Northern Territory Government

Geology and mineral resources of the Northern Territory

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Northern Territory Geological Survey
Special Publication 5

Chapter 28: Georgina Basin

BIBLIOGRAPHIC REFERENCE: Kruse PD, Dunster JN and Munson TJ, 2013. Chapter 28: Georgina Basin: in Ahmad M and Munson TJ (compilers). *'Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey, Special Publicatio*n 5.

Chapter 28: GEORGINA BASIN

PD Kruse, JN Dunster and TJ Munson

INTRODUCTION

The Georgina Basin is a polyphase intracratonic basin containing unmetamorphosed Cryogenian to Devonian sedimentary rocks (**Figure 28.1**). It covers an area of 330 000 km^2 in the central-eastern NT and extends into western Queensland. The basin is bounded to the northeast and east by Proterozoic terranes of the McArthur Basin, South Nicholson Basin, Lawn Hill Platform and Mount Isa Inlier, and to the west by the Proterozoic Tomkinson, Warramunga and Davenport provinces of the Tennant Region. To the south, the contact with the Palaeoproterozoic Aileron Province of the Arunta Region is a steep south-side-up thrust fault system. The Georgina Basin is continuous with the Daly and Wiso basins, to the northwest and southwest of the Tennant Region, respectively. These neighbouring basins contain stratigraphic successions of similar age to the Georgina Basin and form distinct depocentres that are separated from the Georgina Basin by basement ridges formed by basaltic rocks of the Kalkarindji Province (Tickell 2005, see **Daly Basin: figure 31.2**). In the middle Cambrian, the interconnected Georgina, Wiso and Daly basins collectively formed part of a vast depositional area that extended across northern, central and southern Australia; contiguous portions of this depositional system in northern and central Australia are referred to in this volume as the Centralian B Superbasin (see **Centralian Superbasin**). The northern and southeastern portions of the Georgina Basin are overlain by Mesozoic sedimentary rocks of the onshore Carpentaria and Eromanga basins, respectively.

The Georgina Basin comprises two distinct domains: a southern basinal depocentre (southern Georgina Basin), essentially south of latitude 21°S, incorporating Cryogenian,

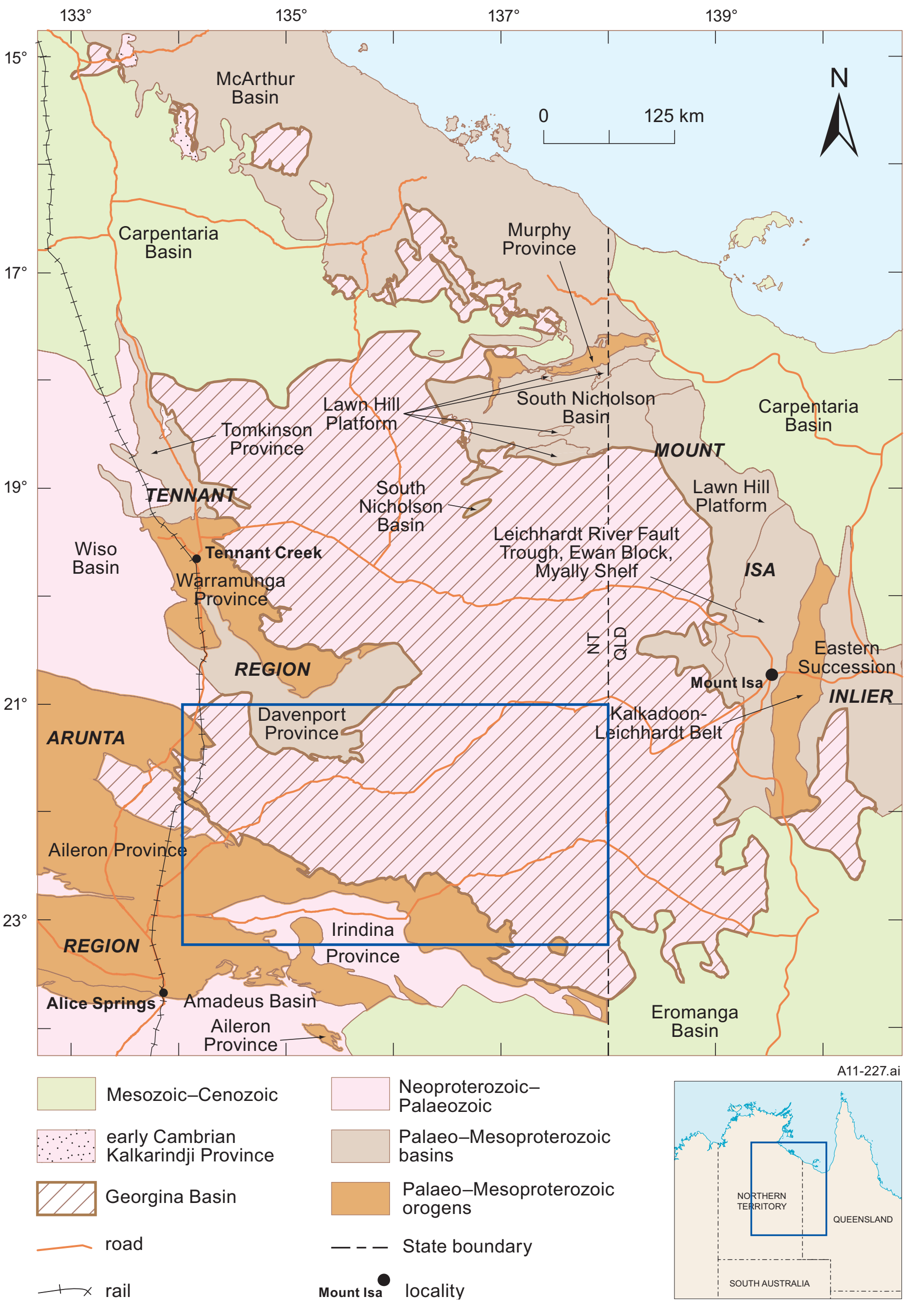


Figure 28.1. Regional geology of Georgina Basin. NT geological regions from NTGS 1:2.5M GIS database. Qld geological regions simplified and slightly modified from Denaro and Dhnaram (2009). Box shows area of **Figure 28.2**.

Ediacaran, Cambrian, Ordovician and Devonian successions (Dunster *et al* 2007); and a central-northern, quiescent platform (central and northern Georgina Basin) north of that latitude, including some late Neoproterozoic sedimentary rocks, early Cambrian Kalkarindji Province rocks and a relatively thin, platformal middle Cambrian succession. Neoproterozoic rocks in the southern Georgina Basin form a part of the 'Centralian Superbasin' succession of Walter *et al* (1995), referred to in this volume as the Centralian A Superbasin (see **Centralian Superbasin**).

Basement

Palaeo–Mesoproterozoic strata of the McArthur Basin are presumed to underlie the central and northern parts of the Georgina Basin; these rocks are probably continuous with equivalent strata of the Tomkinson Province of the Tennant Region. Similarly aged strata of the South Nicholson Basin, Lawn Hill Platform and Mount Isa Inlier underlie the basin in the east. Older Palaeoproterozoic rocks, equivalent to those in the Murphy Province and/or Warramunga Province of the Tennant Region, may in turn underlie these strata, at least in part. Basaltic rocks of the Kalkarindji Province immediately underlie and form basement for middle Cambrian successions over most of the central and northern Georgina Basin and the contiguous northern Wiso and Daly basins. In the southern Georgina Basin, basement consists of probable Palaeoproterozoic rocks that were assigned by Teasdale and Pryer (2002) and Dunster *et al* (2007) to three proposed basement domains (**Figure 28.2**): the Davenport domain was interpreted as being a ca 10 km-thick Palaeoproterozoic rift-basin succession; the Dulcie domain was interpreted as a Palaeoproterozoic felsic gneiss terrane intruded by voluminous syn- to post-tectonic non-magnetic granitoids; and the Altjawarra domain was interpreted as comprising large mafic-intermediate intrusive bodies and late non-magnetic granitoids, forming a region of thickened, stable crust with relatively low heat flow and low crustal temperatures. These last two domains were inferred to underlie the majority of the southern Georgina Basin.

The age of the Altjawarra domain is controversial. Several authors, including Elkedra (2001), inferred an Archaean age, but all available geochronological data (Cross *et al* 2005) and extrapolation of the magnetic signature in the subsurface from the Jervois district suggest that it is Palaeoproterozoic. The lack of any preferred mineral orientation in the oldest absolutely dated granitoids in the domain (1846 Ma in NTGS99/1, 1805 Ma in Lucy Creek-1), together with the lack of any pervasive geophysical grain, suggest that the domain has behaved as a rigid block, at least since that time. A second major phase of moderately to non-magnetic granitoids was intruded into the Altjawarra domain at about 1750 Ma.

Southern Georgina Basin

The NT portion of the southern Georgina Basin, south of latitude 21°S, encompasses the following mapsheets: in the southeast, northern HAY RIVER[1], TOBERMOREY, SANDOVER RIVER, HUCKITTA and ELKEDRA; and in the southwest, northern ALCOOTA, BARROW CREEK, northeastern NAPPERBY and eastern MOUNT PEAKE (Kruse and Mohammed 2005, **Figure 28.1**). The southern part of the basin includes the thickest sedimentary successions and is the most structured.

The southern Georgina Basin includes strata of Neoproterozoic (Cryogenian to Ediacaran), early Palaeozoic (Cambrian to Ordovician) and Devonian age (**Figures 28.3**, **28.4**). The Neoproterozoic succession comprises the Plenty, Aroota, Keepera and Mopunga groups;

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

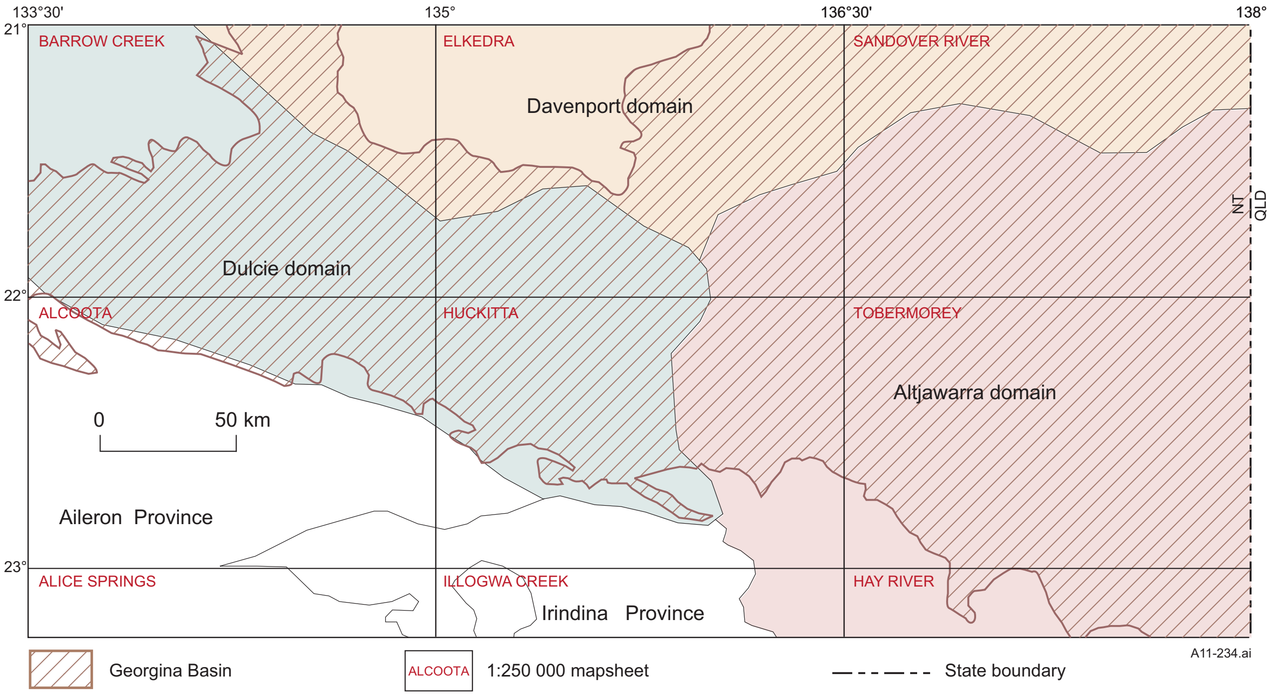


Figure 28.2. Basement domains of Northern Territory portion of southern Georgina Basin (modified from Teasdale and Pryer 2002). Location shown in **Figure 28.1**.

