimentary rocks. The shelves to the east include the Kulshill Terrace and Moyle Platform, which extend to the north-northeast into the Darwin

[1] Names of 1:250 000 and 1:100 000 mapsheets are in large and small capital letters respectively, eg AUVERGNE, LEGUNE.

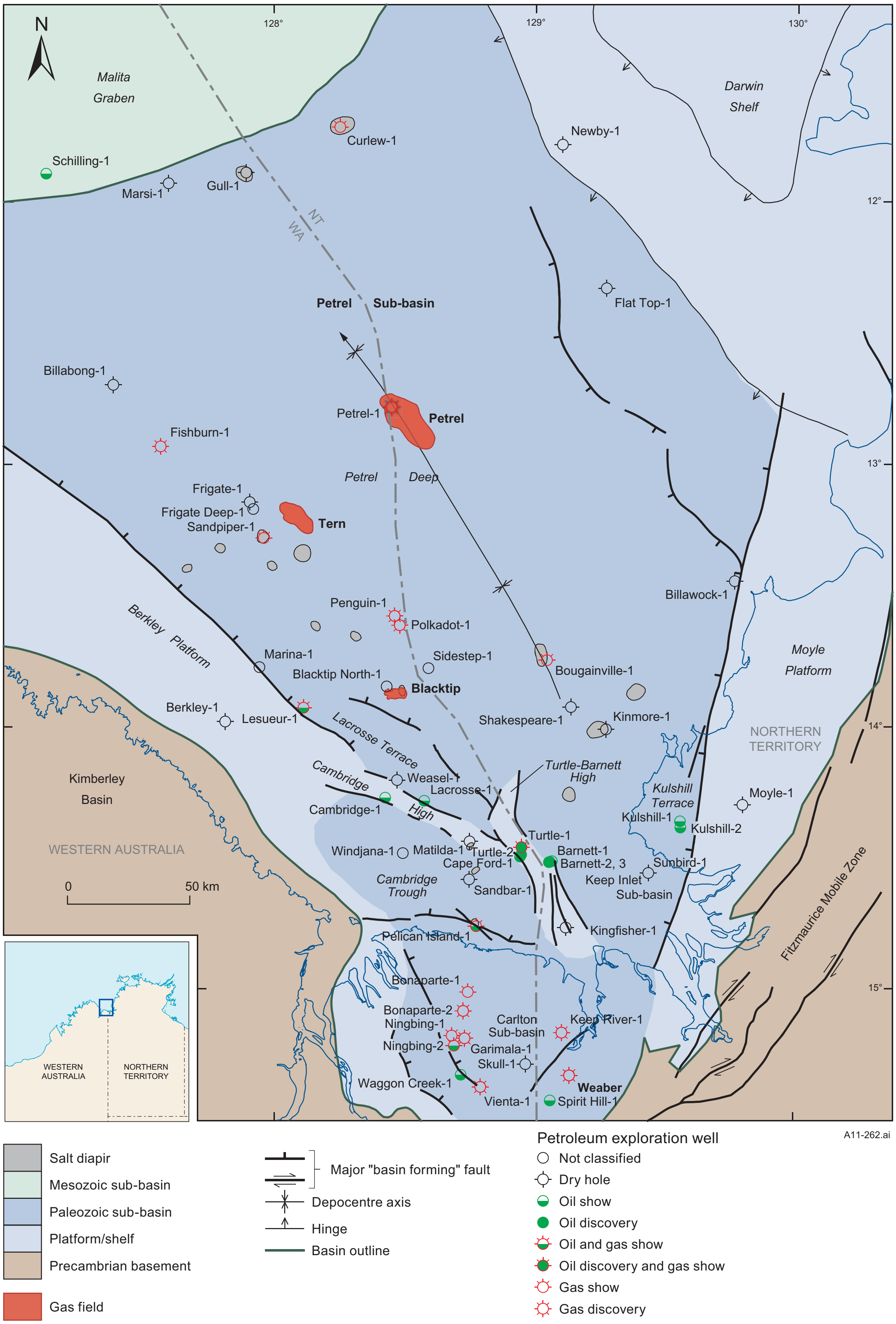

Figure 36.2. Regional structural elements of the Carlton, Petrel and Keep Inlet sub-basins, showing petroleum fields, drillholes and salt diapirs (slightly modified after Geoscience Australia 2009: figure 2). Location shown in **Figure 36.1.**

Shelf. The Berkley Platform to the west extends eastward into the Cambridge and Turtle-Barnett highs, where it is flanked by the Lacrosse Terrace. A large-scale northwest-plunging syncline extends along the axis of the Petrel Sub-basin, parallel to the prevailing structural grain, and regional dips within the sub-basin are also to the northwest, resulting in a progressive younging of the sedimentary succession in that direction from early Palaeozoic in onshore areas, through late Palaeozoic and Mesozoic to Cenozoic offshore (**Figures 36.1**, **36.3**). The Late Palaeozoic–Mesozoic succession exceeds 15 000 m in thickness in the central and northern parts of the Petrel Sub-basin.

Late Middle Devonian to Early Carboniferous upper-crustal extension resulted in the formation of a number of rift-related structures, particularly in the south and southwest of the basin (**Figure 36.2**, Gunn 1988, O'Brien *et al* 1993, Colwell and Kennard 1996). These structures are bounded by major normal faults and/or fault systems, and include planated basement platforms (eg Berkley Platform and Moyle Platform), horst blocks (eg Cambridge High and Turtle-Barnett High), rotated fault-blocks (eg Lacrosse Terrace and Kulshill Terrace), and grabens (eg, Cambridge Trough and Keep Inlet Sub-basin). In onshore areas of the NT, the major structural elements include the Moyle Platform, Kulshill Terrace, and the Keep Inlet, Burt Range and Carlton sub-basins. The *Moyle Platform* is bounded to the east by major faults of the Fitzmaurice Mobile Zone and to the west by the Moyle River Fault. It consists of crystalline basement rocks that are probably equivalent to those of the Pine Creek Orogen and Victoria Basin, overlain by shallow Late Carboniferous to Early Permian sedimentary rocks. The *Kulshill Terrace* refers to the onshore parts of the Petrel and Keep Inlet sub-basins to the west of the Moyle River Fault where a thick, poorly exposed Palaeozoic succession has been intersected in drillholes.

The stratigraphic succession of the southeastern Bonaparte Basin in the NT (**Table 36.1**) is complex and has been defined and described in a number of publications including Beere and Mory (1986), Mory and Beere (1988), Mory (1991), Gorter (1998) and Gorter *et al* (1998, 2004, 2005, 2008, 2009). Useful recent summaries of the Petrel and Keep Inlet sub-basins are in Geoscience Australia (2009, 2011).

Palaeozoic sedimentary rocks outcrop along the coast and hinterland in southernmost FOG BAY, CAPE SCOTT, western PORT KEATS and northwestern AUVERGNE in the NT, and in LISSADELL, CAMBRIDGE GULF and southernmost MEDUSA BANKS in Western Australia. The onshore succession of the Bonaparte Basin ranges from Cambrian to early Middle Triassic in age. Siliciclastic and carbonate rocks of the middle Cambrian–Early Ordovician Carlton Group outcrop along the southwestern margin of the Bonaparte Basin in Western Australia, within the Carlton Sub-basin (Mory and Beere 1988) and are the oldest sedimentary rocks within the basin. An unnamed subsurface evaporitic unit of uncertain lateral extent, penetrated in deep drillholes and interpreted from seismic data, is most likely to be Late Ordovician in age (Edgerley and Crist 1974, Woodside 2002, Leonard *et al* 2004). In the NT, the succession comprises the Late Devonian Cockatoo and Ningbing groups, the Late Devonian–Early Mississippian Langfield Group, Mississippian Weaber Group, Late

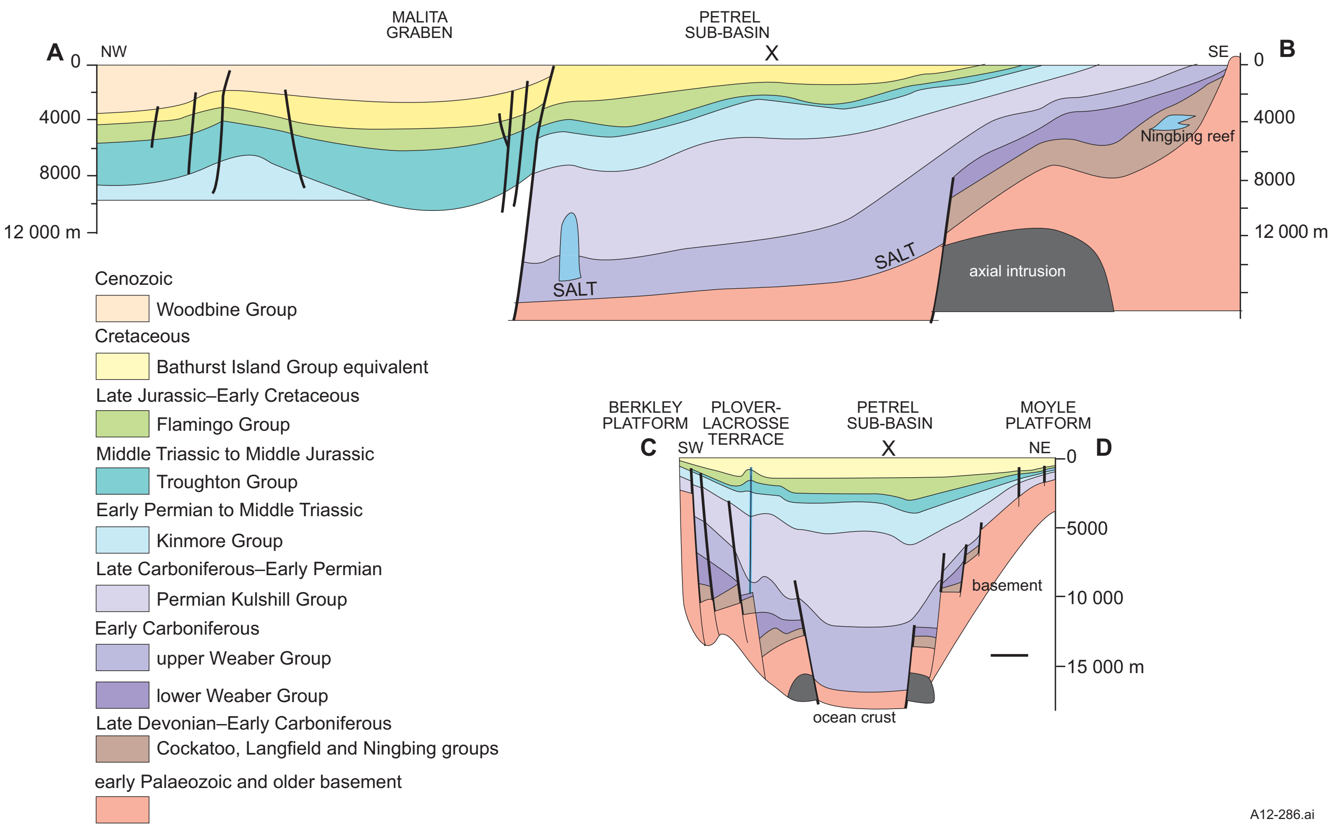

Figure 36.3. Simplified diagrammatic cross-sections across southeastern Bonaparte Basin (redrawn and slightly modified after Bishop 1999: figure 4). Locations shown in **Figure 36.1**. Cross-sections intersect at X. (**a**) Northwest–southeast cross-section across southern portion of Malita Graben and Petrel Sub-basin. (**b**) Southwest–northeast cross-section across Petrel Sub-basin.

Mississippian–Early Pennsylvanian Wadeye Group, Early Pennsylvanian–Cisuralian Kulshill Group and Cisuralian to Middle Triassic Kinmore Group. In offshore areas, these are overlain by the Middle Triassic–Jurassic Troughton Group, Jurassic–Early Cretaceous Flamingo Group, Cretaceous Bathurst Island Group equivalent and Cenozoic Woodbine Group. The only onshore outcrops of these offshore Middle Triassic and younger successions are isolated Early Cretaceous rocks in PORT KEATS and CAPE SCOTT.

CAMBRIAN–ORDOVICIAN

Carlton Group

Over 1200 m of clastic and carbonate rocks of the middle Cambrian–Early Ordovician *Carlton Group* (Caye 1968) outcrop along the southwestern basin margin in LISSADELL, CAMBRIDGE GULF and southernmost MEDUSA BANKS in Western Australia, unconformably overlying tholeiitic basalts of the late early Cambrian Antrim Plateau Volcanics (Kalkarindji Province). These are the oldest sedimentary rocks within the Bonaparte Basin. The Carlton Group does not outcrop in the NT portion of the basin, although it is possible that it may occur in the subsurface, and it is only tentatively identified in the subsurface in offshore areas (Petroconsultants 1990). The group is best developed in the Onslow and Pretlove Hills areas of Western Australia, where it has been subdivided into six conformable formations (**Figure 36.4**), from base to top, the Tarrara Formation, Hart Spring Sandstone, Skewthorpe Formation, Pretlove Sandstone, Clark Sandstone and Pander Greensand (Veevers and Roberts 1968, Kaulback and Veevers 1969, Mory and Beere 1988, Petroconsultants 1990). These were deposited in a range of environments, from intertidal to subtidal shallow marine to deeper marine towards the top. The top of the group is everywhere eroded.

Trilobite faunas from the Carlton Group were described in Shergold *et al* (2007) and enable a correlation of the middle Cambrian strata with the two successive sedimentary successions that have been recognised from sequence stratigraphic studies in the Georgina Basin in the NT to the east (Shergold *et al* 1988, Southgate and Shergold 1991, Laurie 2006): sequence 1 (Ordian) and sequence 2 (latest Ordian–early Mindyallan). The Tarrara Formation represents sequence 1, whereas the interval from Hart Spring Sandstone to Pretlove Sandstone probably represents sequence 2. A correlation chart showing the relationships of these units to successions in similar-aged NT basins is in **Centralian Superbasin: figure 22.6**.

?LATE ORDOVICIAN–?SILURIAN

Sedimentary rocks are absent from the late Early Ordovician to Middle Devonian interval in the onshore Bonaparte Basin, but extensive evaporite deposits of unknown lateral continuity are known from the southernmost offshore parts of the basin (Edgerley and Crist 1974, Woodside 2002, Leonard *et al* 2004). These include salt piercement diapirs and salt pillows, penetrated in deep drillholes and interpreted from seismic data, that developed during Late Devonian–earliest Carboniferous extensional faulting and by passive rise during the Carboniferous–Permian (**Figure 36.2**). There is no direct evidence of the depositional age of this evaporitic succession, but it most likely is in the range Late Ordovician to Silurian (Leonard *et al* 2004, Geoscience Australia 2009), from comparative stratigraphic relationships with similar successions in the Canning Basin of Western Australia (Jones *et al* 1997).

LATE DEVONIAN

Cockatoo Group

The Petrel Sub-basin developed as a rift basin in the Late Devonian as a consequence of northeast-oriented extension,

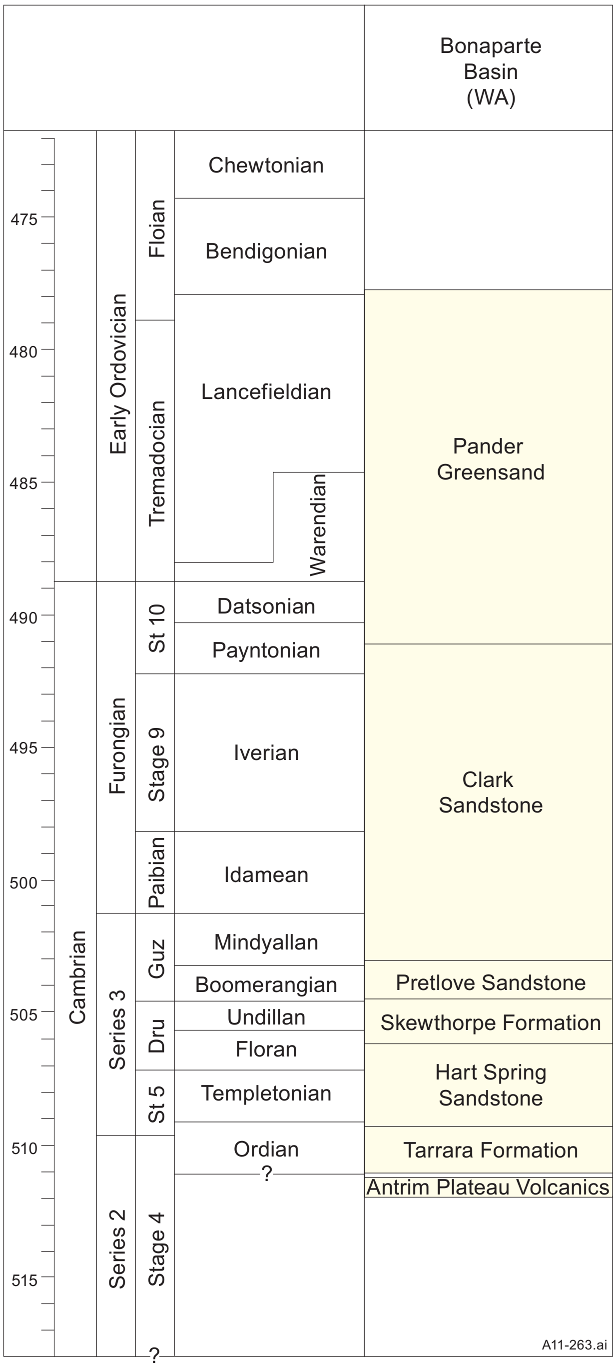

Figure 36.4. Generalised stratigraphic succession of the Cambrian–Early Ordovician succession of the Carlton Sub-basin in Western Australia. Abbreviations: Dru = Drumian; Guz = Guzhangian; St = Stage.

resulting in the deposition of siliciclastic and carbonate rocks in terrestrial and shallow marine environments. Devonian–Carboniferous sedimentation within the sub-basin was associated with the a succession of discrete transgressive/regressive cycles (Petroconsultants 1990, McConachie *et al* 1996). During the first cycle, up to 2730 m of Cockatoo Group sedimentary rocks were deposited during the Late Devonian (Laws 1981, Mory and Beere 1988). Coarse clastic rocks are associated with the eastern and western faulted basin margins and grade basinward into marine siliciclastic rocks, including siltstone and shale with interbedded sandstone and sandy limestone of the lower Bonaparte Formation of the Langfield Group (Mory and Beere 1988, **Figure 36.5**). Interbeds of dolostone, marl and limestone are found along the western margin. In the NT, the group is exposed in western AUVERGNE (**Figure 36.6**).

The Cockatoo Group (Rowley and Lee 1986) has been divided into ten formations, as summarised by Mory and Beere (1988), but only two formations are recognised in the NT (Dunster *et al* 2000): the Ragged Range Conglomerate and overlying Kellys Knob Sandstone (**Figure 36.7**, **Table 36.1**). Constituent units occurring within Western Australia include the Steeple Peak Sandstone, Cyril Sandstone, Kununurra Formation, Galloping Creek Formation, Abney Sandstone, Cecil Sandstone, Maudoobar Sandstone and Hargreaves Formation. These have complex lateral and vertical stratigraphic relationships, and several unconformities have been recognised within the succession (Mory and Beere 1988). The Cockatoo Group is regarded as being Frasnian in age (Veevers and Roberts 1968). It is unconformable on Proterozoic rocks of the Halls Creek Orogen, the late early Cambrian Antrim Plateau Volcanics (Kalkarindji Province), and in Western Australia, Cambrian and Ordovician rocks of the Carlton Group (Mory and Beere 1988).

Ragged Range Conglomerate

The Ragged Range Conglomerate (Veevers and Roberts 1968; equivalent to 'Ragged Range Conglomerate Member' of Plumb 1968) outcrops as low ridges and benches and is unconformable on Proterozoic rocks, the Antrim Plateau Volcanics and the Whitewater Volcanics of the Halls Creek Orogen (Whitehead and Fahey 1985). It both interfingers with and conformably underlies the Kellys Knob Sandstone (Whitehead and Fahey 1985, Dunster *et al* 2000), and these two units are at least partially equivalent to several other formations in Western Australia, including the Steeple Creek and Cyril sandstones. The formation typically comprises flat-lying beds of polymictic conglomerate and red-brown sandstone with occasional cross-beds (**Figure 36.8**) and reaches a maximum thickness of about 300 m (Pontifex and Sweet 1972). Conglomerate clasts are set in a sandy matrix and are up to cobble/boulder size. They include a range of rock types, including quartzite, rhyolite, shale, phyllite and siltstone (Whitehead and Fahey 1985). Mory and Beere (1988) reported an intraformational angular unconformity within the Ragged Range Conglomerate in Western Australia. The formation was deposited in alluvial fan to shallow tidal conditions, proximal to uplifted Proterozoic rocks. Pelecypods and gastropods at the base and pelecypods at the top of the type section demonstrate a marine setting and a Frasnian age, at least in part (Veevers and Roberts 1968).