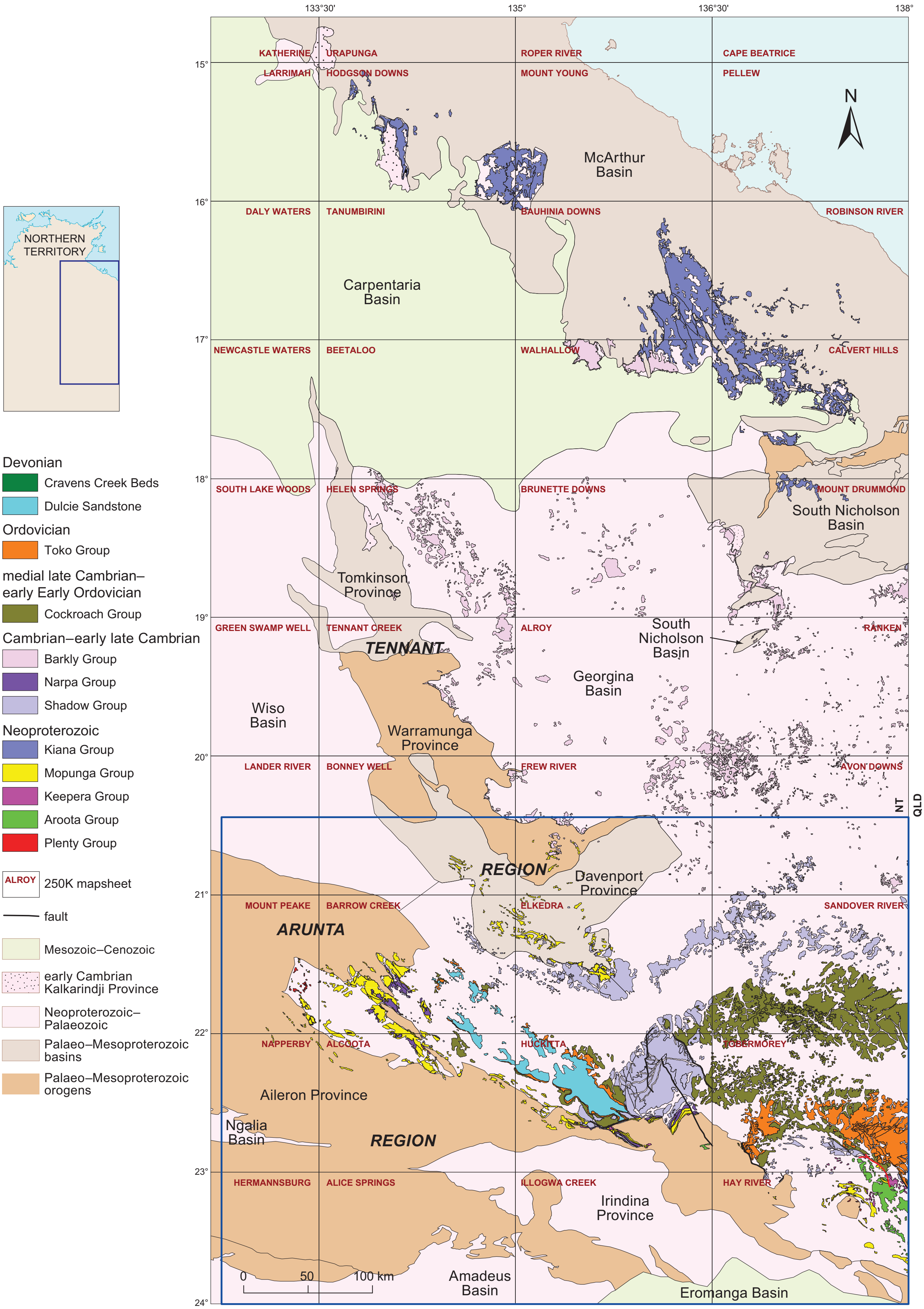


Figure 28.3. Northern Territory portion of Georgina Basin, showing outcrop geology, derived from GA 1:1M geology and NTGS 1:2.5M geological regions GIS datasets. Outcrop geology of southern Georgina Basin (box) shown in more detail in **Figure 28.4**.

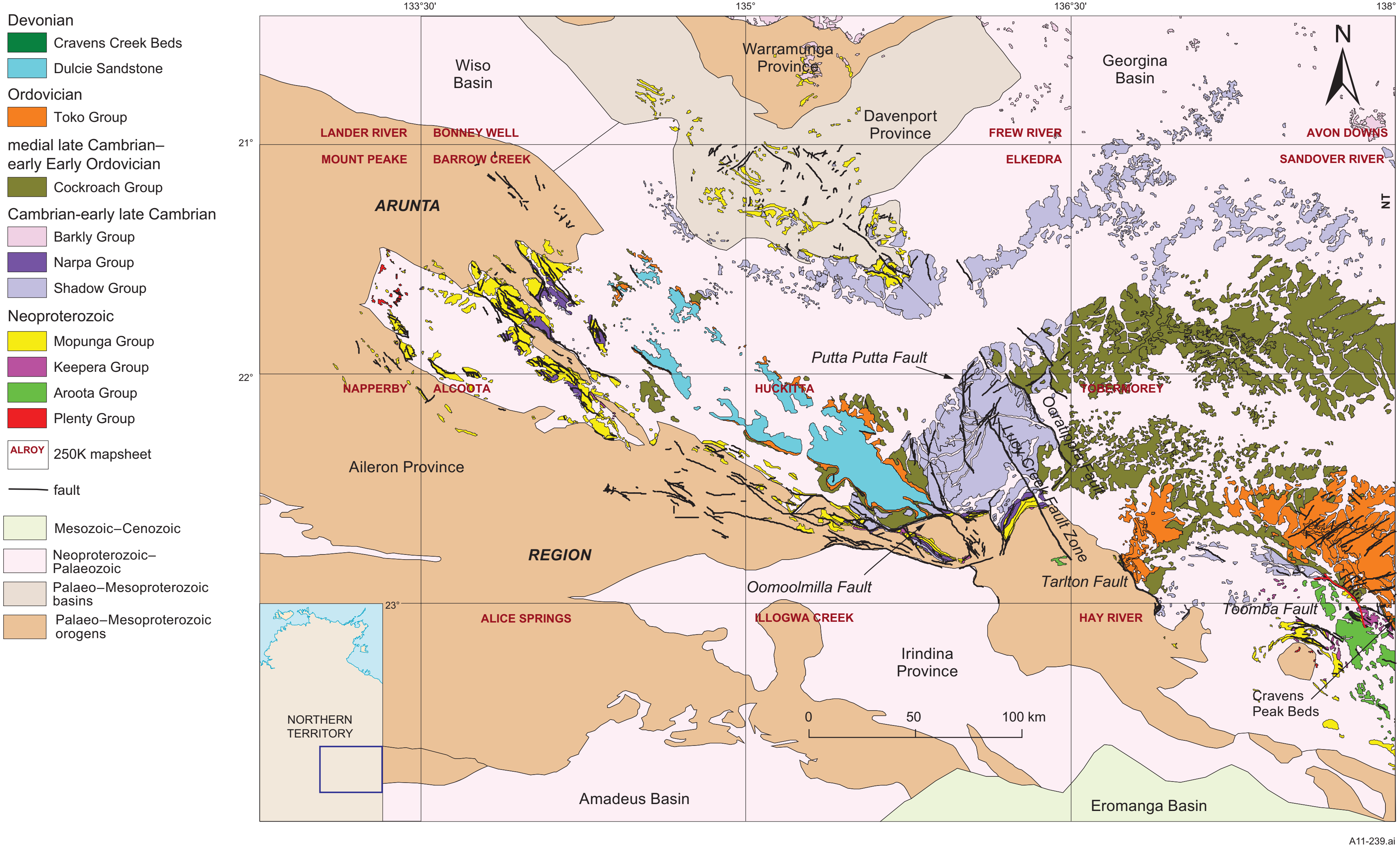


Figure 28.4. Outcrop geology of Northern Territory portion of southern Georgina Basin, derived from GA 1:1M geology and NTGS 1:2.5M geological regions GIS datasets. Location shown in **Figure 28.3**.

early Palaeozoic rocks are assigned to the Shadow, Narpa, Cockroach and Toko groups. Devonian strata are included within the Cravens Peak beds and Dulcie Sandstone. In excess of 1.5 km of Neoproterozoic sedimentary rocks are preserved in downfaulted blocks and half-grabens along the southern margin of the basin in the NT. Depocentres and synclines contain up to 2.2 km of Cambrian to Devonian section.

Central and northern Georgina Basin

The NT portion of the central Georgina Basin, north of latitude 21°S, embraces much of AVON DOWNS, RANKEN, southern MOUNT DRUMMOND, northern and eastern FREW RIVER, ALROY, BRUNETTE DOWNS, southern WALHALLOW, northeastern BONNEY WELL, eastern TENNANT CREEK and eastern HELEN SPRINGS. That portion concealed beneath the onshore Carpentaria Basin and exposed northward of it is assigned to the northern Georgina Basin. The southern boundary of this latter region approximates to latitude 18°S, so that the northern Georgina Basin is present in parts of northern MOUNT DRUMMOND, CALVERT HILLS, ROBINSON RIVER, WALHALLOW, BAUHINIA DOWNS, MOUNT YOUNG, BEETALOO, TANUMBIRINI and HODGSON DOWNS (**Figure 28.1**).

The central-northern Georgina Basin includes Ediacaran rocks of the Kiana Group and a relatively thin, entirely middle Cambrian platform succession (**Figure 28.3**). Intervening volcanic and minor sedimentary rocks of the early Cambrian Helen Springs Volcanics are assigned to the Kalkarindji Province (Glass 2002, Glass and Phillips 2006), which extends across large parts of northern Australia, central Western Australia and western South Australia. The central portion of the basin is divided by the meridional Alexandria-Wonarah Basement High (Howard 1971) into a western Barkly Sub-basin (Brunette Basin of Howard 1989, Brunette Sub-basin of Howard 1990), and an eastern Undilla Sub-basin which extends into western Queensland (**Figure 28.5**). Other than middle Cambrian rocks of the Narpa Group in eastern MOUNT DRUMMOND, all exposed formations in the NT portion of the region are included in the Barkly Group (Noakes and Traves 1954, Kruse in Kruse and Radke 2008). Both sub-basins are floored by early middle Cambrian (sequence 1 of Southgate and Shergold 1991) rocks, but these did not overtop the Alexandria-Wonarah Basement High, which is mantled by early sequence 2 rocks. The high appears to have been a topographically positive feature delineated by the Helen Springs Volcanics and/or the Mesoproterozoic South Nicholson Group, and was a focus of phosphatic sedimentation. The successions in the two sub-basins differ in detail and bear differing lithostratigraphic nomenclatures.

NEOPROTEROZOIC

Neoproterozoic sedimentary rocks outcrop adjacent to the faulted southern basin margin (**Figure 28.4**), where initial siliciclastic sedimentation took place in fault-bounded grabens and half-grabens (Walter 1980, Greene 2010, see **Structure**). Deposition was episodic through the Cryogenian and Ediacaran, producing discrete hiatus-bounded tectosomes, termed supersequences by Walter *et al* (1994, 1995). Group names (**Figure 28.6**) that are broadly coincident with these supersequences were introduced by Dunster *et al* (2007), where these were lacking. Their constituent lithostratigraphic nomenclature is essentially that of Walter (1980), with additions by Stidolph *et al* (1988) and Haines *et al* (1991). Neoproterozoic stratigraphic correlation charts for the Georgina and other NT basins are presented in **Centralian Superbasin: figure 22.3a**, **b**.

The Neoproterozoic succession in the southern Georgina Basin is significantly thinner than counterparts in other component basins of the Centralian A Superbasin. The best-constrained section on the fault-dissected southwestern margin of the Georgina Basin occurs at Mount Skinner, and is modelled as having a maximum preserved thickness of around 1150 m (Dunster *et al* 2007). Geophysically modelled sections further east, in HUCKITTA, indicate that significant thicknesses (hundreds of metres) of Neoproterozoic sedimentary rocks are associated with fault-controlled depocentres near the preserved southern edge of the basin, but wedge out to the north. Within the NT portion of the basin, preserved Neoproterozoic successions are both most extensively exposed and deepest (up to 2 km) in HAY RIVER, west of the Toomba Fault. Subtle strike-concordant magnetic anomalies in that area are traceable southwestward under cover into Irindina Province rocks. Slight changes in apparent magnetic susceptibility are postulated to be due to differences in metamorphic grade, rather than to primary lithology.

Widespread Neoproterozoic rocks along the relatively quiescent northern Georgina Basin margin are included within the Kiana Group (Kruse and Rawlings in Rawlings *et al* 2008). This Neoproterozoic succession is relatively thin compared to that in the southern Georgina Basin and reaches a maximum thickness of about 300 m in BAUHINIA DOWNS (JW Smith 1964). Widespread flood basalts that occur between the Kiana Group and the Palaeozoic succession of the northern Georgina Basin are referred to the Kalkarindji Province.

Plenty Group

The early Cryogenian Plenty Group (Kruse in Dunster *et al* 2007) includes the Yackah beds and Amesbury Quartzite, which are exposed in relatively small areas along the southern margin of the basin (**Figure 28.4**). The group is included within Supersequence 1 of Walter *et al* (1995) and is equivalent to the Ꝑ10_1 subdivision of Ahmad and Scrimgeour (2006). It is correlated with the Heavitree Quartzite and Bitter Springs Formation of the Amadeus Basin, and with the Vaughan Springs Quartzite and Albinia Formation of the Ngalia Basin.

Yackah beds

The informally named Yackah beds (Walter 1980) attain a maximum thickness of about 250 m and are poorly exposed in the southeastern Georgina Basin in the NT. The unit nonconformably overlies basement Proterozoic granitoids and is disconformably overlain by the Yardida Tillite in the Desert Syncline and Field River Anticline in HAY RIVER and the Mount Cornish Formation at Mount Cornish in HUCKITTA. It consists of a lower interval of interbedded, fine to very coarse (to granule) arkose, sandstone and laminated shale, overlain by or interbedded with an upper interval of silicified, locally stromatolitic dolostone (Dunster *et al* 2007). Based on their similar stratigraphic positions, lithological similarities and the mutual occurrence of the stromatolite *Acaciella australica* (Walter 1972, Walter *et al* 1979), the lower interval of the Yackah beds is correlated with the Heavitree Quartzite and the upper interval with the Bitter Springs Formation of the Amadeus Basin. The lower siliciclastic interval probably correlates with the Amesbury Quartzite of the southwestern Georgina Basin. The lower Yackah beds are considered to be dominantly fluviatile, with minor intertidal to very shallow-marine constituents, by analogy with Heavitree Quartzite, whereas the upper interval is considered to have been deposited under partially emergent metahaline–hypersaline lacustrine to anoxic

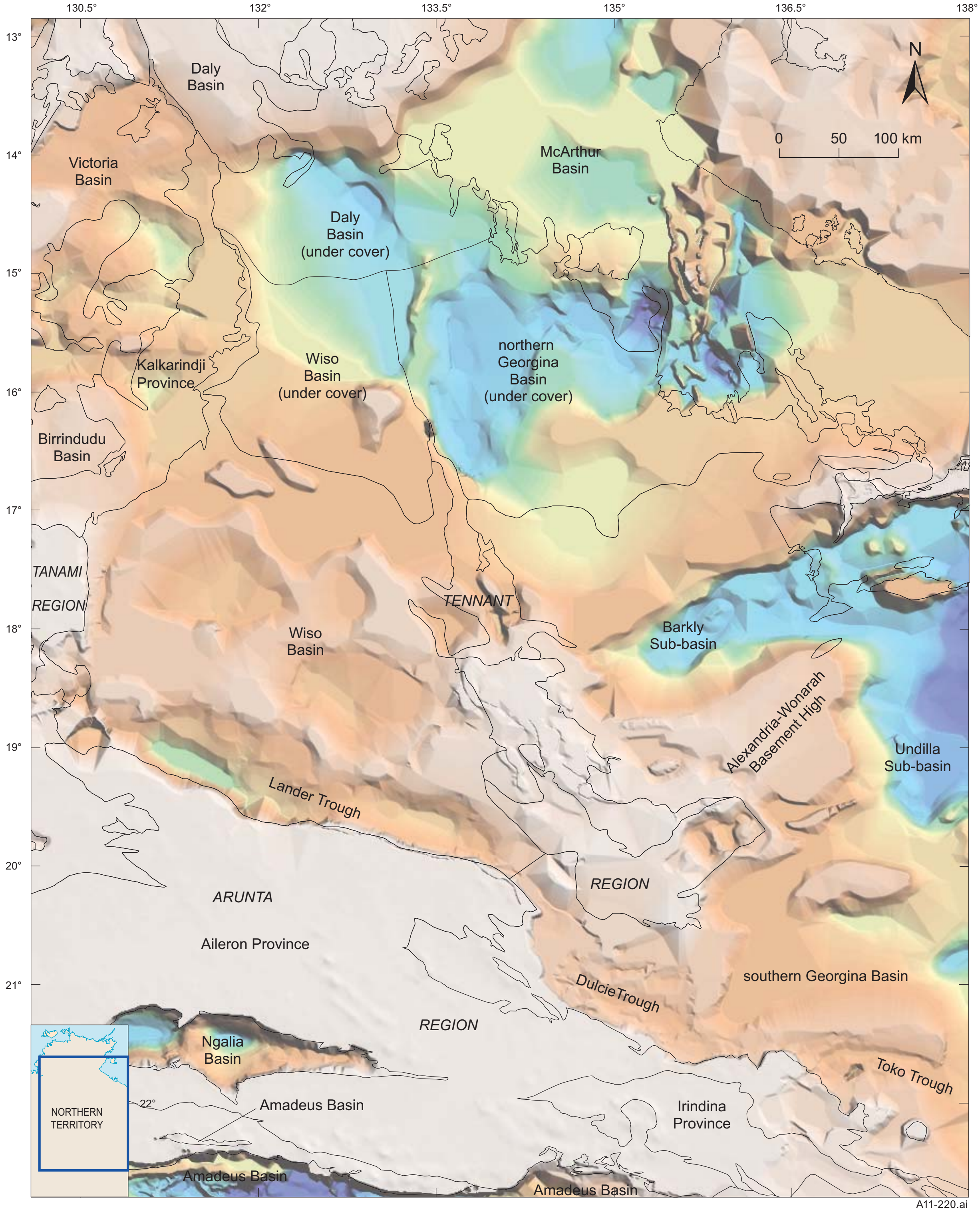


Figure 28.5. SEEBASE™ depth-to-basement image (after Pryor and Loutit 2005) with NT province boundaries for reference, showing interpreted Proterozoic basement highs (yellow–brown tones) and depocentres (blue–green tones) of NT portion of Georgina and adjacent basins. Alexandria-Wonarah Basement High separates Barkly and Undilla sub-basins in central Georgina Basin. Boundary between Wiso Basin and southern Georgina Basin is not clearly defined, but is arbitrarily positioned on a basement high. Boundaries between Georgina and Daly basins and between Wiso and Daly basins are positioned on ridges formed by basaltic rocks of Kalkarindji Province, which form basement to the sedimentary successions in this region (after Tickell 2005; see **Daly Basin: figure 31.2**).

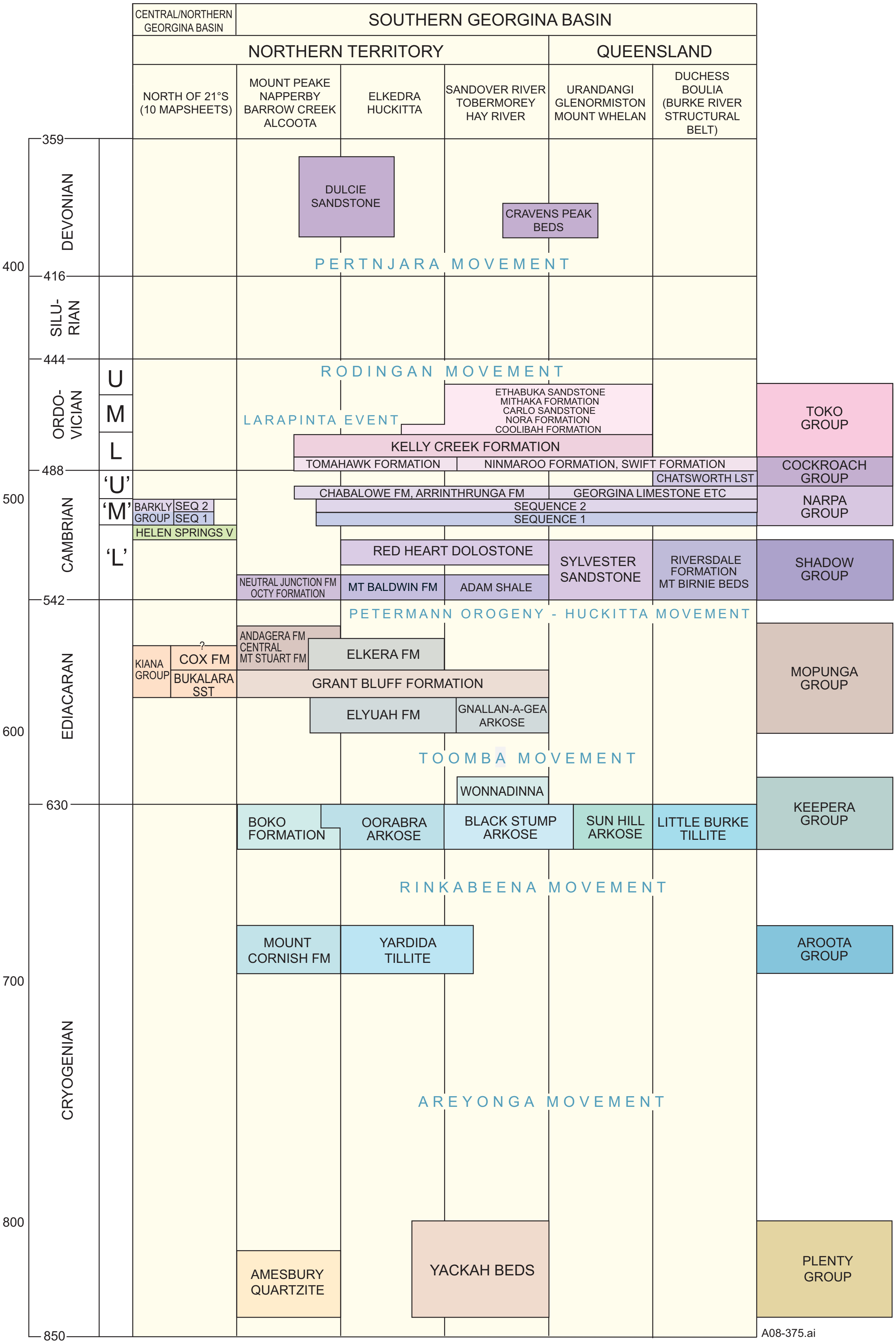


Figure 28.6. Lithostratigraphic time-space diagram for Georgina Basin. Timescale (in Ma) at left; meridional slices (map areas) across top; group names at right. Fm = Formation; SEQ = Sequence; Wonnadinna = Wonnadinna Dolostone; Mt = Mount; Lst = Limestone (slightly modified after Dunster *et al* 2007). Note that Helen Springs Volcanics are included within Kalkarindji Province.

deep marine conditions, by analogy with the Bitter Springs Formation (Walter and Veevers 1997).

Amesbury Quartzite

The unfossiliferous Amesbury Quartzite (Haines *et al* 1991) is about 20 m thick, and forms cuestas and low rounded ridges in central eastern MOUNT PEAKE and central western BARROW CREEK. It nonconformably overlies basement Palaeo–Mesoproterozoic granitoids or unconformably overlies Palaeoproterozoic metamorphic rocks, and is unconformably overlain by the latest Neoproterozoic Boko and Central Mount Stuart formations. The unit consists of rippled and cross-bedded orthoquartzite and quartz sandstone (**Figure 28.7**) with desiccation cracks and clay galls. Bimodal quartz granule to pebble beds occur near the base of the formation and a thin basal conglomerate occurs locally (Dunster *et al* 2007). Based on their similar stratigraphic positions and lithological similarities, the Amesbury Quartzite probably correlates with the lower siliciclastic interval of the Yackah beds. The depositional environment is uncertain, but probably fluviatile (Dunster *et al* 2007).

Aroota Group

The mid-Cryogenian Aroota Group (Kruse in Dunster *et al* 2007) contains the Yardida Tillite and the correlative Mount Cornish Formation. It is included within Supersequence 2 of Walter *et al* (1995) and is equivalent to the Ꝑ10_2 subdivision of Ahmad and Scrimgeour (2006). The group is essentially a glaciogene succession that is correlated (Walter 1980, Walter *et al* 1995) with the Sturtian glaciation of the Adelaide Fold Belt (Preiss *et al* 1978). It is therefore equivalent to the Areyonga Formation and lower Inindia beds of the Amadeus Basin and to the Naburula Formation of the Ngalia Basin. A disconformity between the Plenty and overlying Aroota groups was attributed to the Areyonga Movement by Walter (1980).

Yardida Tillite

The unfossiliferous Yardida Tillite (Walter 1980) outcrops in the in the Desert Syncline and Field River Anticline in the southeastern Georgina Basin, in southwestern TOBERMOREY and northeastern HAY RIVER in the NT and western MOUNT WHELAN in Queensland. It is generally recessive and poorly exposed, except for scattered erratics and a shale cap, which forms low ridges. The formation consists of diamictite and laminated siltstone, and minor fine to very coarse (to pebbly) quartz sandstone and arkose. This is locally capped by laminated dolomitic shale and lenticular dolostone, which ranges up to 100 m in thickness (Shergold and Walter 1979). The unit is probably about 650 m thick; the 2900 m claimed for the composite type section (Walter 1980) is either a local variation, or contains structural repeats (Dunster *et al* 2007). The Yardida Tillite overlies the Yackah beds with an inferred disconformity and is disconformably overlain by the Black Stump Arkose. It was deposited in glacial and periglacial environments; the upper dolomitic shale-dolostone interval is interpreted as a postglacial cap succession (Kruse *et al* 2002a).

Figure 28.7. Amesbury Quartzite. Thin interval of dark, ferruginised and feldspathic fine-grained sandstone (MOUNT PEAKE, 53K 330986mE 7604505mN, after Donnellan 2008: figure 25a).