Kellys Knob Sandstone

The Kellys Knob Sandstone (Rowley and Lee 1986; equivalent to 'Kellys Knob Sandstone Member' of Veevers and Roberts 1968) conformably overlies and interfingers with the Ragged Range Conglomerate. It outcrops as prominent, deeply dissected plateaux that dominate the topography and are a scenic attraction in northern Keep River National Park (Whitehead and Fahey 1985, **Figures 36.9**, **10**). South of Burt Range, conglomeratic beds that are assigned to the Kellys Knob Sandstone are unconformable on rocks of the Halls Creek Group and the Whitewater Volcanics (Halls Creek Orogen, Dunster *et al* 2000). The unit is also in faulted contact with the Enga Sandstone and Burt Range Formation of the Carboniferous Langfield Group. Pontifex and Sweet (1972) described the Kellys Knob Sandstone as a tabular body of cross-bedded quartz sandstone at least 300 m thick. In Keep River National Park, the formation consists of red to orange, tabular, cross-bedded, medium-grained, pebbly quartz sandstone with conglomeratic beds towards the base (Whitehead and Fahey 1985). Facies analysis of

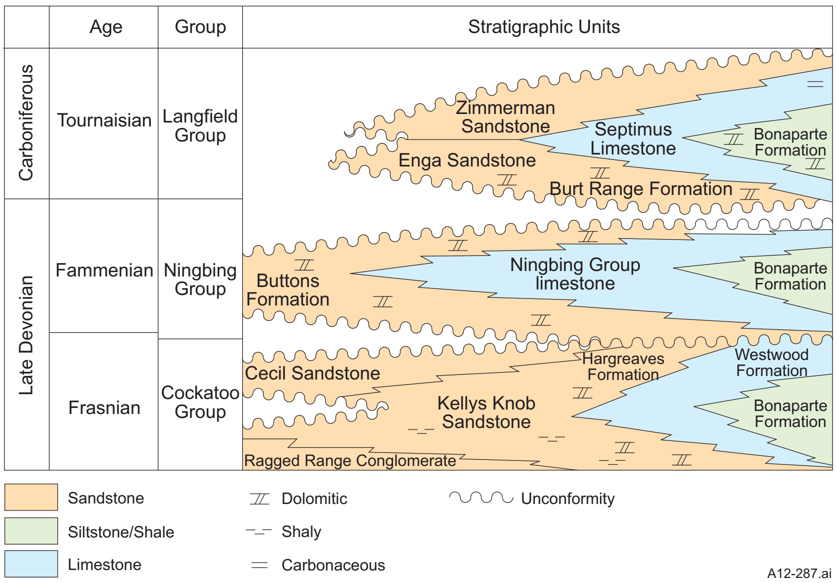

Figure 36.5. Schematic stratigraphic and facies relationships between units of Cockatoo, Ningbing and Langfield groups in onshore southern Petrel Sub-basin in NT and easternmost Western Australia (modified from Petroconsultants 1990, McConachie *et al* 1996, Dunster *et al* 2000).

the Kellys Knob Sandstone in Western Australia led to the recognition of aeolian, fluvial and tidal environments of deposition (Mory and Beere 1988). In Keep River National Park, the Kellys Knob Sandstone is a distal facies equivalent of the Ragged Range Conglomerate and contains fluvially-reworked alluvial fan deposits (Dunster *et al* 2000).

Ningbing Group

The Ningbing Group (Mory and Beere 1988; equivalent to 'Buttons Beds'–'Ningbing Limestone' interval of Veevers and Roberts 1968) is only exposed in a narrow north-northwest-trending belt in northeastern CAMBRIDGE GULF and southernmost MEDUSA BANKS in Western Australia. In the NT, it is entirely subsurface and is only known from petroleum and deep mineral drillholes in AUVERGNE and PORT KEATS (Dunster *et al* 2000, Gorter *et al* 2005). In Western Australia, the group has been subdivided into five formations, in ascending stratigraphic order, the Djilirri Limestone, Kamilili Formation, Wungabal Limestone, and the laterally equivalent Garimala Limestone and Buttons Formation (Mory and Beere 1988). In the NT, only the Buttons Formation is recognised, the remainder of the succession being undivided (**Table 36.1**). As a result of local disconformities and rapid lateral facies changes, the thickness of the group varies considerably from 171 m in drillhole Ningbing-1 in Western Australia (Mory and Beere 1988) to a maximum of 1166 m in drillhole Keep River-1 in northwest LEGUNE in AUVERGNE (Caye 1969). The group is Late Devonian (Famennian) in age (Mory and Beere 1988) and consists predominantly of carbonate rocks deposited as a reef complex similar to those of the Canning basin in Western Australia (Playford *et al* 2009). In offshore parts of the Bonaparte Basin, deeper marine rocks of the Bonaparte Formation (Langfield Group) continued to be deposited at this time and are in part laterally equivalent to the Ningbing Group (**Figure 36.5**). The group is conformable or disconformable on the Cockatoo Group, or is disconformable on Proterozoic rocks, or on the Antrim Plateau Volcanics. It is conformably or disconformably overlain by the Langfield Group, or is disconformably overlain by the Weaber Group (Mory and Beere 1988).

Undivided Ningbing Group

A thick section of undivided Ningbing Group (referred to as 'unassigned Ningbing Group' in Dunster *et al* 2000) occurs in the subsurface in northwestern AUVERGNE, where it was intersected in Keep River-1 (Caye 1969). In this drillhole, a 1024.2 m-thick section identified as 'Ningbing Limestone' by Caye (1969) is overlain by 141.7 m of 'unnamed formation', both included in the Ningbing Group by Mory and Beere (1988) for a total thickness of 1166 m. The 'unnamed formation' was subsequently identified as Buttons Formation by Gorter *et al* (2005, **Figure 36.11**). The basal 743.7 m of undivided Ningbing Group in Keep River-1 consists of fine-grained and lesser medium-grained limestone and dolostone with authigenic quartz and rare ostracodes, calcispheres and mollusc fragments, interpreted by Caye (1969) as representing a back reef lagoonal environment. This is overlain by 280.5 m of bioclastic and mottled

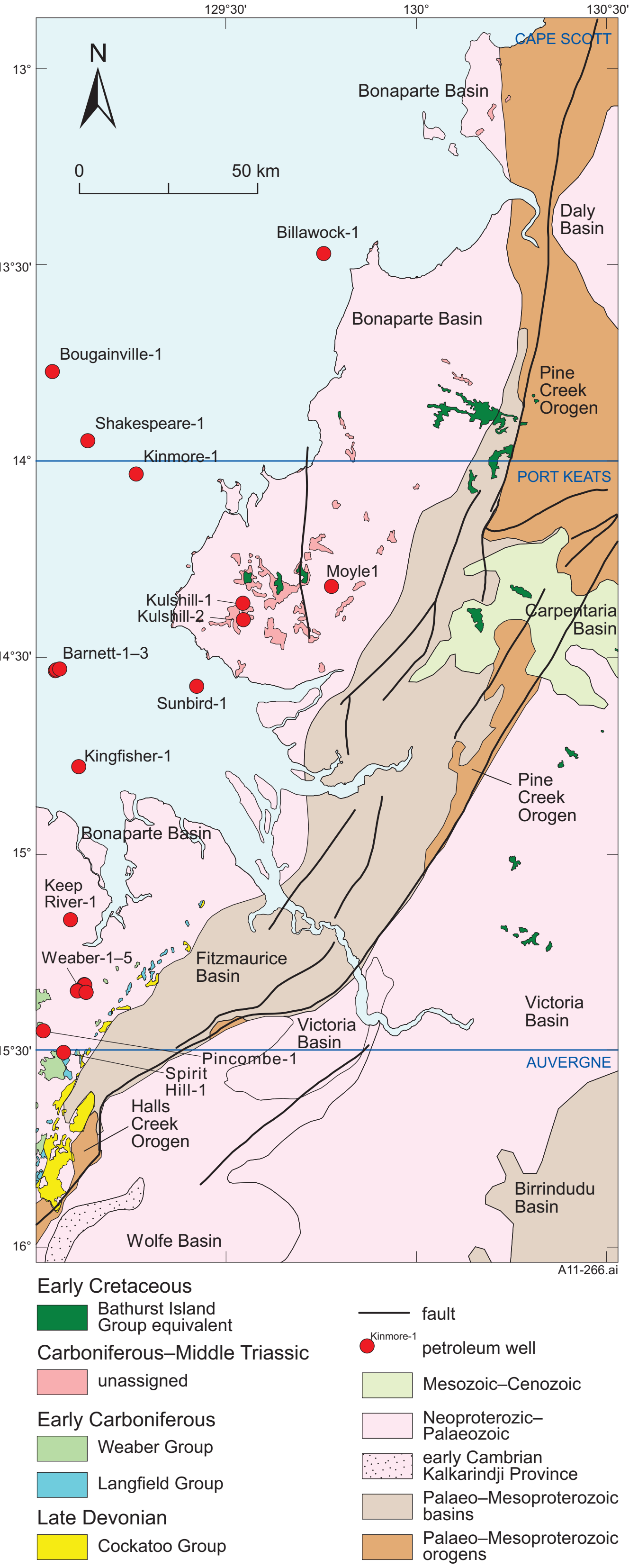

Figure 36.6. Northern Territory portion of Bonaparte Basin, showing simplified outcrop geology, derived from GA 1:1M geology and NTGS 1:2.5M geological regions GIS datasets. Outcropping units in PORT KEATS and CAPE SCOTT are too poorly mapped to assign to revised stratigraphic succession of Gorter (1998) and Gorter *et al* (2005, 2008, 2009). Cretaceous rocks in eastern PORT KEATS are arbitrarily assigned to onshore Carpentaria Basin, but are same age as, and were almost certainly continuous with Bathurst Island Group equivalent rocks of Bonaparte Basin.

Unit, thickness (distribution)	Lithology	Depositional environment	Stratigraphic relationships
Cenozoic			
WOODBINE GROUP			
undifferentiated Woodbine Group <1300 m (offshore)	Siliciclastic and carbonate rocks.	Marine shelf.	Unconformable on Bathurst Island Group equivalent.
Cretaceous			
BATHURST ISLAND GROUP EQUIVALENT			
Wangarlu Fm equivalent <2000 m (offshore)	Claystone with subordinate siltstone and minor sandstone, grading upward into claystone, calcimudstone and marl.	Inner to distal marine shelf.	Conformable on Darwin Fm.
Darwin Fm equivalent <52 m (onshore and offshore)	Radiolarian chert, claystone and calcimudstone	Shallow marine.	Conformable on Echuca Shoals Formation (offshore). Unconformable on ?Kinmore Group (onshore).
Echuca Shoals Formation >250 m (offshore)	Glauconitic claystone and siltstone.	Shallow marine.	Unconformable on Flamingo Group
Late Jurassic–Early Cretaceous			
FLAMINGO GROUP			
In ascending order: **Elang Fm** <50 m?; **Frigate Shale** <250 m; **Sandpiper Sandstone** <270 m;	Siliciclastic and lesser carbonate rocks.	Deltaic to shallow marine to open marine shelf.	Disconformable to unconformable on Troughton Group.
Middle Triassic to Middle Jurassic			
TROUGHTON GROUP			
In ascending order: **Cape Londonderry Fm** <400 m; **Malita Fm** <300 m; **Plover Fm** <500 m (offshore).	Dominantly siliciclastic rocks.	Fluvial braided-stream, continental, deltaic fluvial to coastal.	Unconformable on Mount Goodwin Sub-group.
Early Permian to Middle Triassic			
KINMORE GROUP			
MOUNT GOODWIN SUB-GROUP			
undifferentiated Ascalon Fm /Mairmull Fm 20 m (onshore)	Shale and siltstone.	Marginal marine to shallow marine.	Unconformable on Hyland Bay Sub-group
In ascending order: **Penguin Fm** <49 m; **Mairmull Fm** 199 m; **Ascalon Fm** <50 m; **Fishburn Fm** 180 m (offshore)	Claystone, siltstone and minor sandstone.	Marginal marine, shallow marine, low-relief delta plain, nearshore marine.	Unconformable on Hyland Bay Sub-group.
HYLAND BAY SUB-GROUP			
Tern Fm <73 m (offshore and onshore)	Sandstone, siltstone and mudstone in repeating cycles.	Offshore and prograding sandy shoreface to estuarine.	Unconformable on Dombey Fm. Unconformably overlain by Penguin Fm.
Dombey Fm <30 m (offshore and onshore)	Limestone and sandstone.	Marine shelf.	Unconformable on Cape Hay Fm.
Cape Hay Fm <450 m (offshore and onshore)	Shale, sandstone and siltstone.	River-dominated delta system with restricted shoreface.	Unconformable on Pearce Fm.
Pearce Fm <50 m (offshore and onshore)	Limestone and shale and lesser sandstone. Sandstone more dominant in onshore areas.	Offshore marine to marine shelf.	Unconformable on Fossil Head Fm.
NOT SUB-GROUPED			
Fossil Head Fm <590 m (offshore and onshore)	Carbonaceous siltstone and mudstone with sandstone and minor limestone.	Marine-shelf. Lower part may be prodeltaic.	Unconformable to conformable (in north) on Keyling Fm.
Late Carboniferous–Early Permian			
KULSHILL GROUP			
Keyling Fm >500 m (offshore and onshore)	Mostly sandstone, with lesser siltstone, shale, coal, conglomerate and minor limestone.	Fluvial, subordinate lacustrine and paludal. Lesser marginal marine and intertidal.	Probably unconformable on Ditji Fm.
Ditji Fm <130 m (offshore)	Calcareous sandstone, sandy limestone with minor coal.	Marine or marginal marine.	Probably unconformable on Quoin Fm.
Quoin Fm <750 m (offshore and onshore)	Sandstone, siltstone and shale.	Mostly fluvial following de-glaciation; also intertidal, nearshore and continental.	Probably unconformable on Treachery Fm.

Table 36.1. Summary of onshore and offshore stratigraphic succession of Petrel Sub-basin in the NT. Abbreviation: Fm = Formation (continued on **next page**).

Unit, thickness (distribution)	Lithology	Depositional environment	Stratigraphic relationships
Treachery Fm >300 m (offshore and onshore)	Tillite, diamictite, carbonaceous shale, varved siltstone, sandstone, and minor limestone and coal.	Glaciogenic; marine at least in part, possibly marginal marine or non-marine.	Unconformable on Border Creek and Kuriyippi formations.
Border Creek Fm >111 m (onshore)	Sandstone and conglomerate, minor siltstone.	Fluvial to deltaic.	Unconformable on various units of the Langfield, Weaber and Wadeye groups.
Keep Inlet Fm <480 m (onshore)	Calcareous, feldspathic and lithic quartz sandstone; minor coal.	Fluvial and fan delta, glaciogenic.	Not defined.
Kuriyippi Fm <1017 m (offshore and onshore)	Sandstone and lesser amounts of siltstone, shale and minor coal in upward-fining cycles.	Mainly fluvial in lower part, glaciogenic in upper part.	Unconformable on Wadeye Group and possibly on older units.
Late Devonian–Early Carboniferous			
WADEYE GROUP			
Aquitaine Fm >200 m (offshore and onshore).	Sandstone grading up into siltstone.	Mostly non-marine.	Unconformable on Arco Fm. Lateral equivalent of Point Spring Sandstone in WA.
Arco Fm <650 m (offshore and onshore).	Siltstone, shale, sandstone.	Shallow marine	Unconformable on Sunbird Fm or Tanmurra Fm. Lateral equivalent of Point Spring Sandstone (WA).
WEABER GROUP			
Tanmurra Fm <277 m (offshore and onshore)	Calcareous and dolomitic sandstone with minor limestone, siltstone and shale.	Transgressive, delta to shallow marine shelf.	Unconformable on Kingfisher Shale and Burvill Fm.
Burvill Fm <80 m (onshore)	Sandstone, siltstone, shale, calcareous sandstone and quartzose limestone.	Lower shoreface and offshore delta front or prodelta.	Conformable on Milligans Formation (?Yow Creek Formation). Lateral equivalent of Utting Calcarenite and Kingfisher Shale.
Kingfisher Shale <200 m (offshore and onshore)	Claystone with minor siltstone and fine to very fine sandstone.	Moderately deep marine.	Conformable on Utting Calcarenite. Lateral equivalent of Burvill Fm.
Utting Calcarenite <120 m (offshore and onshore)	Sandy limestone, calcareous sandstone, minor sandstone.	Marine.	Unconformable on Yow Creek Fm or Milligans Fm. Lateral equivalent of Burvill Fm.
Yow Creek Fm <400 m (offshore and onshore)	Shale, ironstone and siltstone.	Prograding delta.	Unconformable on Milligans Fm.
Milligans Fm <2143 m (offshore and onshore)	Mostly silty shale and lesser sandstone, limestone, conglomerate.	Moderately deep marine.	Unconformable on Langfield Group units.
LANGFIELD GROUP			
Zimmerman Sandstone <133 m (onshore)	Quartzic to feldspathic and lithic sandstone; minor siltstone and shale.	Shoreface to shallow marine.	Conformable on Septimus Limestone.
Septimus Limestone 300 m (onshore)	Limestone, quartzose limestone and and calcareous sandstone.	High-energy shallow marine.	Conformable on Enga Sandstone.
Enga Sandstone <320 m (onshore)	Quartz sandstone, minor siltstone, shale and quartzose limestone.	Shallow marine, tidal channel, barrier/lagoon, beach.	Conformable on Burt Range Fm.
Burt Range Fm <460 m (onshore)	Calcareous sandstone, quartzose limestone and dolostone, minor carbonaceous shale.	Inner shelf to shoreface on a clastic-influenced carbonate platform.	Disconformable on Ningbing Group.
Bonaparte Fm >930 m (onshore and probably offshore)	Shale, siltstone with interbedded dolomitic sandstone and minor quartzose limestone	Quiet relatively deep marine.	Conformable and disconformable on Ningbing Group. Long-ranging unit is also a lateral equivalent of Cockatoo, Ningbing and other Langfield group units.
NINGBING GROUP			
Buttons Fm <350 (onshore)	Thinly bedded limestone and cross-bedded sandstone.	Lagoonal to ?back reef.	Conformable on undivided Ningbing Group, or unconformable on Cockatoo Group.
undivided Ningbing Group, 1024 m (onshore)	Limestone and dolostone.	Back reef lagoonal, reef crest and fore reef.	Conformable or disconformable on the Cockatoo Group, or disconformable on Proterozoic rocks, or on Antrim Plateau Volcanics. Lateral equivalent in part of Bonaparte Fm (Langfield Group).
COCKATOO GROUP			
Kellys Knob Sandstone >300 m (onshore)	Quartz sandstone with conglomerate towards base.	Aeolian, fluvial and tidal.	Conformably overlies and interfingers with Ragged Range Conglomerate. Unconformable on Halls Creek Group and Whitewater Volcanics.
Ragged Range Conglomerate <300 m (onshore)	Polymictic conglomerate and sandstone.	Alluvial fan to shallow tidal.	Unconformable on Proterozoic rocks, Antrim Plateau Volcanics and Whitewater Volcanics. Conformably underlies and interfingers with Kellys Knob Sandstone.

Table 36.1. Summary of onshore and offshore stratigraphic succession of Petrel Sub-basin in the NT (continued from **previous page**).

Figure 36.7. View south from Nigli Gap, showing Late Devonian strata of Cockatoo Group overlying early Palaeozoic and Proterozoic strata (AUVERGNE, KEEP, 52L 509500mE 8259300mN, after Whitehead and Fahey 1985: plate 5). Cockatoo Group: a = Kellys Knob Sandstone; b = Ragged Range Conglomerate. c = late early Cambrian Antrim Plateau Volcanics. d = Meso–Neoproterozoic rocks of Victoria and Wolfe basins. e = Palaeo–?Mesoproterozoic Legune Formation of Fitzmaurice Basin. f = Palaeoproterozoic rocks of Halls Creek Orogen.

Figure 36.8. Gradational contact between Ragged Range Conglomerate (lower half of image) and steep scarp of Kellys Knob Sandstone (AUVERGNE, KEEP, Nigli Gap area, precise location unknown, after Whitehead and Fahey 1985: plate 7).

Figure 36.9. Kellys Knob Sandstone. Typical scarp-forming exposure showing large-scale cross-bedding (AUVERGNE, KEEP, Nigli Gap area, precise location unknown, after Whitehead and Fahey 1985: plate 10).

Figure 36.10. Kellys Knob Sandstone. (**a**) Basal conglomerate with sandstone lenses (AUVERGNE, KEEP, 52L 505900mE 8241200mN, after Whitehead and Fahey 1985: plate 8). (**b**) Large-scale trough cross-bedding in pebbly quartz sandstone (AUVERGNE, KEEP, southern Burt Range Amphitheatre, precise location unknown, after Whitehead and Fahey 1985: plate 9).

limestone that contains algal bioherms and abundant bioclastic fragments of brachiopods, bryozoans, crinoids, gastropods, and encrusting and other algae. Caye (1969) interpreted this limestone as representing a shallow water turbulent environment, presumably in the reef crest or fore reef zones.

Buttons Formation

The uppermost Devonian (upper Famennian) Buttons Formation (Mory and Beere 1988; equivalent to 'Buttons Beds' of Veevers and Roberts 1968 and 'Buttons beds' of Playford 1982) outcrops in the Burt Range area in Western Australia, but is only known from the subsurface in the NT.