Mount Cornish Formation

The unfossiliferous Mount Cornish Formation (KG Smith 1964) forms small discontinuous outcrops in the southern Georgina Basin in south-central (Elua Range) and southeastern (Mount Cornish) HUCKITTA. It consists of diamictite with interbeds of varvite and siltstone, and minor sandstone, arkose and dolostone. Some clasts within the diamictite are faceted and striated and an interpreted moraine deposit was reported by Condon (1958). The unit reaches a thickness of 680 m in the type section (Walter 1980), although this may include some fault repetition (Freeman 1986), and a thickness of 365 m was reported for a measured section by Dunster *et al* (2007). In other areas, the formation is much thinner and generally in the range 12–34 m (Smith 1972). The Mount Cornish Formation is nonconformable on Proterozoic granite, or is disconformable on the Yackah beds, and is disconformably overlain by the Oorabra Arkose. It was deposited in glacial and periglacial environments (Dunster *et al* 2007).

Keepera Group

Uplift associated with the Rinkabeena Movement preceded deposition of the Keepera Group (Walter 1980, redefined by Kruse in Dunster *et al* 2007). This group contains late Cryogenian glaciogene and post-glacial units in the southern Georgina Basin, including the Black Stump Arkose, Oorabra Arkose, Boko Formation and Wonnadinna Dolostone in the NT, and the Sun Hill Arkose and Little Burke Tillite in adjacent Queensland. The group is included within Supersequence 3 of Walter *et al* (1995) and is equivalent to the Ꝑ10_3 subdivision of Ahmad and Scrimgeour (2006). It is equated with glaciogene and post-glacial deposits related to the widespread Elatina (previously Marinoan) glaciation of the Adelaide Fold Belt, including the Olympic Formation, Pioneer Sandstone, and the middle–upper Inindia beds and Boord Formation of the Amadeus Basin, and the Mount Doreen Formation of the Ngalia Basin. The age of the Elatina glaciation is uncertain and may be about 635 Ma (Grey 2008) or a much younger 580 Ma (Calver *et al* 2004, see **Centralian Superbasin**).

Black Stump Arkose
The Black Stump Arkose (Walter 1980) outcrops in northeastern HAY RIVER and southeastern TOBERMOREY in the NT, and in western MOUNT WHELAN (Queensland). It reaches a thickness of greater than 700 m and consists of micaceous, fine to very coarse (to pebbly) arkose, sandstone, laminated micaceous mudstone and siltstone (Dunster *et al* 2007). The unfossiliferous unit disconformably overlies the Yardida Tillite and is conformable and gradational beneath the Wonnadinna Dolostone (Walter 1980). It is interpreted as a glacial outwash deposit resulting from rapid erosion and mass transport of eroded material from proximal source areas (Walter *et al* 1995, Walter and Veevers 1997).

Oorabra Arkose
The unfossiliferous Oorabra Arkose (Joklik 1955) forms rugged outcrops with tors in the southern Georgina Basin in southern HUCKITTA (Mopunga, Elua and Jervois ranges) and northern ALCOOTA. It consists of medium-grained to pebbly arkose to lithic arkose, micaceous siltstone, shale and conglomerate, and minor dolostone and sandstone (Dunster *et al* 2007, **Figure 28.8**), and is very variable in thickness over relatively short distances within the range 17–1165 m (Smith 1963b, Shergold and Druce 1980). A local basal conglomerate features glacially faceted and striated clasts. The Oorabra Arkose disconformably overlies the Mount Cornish Formation, or where this is absent, overlies a variety of Palaeoproterozoic units with angular unconformity. It is possibly locally conformable on the Boko Formation (Haines *et al* 2007). The unit underlies the Elyuah Formation with an intervening disconformity, or slight angular unconformity (Walter 1980, Haines *et al* 2007). It is interpreted as a glacial outwash deposit, similar to the Black Stump Arkose (Freeman 1986).

Boko Formation
The Boko Formation (Haines in Haines *et al* 1991) is poorly exposed in western BARROW CREEK and northern ALCOOTA as low rounded hills mantled by rounded cobbles and boulders, many of which are glacially faceted and striated. The unfossiliferous formation consists of massive diamictite with a mudstone matrix (**Figure 28.9**) and is interpreted as a glacial tillite. It is 20 m thick at its type locality, but is 'considerably thicker' elsewhere (Haines *et al* 1991). The formation is unconformable on the Amesbury Quartzite, or where this is absent, is nonconformable on unnamed ?Palaeoproterozoic granite. It is overlain disconformably by the Central Mount Stuart Formation and possibly conformably by the Oorabra Arkose, or where this is absent, unconformably by the Elyuah Formation (Haines *et al* 2007).

Wonnadinna Dolostone
The Wonnadinna Dolostone (Walter 1980) outcrops in northeastern HAY RIVER and southern TOBERMOREY, where it forms low rises, hills and moderate ridges of dolostone, but is otherwise recessive (Shergold and Walter 1979). It is up to 460 m thick and consists of dolostone and quartzose dolostone, interbedded with dolomitic arkose, siltstone and shale. The dolostone bears oncoids, fenestrae and possible columnar stromatolites (Dunster *et al* 2007). The formation conformably and gradationally overlies the Black Stump Arkose, and probably overlies or is partly laterally equivalent to other units of the Keepera Group. It underlies the Gnallan-a-Gea Arkose disconformably, or with slight angular unconformity. The unit occupies a stratigraphic position equivalent to the widespread 'cap dolostone' that characterises post-glacial deposits associated with the Ediacaran Elatina (formerly Marinoan) glaciation (Priess *et al* 1978) in the Adelaide Fold Belt and

Figure 28.8. Oorabra Arkose. Coarse massive arkose (behind hammer) overlain by sharp-based, channelised cobble conglomerate (ALCOOTA, WOODGREEN, 53K 432780mE 7551039mN, after Haines *et al* 2007: figure 15).

Figure 28.9. Boko Formation. (**a**) Clasts of quartzite, granite and other rock types are supported by dark red-brown mudstone matrix; boulder-size granite clast above and to right of hammer (ALCOOTA, WOODGREEN, 53K 428590mE 7554789mN, after Haines *et al* 2007: figure 12). (**b**) Well developed glacial striations on large quartzite clast (ALCOOTA, WOODGREEN, 53K 434259mE 7535454mN, after Haines *et al* 2007: figure 13).

Centralian A Superbasin (see **Centralian Superbasin**). It was deposited in a range of environments, including intertidal, shallow subtidal and deeper marine (Dunster *et al* 2007).

Mopunga Group

Postglacial Ediacaran sediments of the Mopunga Group (Noakes 1956, redefined by Kruse in Dunster *et al* 2007), deposited following the Toomba Movement, include the Gnallan-a-Gea Arkose, Elyuah Formation, Grant Bluff Formation, Elkera Formation, Central Mount Stuart Formation and Andagera Formation. The group is widely distributed through the southern Georgina Basin in MOUNT PEAKE, NAPPERBY, BARROW CREEK, ALCOOTA, HUCKITTA, TOBERMOREY, HAY RIVER and MOUNT WHELAN. Patchy outcrop of this group also extends across the present faulted margin of the Georgina Basin over parts of the northernmost Aileron Province (Arunta Region), and across the Davenport and southern Warramunga provinces (Tennant Region). Walter *et al* (1995) and Walter and Veevers (1997) assigned most of the Mopunga Group to their Supersequence 3, which is equivalent to the Ꝑ10_3 subdivision of Ahmad and Scrimgeour (2006). However, the upper part of the Central Mount Stuart Formation and questionably, the uppermost sandstone of the Elkera Formation were placed in Supersequence 4, equivalent to the Ꝑ10_4 subdivision of Ahmad and Scrimgeour (2006). The Andagera Formation is presumably also a part of Supersequence 4. The group as a whole is correlated with the Gaylad Sandstone, Pertatataka Formation, Julie Formation, uppermost Inindia beds, upper Boord Formation and lower Arumbera Sandstone of the Amadeus Basin, and with the Mount Doreen Formation and lower Yuendumu Sandstone of the Ngalia Basin.

Gnallan-a-Gea Arkose

The Gnallan-a-Gea Arkose (Walter 1980) forms moderate to prominent outcrops in northeastern HAY RIVER and southern TOBERMOREY in the NT and western MOUNT WHELAN in Queensland. It consists of unfossiliferous, fine to very coarse pebbly arkose, sandstone, siltstone and shale, and ranges considerably in thickness from as little as 10 m to greater than 1450 m (Kruse *et al* 2002a). Arkose and sandstone are commonly cross-stratified. The formation overlies the Wonnadinna Dolostone with an inferred disconformity, and it both laterally interdigitates with and is gradational upwards into the Elyuah Formation. It is also apparently conformably and gradationally overlain by the Grant Bluff Formation. The arkose is interpreted as a shallow-marine deposit with a proximal source (Dunster *et al* 2007).

Figure 28.10. Grant Bluff Formation. Thickening-upward interval of tabular white sandstone and quartzite (ALCOOTA, Woodgreen, 53K 421402mE 7564646mN, after Haines *et al* 2007: figure 17).

Elyuah Formation

The Elyuah Formation (KG Smith 1964, modified by Walter 1980) is a poorly exposed, recessive unit that occurs in southern HUCKITTA (Mopunga, Elua and Jervois ranges and environs), southwestern TOBERMOREY (Keepera Ridges), and northeastern and north-central ALCOOTA, including a few small outliers on the northernmost Aileron Province. It consists of micaceous shale and siltstone, and has a thin but persistent basal sandstone or pebbly arkose. Minor black micaceous shale and minor micaceous and quartz sandstone interbeds are also present (Kruse *et al* 2002a). The formation is 36 m thick in the type section and ranges up to 210 m elsewhere. It overlies the Boko Formation and Oorabra Arkose disconformably or with a slight angular unconformity, and is also conformable on and/or interdigitates with the Gnallan-a-Gea Arkose. Where these units are absent, the unit is unconformable on Palaeoproterozoic units. It is apparently conformably and gradationally overlain by the Grant Bluff Formation. The environment of deposition is interpreted to have been low-energy, shallow- to moderately deep-marine, mainly below wave base (Dunster *et al* 2007).

Grant Bluff Formation

The Grant Bluff Formation (KG Smith 1964, modified by Walter 1980) forms widespread prominent strike ridges and hills in southwestern BARROW CREEK, northern ALCOOTA, southern HUCKITTA, southwestern TOBERMOREY and northeastern HAY RIVER, including scattered outliers on the northernmost Aileron Province. It consists mainly of laminated to medium undulose-bedded quartz sandstone and quartzite (**Figure 28.10**) with micaceous partings (Freeman 1986). Quartz greywacke, arkose, siltstone, shale, minor dolostone and a local basal polymict conglomerate were also listed by Dunster *et al* (2007). The sandstone is medium to coarse and contains common centimetre- and rare decimetre-scale asymmetric and some symmetric ripples, small- to large-scale trough cross-beds and dewatering structures, including synaeresis features (Freeman 1986). The thickness of the Grant Bluff Formation is in the range 20–30 m in ALCOOTA, 50–100+ m in HUCKITTA, >248 m in TOBERMOREY and reaches a maximum of 1170 m in HAY RIVER (Dunster *et al* 2007). It is apparently conformable and gradational above the Gnallan-a-Gea Arkose and Elyuah Formation, or where these are absent, unconformably overlies Palaeoproterozoic sedimentary and metamorphic rocks, or nonconformably overlies Palaeoproterozoic intrusive rocks. The formation is conformably and gradationally overlain by the Elkera and Central Mount Stuart formations. Its stratigraphic position above Elatina-equivalent glacigene units indicates an Ediacaran age and ichnofossils (simple horizontal trails) are consistent with this age assignment. The formation was deposited as a transgressive sand sheet in a shallow- to marginal-marine depositional environment.

Elkera Formation

The generally recessive Elkera Formation (Walter 1980, modified by Freeman 1986) outcrops in southern HUCKITTA, northeastern ALCOOTA, and possibly southeastern MOUNT PEAKE, including a few scattered outliers on the northernmost Aileron Province. It consists of a succession of interbedded siltstone, quartz sandstone to sublithic sandstone, and shale, which is capped by dolostone (locally with columnar stromatolites) and which is locally evaporitic (Freeman 1986, Dunster *et al* 2007). Freeman (1986) also included an additional 43 m of silty sandstone and a granule orthoquartzite bed in the Jervois Range (HUCKITTA) within the formation, where the upper stromatolitic dolostone is absent. The thickness of the Elkera Formation is in the range 70–270 m, largely depending on the level of sub-Cambrian erosion (Walter 1980, Freeman 1986). The unit is conformable and gradational on the Grant Bluff Formation and is disconformably overlain by the Mount Baldwin Formation, or where this is absent, by the Red Heart Dolostone. It is a partial lateral equivalent of the Andagera Formation (Haines in Haines *et al* 1991) and of the Central Mount Stuart Formation. Like the Grant Bluff Formation, the stratigraphic position of the Elkera Formation above Elatina-equivalent glacigene units, and the presence of ichnofossils (simple horizontal trails) and distinctive stromatolites indicate an Ediacaran age. A peritidal to shallow-marine environment is interpreted for the formation (Dunster *et al* 2007).

Central Mount Stuart Formation

The Central Mount Stuart Formation (Offe 1978, after Smith and Milligan 1964 and modified by Walter 1980, Haines in Haines *et al* 1991 and Haines *et al* 2007) outcrops in southeastern MOUNT PEAKE, southwestern BARROW CREEK, northern ALCOOTA and northeastern NAPPERBY, including a few scattered outliers on the northern Aileron Province. The formation consists of a basal polymict conglomerate and succeeding quartzic, feldspathic and lithic sandstone, arkose, siltstone, dolostone and minor conglomerate (**Figure 28.11**). It reaches an estimated maximum thickness of 780 m in north-central ALCOOTA (Haines *et al* 2007) and contains two members, in ascending order, the recessive Tops Member and the Adnera Member, the latter forming prominent hills and uplands (Haines 1990, 2004, Haines in Haines *et al* 1991). The *Tops Member* comprises a lower interval of evaporitic and chertified dolostone and dolomitic sandstone, and an upper interval of arkose, feldspathic sandstone, siltstone, mudstone and minor conglomerate (**Figure 28.12**). This is generally conformably and gradationally overlain, probably diachronously, by the *Adnera Member*, which consists of cross-bedded, medium-grained feldspathic quartz sandstone and orthoquartzite, with a local upper interval of red-brown sandstone and siltstone (**Figure 28.13**). The formation conformably overlies the Elkera and Grant Bluff formations

Figure 28.11. Central Mount Stuart Formation on southern flanks of Central Mount Stuart (MOUNT PEAKE, near 53K 338500mE 7573750mN, after Donnellan 2008: figure 27c).

Figure 28.12. Tops Member of Central Mount Stuart Formation. Exploration costean exposing characteristic red-brown sandstone and mudstone, with green mudstone-dominated interval in foreground (beneath hammer at bottom right). Such green intervals typically display minor malachite staining at surface (Mount Skinner area, ALCOOTA, WOODGREEN, 53K 429223mE 7543511mN, after Haines *et al* 2007: figure 18).

Figure 28.13. Adnera Member of Central Mount Stuart Formation. Trough cross-bedded sandstone (Mount Skinner area, ALCOOTA, WOODGREEN, 53K 429170mE 7540342mN, after Dunster *et al* 2007: figure 41).

in northeastern ALCOOTA, and elsewhere, unconformably overlies Palaeoproterozoic sedimentary and metamorphic rocks, or nonconformably overlies Palaeoproterozoic intrusive rocks. It is overlain with probable disconformity by the Octy Formation. The unit is a probable correlative of the Andagera Formation (Haines *et al* 1991) and is a partial lateral equivalent of the Elkera Formation.

The Central Mount Stuart Formation bears a fossil assemblage that includes soft-bodied medusoids and problematic macrofossils (Dunster *et al* 2007), a dubiofossil (Walter *et al* 1989), and indeterminate leiospheres, other spheroidal and undifferentiated acritarchs, vendotaeniid fragments, filaments and large organic amorphous fragments (Grey 2005). These collectively indicate a terminal Ediacaran age. The formation was deposited at a time of mild tectonism, broadly coincident with the beginning of the 580–530 Ma Petermann Orogeny. Sediments were shed into southeast-trending fault troughs in the southern Georgina Basin from granitic and metamorphic source terranes to the west and northwest of the current exposures (Haines *et al* 1991). The Tops Member was probably deposited under conditions ranging from marginal marine sabkha in the lower third to deltaic in the upper two thirds, whereas the Adnera Member accumulated under shallow-marine and deltaic conditions similar to those interpreted for the upper Tops Member (Haines *et al* 2007). High-energy fluviatile facies may also be present in the Tops Member (Shaw and Warren 1975, Haines *et al* 1991).

Andagera Formation

The Andagera Formation (Bagas *et al* in Stidolph *et al* 1988) is exposed as terraces and mesas within extant valleys and on the tops of ridges within and around the margins of the Davenport Range in northwestern ELKEDRA, southwestern FREW RIVER, northeastern BARROW CREEK and southeastern BONNEY WELL. Most exposures therefore occur across the Davenport and southern Warramunga provinces of the Tennant Region with only small areas exposed along the margin of the Georgina Basin, mainly in ELKEDRA. The formation is up to 50 m thick and consists of pebble to boulder conglomerate, pebbly sublithic sandstone and minor siltstone. Coarser beds are poorly sorted and feature normal grading, ripples and cross-beds (Haines *et al* 1991). The unit is generally unfossiliferous, except for 'bioturbated beds and burrows' in FREW RIVER (Walley 1987) and Neoproterozoic microfossils in sandstone considered to be a distal equivalent of the Andagera Formation in NTGS drillhole ELK3 (Stidolph *et al* 1988, Haines *et al* 1991, **Figure 28.14**). The formation overlies the Palaeoproterozoic Hatches Creek Group with angular unconformity, or is nonconformable on the Palaeoproterozoic Elkedra Granite; these rocks were a major source of sediment for the unit. It is disconformably overlain by the Thorntonia Limestone, or is transitionally or disconformably overlain by the Gum Ridge Formation. The age of the formation was initially thought to be early to early middle Cambrian (Walley 1987, Wyche and Simons 1987, Stidolph *et al* 1988), on the basis of inferred correlation with the basal Red Heart Dolostone and an inferred transitional contact with overlying early middle Cambrian Gum Ridge Formation, but a Neoproterozoic age was preferred by Haines *et al* (1991), who postulated that the Andagera and Central Mount Stuart formations were both direct results of the 580–530 Ma Petermann Orogeny. The environment of deposition is considered to have been mainly fluviatile, ranging from proximal high-energy valley fill to distal alluvial fan to braidplain, but more distal parts of the formation are possible shoreline or shallow-marine deltaic deposits (Haines *et al* 1991).

Kiana Group

Kalkarindji Province volcanic and minor sedimentary rocks in the northern Georgina Basin are underlain by a 300 m-thick sedimentary succession referred to the Kiana Group (Rawlings *et al* 2008). The constituent Bukalara Sandstone (Dunn 1963) is widespread, tracking the onshore Carpentaria Basin margin from northern MOUNT DRUMMOND to northwestern HODGSON DOWNS. This predominantly coarse siliciclastic formation passes conformably upward in southwestern MOUNT YOUNG and adjacent HODGSON DOWNS into the more geomorphically subdued, finer-grained Cox Formation. Strong lithological similarities permit correlation of these two formations, respectively, with the Buckingham Bay Sandstone and Raiwalla Shale of the Wessel Group in the onshore Arafura Basin (see **Centralian Superbasin: figure 22.3a**, **b**). Earlier reports of the Cambrian-aspect ichnofossil *Skolithos* in the Bukalara Sandstone and Buckingham Bay Sandstone (Plumb *et al* 1976) were discounted by Rawlings *et al* (1997), who reinterpreted these features as dewatering structures. The later find of the carbonaceous macrofossil *Chuaria* in the Raiwalla Shale (Haines 1998) favours a Neoproterozoic age. The absence of glacial deposits in the Kiana Group, in conjunction with its undisturbed, flat-lying attitude and stratigraphic position immediately below fossiliferous middle Cambrian rocks, suggests that the group is equivalent to post-glacial (Ediacaran) Supersequence 3 (Walter *et al* 1995) units of the Centralian A Superbasin (Ꝑ10_3 subdivision of Ahmad and Scrimgeour 2006).

Bukalara Sandstone

The Bukalara Sandstone (Dunn 1963) outcrops as sandstone mesas and plateaux with a characteristic strongly jointed photopattern along the northeastern margin of the Georgina Basin in HODGSON DOWNS, southeastern MOUNT YOUNG, northeastern TANUMBIRINI, BAUHINIA DOWNS, northeastern WALHALLOW, southern ROBINSON RIVER, CALVERT HILLS and northern MOUNT DRUMMOND. The formation rests unconformably on various Palaeo- and Mesoproterozoic units of the McArthur and South Nicholson basins and Murphy Province, the youngest of these (topmost units of Roper and South Nicholson groups) being of Calymmian age. It is overlain unconformably by the early Cambrian Helen Springs Volcanics of the Kalkarindji Province, and conformably by the unfossiliferous Cox Formation in MOUNT YOUNG (Haines *et al* 1993). The formation reaches a maximum thickness of about 300 m in BAUHINIA DOWNS (JW Smith 1964) and consists of fine- to medium-grained quartz sandstone and associated pebble conglomerate, fine- to very coarse-grained feldspathic sandstone, friable, medium- to coarse-grained lithic sandstone, lesser fine-grained sandstone and cobble conglomerate, and minor interbedded shale (Smith and Roberts 1963, Plumb and Rhodes 1964, Jackson *et al* 1987, Rawlings *et al* 2008, **Figure 28.15**). Sandstone bedding is thick to very thick, with metre-scale planar and trough cross-beds (locally slumped), mudclasts and symmetric ripples; finer-grained lithofacies locally bear desiccation cracks (Rawlings *et al* 2008). A high-energy braided fluviatile to shallow-marine depositional environment has been interpreted for the formation (Rawlings 2004).

Cox Formation

The Cox Formation (Dunn 1963) outcrops as rubbly outcrops on low plateaux in southwestern MOUNT YOUNG and eastern HODGSON DOWNS, but unlike the Bukalara Sandstone, does not display strong joint patterns on aerial photographs. The unfossiliferous formation conformably overlies the Bukalara Sandstone and is unconformably overlain by Cretaceous and Cenozoic rocks. It reaches a maximum thickness of about 50 m and consists of very fine- to fine-grained, usually micaceous sandstone, thinly interbedded with micaceous siltstone and shale, overlain by finely laminated siltstone and shale. Finer-grained lithofacies may be low-angle cross-stratified. The environment of deposition was relatively deeper (storm-influenced subtidal marine) than that of the Bukalara Sandstone (Haines *et al* 1993).

EARLY CAMBRIAN–EARLY LATE CAMBRIAN

All early Cambrian strata of the southern Georgina Basin are included within the Shadow Group. Overlying middle and

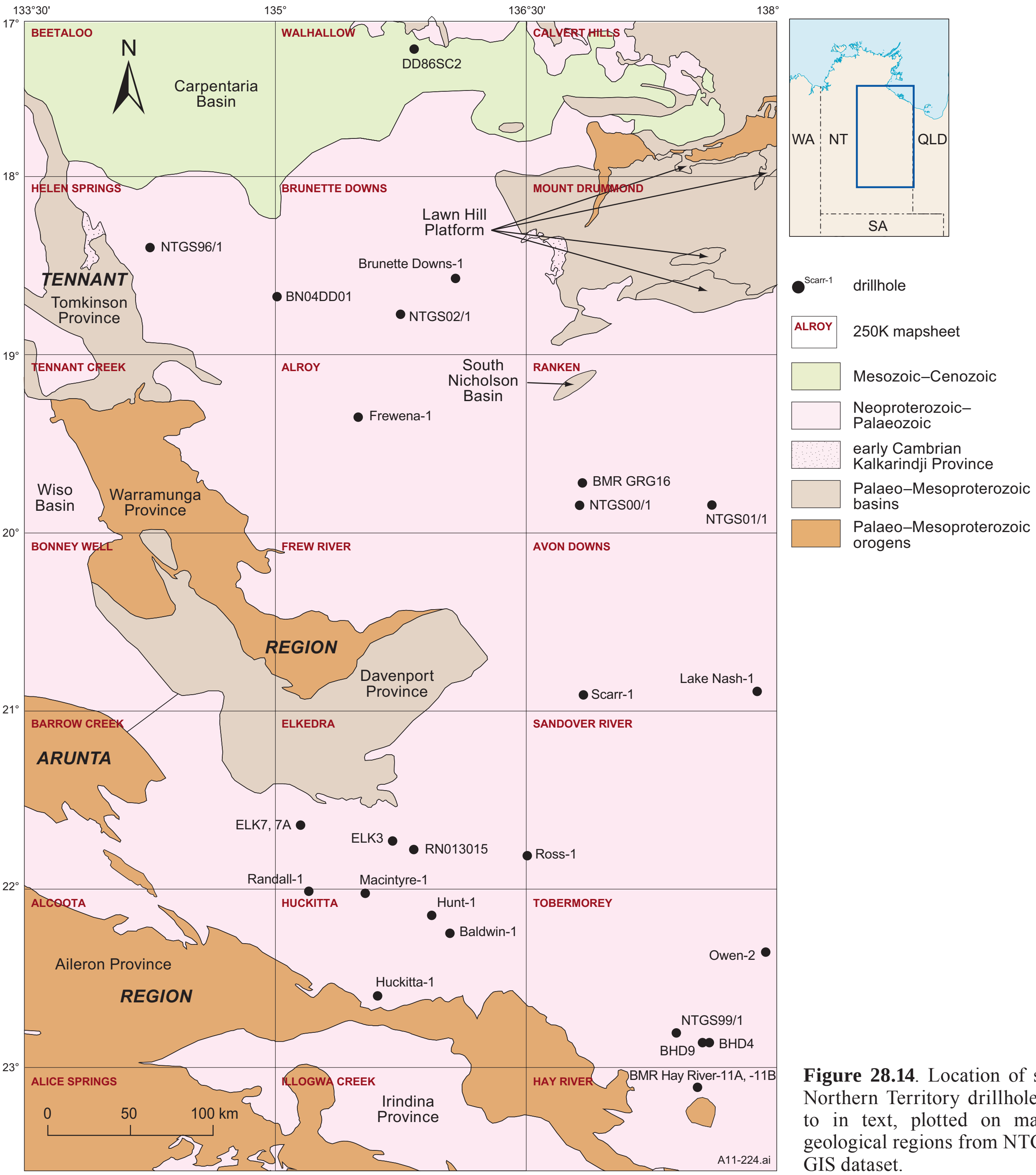


Figure 28.14. Location of significant Northern Territory drillholes referred to in text, plotted on map of NT geological regions from NTGS 1:2.5M GIS dataset.

early late Cambrian rock units in the southern and eastern Georgina Basin, including much of the Undilla Sub-basin, are included within the Narpa Group, whereas correlative middle Cambrian rock units in the central, western and northern Georgina Basin, including the Barkly Sub-basin and some exposed units of the Undilla Sub-basin, are referred to the Barkly Group. All middle Cambrian units of the Narpa and Barkly groups are included in one or the other of two successive sedimentary successions that have been recognised from sequence stratigraphic studies of middle Cambrian strata in the basin (Shergold *et al* 1988, Southgate and Shergold 1991, Laurie 2006). These successions are characterised by distinctive invertebrate faunas and are informally named sequence 1 (Ordian) and sequence 2 (latest Ordian–early Mindyallan). Sequence 1 and 2 faunas are widespread and have been documented from middle Cambrian strata in other northern and southern Australian basins, enabling all of these successions to be readily correlated (see **Centralian Superbasin: figure 22.6**).