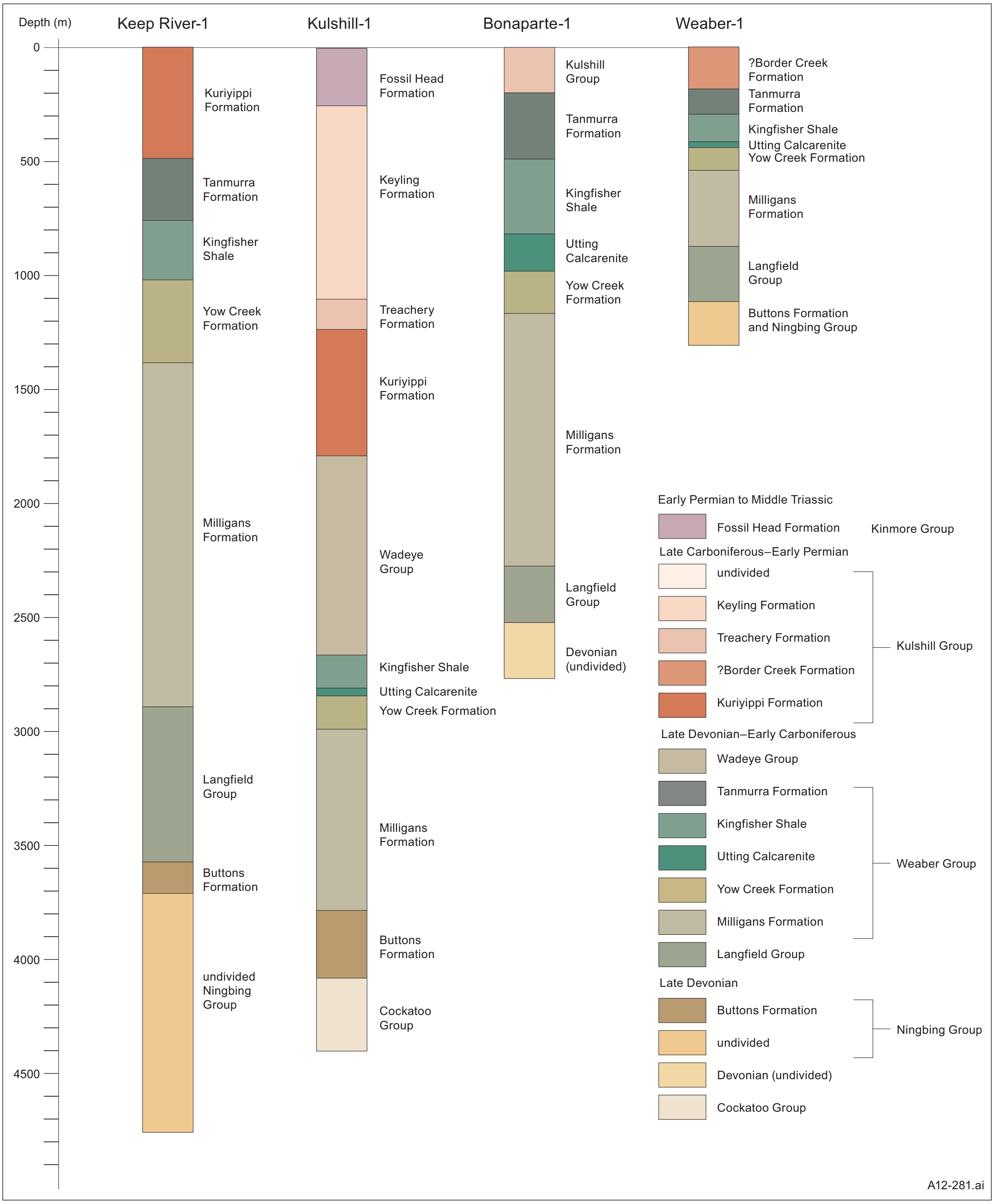

Figure 36.11. Simplified stratigraphic logs of drillholes Keep River-1, Kulshill-1, Bonaparte-1 and Weaber-1 in the onshore Bonaparte Basin. Stratigraphic picks are after Gorter *et al* (2005: figures 5, 7 and 8).

It is a stratigraphic equivalent of the Garimala Limestone, which outcrops in the Ningbing Range in Western Australia. Drillholes Keep River-1 (AUVERGNE) and Kulshill-1 (PORT KEATS) intersected 141.7 m and about 300 m, respectively, of Buttons Formation (Caye 1969, Gorter *et al* 2005: figure 7), but these intersections have not been described in any detail. Mory and Beere (1988) described the Buttons Formation in Western Australia as being 300–350 m thick and consisting of thinly bedded limestone (wackestone, grainstone, calcimudstone) and cross-bedded sandstone, with sandy and laminated carbonate beds. In Keep River-1, the formation is a silty dolomudstone that overlies undivided Ningbing Group and is unconformably overlain by Langfield Group sedimentary rocks (Caye 1969).

In Kulshill-1, the formation is unconformable between Cockatoo Group rocks and the Milligans Formation (Weaber Group), with other components of the Ningbing Group being absent. A lagoonal to ?back reef setting has been interpreted for the formation (Mory and Beere 1988).

LATE DEVONIAN–EARLY CARBONIFEROUS

By the Mississippian, the Petrel Sub-basin had developed via rifting into a northwest-trending basin that accumulated marine, fluvial-deltaic and glacial sediments as a result of post-rift subsidence and salt withdrawal during the Carboniferous and Permian (Geoscience Australia 2009).

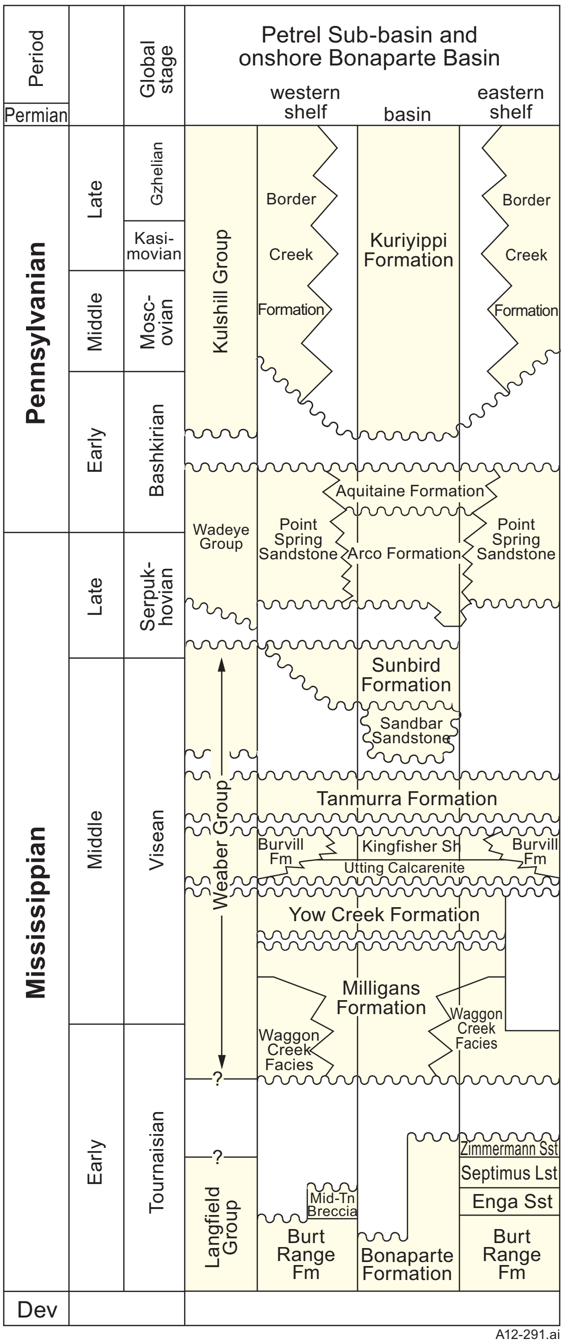

Figure 36.12. Carboniferous stratigraphic succession of southeastern Bonaparte Basin showing facies relationships (redrawn and slightly modified after Gorter *et al* 2005: figure 2). Timescale slightly modified after Gradstein and Ogg (2004). Abbreviations: Dev = Devonian; Fm = Formation; Perm = Permian; Sh = Shale; Sst = Sandstone; Tn = Tournaisian.

These Carboniferous–Permian sedimentary rocks form the majority of the basin-fill in the Petrel Sub-basin.

Langfield Group

The Langfield Group (Beere and Mory 1986) reaches a maximum thickness of about 900 m and has been divided into five formations, all of which are present in the NT in AUVERGNE and probably in the subsurface in PORT KEATS (Creevey 1966, Duchemin and Creevey 1966, Dickins *et al* 1972, **Figures 36.6**, **36.12**, **Table 36.1**). It includes, in ascending stratigraphic order, the subsurface Bonaparte Formation, and the outcropping Burt Range Formation, Enga Sandstone, Septimus Limestone and Zimmerman Sandstone (**Figure 36.13**). The Bonaparte Formation has been shown to be also laterally equivalent to formations of the underlying Cockatoo and Ningbing groups (Mory 1990, McConachie *et al* 1996, **Figure 36.5**). It is therefore longer ranging (Late Devonian–Carboniferous) than the remainder of the group, which is Early Carboniferous (Tournaisian). Fine-grained rocks of the Bonaparte Formation were deposited in quiet, relatively deep marine conditions, and this formation is interpreted as the distal equivalent of the other correlative units, which were deposited in a more proximal, shallow marine, clastic-influenced shelf setting. The Langfield Group is conformable and disconformable on the Ningbing Group, and is unconformably overlain by the Weaber Group and by the Border Creek and Keep Inlet formations of the Kulshill Group.

Bonaparte Formation

The Bonaparte Formation (Beere and Mory 1986; equivalent to 'Bonaparte beds' of Veevers and Roberts 1968) is only known from onshore petroleum exploration wells in CAMBRIDGE GULF in Western Australia, although it also possibly occurs in the subsurface in the northwestern NT and in offshore areas of the Petrel Sub-basin. Although it is included within the Langfield Group, Mory (1990) and McConachie *et al* (1996) showed that the formation is a long-ranging unit that is also laterally equivalent to formations of the underlying Cockatoo and Ningbing groups. The type section is defined between 2280 and 3210 m depth in drillhole Bonaparte-1 (Beere and Mory 1986); this is the thickest-known intersection (930 m) of the formation, but the base of the unit was not reached in this drillhole. Several drillhole intersections in the NT were assigned to the Bonaparte Formation by Mory and Beere (1988). These include a 633 m thick intersection in Kulshill-1, a 349 m-thick intersection in Keep River-1, and a 279 m-thick intersection in Weaber-1. However, the Langfield Group is apparently absent in Kulshill-1 (Gorter *et al* 2005: figure 7), and Petroconsultants (1990) reassigned the rocks in Keep River-1 and Weaber-1 to other units of this group. The Bonaparte Formation is therefore limited in areal extent to interpreted deeper-water portions of the Petrel Sub-basin away from the basin's margins. The formation consists of shale and siltstone with interbedded variably dolomitic sandstone and minor quartzose limestone, and was deposited in a quiet-water marine shelf or a deeper basinal setting of uncertain depth (Mory and Beere 1988).

Burt Range Formation

The Burt Range Formation (Veevers and Roberts 1968; equivalent to 'Burt Range Limestone' of Noakes *et al* 1952) outcrops in a north to southeast-trending arcuate belt, mostly in eastern CAMBRIDGE GULF in Western Australia, but extending into western AUVERGNE. In the NT, it is best exposed as low- to moderate-relief benches in the Burt Range Amphitheatre in Keep River National Park (**Figure 36.13**). The formation is conformable or disconformable on the Ningbing Group and is conformably, or locally unconformably (Veevers and Roberts 1968) overlain by the Enga Sandstone. It is also probably unconformably overlain in the subsurface by the Milligans Formation of the Weaber Group (Mory and Beere 1988). Whitehead and Fahey (1985) interpreted the formation to be disconformable on the Cockatoo Group in AUVERGNE, but Dunster *et al* (2000) described the contact between the two formations in this area as being faulted. The formation has been subdivided into three members in the Sorby Hills area in Western Australia (Rowley and Lee 1986), but these units have not been recognised in the NT.

The Burt Range Formation reaches a maximum thickness of 460 m in Western Australia (Mory and Beere 1988). In western AUVERGNE, approximately 450 m of the formation was intersected in drillhole Spirit Hill-1, about 250 m Weaber-1 and about 150 m in Keep River-1 (Petroconsultants 1990). Outcrops in Keep River National Park are about 150 m thick (Whitehead and Fahey 1985). Exposures of the unit are dominated by calcareous sandstone, quartzose limestone and dolostone. Carbonaceous shale has also been intersected in drillholes (d'Auvergne *et al* 1980, Mory and Beere 1988, Jorgensen *et al* 1990). Sedimentary structures include rare intraformational breccias and clasts, ripples and bioturbation. Brachiopods collected from the base of the formation in AUVERGNE indicate a broad Late Devonian to Early Carboniferous age (J Laurie pers comm in Whitehead and Fahey 1985), but a more diverse fossil assemblage including brachiopods, crinoid fragments, bivalves, gastropods, corals, nautiloids, echinoids, bryozoans and conodonts, indicates an early to middle Tournaisian age (Veevers and Roberts 1968, Druce 1969, Roberts 1971). The Burt Range Formation is interpreted to have been deposited during a period of overall shallowing from inner shelf to shoreface on a clastic-influenced carbonate platform. Local environments of deposition include high-energy shoals and lower-energy intertidal–supratidal settings (Mory and Beere 1988).

Enga Sandstone

The Enga Sandstone (Traves 1955; equivalent to 'Snowie Sandstone' of Traves 1949) is exposed in the Burt Range in eastern CAMBRIDGE GULF in Western Australia and in Keep River National Park in western AUVERNGE. In the NT, the formation forms a resistant cap on the Burt Range Formation or is exposed as dissected plateaux. It conformably overlies the Burt Range Formation (Whitehead and Fahey 1985, **Figure 36.13**), although the contact is locally unconformable (Veevers and Roberts 1968), and conformable underlies the Septimus Limestone. Whitehead and Fahey (1985) also described a locally disconformable upper contact with the Border Creek Formation (Kulshill Group). The formation is in faulted contact with the Kellys Knob Sandstone (Cockatoo Group) and Border Creek Formation in Keep River National Park. Mory and Beere (1988) estimated a maximum thickness of about 320 m for the unit in Western Australia, but exposures in the NT are less than 150 m thick (Whitehead and Fahey 1985). The formation has been intersected in Keep River-1, Weaber-1 and Weaber-2A, where it is less than 50 m in thickness (Petroconsultants 1990), but the positioning of the stratigraphic picks in these NT drillholes is uncertain (Dunster *et al* 2000).

The Enga Sandstone consists of fossiliferous quartz sandstone with minor siltstone, shale and quartzose limestone. Beds range from massive to laminated to cross-bedded, and may be bioturbated. Fossils include bivalves, brachiopods, gastropods, bryozoans, trilobites, ostracods, foraminifera, crinoids, conodonts, algae and plant fragments (Mory and Beere 1988). The conodonts indicate a mid-Tournaisian age (Druce 1969). A shallow marine setting, dominated by beach, tidal channel and barrier/lagoon environments, is indicated for the formation (Mory and Beere 1988).

Septimus Limestone

The Septimus Limestone (Veevers and Roberts 1968; equivalent to 'Mount Septimus Limestone' of Noakes

Figure 36.13. Langfield Group. View south from northern end of Burt Range Amphitheatre, showing Burt Range Formation overlain by Enga Sandstone with Zimmerman Sandstone in middle distance. Border Creek Formation of Kulshill Group overlies Enga Sandstone and Zimmerman Sandstone. a = Border Creek Formation; b = Zimmerman Sandstone; c = Enga Sandstone; d = Burt Range Formation; e = Kellys Knob Sandstone of underlying Cockatoo Group (AUVERGNE, KEEP, near 52L 502000mE 8258000mN, after Whitehead and Fahey 1985: plate 11).

et al 1952) outcrops mostly in the central Burt Range in eastern CAMBRIDGE GULF in Western Australia, but a few scattered exposures in westernmost AUVERGNE were assigned to this formation by Pontifex and Sweet (1972) and Whitehead and Fahey (1985). In the Burt Range, the formation is conformable between the Enga Sandstone below and the Zimmerman Sandstone. However, in the type section at Mount Septimus to the north, it is unconformably overlain by Kulshill Group rocks that Mory and Beere (1988) referred to the Keep Inlet Formation, and in the subsurface in the NT, it is unconformably overlain by the Milligans Formation of the Weaber Group (Petroconsultants 1990). In the type section, the formation reaches an estimated maximum thickness of about 300 m, but it thins rapidly away from this area to be only 25 m thick in exposures 9 km to the south (Mory and Beere 1988). The formation has been intersected in Keep River-1 and Weaber-1 in the NT, where it is about 100 m thick (Petroconsultants 1990), but the positioning of the stratigraphic picks in these drillholes is uncertain (Dunster *et al* 2000).

In the type section, the Septimus Limestone consists of limestone, quartzose limestone and calcareous sandstone (Mory and Beere 1988). Elsewhere, the sandstone facies is commonly the only exposed rock type and it can be difficult to distinguish the unit from the sandstone formations above and below (Dunster *et al* 2000). The sparse NT exposures consist of thinly bedded fine-grained dolomitic and calcareous feldspathic sandstone (**Figure 36.14**). A marine fauna of brachiopods, crinoids, minor corals, molluscs, trilobites, blastoids, ostracods, conodonts, echinoids and sponges is present within the formation (Thomas 1962, Roberts 1971) and the conodont fauna indicates a mid-Tournaisian age (Druce 1969). A high-energy shallow water environment of deposition has been interpreted for the unit (Veevers and Roberts 1968, Mory and Beere 1988).

Zimmerman Sandstone

The Zimmerman Sandstone (Veevers and Roberts 1968) outcrops in the central Burt Range in eastern CAMBRIDGE GULF in Western Australia and is also exposed in several low hills in a small area in Keep River National Park in westernmost AUVERGNE (Whitehead and Fahey 1985). It has not been intersected in the subsurface. The formation is conformable on the Septimus Limestone and forms the top of the Langfield Group. It is unconformably or disconformably overlain by Kulshill Group rocks that were referred to the Keep Inlet Formation by Mory and Beere (1988) in Western Australia, and to the Border Creek Formation by Whitehead and Fahey (1985) in the NT. The type section is at Mount Zimmerman in Western Australia, where the formation comprises 133 m of brown to white quartz sandstone with interbedded white siltstone in the upper part (Veevers and Roberts 1968). However, the unit thins rapidly away from this area to be only 25 m thick, 4 km to the south of the type section, and it has been completely removed by erosion about 6 km to the north (Mory and Beere 1988). The NT exposures consist of <30 m of friable, medium-grained, slightly calcareous sandstone. Some beds are almost entirely quartzose, whereas others contain quartz, feldspar and lithic grains. The latter were derived from a mixed igneous and metamorphic provenance, which Dunster *et al* (2000) interpreted as indicating a major clastic influx over a previously carbonate-dominated platform. A shoreface to shallow marine environment of deposition is likely (Mory and Beere 1988). Uncommon marine fossils from this unit in Western Australia include brachiopods, bivalves, bryozoans, crinoids, and trace fossils including *Rhizocorallium*. The brachiopods indicate a late Tournaisian age (Roberts 1971).

Weaber Group

The Weaber Group (Traves 1955, Gorter *et al* 2005) is a complex succession of clastic and carbonate sedimentary rocks that reaches a maximum thickness of about 2400 m and is separated by several unconformities (**Figure 36.12**). The group is exposed in the onshore Petrel Sub-basin in northeastern CAMBRIDGE GULF and southeastern MEDUSA BANKS in Western Australia, and northwestern AUVERNGE in the NT (**Figure 36.6**). It also occurs in the subsurface in the offshore Petrel Sub-basin and in PORT KEATS (Creevey 1966, Duchemin and Creevey 1966, Dickins *et al* 1972). The group contains eight formations (Mory and Beere 1988, Gorter *et al* 2005); these are, in ascending stratigraphic order, the Milligans Formation, which incorporates the former 'Waggon Creek Formation' as a facies association, Yow Creek Formation, Utting Calcarenite, Kingfisher Shale, Burvill Formation, which is laterally equivalent to these last two units, Tanmurra Formation, Sandbar Sandstone and Sunbird Formation (**Figure 36.12**). Of these, the Milligans Formation, including the Waggon Creek facies association, subsurface Yow Creek Formation, subsurface Utting Conglomerate, subsurface Kingfisher Shale, Burvill Formation and subsurface Tanmurra Formation are found in onshore areas of the NT (**Table 36.1**); the other formations occur in Western Australia or offshore (**Figure 36.15**). The group originally included the Point Spring Sandstone at its top (Mory and Beere 1988), but this unit has since been included in the Wadeye Group by Gorter *et al* (2005). The Weaber Group is generally unconformable on the Langfield Group, although the relationship may be conformable in offshore depocentres (Mory 1991), and is unconformably overlain by the Wadeye Group. It is Early Carboniferous

Figure 36.14. Septimus Limestone (darker rock in lower half of image) unconformably overlain by Border Creek Formation in northern end of Burt Range Amphitheatre (AUVERGNE, KEEP, 52L 501900mE 8259100mN, after Whitehead and Fahey 1985: plate 12).