Shadow Group

The early Cambrian Shadow Group (Kruse in Dunster *et al* 2007) is widely distributed in the southern Georgina Basin in BARROW CREEK, ALCOOTA, ELKEDRA, HUCKITTA, TOBERMOREY and HAY RIVER in the NT, and MOUNT WHELAN, GLENORMISTON, URANDANGI and DUCHESS in western Queensland. It embraces all early Cambrian rocks in the southern Georgina Basin, although these do not span the entire epoch, including the Octy Formation, Neutral Junction Formation, Mount Baldwin Formation, Adam Shale and Red Heart Dolostone in the NT; and the Mount Birnie beds, and provisionally the Sylvester Sandstone and Riversdale Formation in western Queensland. The group represents a renewal of sedimentation in the southern part of the basin following the regional Huckitta Movement, evidently a distal effect of the Petermann Orogeny, which was centred in the Musgrave Province and southern Amadeus Basin. As a likely result of this tectonism – with the possible exception of the Mount Baldwin Formation – no Georgina Basin succession spans the Neoproterozoic–Palaeozoic boundary. The distribution of all the sedimentary units is discontinuous, implying some lingering influence of discrete depocentres inherited from the Neoproterozoic. Constituent fan-delta to marine sandstone-dominated units [Octy Formation and overlying Neutral Junction Formation in the southwest (ALCOOTA–BARROW CREEK; Haines *et al* 1991) and Mount Baldwin Formation in the southeast (HUCKITTA; KG Smith 1964, Walter 1980)] preserve a varied Cambrian-aspect ichnofauna, correlative with the early early Cambrian (Walter *et al* 1989).

The Shadow Group unconformably or disconformably overlies formations of the Mopunga and Keepera groups (Shergold 1985, Haines *et al* 1991, Dunster *et al* 2007). It is unconformably (Shergold and Druce 1980) to conformably and gradationally (Shergold *et al* 1985) overlain by the Thorntonia Limestone, or where this is absent, unconformably overlain by the Beetle Creek or Chabalowe formations (all Narpa Group), or by Mesozoic sedimentary rocks. The group is correlated with the upper Arumbera Sandstone, Winnall beds, Quandong Conglomerate, Eninta Sandstone, Mount Currie Conglomerate, Mutitjulu Arkose, Namatjira Formation and Todd River Dolostone of the Amadeus Basin, and with the upper Yuendumu Sandstone of the Ngalia Basin (Shergold *et al* 1985, Young *et al* 2002, see **Centralian Superbasin: figure 22.6**).

Octy Formation

The Octy Formation (Haines in Haines *et al* 1991) is a resistant range-capping unit that outcrops in southwestern BARROW CREEK and northern ALCOOTA in the southwestern Georgina Basin. The formation is up to 150 m thick (Haines *et al* 2007) and consists of locally glauconitic, predominantly medium-grained, cross-bedded and planar laminated feldspathic quartz sandstone (**Figure 28.16**), interbedded with minor siltstone, mudstone and silty sandstone. A thin basal conglomerate occurs locally. Depositional environments ranged from open marine to tidal with occasional exposure (Dunster *et al* 2007). The formation overlies the Adnera Member of the Central Mount Stuart Formation with probable disconformity, and is overlain by the Neutral Junction Formation with probable disconformity, or where this is absent, by chert and sandstone rubble tentatively assigned to the Chabalowe Formation. It is correlated with the lower Mount Baldwin Formation, and possibly with the Sylvester Sandstone of the southeastern Georgina Basin in Queensland (Dunster *et al* 2007).

Figure 28.15. Bukalara Sandstone. Cobble conglomerate and planar stratified coarse-grained lithic sandstone from lower part of formation (CALVERT HILLS, NICHOLSON RIVER, 53K 713800mE 8009650mN, after Rawlings *et al* 2008: figure 53).

Figure 28.16. Octy Formation. Cross-bedded sandstone with surface silicification (ALCOOTA, WOODGREEN, 53K 421092mE 7556678mN, after Dunster et *al* 2007: figure 42).

Neutral Junction Formation
The Neutral Junction Formation (Haines in Haines *et al* 1991) is a recessive unit that is generally poorly exposed on low hills and plains in south-central BARROW CREEK in the southwestern Georgina Basin. The formation overlies the Octy Formation with probable disconformity and is disconformably overlain by the Chabalowe Formation. It is 39 m thick and consists of silty and micaceous sandstone and siltstone, with minor thin intervals of silty and glauconitic limestone. Sandstone is commonly calcareous and glauconitic, and is ripple cross-stratified (Haines *et al* 1991). The unit was probably deposited under low-energy subtidal marine conditions (Dunster *et al* 2007). It is correlated with the upper Mount Baldwin Formation, and possibly with the Sylvester Sandstone (Dunster *et al* 2007).

Mount Baldwin Formation
The Mount Baldwin Formation (KG Smith 1964, redefined by Walter 1980) outcrops in the Elua, Johannsen and Jervois ranges in southern HUCKITTA. It overlies the Elkera Formation with angular unconformity and is unconformably overlain by the Red Heart Dolostone. The formation is 60–320 m thick and consists of quartz sandstone, sublithic sandstone, quartz greywacke, siltstone, shale and minor subarkose. Freeman (1986) noted the presence of rare granule-bearing beds, pebble-sized claystone intraclasts in some beds, prominent cross-beds throughout the formation and various ichnofossils, including networks of fine branching burrows near the base of the unit. The basal beds are recessive, but the remainder of the formation is ridge-forming; less-resistant beds are more thinly bedded and more fissile (Freeman 1986). Ichnofossils together with the stratigraphic position of the formation beneath the mid-early Cambrian Red Heart Dolostone indicate an early early Cambrian age (Dunster *et al* 2007). The formation is correlated with the Octy and Neutral Junction formations, the Adam Shale and possibly with the Sylvester Sandstone. An alluvial fan-delta environment of deposition has been interpreted for the unit (Stidolph *et al* 1988, Eyre 1994).

Adam Shale
The Adam Shale (Walter in Walter *et al* 1979) is a generally recessive unit that outcrops very poorly in the Desert Syncline of northern HAY RIVER and also probably occurs in the subsurface in southern TOBERMOREY (Shergold and Walter 1979). It is disconformable on the Grant Bluff Formation and disconformably underlies the Red Heart Dolostone. The formation is 16 m thick in the type section in cored drillhole BMR Hay River-11B (northeastern HAY RIVER, **Figure 28.14**) and consists of laminated pyritic shale with sandy laminations, and minor medium–coarse sandstone. Acritarchs and bioturbated beds (Walter *et al* 1979), together with the position of the unit stratigraphically beneath the mid-early Cambrian Red Heart Dolostone, indicate an early early Cambrian age. The Adam Shale is correlated with the Mount Baldwin, Octy and Neutral Junction formations, and possibly with the Sylvester Sandstone in Queensland. A marine depositional setting is indicated (Dunster *et al* 2007), presumably below storm wave base.

Red Heart Dolostone
The Red Heart Dolostone (Walter in Walter *et al* 1979) denotes the first Palaeozoic carbonate package within the Georgina Basin succession. It is only exposed in the Desert Syncline of northern HAY RIVER as a gently inclined bench, but occurs in the subsurface in southern TOBERMOREY, HUCKITTA and southwestern ELKEDRA. The formation ranges in thickness from just 9 m in the type section to an estimated 126 m in uncored drillhole Exoil Huckitta-1 in HUCKITTA (**Figure 28.14**). In the type section (cored drillhole BMR Hay River-11B), the formation consists of stylolitic, mottled, brecciated and vuggy dolostone above a basal arkose or sandstone (**Figure 28.17**), with thin mudstone interbeds. HAY RIVER exposures consist of a basal sandstone and quartzose siltstone grading upward into dolomitic sandstone and quartzose dolostone. Other rock types include dolomitic granule conglomerate and marly mudstone (Walter *et al* 1979, Kruse *et al* 2002a, Dunster *et al* 2007). The Red Heart Dolostone contains mid-early Cambrian small skeletal fossils and reef-building archaeocyaths (Kruse and West 1980, Laurie 1986), correlated with the late Atdabanian stage of Siberia (Laurie and Shergold 1985, Debrenne *et al* 1989, 1990, Gravestock and Shergold 2001). An identical archaeocyathan fauna in the correlative Todd River Dolostone of the northeastern

Figure 28.17. Red Heart Dolostone. Basal dolomitic quartz sandstone from drillhole NTGS Elkedra-7A. Arrow marks contact with Palaeoproterozoic basement (ELKEDRA, AMMAROO, 53K 516221mE 7605451mN, after Dunster *et al* 2007: figure 43).

Amadeus Basin indicates basin interconnection at that time, via the intervening Irindina Province. The ichnofossil *?Diplocraterion* sp (Walter *et al* 1979, 1989) has also been recorded from the basal beds. The formation is probably disconformable on the Adam Shale, or where this is absent, is unconformable on the Grant Bluff Formation or nonconformable on Palaeoproterozoic granite. It is disconformable beneath the Thorntonia Limestone. The basal beds accumulated in a low- to high-energy marginal marine environment. The remainder of the formation was deposited under shallow-marine conditions with the development of calcimicrobial-archaeocyathan reefs (Kruse and West 1980, Kennard 1991).

Narpa Group

Following a depositional hiatus in the late early Cambrian coinciding with the outpouring of continental flood basalt in northern Australia (see **Kalkarindji Province**), a widespread marine transgression in the early middle Cambrian for the first time inundated the central-northern platform domain of the Georgina Basin as well as the areas of the present northern Wiso, Daly and Ord basins. These basins were interconnected and shared a similar invertebrate fauna (Kruse 1990, 1991, 1998, Kruse *et al* 2004, see **Centralian Superbasin**). All middle and early late Cambrian rock units in the southern and eastern Georgina Basin, including much of the Undilla Sub-basin, are included within the Narpa Group.

The Narpa Group (Kruse in Dunster *et al* 2007) is widely distributed in the NT through BARROW CREEK, ALCOOTA, ELKEDRA, HUCKITTA, SANDOVER RIVER, TOBERMOREY, HAY RIVER, eastern MOUNT DRUMMOND, southern AVON DOWNS, and the subsurface in RANKEN. In Queensland, the group occurs in MOUNT WHELAN, northwestern BOULIA, GLENORMISTON, URANDANGI, DUCHESS, MOUNT ISA, CAMOOWEAL and LAWN HILL. Within the NT, constituent units occurring in the southern Georgina Basin include the Thorntonia Limestone, Arthur Creek Formation, Steamboat Sandstone, Chabalowe Formation and Arrinthrunga Formation. In the Undilla Sub-basin, Narpa Group units include the Thorntonia Limestone, Border Waterhole Formation and Currant Bush Limestone. Constituent units occurring within Queensland include the Beetle Creek Formation, Blazan Shale, Inca Formation, Quita Formation, Roaring Siltstone, Devoncourt Limestone, Kajabbi Formation, Georgina Limestone, Mungerebar Limestone, Selwyn Range Limestone, O'Hara Shale, Pomegranate Limestone, Gowers Formation, V-Creek Limestone, Mail Change Limestone, Age Creek Formation and Split Rock Sandstone.

The Narpa Group is conformable, unconformable and disconformable on various units of the Shadow Group, or where these are absent, is unconformable on Proterozoic rocks (Shergold and Druce 1980). In Queensland, the group is also conformable and gradational on the Colless Volcanics of the Kalkarindji Province (Carter *et al* 1961, Carter and Öpik 1961). The group passes laterally into the Wonarah Formation, Ranken Limestone and Camooweal Dolostone (Barkly Group) of the central Georgina Basin. It is conformably or disconformably overlain by various units of the Cockroach Group, or by Mesozoic sedimentary rocks (Casey 1959, Shergold *et al* 1976, 1985).

The Narpa Group is correlated (Shergold *et al* 1985, see **Centralian Superbasin: figure 22.6**) with the Gum Ridge Formation, Anthony Lagoon Formation, Wonarah Formation, Ranken Limestone and Camooweal Dolostone of the central and western Georgina Basin, Top Springs Limestone of the northern Georgina Basin, and various units of the Amadeus, Ngalia, Wiso, Daly, Ord, Bonaparte and Arafura basins.

A diverse fauna (particularly of trilobites) in many units indicates an early middle Cambrian (Ordian) to medial late Cambrian (early Iverian) age for the group (Shergold *et al* 1985). Middle Cambrian units are included within stratigraphic sequences 1 and 2 of Southgate and Shergold (1991).

Thorntonia Limestone

The lowermost unit of the Narpa Group is the Thorntonia Limestone (Öpik 1956a), which is widely distributed in the southern Georgina Basin in the NT, as generally poor exposures through HUCKITTA, southern ELKEDRA, southern SANDOVER RIVER, TOBERMOREY and northern HAY RIVER. It also floors the Undilla Sub-basin proper in southern RANKEN and probably more widely, and evidently onlaps the eastern flank of the Alexandria-Wonarah Basement High. It is not exposed within the NT portion of that sub-basin, but has been intersected in cored drillhole NTGS01/1 (Kruse 2003, **Figure 28.14**). In the northeastern parts of the basin in Queensland, the formation is poorly to well exposed, regionally forming cliffs and plateaux, through eastern URANDANGI, central DUCHESS and questionably northeastern GLENORMISTON. It includes chertified dolostone of the Yelvertoft Bed (David 1932) and the 'Ardmore Chert Member' (Henderson and Southgate 1978), both at the top. The formation unconformably (Shergold and Druce 1980) or conformably and gradationally (Shergold *et al* 1985) overlies the Riversdale Formation. It is conformable and gradational on the Colless Volcanics of the Kalkarindji Province (Carter *et al* 1961, Carter and Öpik 1961) and the 'Mount Hendry Formation' (de Keyser and Cook 1972, Rogers and Keevers 1976), which is probably basal Thorntonia Limestone. It is presumed to be unconformable on the Mount Birnie beds and disconformable on the Red Heart Dolostone, or where these are absent, is unconformable on Proterozoic rocks (Shergold and Druce 1980), or nonconformable on Palaeoproterozoic granite. The formation is conformably to disconformably overlain by the Beetle Creek Formation (Shergold *et al* 1985, Southgate and Shergold 1991) and is also disconformably overlain by the Arthur Creek Formation, Inca Formation, Gowers Formation or Bronco Stromatolith Bed (Southgate 1986, Shergold and Southgate 1986).

The Thorntonia Limestone ranges in thickness from 23 m to >400 m, but is usually less than 100 m (Dunster *et al* 2007). It consists mostly of marine bioclastic carbonate rocks, including limestone, partially dolomitised limestone, dolostone, pyritic-carbonaceous dolostone, marl and mudstone, with minor nodular chert and phosphorite (**Figure 28.18**). A thin basal quartz sandstone or arkosic conglomerate lag occurs locally. A diverse fossil assemblage containing numerous species of trilobites, brachiopods, hyoliths, bradoriides, echinoderms, molluscs, chancelloriids, a demosponge, sponge spicules, calcimicrobes and stromatolites was listed by Dunster *et al* (2007) and indicates an early middle Cambrian (Ordian) age (Shergold *et al* 1985). The bulk of this unit therefore represents stratigraphic sequence 1 of Southgate and Shergold (1991). A thin, high-energy upper interval evident in TOBERMOREY (Kruse *et al* 2002a) is possibly attributable to basal sequence 2, if correlative with the Bronco Stromatolith Bed in Queensland (Gravestock and Shergold 2001). The depositional environment is interpreted to have been peritidal to marine, and was partly dysoxic to anoxic in the southern and southwestern Georgina Basin (Dunster *et al* 2007).

Arthur Creek Formation

The top of the Thorntonia Limestone was at least locally exposed and karstified prior to rapid inundation that initiated the thick Arthur Creek Formation (Freeman 1986 after KG Smith 1964, modified by Kruse *et al* 2002a) in the southern part of the basin. This formation is poorly to moderately exposed through ELKEDRA, HUCKITTA, TOBERMOREY and northern HAY RIVER, and occurs in the subsurface in southern SANDOVER RIVER in the NT, and in URANDANGI and GLENORMISTON in Queensland. Exposures are generally scattered and low on open ground, or moderate along watercourses; locally, outcrops form broad rounded prominences. The formation is disconformable on the Thorntonia Limestone, or where this is absent, the Red Heart Dolostone, or is nonconformable on Palaeoproterozoic granite. It is conformably overlain by the Steamboat Sandstone and Chabalowe Formation.

The Arthur Creek Formation has been divided into two informal intervals. The lower interval consists of foetid pyritic-carbonaceous black shale and laminated dolostone (**Figure 28.19a**), and minor dolomitic quartz sandstone and conglomerate. The paler upper interval comprises dolostone, limestone and minor quartzose dolostone and siliciclastic mudstone (**Figure 28.19b**). The transition between the two intervals can be abrupt, or gradational and interdigitating (Kruse *et al* 2002a). Overall, the formation ranges in thickness from <30 m in HUCKITTA to a maximum thickness in the NT of >483 m in cored drillhole BHD9 (TOBERMOREY, **Figure 28.14**). Its thickness is possibly as much as 720 m in uncored drillhole Netting Fence-1 (GLENORMISTON) in Queensland, but this might be a result of structural repetition (Dunster *et al* 2007). The lower black shale interval is 272.1 m thick in cored drillhole NTGS99/1 (TOBERMOREY, Kruse *et al* 2002a). The Arthur Creek Formation is richly fossiliferous and contains a variety of miomeran and polymeran trilobites, lingulate

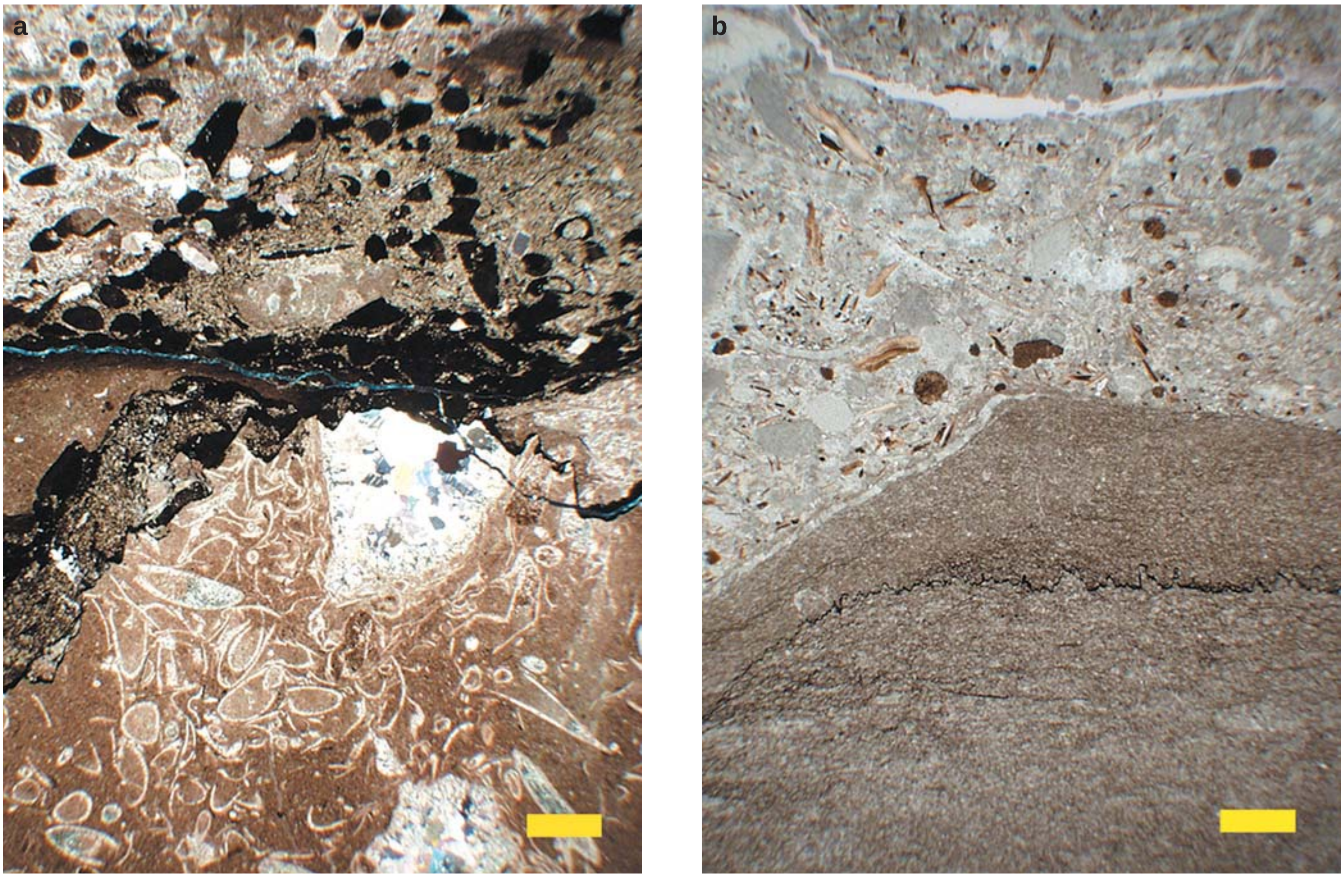


Figure 28.18. Thorntonia Limestone. (**a**) Bioclast coquina of dark medial interval. Packstone of hyolith conchs and some opercula (mainly *Guduguwan hardmani*) at bottom. Wackestone of phosphatic hyolith steinkerns at top. Scale bar = 2 mm (photomicrograph C72845, crossed nicols; 575.2 m depth in drillhole NTGS99/1; TOBERMOREY, MARQUA 53K 746996mE 7474345mN, after Kruse *et al* 2002a: figure 17). (**b**) Erosive contact between phosphatic and glauconitic, bioclast intraclast peloid dolograinstone of upper light grey interval (above) and marly dolomudstone of medial interval. Phosphatic grains in upper interval include originally phosphatic lingulate brachiopods (light brown) and phosphatised hyolith steinkerns (dark brown). Scale bar = 2 mm (photomicrograph C72844, plane polarised light; 558.7 m depth in drillhole NTGS99/1; TOBERMOREY, MARQUA 53K 746996mE 7474345mN, after Kruse *et al* 2002a: figure 18).

and calciate brachiopods, hyoliths, molluscs, echinoderms, sponge spicules, acritarchs and filamentous algae, species of which are listed in Dunster *et al* (2007). These collectively indicate an early middle Cambrian (latest Ordian) to early late Cambrian (Boomerangian) age. The formation thus spans most of the middle Cambrian and constitutes the bulk of stratigraphic sequence 2 of Southgate and Shergold (1991). The environment of deposition for the Arthur Creek Formation is interpreted as being dysoxic to anoxic, deeper marine with some deposition from turbidity currents and debris flows for the lower interval, steadily shallowing upward to aerobic, restricted platform marine, above wave base for the upper interval (Dunster *et al* 2007).

Figure 28.19. Arthur Creek Formation. (**a**) Pyritic-carbonaceous dololaminite of lower interval. Laminations are highlighted by variations in proportions of organic matter and clays (dark) versus fine xenotopic dolomite spar, quartz silt and bedding-subparallel muscovite (light). Scale bar = 2 mm (photomicrograph C72843, crossed nicols; 530.0 m depth in drillhole NTGS99/1; TOBERMOREY, MARQUA, 53K 746996mE 7474345mN, after Kruse *et al* 2002a: figure 19). (**b**) Centimetre-scale interbeds of calcimudstone (pale grey) and dolomitic-siliciclastic mudstone (brown) of upper interval (TOBERMOREY, TOKO, 53K 770500mE 7466400mN, after Kruse *et al* 2002a: figure 21).

Steamboat Sandstone

The Steamboat Sandstone (Noakes *et al* 1959) forms mesa caps and plains (Dunster *et al* 2007) in southeastern SANDOVER RIVER, eastern and southern TOBERMOREY and eastern HUCKITTA in the NT, and in northeastern GLENORMISTON and southeastern URANDANGI in Queensland; it also occurs in the subsurface in southwestern GLENORMISTON and western MOUNT WHELAN. The formation is conformable above the Arthur Creek Formation and beneath the Arrinthrunga Formation in the NT. In Queensland, it conformably (Noakes *et al* 1959) or disconformably (Öpik 1960) overlies the Quita Formation, and laterally interdigitates with and is conformably overlain by the Mungerebar Limestone (Reynolds 1965). The Steamboat Sandstone ranges in thickness from 17 m up to 221 m, and consists of quartz sandstone and calcareous sandstone, with interbeds of quartzose grainstone and quartzose dolostone, and minor siltstone. It contains a diverse fauna of agnostine and polymeran trilobites that indicates a latest middle Cambrian (Boomerangian) age (Shergold *et al* 1985, Shergold 1997). The formation is interpreted to have been deposited as a nearshore sand (Reynolds and Pritchard 1964) to shallow-marine (Harrison 1979), platform-edge grainstone (Southgate and Shergold 1991) and was possibly a shallow-marine barrier bar system that rimmed peritidal flats represented by the Arrinthrunga Formation.