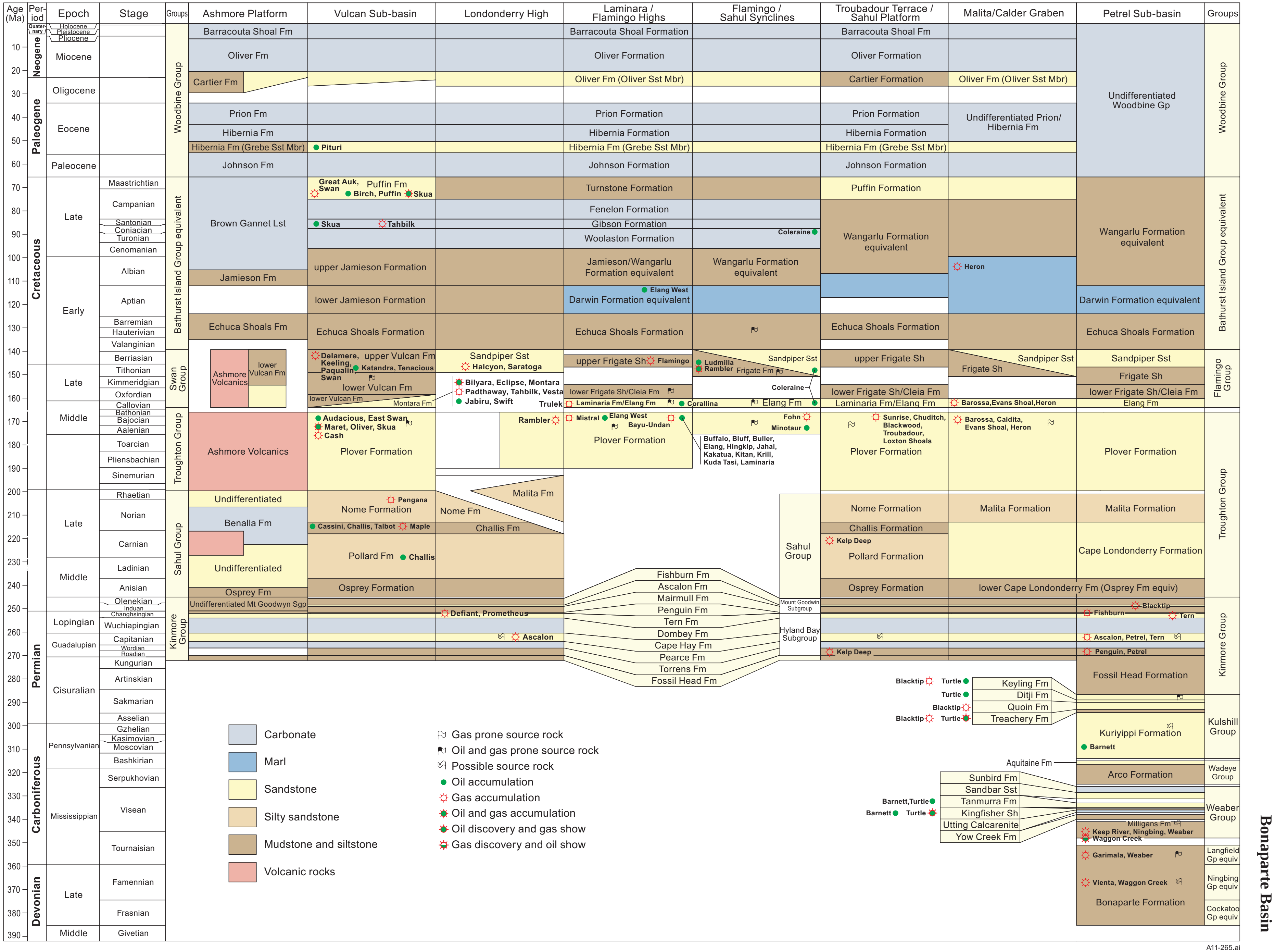

Figure 36.15. Generalised Devonian–Cenozoic stratigraphic succession of the offshore Bonaparte Basin (slightly modified after Geoscience Australia 2011: figure 3), including revisions to the Petrel Sub-basin by Gorter (1998) and Gorter *et al* (2005, 2008, 2009). Cambrian–Carboniferous stratigraphic successions of onshore sub-basins are not included (see **Figures 36.4**, **36.5**, **36.12**). Geological timescale after Gradstein *et al* (2004) and Ogg *et al* (2008). Abbreviations: equiv = equivalent; Fm = Formation; Mt = Mount; Lst = Limestone; Mbr = Member; Sgp = Subgroup; Sh = Shale; Sst = Sandstone.

(Mississippian: latest Tournaisian to early Serpukhovian) in age (Mory and Beere 1988, Gorter *et al* 2005).

Milligans Formation

The Milligans Formation (Caye 1968, Gorter *et al* 2005) is latest Tournaisian to early Visean in age (Gorter *et al* 2004) and occurs throughout the Cambridge Trough, Keep Inlet Sub-basin and onshore parts of the Petrel Sub-basin. The recessive unit outcrops poorly in northwestern AUVERGNE (Dunster *et al* 2000), but is only known from the subsurface in onshore areas further to the north. In the NT, thick sections of Milligans Formation have been penetrated (Gorter *et al* 2005) in drillholes Keep River-1 and Weaber-1 (AUVERGNE), and Kulshill-1 (PORT KEATS). Lee and Gunn (1988) recognised upper and lower intervals within the Milligans Formation, separated by a major sequence boundary; the upper interval has subsequently been assigned to the Yow Creek Formation (Gorter *et al* 2005). The offshore Milligans Formation consists mostly of fossiliferous silty shale, but onshore intersections include interbedded sandstone, limestone (packstone and grainstone) and conglomerate of the Waggon Creek facies association. The Milligans Formation contains an abundant fauna and microflora, including foraminiferans, conodonts, ostracodes and palynomorphs that are consistent with a marine depositional setting for most of the formation (Mory and Beere 1988, Gorter *et al* 2005). The coarser Waggon Creek facies is interpreted as a basin margin equivalent of the basinal Milligans Formation, although the precise depositional environment is uncertain. The facies may in part represent beach rock and dolomitic cliff-foot talus deposits accumulated in a palaeovalley (Jones 1989), or submarine fan deposits (Mory 1991), or turbidite channel deposits capped by marine shale (Gorter 1991, as cited in Gorter *et al* 2005). Significant gas flows were obtained from the Milligans Formation in Keep River-1 and Weaber-1, -2A.

Yow Creek Formation

The subsurface mid-Visean Yow Creek Formation was defined by Gorter *et al* (2005) as the upper part of the Milligans Formation (*sensu* Mory and Beere 1988), unconformably overlying the Milligans Formation (*sensu stricto*). The formation is 180 m thick in the type section in drillhole Bonaparte-1, where it consists of slightly silty and rarely fossiliferous shale, with common ironstone and a basal, weakly fossiliferous sandy siltstone (Gorter *et al* 2005). It was interpreted by Gorter *et al* (2005: figure 7) as being about 400 m thick in Keep River-1 (AUVERGNE), and about 200 m thick in Kulshill-1 (PORT KEATS), but these intersections were not described. Lavering and Ozimic (1989) interpreted the 'upper Milligans Formation' (presumably Yow Creek Formation) as a prograding delta succession and Gorter *et al* (2005) indicated that the formation was deposited during a "regression, possibly driven by tectonics".

Utting Calcarenite

The unconformably overlying subsurface Utting Calcarenite (Veevers and Roberts 1968) was depicted by Gorter *et al* (2005: figure 7) as occurring as a very thin interval in Kulshill-1 (PORT KEATS), and in Weaber-1 and possibly Keep River-1 (AUVERGNE), but these intersections were not described. This unit and the Kingfisher Shale are lateral equivalents of the coarse clastic-dominated Burvill Formation developed near the margins of the Petrel Sub-basin. In the type area in Utting Gap in Western Australia, the formation consists of fossiliferous sandy limestone (wackestone and packstone), calcareous sandstone and minor fine- to medium-grained sandstone (Veevers and Roberts 1968, Mory and Beere 1988). It is richly fossiliferous and contains conodonts, foraminiferans, ostracodes, brachiopods, corals, echinoids, trilobites and shark remains, described in various publications as listed in Gorter *et al* (2005). These indicate a medial Visean age. Mory and Beere (1988) interpreted the formation as a low-energy marine deposit, whereas Gorter *et al* (2005) argued for a more energetic low-stand environment from the presence of large amounts of course-grained detritus and reworked fossils.

Kingfisher Shale

The subsurface Kingfisher Shale (Gorter *et al* 2005) conformably, but abruptly overlies the Utting Calcarenite. These units are both lateral equivalents of the coarse clastic-dominated Burvill Formation, which is developed near the margins of the Petrel Sub-basin. The unit is unconformably overlain by the Tanmurra Formation offshore and in drillhole Keep River-1, where it is over 200 m thick, and by the Wadeye Group in Kulshill-1, where it is about 150 m thick (Gorter *et al* 2005: figure 7). It is 141 m thick in the type section in offshore drillhole Kingfisher-1, where it consists of slightly micaceous and carbonaceous claystone with minor siltstone and fine- to very fine-grained sandstone. The Kingfisher Shale contains a relatively well described fauna and microflora, including foraminiferans, conodonts, ostracodes, scolecodonts, acritarchs and palynomorphs (summarised in Gorter *et al* 2005) that indicate a late Visean age for the formation and a moderately deep marine environment of deposition. Gorter *et al* (2005) interpreted the formation as representing a rapid deepening event following earlier Visean regressions.

Burvill Formation

The Burvill Formation (Cockbain 1985; equivalent to 'Burvill Beds' of Veevers and Roberts 1968 and 'Burvill beds' of Jones 1984) outcrops in the onshore Carlton Sub-basin in Western Australia and is considered to be a lateral equivalent of the Utting Calcarenite and Kingfisher Shale, although the stratigraphic relationships are not entirely clear. The formation is conformable (Mory and Beere 1988) on the Milligans Formation (?Yow Creek Formation of Gorter *et al* 2005) and is unconformably overlain by the Tanmurra Formation (Gorter *et al* 2005). It forms discontinuously exposures in northeastern CAMBRIDGE GULF in Western Australia and a single exposure occurs in westernmost AUVERGNE; otherwise the unit is only known from shallow stratigraphic drillholes (Dunster *et al* 2000). The Burvill Formation consists of sandstone and minor siltstone, shale, calcareous sandstone and quartzose limestone. Sandstone is typically fine- to very fine-grained, but medium to coarse phases are locally common. A diverse assemblage of macrofossils (including brachiopods described by Thomas 1971), trace and microfossils indicate a late Visean to possibly early Namurian age, and the unit may young to the north (Mory and Beere 1988). Mory and Beere (1988) suggested a lower shoreface and offshore depositional environment in a delta front or prodelta setting.

Tanmurra Formation
The subsurface late Visean Tanmurra Formation (Caye 1968; equivalent to 'Medusa Beds' of Kemp *et al* 1977) was deposited throughout the Carlton Sub-basin, Cambridge Trough and Keep Inlet Sub-basin, but is apparently absent in the Kulshill Terrace and Moyle Platform. The formation unconformably overlies the Kingfisher Shale and Burvill Formation, and is unconformably overlain offshore by the Visean Sandbar Sandstone and Visean–Serpukhovian Sunbird Formation, and onshore by the Point Spring Sandstone of the Wadeye Group (Gorter *et al* 2005). It is 277 m thick in the type section in Bonaparte-1 in northeastern CAMBRIDGE GULF and attains a similar thickness in Keep River-1 in AUVERGNE (Gorter *et al* 2005), although the top of the formation has been eroded in this and other AUVERGNE drillholes, including Weaber-1, -2A and -5 (Dunster *et al* 2000). The Tanmurra Formation consists of calcareous and dolomitic sandstone with minor limestone, siltstone and shale. Large amounts of reworked fossil material of Ordovician to Early Carboniferous age indicates the active erosion of earlier rocks (Gorter *et al* 2005) and the formation is regarded as being transgressive. A deltaic to shallow marine shelf environment of deposition has been interpreted for the unit (Mory and Beere 1988, Gorter *et al* 2005).

Wadeye Group

The Late Mississippian–Early Pennsylvanian Wadeye Group (Gorter *et al* 2005) is represented on the margins of the Petrel Sub-basin in northeastern Western Australia by the *Point Spring Sandstone*, consisting of sandstone, pebbly sandstone and minor siltstone, and in deeper parts of the basin and in the subsurface by finer-grained siliciclastic rocks of the Arco and Aquitaine formations (Gorter *et al* 2005, **Figure 36.12**). Gorter *et al* (2008) subsequently referred to this succession as the 'Wadeye Sub-group' of the Weaber Group and commented that it probably should be included in the overlying Kulshill Group. However, Geoscience Australia (2009) have retained the original name and stratigraphic position. The former 'Border Creek Member' (Mory and Beere 1988) of the Point Spring Sandstone was reinterpreted by Gorter *et al* (2005) as being a part of the overlying Kulshill Group and was restored to its original rank as the Border Creek Formation (*sensu* Veevers and Roberts 1968). Consequently, outcrops in AUVERGNE that were identified as 'Border Creek Member' (Dunster *et al* 2000) are excluded from the group. The Wadeye Group is unconformable on formations of the Weaber Group and is unconformably overlain by the Kulshill Group (Gorter *et al* 2005). Its base is characterised by seaward-directed canyon incision as a result of a major fall in sea level. In the NT, the group is represented in PORT KEATS by the subsurface Arco and Aquitaine formations (**Table 36.1**).

Arco Formation
The subsurface Arco Formation (Gorter *et al* 2005) unconformably overlies the Sunbird Formation, or where this is absent, the Tanmurra Formation, and is unconformably overlain by the Aquitaine Formation. The Arco and Aquitaine formations are laterally equivalent to the onshore Point Spring Sandstone (**Figure 36.12**). The formation is 105 m thick in the type section in offshore drillhole Sandbar-1, where it consists of a lower 62 m-thick interval of interbedded siltstone and fine- to very coarse-grained sandstone, and an upper 43 m-thick interval of fine- to coarse- and rarely very coarse-grained sandstone. Sandstone of the lower interval has up to 5% recrystallised limestone grains with occasional fossils and calcite cement is common in the lower beds. In Kulshill-1 (PORT KEATS), the formation is much thicker (ca 650 m) and consists mostly of siltstone/shale with occasional sandstone interbeds except for the uppermost 50 m which is mostly sandstone (Gorter *et al* 2005: figure 17). Gorter *et al* interpreted this succession as representing a basinal facies and noted that it contained a maximum flooding surface. The Arco Formation contains palynomorphs, conodonts and ostracodes that indicate a Serpukhovian to earliest Pennsylvanian age. The upward-coarsening nature of the formation indicates a progradational depositional environment, probably representing the advancement of a broad shelf towards a seaward basinal deep, but there is little evidence of the involvement of deltas (Gorter *et al* 2005).

Aquitaine Formation
The subsurface Aquitaine Formation (Gorter *et al* 2005) unconformably overlies the Arco Formation and is unconformably overlain by the Kuriyippi Formation (Kulshill Group). The Arco and Aquitaine formations are laterally equivalent to the onshore Point Spring Sandstone (**Figure 36.12**). In the type section in Sandbar-1, the Aquitaine Formation is 95 m thick and consists of a lower interval of fine- to coarse-grained sandstone with a few siltstone interbeds and an upper part that is gradational into siltstone (Gorter *et al* 2005). The formation is thicker (>200 m) in Kulshill-1 (PORT KEATS), where it consists mostly of interbedded sandstone and siltstone/shale (Gorter *et al* 2005: figure 17). A mostly non-marine depositional environment was suggested for the formation by Gorter *et al* (2005) from a paucity of *in situ* marine fossils, although it is possible that the upper finer-grained interval is marine.

LATE CARBONIFEROUS–EARLY PERMIAN

Kulshill Group

The Kulshill Group (Gunn 1988; equivalent to Kulshill Formation of Caye 1968, Hughes 1978) is exposed in the onshore Petrel and Keep Inlet sub-basins in northeastern CAMBRIDGE GULF and southeastern MEDUSA BANKS (Western Australia), and in the NT in northwestern AUVERGNE (Dunster *et al* 2000), and in central PORT KEATS and southeastern CAPE SCOTT (Dickins *et al* 1972, Gorter *et al* 2008, **Figure 36.6**). It also occurs extensively in the subsurface in all these mapsheets, and in the offshore Petrel Sub-basin. The group is over 1500 m thick and comprises seven formations; the lowermost are the Kuriyippi Formation and its western basin-margin equivalent, the Border Creek Formation (**Figure 36.12**). These are overlain by, in ascending stratigraphic order, the Treachery Formation, Quoin Formation, Ditji Formation and Keyling Formation (**Table 36.1**). The poorly dated Keep Inlet Formation occurs in the onshore Keep Inlet sub-basin and its relationships to the other formations are uncertain; it may be equivalent to either the upper Kuriyippi Formation or to younger units.

The Kulshill Group is unconformable on the Wadeye Group, or where this is absent, is unconformable on older Palaeozoic units, including the Langfield Group in onshore areas in the NT (Whitehead and Fahey 1985, Petroconsultants 1990, Dunster *et al* 2000). It is unconformable to conformable (in the north) beneath the Fossil Head Formation of the Kinmore Group in offshore areas (Gorter *et al* 2008, **Figure 36.15**). The Kulshill Group was deposited in an overall transgressive cycle and environments of deposition for the group include fluvial, fan delta and shallow marine, overprinted by the onset of glaciation in the upper Kuriyippi Formation (Mory 1991, Mory *et al* 2008). Glacial strata in the Bonaparte Basin are restricted to the Kulshill Group (Mory *et al* 2008).

Kuriyippi Formation

The Pennsylvanian (Bashkirian)–Early Permian (Asselian) Kuriyippi Formation (Mory 1991) is a thick succession of 30–90 m-thick upward-fining cycles of sandstone, siltstone, shale and minor coal, overlain by glacial sandstone and conglomerate. It is extensive in the offshore Petrel Sub-basin and is recognised in the onshore drillholes Kulshill-1 and -2 (PORT KEATS) and by correlation in Keep River-1 (AUVERGNE) and Bonaparte-1 and -2 in Western Australia. The formation reaches a maximum thickness of 1017 m in the type section in offshore drillhole Lesueur 1 (Mory 1991). The upward-fining cycles are indicative of mainly fluvial deposition, including meandering stream deposits, but the presence of glauconite in some drillholes suggests a shallow marine environment at least in part (Gorter *et al* 2008). The top of the Kuriyippi Formation is glaciogenic; Gorter *et al* (2008) tentatively assigned this interval to the informally named Blacktip member and indicated that it probably should be included with genetically related younger glaciogenic strata of the overlying Treachery Formation. A complex incised channel network at the top of the Kuriyippi Formation suggests that the area lay under an ice sheet at this time (Gorter *et al* 2008).

Keep Inlet Formation

The subsurface Keep Inlet Formation (Cockbain 1985; equivalent to 'Keep Inlet Beds' of Veevers and Roberts 1968) is restricted to onshore areas of the Keep Inlet Sub-basin south of 14°S (Mory 1990), but the distinction between this unit and the Kuriyippi Formation is not well defined to the extent that these formations were assigned to the same interval in drillhole Keep River-1 (AUVERGNE) by Mory and Beere (1988) and Petroconsultants (1990) respectively. The Keep Inlet Formation consists of calcareous, feldspathic and lithic quartz sandstone, with clay clasts, and pebbles and boulders of exotic rocks, and minor coal, indicative of fluvial and fan delta environments with a glacial influence (Veevers and Roberts 1968, Gorter *et al* 2008). Spores and palynomorphs, and the interpreted glaciogenic environment of deposition indicate a likely correlation with the upper Kuriyippi to basal Quoin formations (Gorter *et al* 2008).

Border Creek Formation

The Border Creek Formation (Veevers and Roberts 1968) was included as a member of the Point Spring Sandstone by Mory and Beere (1988), but was restored to its original status as a distinct formation of the Kulshill Group by Gorter *et al* (2005), who regarded as being an onshore equivalent of the Kuriyippi Formation. Veevers and Roberts (1968) described the Border Creek Formation as being unconformable on various units of the Langfield and Weaber groups, and Whitehead and Fahey (1985) listed the unit as being unconformable on the Zimmerman Sandstone, Septimus Limestone and Enga Sandstone in AUVERGNE (**Figures 36.13**, **36.14**). Gorter *et al* (2005) described the formation as being unconformable on the Burvill Formation and Tanmurra Formation (Weaber Group) and on the Point Spring Sandstone (Wadeye Group). Veevers and Roberts (1968) reported that the formation is overlain by the Keep Inlet Formation, but the nature of the contact was not specified. Otherwise, it is unconformable beneath the Treachery Formation (Geoscience Australia 2009). The Border Creek Formation is exposed as prominent cliffs of jointed sandstone and flat-topped ridges in southeastern MEDUSA BANKS and northeastern CAMBRIDGE GULF (Western Australia), and in northwestern AUVERGNE (NT). It also occurs in the subsurface in a number of onshore drillholes including Keep River-1 and Weaber-5 (Dunster *et al* 2000) and Weaber-1, Ningbing-1 and Bonaparte-1 and -2 (Gorter *et al* 2005). The formation consists of sandstone and conglomerate (**Figure 36.16**) with lesser interbedded siltstone. The sandstone is generally cross-bedded and contains occasional pebble beds. Whitehead and Fahey (1985) interpreted a high-energy fluvial environment of deposition with siltstone representing overbank fines for the formation in AUVERGNE. However, Mory (1990) preferred a deltaic setting for the unit in Western Australia.

Treachery Formation

The Sakmarian Treachery Formation (Mory 1988) occurs extensively in the offshore subsurface and is also recognised

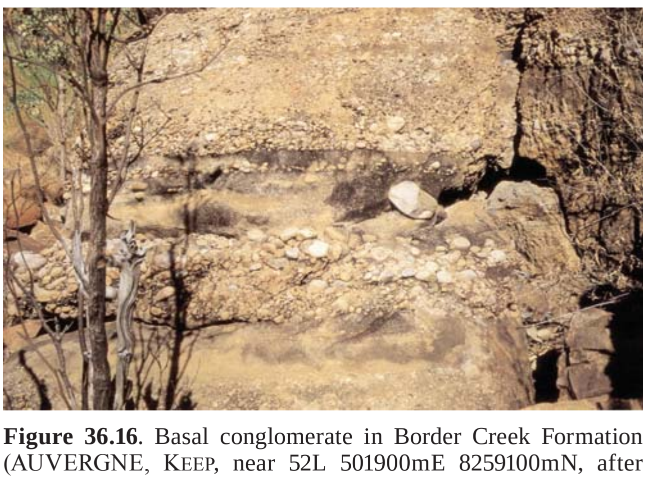

Figure 36.16. Basal conglomerate in Border Creek Formation (AUVERGNE, KEEP, near 52L 501900mE 8259100mN, after Whitehead and Fahey 1985: plate 13).

in onshore drillholes in the eastern side of the Petrel Sub-basin, including Kulshill-1 and -2 and Moyle-1 in PORT KEATS. It also probably includes glaciogenic outcrops on the eastern side of the sub-basin in this area (Dickins *et al* 1972, Gorter *et al* 2008). The informally named glaciogenic *Blacktip member* occurs at the base of the Treachery Formation (Gorter *et al* 2008) and forms a petroleum reservoir at Blacktip-1. The Treachery Formation unconformably overlies the Kuriyippi Formation and is overlain, probably unconformably, by the Quoin Formation. It is about 250 m thick in offshore drillholes, thickens to greater than 300 m in Kulshill-1, but thins towards the basin margins and is only about 130 m thick in Moyle-1 (Gorter *et al* 2008). The formation consists of tillite, diamictite, carbonaceous shale, varved siltstone, sandstone and minor limestone and coal (Mory 1991, Gorter *et al* 2008). The diamictite contains exotic pebbles, some of which are facetted. The depositional environment for the formation is possibly glaciomarine, at least in part, although a marginal marine or non-marine setting is also possible (Gorter *et al* 2008).

Quoin Formation

The subsurface Sakmarian Quoin Formation (Gorter *et al* 2008) and overlying Ditji Formation were originally included within the Keyling Formation of Mory (1991). The Quoin Formation occurs extensively in offshore areas and is intersected in onshore wells in the east of the Petrel Sub-basin. It is probably unconformable on the Treachery Formation and is overlain, probably unconformably, by the Ditji Formation. The unit reaches a maximum thickness of about 750 m in the vicinity of Kulshill-1 and -2 in PORT KEATS, but thins towards the northwest to less than 200 m in offshore areas (Gorter *et al* 2008). The formation is a sharp-based blocky sandstone that fines upwards into thinner beds of sandstone, siltstone and shale. Most sandstone–shale intervals have a sharp base and an upward-fining character. The environment of deposition is interpreted to have been mostly fluvial following de-glaciation, when melt water from ice sheets carried vast quantities of sediments into the basin (Geoscience Australia 2009). In offshore areas around Blacktip-1, the formation was probably deposited in tidal channels and tidal flats, and in the vicinity of Kulshill-1, a nearshore to continental environment has been interpreted (Gorter *et al* 2008).

Ditji Formation

The Sakmarian Ditji Formation (Gorter *et al* 2008) overlies the Quoin Formation, probably unconformably, and is probably unconformably overlain by the Keyling Formation. The unit is only known from offshore wells and appears to be absent in onshore areas. It reaches a maximum thickness of about 130 m and consists of calcareous sandstone grading to sandy limestone with minor interbeds of coal. The formation is interpreted as a transgressive sequence deposited in response to the end of glaciation. A marine or marginal marine setting is likely (Gorter *et al* 2008).

Keyling Formation

The Sakmarian Keyling Formation (Mory 1991, redefined in Gorter *et al* 2008) unconformably overlies the Ditji Formation and is unconformably to conformably (in the north) overlain by the Fossil Head Formation (Kinmore Group). It comprises mostly sandstone, with lesser siltstone, shale, coal, conglomerate and minor limestone. The formation occurs throughout the offshore southeastern Bonaparte Basin and is found in the subsurface in onshore drillholes Kulshill-1 and -2 and Moyle-1 (PORT KEATS), but thins towards the southern basin margin, where it is truncated below the base of the Fossil Head Formation (Geoscience Australia 2009). In the vicinity of the Kulshill drillholes, the formation is about 300 m thick, but it thickens to greater than 500 m offshore. Gorter *et al* (2008) interpreted a mostly non-marine environment of deposition for the unit, possibly as part of a broad belt of meandering streams, with subordinate lacustrine facies and coal swamps. Lesser marginal marine and intertidal environments are also interpreted from intervals in some offshore drillholes.

EARLY PERMIAN TO MIDDLE TRIASSIC

Kinmore Group

The Kinmore Group (Mory 1991, redefined in Gorter 1998, Gorter *et al* 2009; equivalent to 'Port Keats Group' of Noakes 1949) outcrops discontinuously along the coast and hinterland of PORT KEATS and southern CAPE SCOTT in the Northern Territory (**Figure 36.6**) and is extensive in the subsurface in the offshore Bonaparte Basin (**Figure 36.15**). The group comprises, in ascending stratigraphic order, the Fossil Head Formation, and the Hyland Bay and Mount Goodwin sub-groups, each of which contains a number of constituent formations (**Table 36.1**). The group is best known from offshore drillhole intersections, and although most units are represented in onshore parts of the basin in PORT KEATS and CAPE SCOTT (Dickins *et al* 1972, Mory 1991), they have not generally been distinguished on geological maps due to discontinuous exposures, low dips and poor age controls. The Kinmore Group is unconformable between the Kulshill Group below and Troughton Group above (Gorter 1998, Robinson and McInerney 2004). Detailed palaeogeographic reconstructions of units within the Hyland Bay Subgroup are in Robinson and McInerney (2004).

Fossil Head Formation

The Fossil Head Formation (Bhatia *et al* 1984; equivalent to 'Fossil Head beds' of Caye 1968) is widespread in the southern Petrel Sub-basin and is also questionably present on the Londonderry High (Mory 1991). It occurs onshore in PORT KEATS and is recognised in the subsurface in drillhole Kulshill-1 (Gorter *et al* 2005). The formation unconformably to conformably (in the north) overlies the Keyling Formation (Kulshill Group) and is overlain unconformably or with a sharp boundary by the Pearce Formation of the Hyland Bay Sub-group. It varies in thickness in the range 116–590 m (Mory 1991) and consists of carbonaceous siltstone and mudstone with sandstone and minor limestone. Abundant fossils, including bryozoans, brachiopods, echinoderms, corals, gastropods, ostracodes and microflora, indicate a Sakmarian–Roadian age (Geoscience Australia 2009) and a marine shelf environment of deposition. The lower part of the formation may have been deposited in a prodeltaic setting (Mory 1991).

Hyland Bay Subgroup

The Hyland Bay Subgroup (Hughes 1978, redefined in Gorter 1998) comprises mudstone, siltstone, sandstone and carbonate rocks that collectively attain a thickness of up to ca 2300 m in the central and outer parts of the Petrel Sub-basin. The subgroup comprises five formations, in ascending stratigraphic order, the Torrens, Pearce, Cape Hay, Dombey and Tern formations (Gorter 1998) that were deposited in a range of environments, including prodelta, deltaic, shoreface and open marine shelf. These units have been relatively well described in offshore drillholes, but are poorly mapped in onshore areas. Very little information is available on the offshore *Torrens Formation* (Gorter 1998), which was given formation status in Gorter *et al* (2009). This unit is 22 m thick in drillhole Torrens-1 and has a limited areal distribution. It has not been fully described and was not included as a part of the original 'Hyland Bay Formation' as defined by Mory (1988).

Pearce Formation

The 'Pearce Member' of the ' Hyland Bay Formation' was defined by Mory (1988) and raised to formation status by Gorter (1998). Mory (1991) noted that the 'Pearce Member' and basal undifferentiated 'Hyland Bay Formation' are probably equivalent to the 'marine horizon of Fossil Head' of Dickins *et al* (1972) in PORT KEATS, which is dated as Kungurian–Capitanian (Gorter 1998). The Pearce Formation is unconformable between the Fossil Head and Cape Hay formations and was subdivided by Gorter (1998) into lower and upper units. The lower unit is an 8 m-thick limestone in the type section in offshore drillhole Penguin-1 and consists of bioclastic limestone with abundant bryozoans and minor shelly debris. The unit becomes increasingly dominated by clastic rocks to the southeast and onshore is probably a sandstone (Gorter 1998). The upper unit is 42 m thick in Penguin-1 and consists of a basal dark shale overlain by allochthonous bioclastic limestone, with brachiopods, bryozoans and other shelly debris. An offshore marine to marine shelf environment of deposition was considered likely for the formation by Gorter (1998).

Cape Hay Formation

The Cape Hay Formation (Bhatia *et al* 1984, redefined in Mory 1988 and Gorter 1998) forms the bulk of the Hyland Bay Subgroup and is probably equivalent to the onshore 'plant-bearing beds' of Dickins *et al* (1972) in PORT KEATS (Mory 1991). It is unconformable beneath the Dombey Formation and can be subdivided into at least two and possibly more subunits (Gorter 1998, Robinson and McInerney 2004). The lower unit comprises thick basal shale overlain by thinly bedded sandstone, siltstone and shale, that grade in the southeast to more massive sandstone. This overall regressive succession is unconformably overlain by a thin interval of marine shale, followed by at least two regressive sandstone-dominated cycles of the upper Cape Hay Formation (Robinson and McInerney 2004). The upper succession is generally restricted to the central areas of the Petrel Sub-basin due to uplift and erosion prior to the deposition of overlying strata. The Cape Hay Formation contains microfloras consistent with a Wordian to Capitanian age (Gorter 1998) and was deposited as part of a widespread, river-dominated delta system with restricted shoreface conditions (Robinson and McInerney 2004).

Dombey Formation

The Dombey Formation (Bhatia *et al* 1984, redefined in Mory 1988, Gorter 1998) is a laterally extensive limestone-dominated unit that represents a widespread marine transgression. Mory (1991) indicated that the formation is possibly equivalent, at least in part, to the onshore 'Upper Permian marine beds' of Dickins *et al* (1972) and Gorter (1998) tentatively correlated the unit with onshore fossiliferous sediments at Cape Dombey (Archbold *et al* 1993), in CAPE SCOTT. The formation generally consists of a lower unit of limestone with shale intercalations, overlain by an upper unit consisting of basal fine-grained sandstone, shale and marl below a second interval of limestone with shale interbeds (Gorter 1998). The bryozoan-rich limestone of the Dombey Formation contains a fauna and microflora, briefly summarised in Gorter (1998), that are consistent with a marine shelf environment of deposition and a Wuchiapingian age (Gorter 1998).

Tern Formation

The Tern Formation (Mory 1988, redefined in Gorter 1998) is unconformable on the Dombey Formation and is overlain, probably unconformably, by the Penguin Formation of the Mount Goodwin Subgroup. It is probably equivalent (Mory 1991, Gorter 1998) to onshore sandstone at Cape Dombey (CAPE SCOTT), which is part of the 'Upper Permian marine beds' of Dickins *et al* (1972). The formation is 64 m thick in the type section in offshore drillhole Tern-1 and 73 m thick in Tern-3 Gorter 1998). It consists of repeating cycles of sandstone, siltstone and mudstone that were interpreted by Bann *et al* (2004) as bioturbated offshore and prograding sandy shoreface successions deposited in a well oxygenated marine environment, overlain by a bioturbated estuarine succession that was deposited in a brackish water setting. A latest Wuchiapingian to Changhsingian age is likely for the formation (Geoscience Australia 2009).

Mount Goodwin Subgroup

The Mount Goodwin Subgroup (Helby 1974, redefined in Gorter *et al* 2009) consists predominantly of siltstone and shale and is extensive in the subsurface over much of the offshore Bonaparte Basin (**Figure 36.15**). It reaches a maximum thickness of 670 m in drillhole Dillon Shoals-1 (Mory 1991) and is 570 m thick in the type section in Petrel-1 (Helby 1974, as reported in Gorter *et al* 2009), but thins towards the southern and eastern basin margins. The sub-group is unconformable between the Hyland Bay Sub-group and either the Osprey Formation in the eastern Bonaparte Basin or the Sahul Group elsewhere. The succession consists of the latest Permian Penguin Formation overlain by the Early Triassic Mairmull, Ascalon and Fishburn formations (Gorter *et al* 2009).

The subgroup is represented onshore by a thin 20 m-thick succession in the vicinity of Port Keats (northern PORT KEATS; Dickins *et al* 1972, Mory 1991).

Penguin Formation

The Upper Permian (Changhsingian) Penguin Formation is 49 m thick in the type section in drillhole Tern-3 and consists of claystone, carbonaceous siltstone and minor calcareous sandstone in upward-coarsening cycles. It is unconformable on the Hyland Bay Sub-group and was deposited in a transgressive marginal marine environment (Gorter 1998, Gorter *et al* 2009). The formation is not recognised in onshore areas.

Mairmull Formation

The Lower Triassic (Induan–lower Olenekian) Mairmull Formation (Gorter *et al* 2009) is equivalent to the 'Lower Mount Goodwin Formation' of Gorter (1998) and Gorter *et al* (1998). It conformably overlies the Penguin Formation, or where this is absent, unconformably overlies the Hyland Bay Subgroup, and is unconformably overlain by the Ascalon Formation. The unit is 199 m thick in the type section in drillhole Fishburn-1 and consists of claystone and siltstone with rare thin sandstone interbeds, which are more common towards the top. The Mairmull and Ascalon formations outcrop in northern PORT KEATS near Mount Goodwin (Dickins *et al* 1972, Gorter *et al* 2009), but these units have not been differentiated in maps of the area. Dickins *et al* (1972) referred to exposures of the two formations as 'outcrops of probable Lower Triassic age' and described them as consisting of siltstone and shale with minor fine-grained sandstone. The rocks have a distinctive low-angle cross-lamination and contain lingulid brachiopods, estheriid conchostracens, indeterminate plants and vertebrate remains. In general, a shallow marine environment has been interpreted for the Mairmull Formation (Gorter *et al* 2009), Dickins *et al* (1972) suggested that the onshore exposures may have been deposited in a brackish estuary or bay.

Ascalon Formation

The Lower Triassic (Olenekian) Ascalon Formation (Gorter *et al* 2009) is equivalent to the 'Intra Mount Goodwin Formation sandstone' of Gorter *et al* (1998). It is 32.5 m thick in the type section in offshore drillhole Ascalon-1A and is a prominent sandstone and siltstone unit, developed along the southern margin of the Bonaparte Basin, that becomes increasingly shaly to the northwest. The formation unconformably overlies the Mairmull Formation and is conformably and transitionally succeeded by the Fishburn Formation (Gorter *et al* 2009). It outcrops in northern PORT KEATS near Mount Goodwin along with the Mairmull Formation (Dickins *et al* 1972, Gorter *et al* 2009), but these units have not been differentiated in maps of the area. The Ascalon Formation was probably deposited during a sea level lowstand in a transitional paralic to shallow marine setting. Seismic surveys show that in the vicinity of offshore drillhole Blacktip-1, sandstone of this unit is associated with a series of anastomosing channels, many of which appear to be meandering, suggesting a low-relief delta plain depositional environment (Gorter *et al* 2009).

Fishburn Formation

The Lower–early Middle Triassic (Olenekian–early Anisian) Fishburn Formation (Gorter *et al* 2009) is equivalent to the 'Upper Mount Goodwin Formation' of Gorter (1998). It is widespread in the offshore Bonaparte Basin, but is truncated by erosion towards the southern margin and is not recognised in onshore areas. The formation consists of claystone with minor siltstone and sandstone and is 179.5 m thick in the type section in drillhole Fishburn-1. A nearshore depositional environment was interpreted by Gorter *et al* (2009).

MIDDLE TRIASSIC TO MIDDLE JURASSIC

Troughton Group

The Troughton Group (Gunn 1988) is an offshore succession unconformably overlying the Mount Goodwin Subgroup and extending across much of the Bonaparte Basin (**Figure 36.15**). In the southeastern part of the basin, this group consists of the Cape Londonderry, Malita and Plover formations. The Middle to Upper Triassic (Anisian–Norian) *Cape Londonderry Formation* is a regressive succession of sandstone and minor siltstone and shale that was deposited over most of the Petrel Sub-basin. It attains a thickness of up to 400 m (Helby 1974, Mory 1991) and thins onto the basin margins. The lower and upper parts of the formation are respectively equivalent to the Osprey and Pollard formations elsewhere in the Bonaparte Basin. The Cape Londonderry Formation was deposited during a relatively stable sag phase in an interpreted fluvial to braided stream environment (Geoscience Australia 2009). The Late Triassic (Norian–Rhaetian) *Malita Formation* attains a thickness of approximately 300 m in the Petrel Sub-basin (Helby 1974, Mory 1991), but thins towards the basin margins in the east and south. The red bed character of the formation suggests a generally non-marine, possibly arid environment. Following deposition of the Malita Formation, an Early Jurassic transgression resulted in the deposition of deltaic to nearshore sandstone and shale of the Early–Middle Jurassic *Plover Formation* over large parts of the offshore Bonaparte Basin, including the central and northern Petrel Sub-basin. The formation thickens from the basin margins to over 500 m in the centre of the basin.

LATE JURASSIC–EARLY CRETACEOUS

Flamingo Group

The offshore Middle Jurassic–Early Cretaceous Flamingo Group (Gunn 1988; equivalent to 'Flamingo Shale' of Botten and Wulff 1990) is disconformable on the Troughton Group and comprises the Elang Formation, Lower Frigate Shale/ Cleia Formation, Frigate Shale and Sandpiper Sandstone (Mory 1991, Pattillo and Nicholls 1990, Whittam *et al* 1996, Geoscience Australia 2009), deposited during a time of minor extension and subsidence. The Middle–Upper Jurassic (Callovian–Oxfordian) *Elang Formation* consists of retrogradational deltaic sandstone deposited as a result of a widespread mid- Callovian marine transgression and is equivalent to the Laminaria and Montara formations elsewhere in the Bonaparte Basin (**Figure 36.15**). After deposition of the Elang Formation, continued rapid subsidence resulted in the deposition of a an up to 250 m-thick succession of marine mudstone (*Frigate Shale* and equivalents). The upper part of the Flamingo Group is the *Sandpiper Sandstone*, a 30–270 m-thick fluvial to deltaic sandstone-dominated unit of Late Jurassic to earliest Cretaceous (Tithonian–Berriasian) age (Mory 1991).

CRETACEOUS

Bathurst Island Group equivalent

The Bathurst Island Group (Mory 1988) was originally defined in the Money Shoal Basin as the 'Bathurst Island Formation' (Hughes and Senior 1974, Hughes 1978), but the group extends across the Bonaparte Basin, and elements of the group are also known from the adjoining Browse Basin to the west. A regional unconformity of Early Cretaceous (Valanginian) age underlies the group and is associated with interrupted sedimentation and erosion that removed large volumes of sediment from the basin's margins, platforms and highs, but only a minor sedimentary hiatus occurred in the Petrel Sub-basin and adjacent depocentres. Bathurst Island Group equivalent rocks consist of thick, shale-dominated marine sedimentary rocks, with thick successions accumulated in the Petrel Sub-basin, Malita Graben and Calder Graben. In the Petrel Sub-basin, the group comprises the Echuca Shoals Formation and two units that are equivalent to the Darwin Formation and Wangarlu Formation of the Money Shoal Basin, but a number of other formations have been defined in other parts of the basin (Mory 1988, **Figure 36.15**). The basal Valanginian–Aptian interval of glauconitic shale was originally referred to the Darwin Formation, but has since been renamed the Echuca Shoals Formation, with the term 'Darwin Formation' being applied to the overlying Aptian to Albian section (Whittam *et al* 1996); this interval was referred to as the 'Darwin Radiolarite' by Geoscience Australia (2009, 2011). Bathurst Island Group equivalent strata attain a thickness of up to 2000 m (mostly Wangarlu Formation equivalent) in the Petrel Sub-basin and Malita Graben, but thin to the west to be 100–300 m thick on the Ashmore Platform (Mory 1988).

The mid-Valanginian–early Aptian *Echuca Shoals Formation* (Pattillo and Nicholls 1990) consists of glauconitic marine claystone and siltstone that were deposited widely across the Bonaparte Basin as a result of the foundering of the Australian margin following continental break up, sea-floor spreading and subsidence (Geoscience Australia 2009). Overlying Aptian–Albian *Darwin Formation equivalent* strata consist of radiolarian chert, claystone and calcimudstone and represents the peak of the Early Cretaceous transgression. Much of the northern NT was inundated by a shallow marine sea at this time (see **Carpentaria Basin**) and isolated onshore exposures of Early Cretaceous age, corresponding to this formation, are scattered across CAPE SCOTT and PORT KEATS. Dickins *et al* (1972) described two localities containing Early Cretaceous marine fossils (belemnites and radiolaria) in southern CAPE SCOTT, including a measured section of up to 49 m of near Mount Greenwood, although this section has been affected by slumping, so the thickness is possibly excessive. These outcrops consist of claystone, pebbly siltstone, pebbly sandstone and sandstone. A siliceous duricrust may be developed on other Early Cretaceous outcrops in places. Thick Albian to mid-Campanian *Wangarlu Formation equivalent* strata (Hughes and Senior 1974, Hughes 1978, redefined in Mory 1988) conformably overlie the Darwin Formation equivalent in offshore areas. The basal interval of this formation comprises massive claystone with subordinate siltstone and minor sandstone, which grade up-section into claystone, calcimudstone and marl. Sandstone of Santonian age is locally developed in the upper part of the formation, in the Vulcan Sub-basin and northern Bonaparte Basin (Geoscience Australia 2009). A inner to distal marine shelf depositional setting is likely for the unit (Petroconsultants 1990).

CENOZOIC

Woodbine Group

The northward tilt of the Bonaparte Basin, established during the Cretaceous was maintained throughout the Cenozoic. Along the axis of the Petrel Sub-basin and in the Malita Graben and Sahul Syncline, Paleocene to Holocene sedimentary rocks of the Woodbine Group (McLennan *et al* 1990) were deposited with a hiatus occurring during the Oligocene (Mory 1988, **Figure 36.15**). The lower section is generally a sandy succession grading upwards into widespread shelf carbonate development during Miocene time, which appears to have transgressed the palaeohighs (Petroconsultants 1990). The Woodbine Group is up to 1300 m thick and comprises the Johnson, Hibernia, Prion, Oliver and Barracouta Shoal formations, but these units have not been differentiated in the southeastern Bonaparte Basin.

TECTONIC HISTORY

The Bonaparte Basin has a long and complex Phanerozoic structural history that has been described in numerous publications including Gunn (1998), Veevers (1988), McCaffrey (1988), Gunn and Ly (1989), Pattillo and Nicholls (1990), O'Brien *et al* (1993, 1996), AGSO NW Shelf Study Group (1994), Baillie *et al* (1994), Whittam *et al* (1996), Shuster *et al* (1998), Keep *et al* (1998, 2002), Kennard *et al* (2002) Longley *et al* (2002), Peresson *et al* (2004), Geoscience Australia (2009, 2011) and Bourget *et al* (2012). The basin has undergone two phases of Palaeozoic extension, a Late Triassic compressional event and further extension in the Mesozoic that led to the break-up of Gondwana in the Middle Jurassic. Miocene to Holocene convergence of the Indo-Australian and Southeast Asian microplates has resulted in the formation of a major tectonic collision zone (Banda Orogen), the 2000–3000 m-deep Timor Trough and widespread fault reactivation across the western portion of the basin.

Geoscience Australia (2009, 2011) have outlined the principle events in the evolution of the Bonaparte Basin, and the following brief summary is mainly derived from these sources:

- Following the emplacement of the Kalkarindji Large Igneous Province (see **Kalkarindji Province**) in the late early Cambrian, widespread regional subsidence resulted in transgression across much of the northern part of Australia and initiated deposition in the Carlton Sub-basin.
- The northwest-trending Petrel Sub-basin formed during Late Devonian to Mississippian extension.
- Pennsylvanian to Early Permian extension overprinted the older northwesterly trend with a northeasterly structural grain and formed the proto-Vulcan Sub-basin and Malita Graben.
- Late Triassic compression caused uplift and erosion on the southern margins of the Petrel Sub-basin, Londonderry High, and Ashmore and Sahul platforms.
- Jurassic extension coinciding with the commencement of sea-floor spreading to the west of the Browse Basin resulted in the development of the Vulcan Sub-basin, Sahul Syncline, and Malita and Calder grabens as major depocentres.
- Early Cretaceous thermal subsidence resulted in a thick wedge of fine-grained, clastic and carbonate sediments prograding across the offshore basin throughout the Cretaceous and Cenozoic.
- Miocene to Holocene collision of the Indo-Australian tectonic plate and Southeast Asian microplates formed the Timor Trough and the strongly faulted northern margin of the adjacent Sahul Platform.

MINERAL RESOURCES

The onshore Bonaparte Basin contains a total of 37 recorded mineral occurrences, 12 each of heavy mineral sands, coal and base metals, and one occurrence of ochre (**Figure 36.17**). The Sandy Creek (Manbarrum) and Djibitgun zinc-lead deposits in western AUVERGNE are currently being actively explored by TNG Ltd. Near Sandy Creek, but just across the border in Western Australia, a significant zinc-lead resource has been outlined at Sorby Hill. All of these zinc-lead occurrences could be classified as Mississippi Valley-type (MVT). Heavy mineral sands occurrences are located in beach sands along the coastline and offshore islands in PORT KEATS and CAPE SCOTT, but no economic deposits have been identified. Coal seams have been noted in onshore and offshore drillholes penetrating Permian strata and diapiric salt has been an exploration play within the basin since the 1970s. The offshore Bonaparte Basin is a world-class oil and gas province with proven resources and currently producing fields. Onshore drillholes have flowed dry gas in the southern Petrel Sub-basin.

Base metals

Cerussite, a lead carbonate mineral, was discovered in the Spirit Hill area (western AUVERGNE) before 1900 (Legge *et al* 1984). Other indications of base metals mineralisation in the same area were reported during an oil search program in 1956. Since that time, numerous Zn/Pb occurrences and prospects have been discovered within the NT in a belt from Spirit Hill to Landandi (**Figure 36.18**), all within the Early Carboniferous Burt Range Formation (Langfield Group). Just across the border in Western Australia, the significant Sorby Hills Ag-Pb-Zn deposit was discovered by Aquitaine Australia Minerals Pty Ltd in 1971 (Rowley and Lee 1986, Jorgensen *et al* 1990) and this deposit is also hosted by the Burt Range Formation. A number of other base metals prospects and occurrences are present within the Bonaparte Basin in Western Australia, mostly in older Late Devonian strata (**Figure 36.18**).

In the NT portion of the basin, Aquitaine and its Bonaparte Gulf JV partners commenced exploration for base metals in

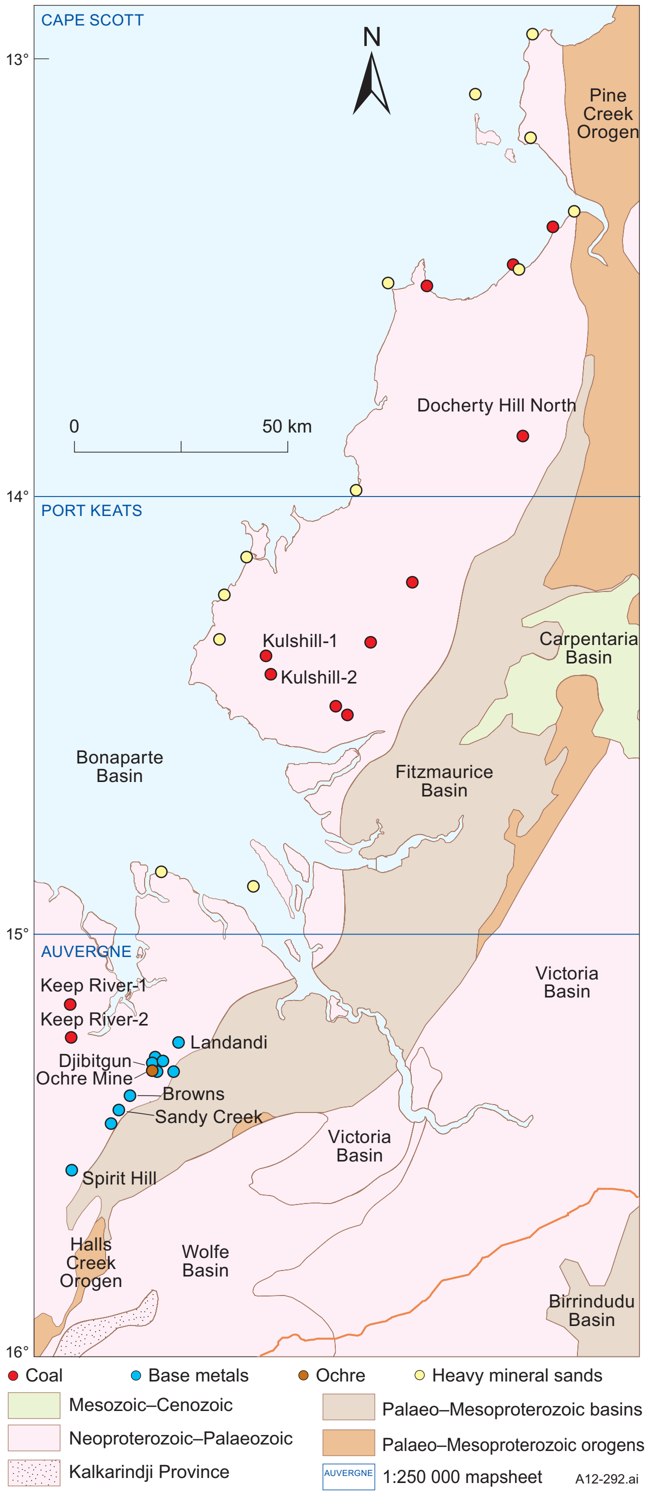

Figure 36.17. Locations of mineral occurrences in the onshore Bonaparte Basin in the NT, derived from NTGS Mineral Occurrence Database (MODAT).

1972. Exploration methods included detailed geophysical surveys, stream/soil geochemistry and drilling. By 1984, a total of 19 diamond drillholes and 50 percussion drillholes had been drilled in the region. In 1989, BHP Minerals Ltd entered the JV with Triako Resources Ltd, which had acquired the project from Aquitaine and completed an IP survey which demonstrated the prospectivity of the Burt Range Formation along the Sandy Creek trend. BHP subsequently drilled several diamond holes to test one of the IP anomalies. In 1994, Delta Gold NL conducted detailed gravity surveys and TEM soundings and concluded that gravity anomalies within the Burt Range Formation had considerably increased the prospectivity of the Sandy Creek area, with the potential for extensions to the mineralised zone both north and south along strike to be tested by further drilling (TNG 2008). In August 2005, titles were granted to Tennant Creek Gold Ltd (now TNG Ltd) which named the area the Manbarrum Project. Tennant Creek Gold commenced a resource drilling program in 2006 leading to the first JORC-compliant Resource announcement of 10.5 Mt at 3.3% combined Pb-Zn at Sandy Creek. After 2006, Tennant Creek Gold/TNG conducted extensive exploration in the area and outlined a number of prospects in the region. In 2011, TNG signed a Joint Venture Agreement on its Manbarrum Project with the Sorby Hills Joint Venture (SHJV). The SHJV is between Kimberley Metals Ltd (now KBL Mining Ltd) and Yuguang (Australia) Pty Ltd, a subsidiary of Hunan Yuguang Gold & Lead Co Ltd.

Sandy Creek

The Sandy Creek Pb-Zn-Ag deposit, on the eastern margin of the Bonaparte Basin, is hosted within carbonate rocks of the Burt Range Formation (**Figure 36.18**). It is located 24 km to the northeast of The Sorby Hills deposit in WA, which is also hosted by carbonate rocks of this formation. Discontinuous Zn-Pb-Ag mineralisation is present over a 15 km strike length at Sandy Creek, which is a typical MVT deposit. The mineralisation is irregularly distributed below the contact between quartzose carbonate rocks of the Burt Range Formation and shale and sandy siltstone of the overlying Milligans Formation (**Figure 36.19**). This contact forms the hangingwall to the deposit and no zinc-lead mineralisation

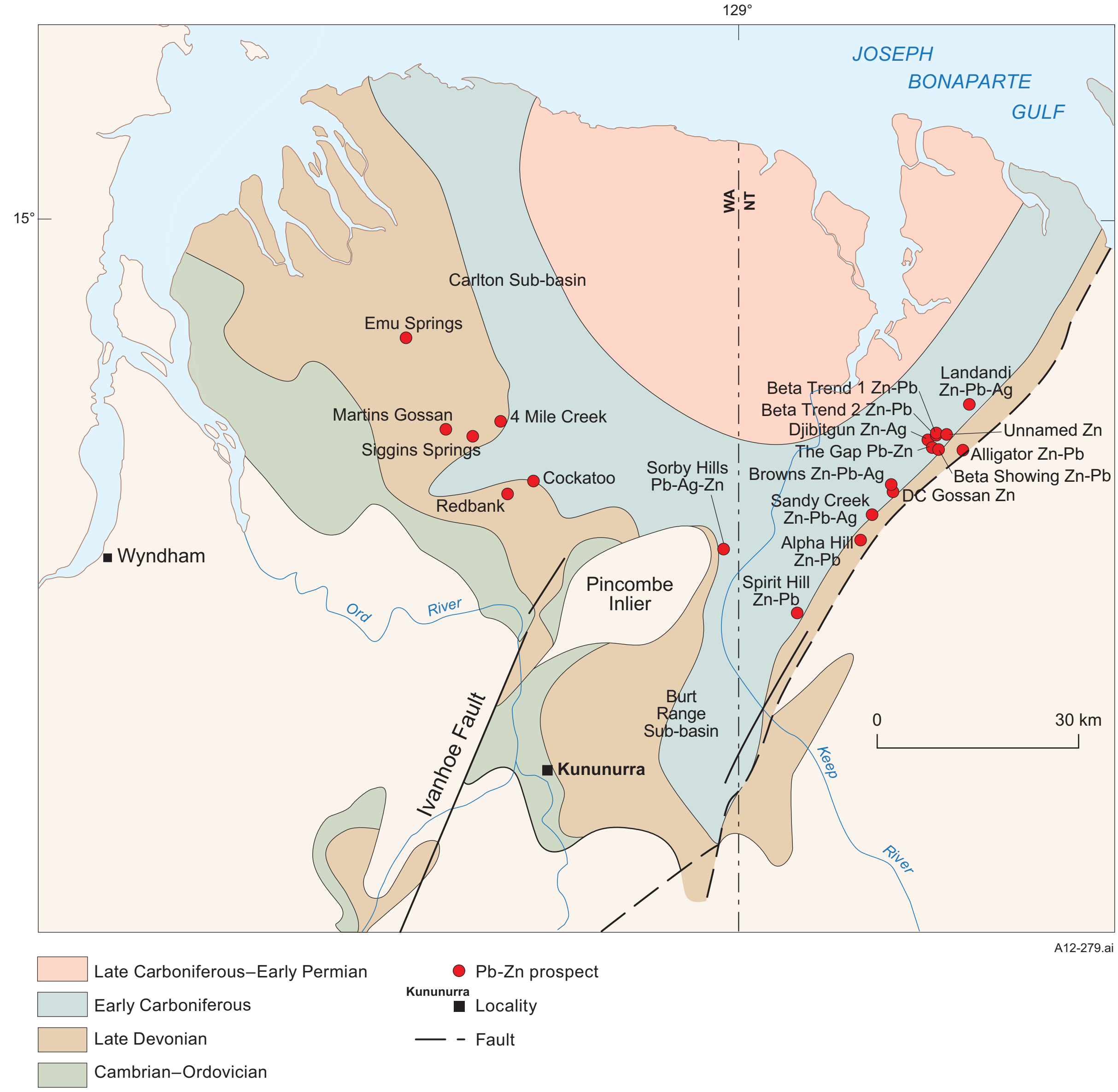

Figure 36.18. Locations and geological setting of base metals occurrences and prospects in the onshore southern Bonaparte Basin. Interpreted solid geology modified from Veevers and Roberts (1968), Jorgensen *et al* (1990), Burton (2010) and AUVERGNE. Location of Western Australian base metals prospects after Burton (2010); location of NT base metals prospects from MODAT.

has penetrated into the overlying shale, which acted as a seal to the mineralising brine. Mineralisation (**Figure 36.20**) consists of sphalerite, silver-bearing galena and pyrite, and is predominantly hosted by a quartzose dolostone (100–120 m thick) within the Burt Range Formation. In places, it appears to extend into underlying silty carbonate rocks. Two distinct styles of mineralisation are present: (a) high-grade (eg 16 m at 9.5% Pb and 2% Zn) breccia zones, within and proximal to north-trending, near-vertical basement-related faults; and (b) lower-grade (eg 5 m at 1.6% Pb and 1.4% Zn) stratabound sedimentary carbonate breccia and porous dolomitic sandstone (Ferenczi 2005). Mineralisation includes a near-surface zone of supergene mineralisation, which is predominantly sphalerite with locally high-grade galena in a clay matrix. The oxide mineralisation is estimated to represent 20% of the total metal content. The sulfide minerals range from very fine sparsely disseminated grains of pyrite-marcasite-sphalerite-galena, to spongiform aggregates, through to massive polysulfide aggregates that completely replace the host rock. Open-space filling by colloform, textured, rhythmically banded sphalerite-marcasite and coarse euhedral marcasite is also evident. Minor fine veins of crystalline barite are associated with some sulfides (Biddle 2007). The Sandy Creek deposit contains a JORC-compliant global Resource of 24.38 Mt at 1.81% Zn, 0.45% Pb and 4.57 g/t Ag at a cut-off grade of 1% zinc. A high-grade lead Resource component of 0.814 Mt at 1.68% Zn, 4.08% Pb and 16.83 g/t Ag at a 2.5% Pb cut-off has also been identified (TNG 2010).

Djibitgun

The Djibitgun Zn-Ag-Pb deposit, situated about 25 km northeast of Sandy Creek (**Figure 36.18**), was located by TNG in 2008 during a broadly spaced reconnaissance drilling program. This deposit is composed predominantly of zinc and silver mineralisation within the oxidised zone of a quartz sandy carbonate unit of the Burt Range Formation, similar to the host rock for the Sandy Creek Deposit. The mineralisation commences at approximately 30 m depth and extends to 90 m. Higher-grade zones are evident within the broad mineralised envelope (TNG 2008, Kimberley Metals 2011). The Djibitgun deposit contains a JORC-compliant Inferred Resource (oxide silver ore at 15 g/t Ag cut-off) of 9.5 Mt at 20.2 g/t Ag and 0.6% Zn. It also contains an oxide zinc Resource (at 1.5% Zn cut-off) of 3.8 Mt at 2.2% Zn, 0.5% Pb and 15.3 g/t Ag (Kimberley Metals 2011).

Coal

Coal was first recognised in the onshore Bonaparte Basin prior to 1894 (Brown 1895). The Permian Keep Inlet Formation (Kulshill Group) has been the subject of reconnaissance

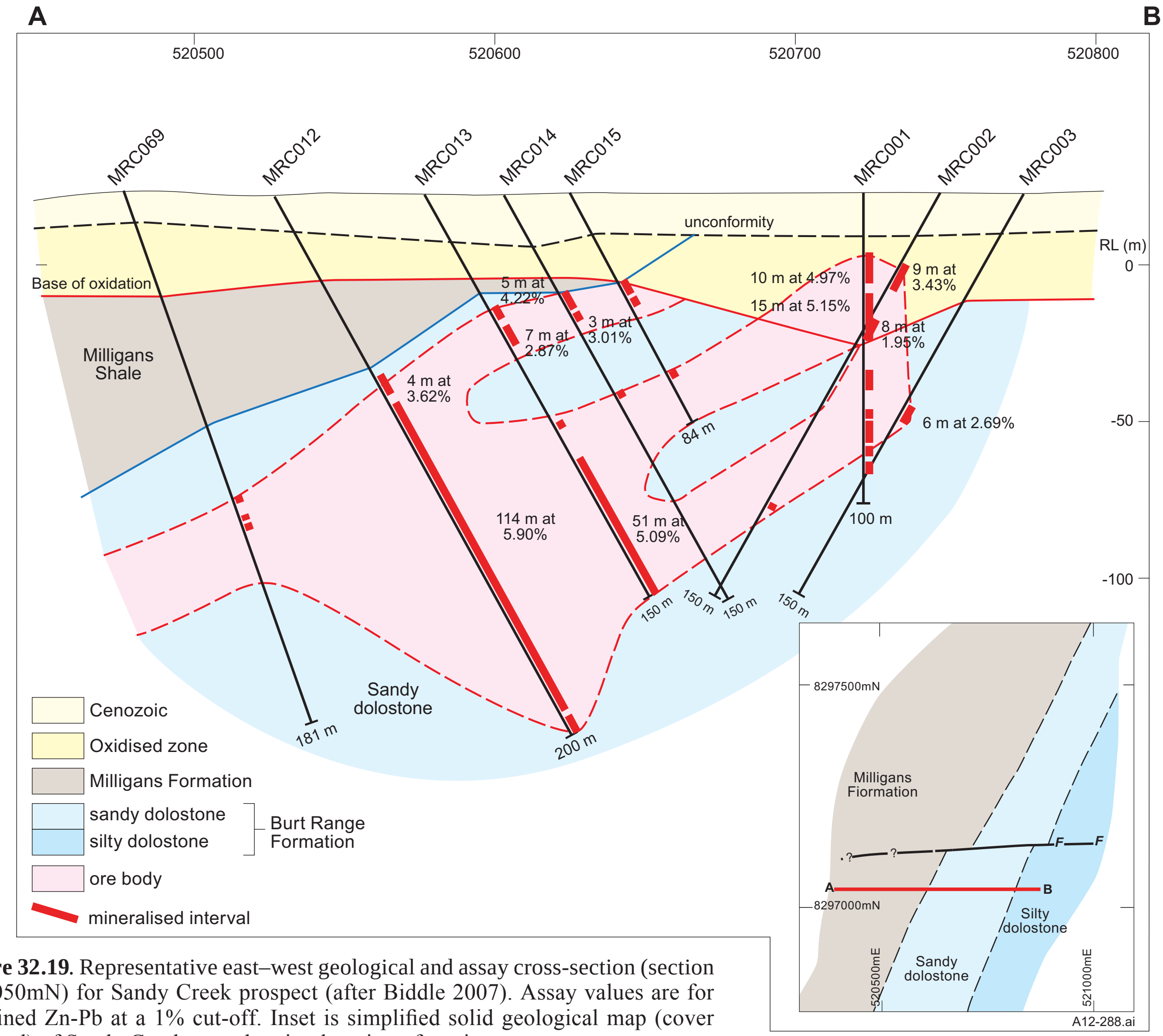

Figure 32.19. Representative east–west geological and assay cross-section (section 8297050mN) for Sandy Creek prospect (after Biddle 2007). Assay values are for combined Zn-Pb at a 1% cut-off. Inset is simplified solid geological map (cover removed) of Sandy Creek area showing location of section.

exploration in onshore areas of Western Australia and the NT, and minor coal has been reported from other formations of the Kulshill Group. Coal beds up to 3 m thick were intersected within the Keep Inlet Formation in drillhole Keep River-1, with assays provided in Meyer (1983). However, a nearby shallow drillhole, completed by CRA Exploration Pty Ltd, failed to intersect any significant coal. CRA reported a best drill intersection of 0.4 m of shaly coal at a depth of 33.6 m to the south of Keep River-1 (Johnston 1983).

Iron ore

In 2008, during a soil and rock chip sampling program by TNG Ltd, high-grade haematite iron mineralisation was discovered from an area known as *Legune Prospect* (formerly *Ochre Mine*). Legune Prospect (**Figure 36.17**) extends over an area of about 900 x 500 m and comprises a low-lying hill with an extensive haematite cap. Samples analysed in the laboratory and in the field have returned assay results of greater than 60% Fe and relatively low levels of silica and phosphorous (TNG 2008).

Ochre

Limonitic and haematitic sandy clay has been mined from weathered Burt Range Formation at the *Ocher Mine* (*Wicklow Claim*) in northwestern AURVERGNE. Wygralak and Ahmad (1995) described the geology and the old workings, which consisted of a 10 x 10 x 5 m pit, adjacent to which 260 forty-four-gallon drums of ochre had been stockpiled and abandoned.

Salt

The Bonaparte Basin contains several diapiric structures that have been interpreted as salt domes. Salt Exporters Australia (1993) conducted gravity surveys in conjunction with existing seismic surveys near the mouth of the Keep River, but their tenements were surrendered without drilling. In 1974, Australian Aquitaine Petroleum Pty Ltd drilled Kinmore-1, located offshore about 30 km west of Port Keats. This drillhole intersected a salt column over 200 m thick, with the well bottoming in salt. The operator estimated the salt thickness as being more than 1200 m, as the intersected salt was on the shoulder of the dome and 1000 m deeper than the top of the structure. With an interpreted diameter of up to 10 km, the Port Keats diapir potentially hosts up to 150 million tonnes of salts per vertical metre. The oil explorers estimated the top of the dome to be only about 350 m deep (Minemakers 2008). The Port Keats diapir lies under shallow waters adjacent to the coast and Minemakers planned to drill test this structure, but the cost of testing the target by a barge mounted drilling program was deemed prohibitive and the EL was surrendered (Minemakers 2011).

Figure 36.20. Base metals mineralisation at Sandy Creek (images IR Scrimgeour). (**a**) Surface exposure of MVT Zn-Pb mineralisation in quartzose dolostone of Burt Range Formation. (**b**) Sphalerite-galena mineralisation in drill core. (**c**) Coarse sphalerite crystals infilling void in drill core. (**d**) Coarse galena crystals and sphalerite.

Petroleum

The Bonaparte Basin is a well established oil and gas province, with proven resources and a number of currently producing fields in offshore areas. There are numerous publications on the petroleum geology of the basin and the more significant of these were listed and summarised in Geoscience Australia (2011).

Most exploration activity within the basin has been focused offshore, where numerous petroleum accumulations have been identified (**Figures 36.2**, **36.21**). However, some potential remains onshore, where exploration costs are

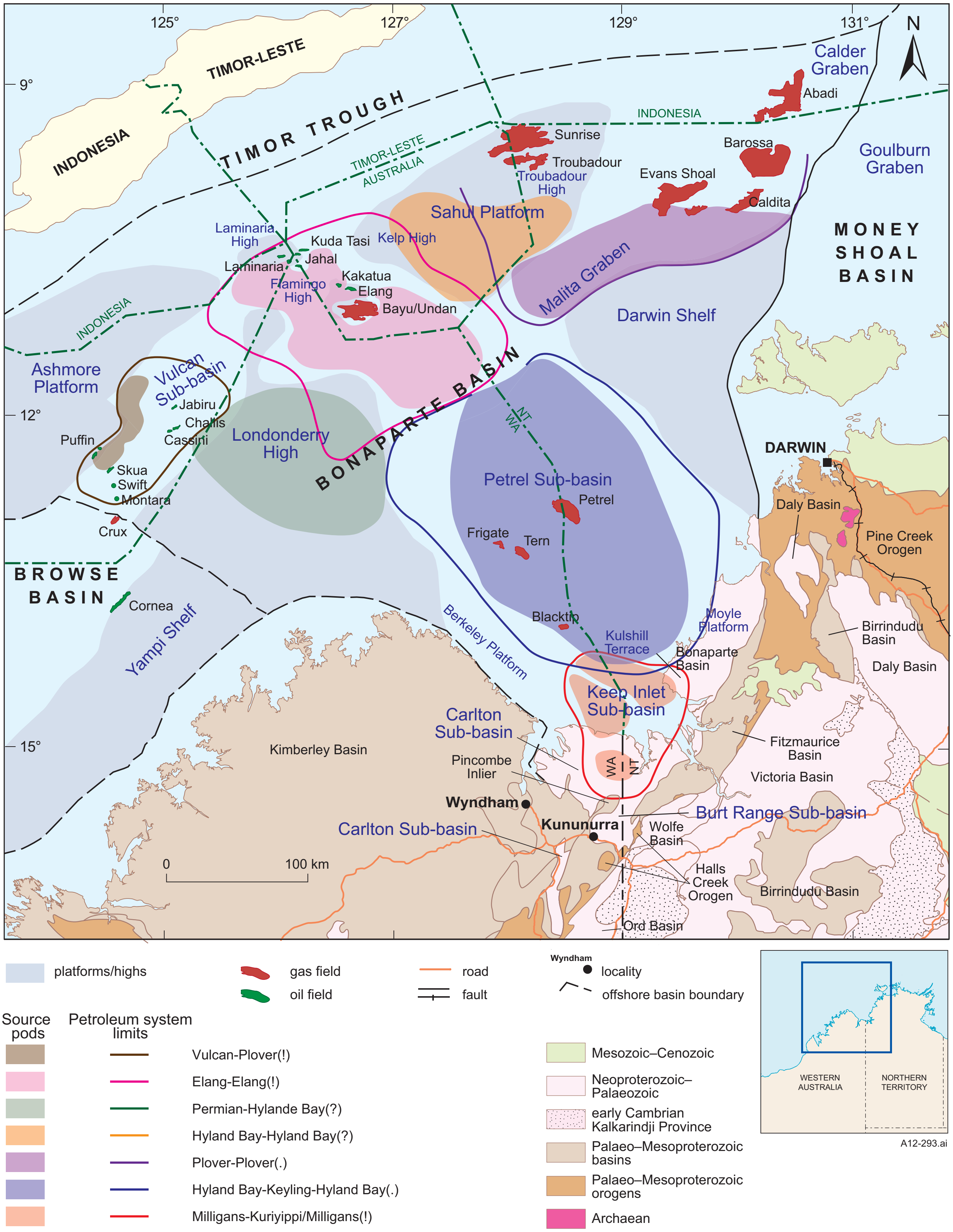

Figure 36.21. Distribution of Bonaparte Basin petroleum systems (redrawn and slightly modified from GA 2011: figure 5).

significantly cheaper. A number of stratigraphic wells were drilled onshore near Spirit Hill in AUVERNGE; these failed to detect significant oil, but dry gas flows were achieved from the Enga Sandstone and/or Milligans Formation in most cases where these units were intersected. Notable previous publications on onshore areas of the basin, mostly focused on the Petrel Sub-basin, include Mory and Beere (1988), Petroconsultants (1990), McConachie *et al* (1996), Edwards *et al* (1997, 2000, 2004, 2006), Edwards and Summons (1996), Edwards and Zumberge (2005), Gorter *et al* (2004, 2005) and Gorter (2006).

The Phanerozoic succession of the Bonaparte Basin contains good potential source rocks, reservoir rocks and seals at a number of levels, with late Palaeozoic and Mesozoic intervals considered to be particularly highly prospective. These have been described in terms of seven defined petroleum systems (Barrett *et al* 2004, **Figure 36.21**), following the nomenclature proposed by Magoon and Dow (1994). The oldest is Permian–Carboniferous in age, three are Permian and three are Jurassic. These are respectively included in the Larapintine, Gondwanan and Westralian petroleum supersystems of Bradshaw (1993).

Permian–Carboniferous petroleum system

Milligans-Kuriyippi/Milligans(!) Petroleum System

This system occurs in the southern Petrel Sub-basin and is the only one to extend onshore. It incorporates a number of non-commercial discoveries of oil, gas, and oil plus gas, including Barnett and Turtle (offshore), and Bonaparte, Garimala-1, Kulshill, Ningbing, Pelican Island-1, Spirit Hill-1, Vienta-1, Waggon Creek-1A and Weaber, either onshore or on islands. Although the active source rocks for this system were originally assigned to the Milligans Formation, hydrocarbons were probably generated from older Langfield Group source rocks (Gorter *et al* 2004, 2005, Gorter 2006), so this system requires redefinition and remapping (Geoscience Australia 2011).

Permian petroleum systems

Hyland Bay-Hyland Bay(?) Petroleum System

This system is only recognised from the Sahul Platform in the vicinity of the Kelp High (see **Figure 36.1**). It is bounded to the south and east by the limits of the Sahul Platform, and to the north by the limits of Permian deposition. The system is gas-prone, with no oil potential, and is defined by only one non-commercial gas discovery in drillhole Kelp Deep-1.

Hyland Bay/Keyling-Hyland Bay(.) Petroleum System

This system is confined to the Petrel Sub-basin. It is gas-dominated, but geochemical data indicate that coaly shales of the Lower Permian Keyling Formation have some oil potential. Gas discoveries attributed to this system include Fishburn-1, Penguin-1, Petrel and Tern, and the producing Blacktip field (**Figure 36.2**).

Permian-Hyland Bay(?) Petroleum System

This system is restricted to the Londonderry High, but is poorly constrained. It is gas-prone, but has some oil potential, and includes small gas discoveries at Prometheus-1 and Rubicon-1, and oil shows in Torrens-1.

Jurassic petroleum systems

Elang-Elang(!) Petroleum System

This system extends across the Sahul Syncline, Flamingo High and Flamingo Syncline. It includes oil, gas, or oil plus gas accumulations of the Bayu-Undan, Buffalo, Corallina, Elang, Kakatua and Laminaria commercial fields, as well as other small non-commercial discoveries.

Plover-Plover(.) Petroleum System

This system extends north from the Malita and Calder grabens across the Sahul Platform and Troubadour High into Indonesian waters. The system is gas-prone (with moderate liquids), but has little or no oil potential. It includes the gas discoveries at Chuditch-1, Evans Shoal, Lynedoch, Sunrise and Troubadour, and probably the Abadi gas discovery in Indonesian waters.

Vulcan-Plover(!) Petroleum System

This system is mostly restricted to the Vulcan Sub-basin, but extends a short distance onto the Ashmore Platform to the west and Londonderry High to the east. It includes oil, gas, or oil plus gas accumulations of the Cassini, Challis, Jabiru and Skua commercial fields, as well as other small non-commercial discoveries.

Oil and gas production

Figure 36.21 shows the distribution of major oil and gas fields in the Bonaparte Basin. Fields with current or historical production are briefly described below. In addition, there are a number of substantial undeveloped gas discoveries within the basin, including the *Petrel*, *Tern*, *Sunrise*, *Troubadour*, *Evans Shoal*, *Caldita* and *Barossa* fields in Australian waters, and the *Abadi* field in Indonesian waters.

Jabiru

The Jabiru oil field is located in the Timor Sea, approximately 650 km due west of Darwin. It was discovered in 1983 when drillhole Jabiru-1A intersected at 57 m gross oil column within sandstone of the upper Plover Formation (Troughton Group) and basal Flamingo Group. The field was operated by PTTEP Australasia (Ashmore Cartier) Pty Ltd (PTTEPAA) and produced 112.5 mmbbl of oil from 1986 until it was decommissioned in 2010 (Department of Resources, Minerals and Energy Group 2012).

Challis/Cassini

The Challis and Cassini oil fields are located approximately 600 km west of Darwin. The Challis oil field was discovered in 1984, when Challis-1 was drilled on a Triassic horst block in the Vulcan Sub-basin, and the Cassini field in 1988, when drillhole Cassini-1 tested a separate culmination on the same structural trend, 5 km to the southwest of Challis-1. Production from Challis/Cassini commenced in 1989 and the fields produced

60 mmbbl of oil before being decommissioned in 2010 (Department of Resources, Minerals and Energy Group 2012). The field was operated by PTTEPAA.

Skua-Swift/Swallow-Montara

The Skua oil field was discovered by BHP Petroleum Ltd in 1985, when Skua-1 was drilled to test a tilted horst block within the Vulcan Sub-basin. Seven reservoir units are recognised in the field, all of which are within sandstone of the Early to Middle Jurassic Plover Formation (Troughton Group). Oil production commenced in 1991 and the field produced 20.5 mmbbl of oil before being decommissioned in 1997 (Department of Resources, Minerals and Energy Group 2012). The Montara oil field is located about 20 km southeast of Skua and was discovered by BHP in the 1980s. The Swift and Swallow oil fields are located 9 km southeast of Skua and were discovered in 2006 by Coogee Resources (Ashmore Cartier) Pty Ltd, which owned and operated the fields until 2008. All are currently included in the Montara Project, owned and operated by PTTEPAA, and are currently under development.

Laminaria/Corallina

These oil fields are located about 550 km west-northwest of Darwin and are operated by Woodside Energy Ltd. Laminaria was discovered in 1994 and Corallina in 1995. Production commenced in 1999 and these fields currently produce all of the NT's offshore oil. The total production from these fields to 2011 has been 187.8 mmbbl of oil.

Elang/Kakatua/Kakatua North

These now-decommissioned fields are located in the Joint Petroleum Development Area, approximately 500 km northwest of Darwin. Elang and Kakatua were discovered by Petroz NL-BHP Petroleum Ltd in 1994 and Kakatua North in 1997. Production commenced in 1998, with ConocoPhillips Australasia as operator, and the three fields produced 31.3 mmbbl of light, low sulfur crude oil from an originally estimated recoverable reserve of 32.6 mmbbl until 2007. Drillhole Elang West-1 and its sidetrack intersected an oil column in the nearby Elang West structure, but this discovery was never developed.

Bayu-Undan

The Bayu and Undan fields are located approximately 500 km northwest of Darwin on the Sahul Platform (Flamingo High), within the Joint Petroleum Development Area (JPDA). The fields were discovered in 1995 and are operated by ConocoPhillips Australasia. They have recoverable reserves of more than 3.4 Tcf (trillion cubic feet) of natural gas and approximately 400 mmbbl (million barrels) of liquid hydrocarbons (LPG and condensate). Production of liquids commenced in April 2004 via an offshore processing facility. Dry gas is transported via a 500 km subsea pipeline to a single-train LNG plant at Wickham Point, Darwin, which commenced operations in 2006. All of the LNG is exported to Japan.

REFERENCES

AGSO NW Shelf Study Group, 1994. Deep reflections on the North West Shelf: changing perceptions of basin formation: in Purcell PG and Purcell RR (editors) *The Sedimentary Basins of Western Australia, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1994*, 63–76.

Archbold NW, Dickins JM and Thomas GA, 1993. Correlations and age of the Western Australian Permian marine faunas. *Geological Survey of Western Australia, Bulletin* 136, 11–18.

Baillie PW, Powell CMcA, Li ZX and Ryall AM, 1994. The tectonic framework of western Australia's Neoproterozoic to Recent sedimentary basins: in Purcell PG and Purcell RR (editors) *The Sedimentary Basins of Western Australia, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1994*, 45–62.

Bann KL, Lang SC, Kloss O, Wood G and Benson J, 2004. Palaeoenvironments and depositional history of the Tern Field, Bonaparte Basin: in Ellis GK, Baillie PW and Munson TJ (editors) *'Timor Sea Petroleum Geoscience. Proceedings of the Timor Sea Symposium, Darwin, Northern Territory, 19–20 June, 2003'. Northern Territory Geological Survey, Special Publication* 1, 521–536.

Barrett AG, Hinde AL and Kennard JM, 2004. Undiscovered resource assessment methodologies and application to the Bonaparte Basin: in Ellis GK, Baillie PW and Munson TJ (editors) *'Timor Sea Petroleum Geoscience. Proceedings of the Timor Sea Symposium, Darwin, Northern Territory, 19–20 June, 2003'. Northern Territory Geological Survey, Special Publication* 1, 353–372.

Beere GM and Mory AJ, 1986. Revised stratigraphic nomenclature for the onshore Bonaparte and Ord Basins, Western Australia. Geological Survey of Western Australia, *Record* 1986/5.

Bhatia MR, Thomas M and Boirie JM, 1984. Depositional framework and diagenesis of the Late Permian gas reservoirs of the Bonaparte Basin: *APEA Journal* 24(1), 299–313.

Biddle NG, 2007. *The Manbarrum zinc-lead-silver project, Bonaparte Basin, NT, Australia. Zinc Conference, Radisson Plaza Hotel, Sydney, Australia, 3 July 2007, Abstract.* Tennant Creek Gold Ltd. *Northern Territory Geological Survey, Open File Company Report* CR2007-0455.

Bishop MG, 1999. Total Petroleum Systems of the Bonaparte Gulf Basin area, Australia. *US Geological Survey, Open-File Report* 99-50-P (on line edition) **http://pubs.usgs.gov/of/1999/ofr-99-0050/OF99-50P/index.html#TOP** (accessed October 2012).

Botten PR and Wulff K, 1990. Exploration potential of the Timor Gap Zone of Cooperation. *APEA Journal* 30, 53–68.

Bourget J, Ainsworth RB, Backé G and Keep M, 2012. Tectonic evolution of the northern Bonaparte Basin: impact on continental shelf architecture and sediment distribution during the Pleistocene. *Australian Journal of Earth Sciences* 59(6), 877–897.

Bradshaw MT, Yeates AN, Beynon RM, Brakel AT, Langford RP, Totterdell JM and Yeung M, 1988. Palaeogeographic history of the North West Shelf Region: in Purcell PG and Purcell RR (editors) *The North West Shelf Australia, Proceedings of Petroleum*

Exploration Society of Australia Symposium, Perth, 1988, 29–54.

Bradshaw MT, 1993. Australian petroleum systems. *PESA Journal* 21, 43–53.

Brady JW, Stein J and Stein C, 1966. The geology of the Bonaparte Gulf Basin. *APEA Journal* 6, 7–11.

Brown HYL, 1895. Government geologist's report on explorations in the Northern Territory. *South Australian Parliamentary Papers* 82.

Burton P, 2010. *TNG Ltd. Projects update & outlook. Manbarrum Project – base metals.* Mining the Territory 2010 presentation. **http://www.aspecthuntley.com.au/asxdata/20100930/pdf/01102962.pdf** (accessed October 2012).

Cadman SJ and Temple PR, 2004. *Bonaparte Basin, NT, WA, AC & JPDA, Australian Petroleum Accumulations Report* 5 (2nd Edition). Geoscience Australia, Canberra.

Caye JP, 1968. The Timor Sea–Sahul Shelf. *APEA Journal* 8(2), 35–41.

Caye JP, 1969. Keep River No 1, OP 162 Northern Territory, well completion report. Australian Aquitaine Petroleum Pty Ltd. *Northern Territory Geological Survey, Open File Petroleum Report* PR1969-0009.

Cockbain AE, 1985. Carboniferous of Western Australia – a review. *Geological Survey of Western Australia, Report* 14, 14–35.

Colwell AB and Kennard JM (compilers), 1996. Petrel Sub-basin study 1995–1996: Summary report. *Australian Geological Survey Organisation, Record* 1996/40.

Creevey K, 1966. Aquitaine Kulshill No 2 – OP 2 Northern Territory. Well completion report. Australian Aquitaine Petroleum Pty Ltd. *Northern Territory Geological Survey, Open File Petroleum Report* PR1966-0007.

D'Auvergne P, Heuillon B and Lee J, 1980. Aquitaine Australia Minerals Pty Ltd–MIMETS Exploration Pty Ltd Joint Venture, 1979 mineral exploration in the Northern Territory tenements, Bonaparte Gulf Basin. *Northern Territory Geological Survey, Open File Company Report* CR1980-0092.

Department of Resources, Minerals and Energy Group, 2012. *EnergyNT 2011.* Northern Territory Government, Darwin.

Dickins JM, Roberts J and Veevers JJ, 1972. Permian and Mesozoic geology of the northeastern part of the Bonaparte Gulf Basin. *Bureau of Mineral Resources Australia, Australia, Bulletin* 125, 75–102.

Druce EC, 1969. Devonian and Carboniferous conodonts from the Bonaparte Gulf Basin, Northwestern Australia, and their use in international correlation. *Bureau of Mineral Resources, Australia, Bulletin* 98.

Duchemin AE and Creevey K, 1966. Aquitaine Kulshill No.1 – Authority to Prospect OP.2 Northern Territory. Well completion report. Australian Aquitaine Petroleum Pty Ltd. *Northern Territory Geological Survey, Open File Petroleum Report* PR1966-0022.

Dunster JN, Beier PR, Burgess JM and Cutovinos A, 2000. *Auvergne, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SD 52-15.* Northern Territory Geological Survey, Darwin.

Edgerley DW and Crist RP, 1974. Salt and diapiric anomalies in the southern Bonaparte Basin. *APEA Journal* 14, 84–94.

Edwards DS, Boreham CJ, Zumberge JE, Hope JM, Kennard JM and Summons RE, 2006. Hydrocarbon families of the Australian North West Shelf: a regional synthesis of the bulk, molecular and isotopic composition of oils and gases. *AAPG International Conference and Exhibition, Perth, Australia, 5–8 November 2006, Abstract.*

Edwards DS, Kennard JM, Preston JC, Summons RE, Boreham CJ and Zumberge JE, 2000. Bonaparte Basin: Geochemical characteristics of hydrocarbon families and petroleum systems. *AGSO Research Newsletter, December,* 14–19.

Edwards DS, Preston JC, Kennard JM, Boreham CJ, van Aarssen BGK, Summons RE and Zumberge JE, 2004. Geochemical characteristics of hydrocarbons from the Vulcan Sub-basin, western Bonaparte Basin, Australia: in Ellis GK, Baillie PW and Munson TJ, (editors) *'Timor Sea Petroleum Geoscience. Proceedings of the Timor Sea Symposium, Darwin, Northern Territory, 19–20 June, 2003'. Northern Territory Geological Survey, Special Publication* 1, 169–201.

Edwards DS and Summons RE, 1996. Petrel Sub-basin study 1995–1996: Organic geochemistry of oils and source rocks. *Australian Geological Survey Organisation, Record* 1996/42.

Edwards DS, Summons RE, Kennard JM, Nicoll RS, Bradshaw J, Bradshaw M, Foster CB, O'Brien GW and Zumberge JE, 1997. Geochemical characterisation of Palaeozoic petroleum systems in north-western Australia. *APPEA Journal* 37(1), 351–379.

Edwards DS and Zumberge JE, 2005. *The oils of Western Australia II. Regional petroleum geochemistry and correlation of crude oils and condensates from Western Australia and Papua New Guinea*. Geoscience Australia, Canberra and GeoMark Research Ltd, Houston.

Ellis GK, Baillie PW and Munson TJ, (editors), 2004. Timor Sea Petroleum Geoscience. Proceedings of the Timor Sea Symposium, Darwin, Northern Territory, 19–20 June, 2003. *Northern Territory Geological Survey, Special Publication* 1.

Ferenczi PA, 2005. Low-profile base metal deposits in the Northern Territory: in *'Annual Geoscience Exploration Seminar (AGES) 2005. Record of abstracts'. Northern Territory Geological Survey, Record* 2005-001.

Geoscience Australia, 2009. *Release area geology.* 2009 Special petroleum offshore acreage release. **http://www.ret.gov.au/resources/upstream_petroleum/offshore_petroleum_exploration_in_australia/2009_special/geology/release_area/Pages/release_area_geology.aspx** (accessed October 2012).

Geoscience Australia, 2011. *Regional geology of the Bonaparte Basin.* Australia 2011 offshore petroleum exploration acreage release. **http://www.ret.gov.au/Documents/par2011/release-areas/bonaparte/documents/geology-bonaparte-regional.pdf** (accessed October 2012).

Gorter JD, 1991. *An assessment of the petroleum potential in NT/P28 and NT/CP1, southern Bonaparte Basin, north western Australia*. Unpublished report for Petroz NL, February 1991.

Gorter JD, 1998. Revised Upper Permian stratigraphy of the Bonaparte Basin: in Purcell PG and Purcell RR (editors) *The Sedimentary Basins of Western Australia 2, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1998*, 213–228.

Gorter JD, 2006. Fluvial deposits of the Lower Kulshill Group (Late Carboniferous) of the southeastern Bonaparte Basin, Western Australia. *AAPG International Conference and Exhibition, Perth, Australia, 5–8 November 2006, Abstract.*

Gorter JD, Jones PJ, Nicoll RS and Golding CJ, 2005. A reappraisal of the Carboniferous stratigraphy and the petroleum potential of the southeastern Bonaparte Basin (Petrel Sub-basin), northwestern Australia. *APPEA Journal* 45, 275–296.

Gorter JD, McKirdy DM, Jones PJ and Playford G, 2004. Reappraisal of the Early Carboniferous Milligans Formation source rocks system in the southern Bonaparte Basin, northwestern Australia: in Ellis GK, Baillie PW and Munson TJ (editors) *'Timor Sea Petroleum Geoscience. Proceedings of the Timor Sea Symposium, Darwin, 19–20 June 2003'. Northern Territory Geological Survey, Special Publication* 1, 231–255.

Gorter JD, Nicoll RS, Metcalfe I, Willink RJ and Ferdinando D, 2009. The Permian-Triassic boundary in western Australia: evidence from the Bonaparte and northern Perth basins–exploration implications. *APPEA Journal* 49, 311–336.

Gorter JD, Poynter SE, Bayford SW and Caudullo A, 2008. Glacially influenced petroleum plays in the Kulshill Group (Late Carboniferous–Early Permian) of the southeastern Bonaparte Basin, Western Australia. *APPEA Journal* 48, 69–113.

Gorter JD, Ziolkowski V and Bayford SW, 1998. Evidence of Lower Triassic reservoirs with possible hydrocarbon charge in the southern Bonaparte Basin: in Purcell PG and Purcell RR (editors) *The Sedimentary Basins of Western Australia 2, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1998*, 229–235.

Gradstein FM and Ogg JG, 2004. Geological time scale 2004 – why, how and where next! *Lethaia* 37, 175–181.

Gradstein FM, Ogg JG, Smith AG, Agterberg FP, Bleeker W, Cooper RA, Davydov V, Gibbard P, Hinnov L, House MR, Lourens L, Luterbacher H-P, Mcarthur J, Melchin MJ, Robb LJ, Shergold J, Villeneuve M, Wardlaw BR, Ali J, Brinkhuis H, Hilgen FJ, Hooker J, Howarth RJ, Knoll AH, Laskar J, Monechi S, Powell J, Plumb KA, Raffi I, Röhl U, Sanfilippo A, Schmitz B, Shackelton NJ, Shields GA, Strauss H, Van Dam J, Veizer J, Van Kolfschoten TH and Wilson D, 2004. *A geologic time scale 2004.* Cambridge University Press.

Gunn PJ, 1988. Bonaparte Basin: evolution and structural framework: in Purcell PG and Purcell RR (editors) *The North West Shelf Australia, Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1988*, 275–285.

Gunn PJ and Ly KC, 1989. The petroleum prospectivity of the Joseph Bonaparte Gulf area, northwestern Australia. *APEA Journal* 29, 509–526.

Helby R, 1974. *A palynological study of the Cambridge Gulf Group (Triassic–Early Jurassic).* Unpublished report to ARCO Australia Ltd.

Hocking RM, Mory AJ and Williams IR, 1994. An atlas of Neoproterozoic and Phanerozoic basins of Western Australia: in Purcell PG and Purcell RR (editors) *The Sedimentary Basins of Western Australia, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1994*, 21–43.

Hughes RJ, 1978. The geology and mineral occurrences of Bathurst Island, Melville Island, and Cobourg Peninsula, Northern Territory. *Bureau of Mineral Resources, Australia, Bulletin* 177.

Hughes RJ and Senior BR, 1974. New stratigraphic names for Cretaceous and Cainozoic units of Bathurst and Melville Islands and Cobourg Peninsula, Northern Territory. *Australian Oil and Gas Review* 20, 10–17.

Johnston WH, 1983. Coal Licence No.1, Bonaparte NT, Final Report. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1983-0177.

Jones PJ, 1984. Treposellidae (Beyrichiacea: Ostracoda) from the latest Devonian (Strunian) of the Bonaparte Basin, WA. *BMR Journal of Australian Geology and Geophysics* 9(2), 149–62.

Jones PJ, 1989. Lower Carboniferous Ostracoda (Beyrichicopoda and Kirkbyocopa) from the Bonaparte Basin, northwestern Australia. *Bureau of Mineral Resources, Australia, Bulletin* 228.

Jones PJ, Nicoll RS, Shergold JH, Foster CB, Kennard JM and Colwell JB, 1997. *Petrel Sub-basin: Australian Geological Survey Organisation, Biozonation and Stratigraphy Chart* 1. Australian Geological Survey Organisation, Canberra.

Jorgensen GC, Dendle PK, Rowley M and Lee RJ, 1990. Sorby lead-zinc-silver deposit: in Hughes FE (editor) *'Geology and mineral deposits of Australia and Papua New Guinea'. The Australasian Institute of Mining and Metallurgy, Melbourne. Monograph* 14, 1097–1101.

Kaulback JA and Veevers JJ, 1969. Cambrian and Ordovician geology of the southern part of the Bonaparte Gulf Basin, Western Australia. *Bureau of Mineral Resources, Australia, Report* 109.

Keep M, Clough M and Langhi L, 2002. Neogene tectonic and structural evolution of the Timor Sea region, NW Australia: in Keep M and Moss S (editors) *The Sedimentary Basins of Western Australia 3, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 2002*, 341–353.

Keep M, Powell CMcA and Baillie PW, 1998. Neogene deformation of the North West Shelf, Australia: in Purcell PG and Purcell RR (editors) *The Sedimentary Basins of Western Australia 2, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1998*, 81–91.

Kemp EM, Balme BE, Helby RJ, Kyle RA, Playford G and Price PL, 1977. Carboniferous and Permian palynostratigraphy in Australia and Antarctica: a review. *BMR Journal of Australian Geology and Geophysics* 2, 177–208.

Kennard JM, Deighton I, Edwards DS, Boreham CJ and Barrett AG, 2002. Subsidence and thermal history modeling: New insights into hydrocarbon expulsion from multiple petroleum systems in the Petrel Sub-basin, Bonaparte Basin: in Keep M and Moss S (editors) *The*

Sedimentary basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 2002, 409–437.

Kimberley Metals, 2011. *Farm-in agreement for Manbarrum lead-zinc-silver project*. Kimberley Metals Ltd, ASX Announcement, 9 February 2011.

Laurie JR, 2006. Early Middle Cambrian trilobites from Pacific Oil and Gas Baldwin 1 well, southern Georgina Basin, Northern Territory. *Memoirs of the Association of Australasian Palaeontologists* 32, 127–204.

Lavering IH and Ozimic S, 1989. Bonaparte Basin, NT and WA. *Bureau of Mineral Resources, Australia. Australian Petroleum Accumulations Report* 5.

Laws RA, 1981. The petroleum geology of the onshore Bonaparte Basin. *APEA Journal* 21(1), 5–15.

Laws RA and Kraus GP, 1974. The regional geology of the Bonaparte Gulf, Timor Sea area. *APEA Journal* 14, 77–84.

Lee RJ and Gunn PJ, 1988. Bonaparte Basin: in *Petroleum in Australia: the first century*. Australian Petroleum Exploration Association (APEA), Sydney, 252–269.

Legge PJ, Haslam CO and Taylor S, 1984. Lead-zinc-silver exploration and development in Australia. *The Australasian Institute of Mining and Metallurgy, Melbourne, Proceedings* 289, 119–135.

Leonard AA, Vear A, Panting AL, De Ruig MJ, Dunne JC and Lewis KA, 2004. Blacktip-1 gas discovery: an AVO success in the southern Bonaparte basin, Western Australia: in Ellis GK, Baillie PW and Munson TJ (editors) '*Timor Sea Petroleum Geoscience, Proceedings of the Timor Sea Symposium, Darwin, 19–20 June 2003'. Northern Territory Geological Survey, Special Publication* 1, 25–35.

Longley IM, Buessenschuett C, Clydsdale L, Cubitt CJ, Davis RC, Johnson MK, Marshall NM, Murray AP, Somerville R, Spry TB and Thompson NB, 2002. The North West Shelf of Australia – a Woodside Perspective: in Keep M and Moss S (editors) *The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 2002*, 28–88.

McCaffrey R, 1988. Active tectonics of the eastern Sunda and Banda Arcs. *Journal of Geophysical Research* 93(B12), 15, 163–182.

McConachie BA, Bradshaw MT and Bradshaw J, 1996. Petroleum systems of the Petrel Sub-basin – an integrated approach to basin analysis and identification of hydrocarbon exploration opportunities. *APEA Journal* 36(1), 248–268.

MacDaniel RP, 1988. The geological evolution and hydrocarbon potential of the western Timor Sea region: in *Petroleum in Australia: the first century*. Australian Petroleum Exploration Association (APEA), Sydney, 270–284.

McLennan JM, Rasidi JS, Holmes RL and Smith GC, 1990. The geology and petroleum potential of the western Arafura Sea. *APEA Journal* 30(1), 91–106.

Magoon LB and Dow WG, 1994. The Petroleum System: in Magoon LB and Dow WG (editors) '*The Petroleum System – from source to trap*'. *AAPG Memoir* 60, 3–24.

Meyer GM, 1983. Licence to search for coal No. 2, Keep River. Final Report. Western Mining Corporation Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1983-0300.

Minemakers, 2008. *Annual report to shareholders*. Minemakers Ltd.

Minemakers, 2011. *Annual report to shareholders*. Minemakers Ltd.

Mory AJ, 1988. Regional geology of the offshore Bonaparte Basin: in Purcell PG and Purcell RR (editors) *The North West Shelf Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1988*, 287–309.

Mory AJ, 1990. Bonaparte Basin: in '*Geology and mineral resources of Western Australia*'. *Geological Survey of Western Australia, Memoir* 3.

Mory AJ, 1991. Geology of the offshore Bonaparte Basin northwestern Australia. *Geological Survey of Western Australia, Report* 29.

Mory AJ and Beere GM, 1988. Geology of the onshore Bonaparte and Ord Basins in Western Australia. *Geological Survey of Western Australia, Bulletin* 134.

Mory AJ, Redfern J and Martin JR, 2008. A review of Permian–Carboniferous glacial deposits of Western Australia. *Geological Society of America, Special Paper* 441.

Noakes LC, 1949. A geological reconnaissance of the Katherine–Darwin region. *Bureau of Mineral Resources, Australia, Bulletin* 16.

Noakes LC, Öpik AA and Crespin I, 1952. Bonaparte Gulf Basin, northwestern Australia: a stratigraphical summary with special reference to the Gondwana System. *Gondwana Symposium. 19th International Geological Congress, Algiers, 1950*, 91–106.

O'Brien GW, Etheridge MA, Willcox JB, Morse M, Symonds P, Norman C and Needham DJ, 1993. The structural architecture of the Timor Sea, north-western Australia: implications for basin development and hydrocarbon exploration. *APEA Journal* 33, 258–278.

O'Brien GW, Higgins R, Symonds P, Quaife P, Colwell J and Blevin J, 1996. Basement control on the development of extensional systems in Australia's Timor Sea: an example of hybrid hard linked/soft linked faulting? *APPEA Journal* 36(1), 161–201.

Ogg JG, Ogg G and Gradstein FM, 2008. *Concise geologic time scale*. Cambridge University Press, Cambridge, UK.

Pattillo J and Nicholls PJ, 1990. A tectonostratigraphic framework for the Vulcan Graben, Timor Sea region. *APEA Journal* 30, 27–51.

Peresson H, Woods EP and Fink P, 2004. Fault architecture along the southeastern margin of the Cartier Trough, Vulcan Sub-basin, North West Shelf, Australia; implications for hydrocarbon exploration: in Ellis GK, Baillie PW and Munson TJ (editors) '*Timor Sea Petroleum Geoscience, Proceedings of the Timor Sea Symposium, Darwin, Northern Territory, 19–20 June 2003'. Northern Territory Geological Survey, Special Publication* 1, 156–167.

Petroconsultants, 1990. *Bonaparte Basin. Northern Territory Geological Survey Petroleum Basin Study*. Petroconsultants Australasia Pty Ltd.

Playford G, 1982. A latest Devonian palynoflora from the Buttons beds, Bonaparte Gulf Basin, Western Australia.

BMR Journal of Australian Geology and Geophysics 7(3), 149–157.

Playford PE, Hocking RM and Cockbain AE, 2009. Devonian reef complexes of the Canning Basin, Western Australia. *Geological Survey of Western Australia, Bulletin* 145.

Plumb KA, 1968. *Lissadell, Western Australia (First Edition). 1:250 000 geological map series explanatory notes, SE 52-02.* Bureau of Mineral Resources, Australia, Canberra.

Pontifex IR and Sweet IP, 1972. *Auvergne, Northern Territory (First Edition). 1:250 000 geological map series explanatory notes, SD 52-15.* Bureau of Mineral Resources, Australia, Canberra.

Roberts J, 1971. Devonian and Carboniferous brachiopods from the Bonaparte Gulf Basin, northwestern Australia. *Bureau of Mineral Resources, Australia, Bulletin* 122.

Robinson PH and McInerney KB, 2004. Permo-Triassic reservoir fairways of the Petrel Sub-basin, Timor Sea: in Ellis GK, Baillie PW and Munson TJ (editors) *'Timor Sea Petroleum Geoscience. Proceedings of the Timor Sea Symposium, Darwin, Northern Territory, 19–20 June, 2003'. Northern Territory Geological Survey, Special Publication* 1, 295–312.

Rowley M and Lee RJ, 1986. The Sorby Hills (WA) lead-silver-zinc province: in Berkman DA (editor) *Publications of the 13th Council of Mining and Metallurgical Institutions Congress, Singapore, 11–16 May 1986, volume 2, Geology and Exploration*. Congress of the Council of Mining and Metallurgical Institutions and The Australasian Institute of Mining and Metallurgy, Parkville, Victoria, 173–180.

Salt Exporters Australia, 1993. Final report, Keep River Salt Project, El 6561 and El 6562. Salt Exporters (Australia) Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1993-0248.

Shergold JH, Laurie JR and Shergold JE, 2007. Cambrian and Early Ordovician Trilobite Taxonomy and Biostratigraphy, Bonaparte Basin, Western Australia. *Memoirs of the Association of Australasian Palaeontologists* 34.

Shergold JH, Southgate PN and Cook PJ, 1988. Middle Cambrian phosphogenetic system in Australia. *Bureau of Mineral Resources, Australia, Record* 1988/42, 78–81.

Shuster MW, Eaton S, Wakefield LL and Kloosterman HJ, 1998. Neogene tectonics, greater Timor Sea, offshore Australia: implications for trap risk. *APPEA Journal* 38(1), 351–379.

Southgate PN and Shergold JH, 1991. Application of sequence stratigraphic concepts to Middle Cambrian phosphogenesis, Georgina Basin, Australia. *BMR Journal of Australian Geology and Geophysics* 12, 119–144.

Sweet IP, 1977. The Precambrian geology of the Victoria River region, Northern Territory. *Bureau of Mineral Resources, Australia, Bulletin* 168.

Thomas GA, 1971. Carboniferous and Early Permian brachiopods from Western and northern Australia. *Bureau of Mineral Resources, Australia, Bulletin* 56.

TNG, 2008. *Annual Report to shareholders.* TNG Ltd.

TNG, 2010. *Amended resource at Sandy Creek Zinc-Lead-Silver Project increase.* TNG Ltd, ASX announcement, 15 March 2010.

Traves DM, 1949. Preliminary report on survey of Ord–Victoria region, Northern Australian Regional Survey. *Bureau of Mineral Resources, Australia, Record* 1949/22.

Traves DM, 1955. The geology of the Ord-Victoria region, northern Australia. *Bureau of Mineral Resources, Australia, Bulletin* 27.

Tyler IM and Hocking RM, 2001. A revision of the tectonic units of Western Australia. *Geological Survey of Western Australia, 2000–01 Annual Review*, 33–44.

Veevers JJ, 1988. Morphotectonics of Australia's Northwestern margin – a review: in Purcell PG and Purcell RR (editors) *The North West Shelf Australia, Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1988,* 19–27.

Veevers JJ and Roberts J, 1968. Upper Palaeozoic rocks, Bonaparte Gulf Basin of northwestern Australia. *Bureau of Mineral Resources, Australia, Bulletin* 97.

Whitehead BR and Fahey GM, 1985. Geology of the Keep River National Park. *Northern Territory Geological Survey, Report* 1.

Whittam DB, Norvick MS and McIntyre CL, 1996. Mesozoic and Cainozoic tectonostratigraphy of western ZOCA and adjacent areas. *APPEA Journal* 36, 209–231.

Woods EP, 1994. A salt-related detachment model for the development of the Vulcan Sub-basin: in Purcell PG and Purcell RR (editors) *The Sedimentary Basins of Western Australia, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1994*, 260–274.

Woodside, 2002. Well Completion Report, Blacktip-1, Interpretive Data (WA-279-P, Southern Bonaparte Basin). Woodside Australian Energy Ltd. *Western Australian Geological Survey, Open File Petroleum Report* W20723-A2.

Wygralak AS and Ahmad M, 1995. *Victoria River Region. Mineral deposit data series.* Northern Territory Geological Survey, Darwin.