Chabalowe Formation

The Chabalowe Formation (Morris *et al* in Stidolph *et al* 1988) is poorly exposed as low rises, mainly of ferruginised sandstone, in eastern BARROW CREEK, northern ALCOOTA and western ELKEDRA. It also occurs in the subsurface elsewhere in ELKEDRA and in HUCKITTA and SANDOVER RIVER. The formation conformably overlies the Arthur Creek Formation, or where this is absent, disconformably overlies the Neutral Junction Formation, unconformably overlies the Hatches Creek Group (of the Davenport Province), or nonconformably overlies Palaeoproterozoic granite. It is conformably overlain by and partially laterally interdigitates with the basal Arrinthrunga Formation. A single constituent unit, the basal Hagen Member, is known only from the subsurface in HUCKITTA, ELKEDRA, SANDOVER RIVER and possibly BARROW CREEK.

The formation reaches a maximum thickness of 342 m in cored drillhole Randall-1 (HUCKITTA; Wakelin-King 1992, **Figure 28.14**). It comprises evaporitic, medium to coarse, cross-bedded dolomitic quartz sandstone and dolomitic siliciclastic siltstone, commonly with intraformational breccias, and minor quartzose, silty and peloid-intraclast dolostone and mudstone (Dunster *et al* 2007). The proportion of quartz sandstone decreases eastward in ELKEDRA, where the unit comprises fining-upward cycles of sandstone, shale and dolostone, separated by erosional cycles (Stidolph *et al* 1988). A basal arkosic conglomerate may occur above Palaeoproterozoic granite.

The lenticular *Hagen Member* reaches a maximum thickness of 160 m in Randall-1 and is characterised by a relative abundance of evaporite and a greater proportion of dolostone to siliciclastic rocks than the rest of the formation. The dolostone includes microbial (stromatolitic and thrombolitic) and intraclast types, together with dolomudstone, and is characterised by the presence of massive and bedded gypsum and lesser anhydrite (Kruse *et al* 2002b). The entire Chabalowe Formation was deposited under nearshore, restricted marine to peritidal (including hypersaline sabkha) conditions. Its stratigraphic position above the Arthur Creek Formation and lateral to the basal Arrinthrunga Formation suggests an early late Cambrian age for the unit (Kruse *et al* 2002b, Dunster *et al* 2007).

Arrinthrunga Formation

The overlying very thick Arrinthrunga Formation (KG Smith 1964) forms low, rubbly exposures to substantial ridges in eastern BARROW CREEK, ELKEDRA, HUCKITTA, TOBERMOREY, SANDOVER RIVER, southern AVON DOWNS and northern HAY RIVER in the NT, and westernmost MOUNT WHELAN, GLENORMISTON and URANDANGI in Queensland. The formation conformably and gradationally overlies the Chabalowe Formation and Steamboat Sandstone, or where these are absent, the Arthur Creek Formation. It laterally interdigitates with the Georgina Limestone (in Queensland) and its basal beds are partly equivalent to the Chabalowe Formation. The unit is disconformably overlain by the Tomahawk and Ninmaroo formations. The Eurowie Sandstone Member is recognised in the medial Arrinthrunga Formation in central and eastern HUCKITTA, southeastern ELKEDRA and the subsurface in western TOBERMOREY (Dunster *et al* 2007).

The Arrinthrunga Formation attains a maximum thickness of 975 m in HUCKITTA (Smith 1972) and is in the range 300–900 m over most of its wide geographic extent. It comprises locally silicified and evaporitic limestone and dolostone, minor quartz sandstone, siltstone and shale (**Figure 28.20**). Kennard (1981) described a variety of component carbonate rock types including microbial, peloid, ooid and minor mudstone textures, together with quartzose carbonate, marl and minor quartz sandstone. Sedimentary structures include stromatolites, thrombolites, ripple cross-lamination, flat-pebble conglomerate, gypsum pseudomorphs and nodular anhydrite. The formation contains planar, wavy, domical and columnar stromatolites, and rare trilobites, brachiopods, hyoliths, molluscs (Smith 1972) and ichnofossils. These, together with stratigraphic relationships, indicate an early–?mid late Cambrian age. The depositional environment is interpreted to have been shallow subtidal to peritidal on a restricted carbonate platform with intermittent local emergence (Shergold and Druce 1980, Kennard 1981). The formation therefore marks the widespread regional shoaling of the depositional system from a more open shallow subtidal setting (upper Arthur Creek Formation) through a seaward high-energy quartz sand barrier (Steamboat Sandstone) into characteristically restricted, shallow subtidal to peritidal conditions (Kruse *et al* 2002b).

The medial *Eurowie Sandstone Member* (KG Smith 1964) is 40–60 m (maximum 107 m) thick and consists of quartz sandstone and quartzose dolostone with distinctive halite hopper casts, and minor shale, deposited in an intermittently emergent hypersaline shoreline setting (Kennard 1981). This member is associated with the SPICE (Steptoean Positive Isotopic Carbon Excursion) event (Lindsay *et al* 2005), recognised on several continents and correlated with the middle Steptoean Dunderbergia Zone of Laurentia (Saltzman *et al* 2004) and late Idamean stage of Australia (Shergold 1997, Geyer and Shergold 2000). The SPICE event denotes a sudden reversal of the anoxia that had steadily spread throughout oceans and atmosphere during the Cambrian. After the SPICE event, atmospheric oxygen levels may have risen to as high as 30% (cf 21% today). This sudden increase in oxygen led to a substantial increase in biodiversity worldwide (Saltzman *et al* 2011).

Border Waterhole Formation

Isolated exposures of the Border Waterhole Formation (Öpik 1960) occur in eastern MOUNT DRUMMOND (NT) and adjacent western LAWN HILL (Queensland) along the northern margin of the Undilla Sub-basin. The formation is typically obscured by a regolith of chert breccia and pebbles, so that outcrop is mainly limited to creek beds, although the basal beds are better exposed. The unit overlies the Lawn Hill Formation (McNamara Group, Lawn Hill Platform) with angular unconformity and is apparently conformably (Smith 1972), or disconformably

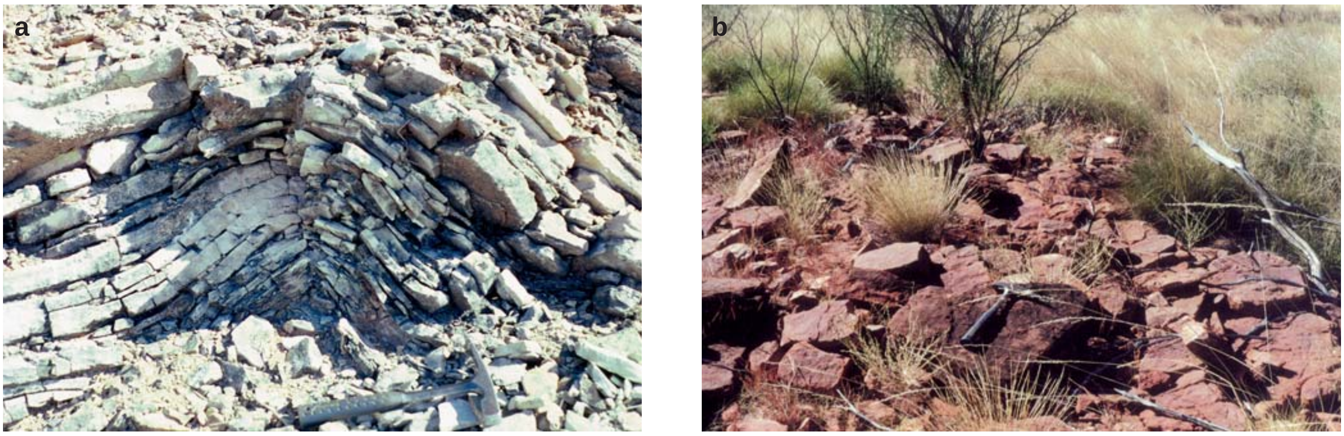


Figure 28.20. Arrinthrunga Formation. (**a**) Light grey, thinly bedded marly dolomudstone in hilltop quarry (SANDOVER RIVER, Georgina, 53K 775800mE 7646000mN, after Kruse *et al* 2002b: figure 5). (**b**) Thick tabular beds of quartz sandstone in medial part of formation (SANDOVER RIVER, Carbeen, PS803339, after Kruse *et al* 2002b: figure 12).

(Shergold *et al* 1985, Rawlings *et al* 2008) overlain by the Currant Bush Limestone. According to de Keyser (1969), it grades laterally into and interfingers with the Thorntonia Limestone, so is a lateral equivalent of this unit, at least in part. The formation comprises 30–180 m (Shergold and Druce 1980) of siliceous shale, siltstone, grey and black chertifed limestone (including bioclast floatstone and rudstone), irregularly bedded to nodular chert, chert breccia, chert conglomerate and a basal pebble conglomerate (Carter and Öpik 1961, Smith and Roberts 1963, McMahon 1969). Fossils reported from the formation, but as yet undocumented, include trilobites, molluscs, hyoliths and sponge spicules (Öpik 1960, Carter and Öpik 1961, de Keyser 1969); the trilobites are indicative of the early middle Cambrian (Ordian) stratigraphic sequence 1 (Southgate and Shergold 1991). A shallow-marine depositional environment has been interpreted for the formation (Rawlings *et al* 2008).

Currant Bush Limestone

The Currant Bush Limestone (Öpik 1956a, 1960) has a similar distribution to the Border Waterhole Formation along the northern margin of the Undilla Sub-basin, in eastern MOUNT DRUMMOND (NT), and in western LAWN HILL and western CAMOOWEAL (Queensland). The relationships of this formation to other units in the northern Georgina Basin are complicated and unclear. It is apparently conformable (Smith 1972) or disconformable (Shergold *et al* 1985, Rawlings *et al* 2008) on the Border Waterhole Formation, or unconformable on the Thorntonia Lst (Shergold *et al* 1985), or disconformable on the Gowers Formation (Southgate 1986). It also overlies and partially interfingers with the Age Creek Limestone and Inca Formation in Queensland (Shergold *et al* 1985). The formation is conformably overlain with a transitional contact (Rawlings *et al* 2008) by the Camooweal Dolostone and is also partially equivalent to this unit (Shergold *et al* 1985).

The Currant Bush Limestone mainly consists of bedded, partially dolomitised foetid argillaceous, quartzose and bioclast limestone (**Figure 28.21**) and dolomitic limestone, with interbeds of ooid grainstone, shale, siltstone, marl and chert, which occurs as discrete layers or irregular patches (Shergold *et al* 1985, Rawlings *et al* 2008). In eastern MOUNT DRUMMOND, limestone beds are composed of partially dolomitised, centimetre-scale, wavy- to nodular-bedded ribbon limestone (mainly bioclast floatstone). The formation is generally 50–75 m thick, but thickens eastward to 116 m in drillhole Morstone-1 in CAMOOWEAL (Stewart and Hoyling 1963). A shallow-marine, carbonate ramp depositional environment has been interpreted for the unit (Southgate and Shergold 1991, Rawlings *et al* 2008).

Figure 28.21. Currant Bush Limestone. Partly dolomitised grey/tan, wavy- to nodular-bedded bioclast floatstone (MOUNT DRUMMOND, CARRARA, 53K 815800mE 7935050mN, after Rawlings *et al* 2008, figure 58).

A very diverse fossil assemblage of trilobites, bradoriides, brachiopods, molluscs, cystoid echinoderms, sponge spicules, algae and hyoliths has been listed and described in numerous publications including Whitehouse (1936, 1939, 1945), Öpik (1956a, 1960, 1970, 1979, 1982), Carter and Öpik (1961), Jell (1975, 1977, 1978), Runnegar and Jell (1976), McKenzie and Jones (1979), Jones and McKenzie (1980), Henderson and MacKinnon (1981) and Rawlings *et al* (2008). Öpik (1956a) initially dated the formation as ranging from the Ptychagnostus (=Triplagnostus) gibbus to Ptychagnostus punctuosus trilobite zones (late Templetonian–early Undillan). Smith (1972) revised the age of the base of the formation to the slightly younger Ptychagnostus (=Acidusus) atavus zone (early Floran) and this was supported by Shergold *et al* (1985) and followed by Rawlings *et al* (2008). Shergold *et al* (1985) also revised the age of the top of the formation to the slightly younger Goniagnostus nathorsti trilobite zone (late Undillan). PA Jell (Geological Survey of Queensland, *in litt* 2011) has proposed that a late Templetonian age for the base of the formation may still be valid, since Shergold *et al* (1985) restricted their study to only a single section of the formation in the Thorntonia area (central CAMOOWEAL) and the initial age determination by Öpik (1956a), which is based on a more regional study, is yet to be discounted. Jell also queried the presence of a Goniagnostus nathorsti zone fauna within the formation and preferred a slightly older early Undillan date for the top of the unit. The formation is assigned to early sequence 2 of Southgate and Shergold (1991).

Barkly Group

Strata of the Barkly Group (Noakes and Traves 1954, modified by Kruse and Radke 2008) are widespread in the central and northern Georgina Basin within both the Undilla and Barkly sub-basins. The group encompasses all middle Cambrian sedimentary rocks in the central, western and northern Georgina Basin, exclusive of the Thorntonia Limestone (Narpa Group). Correlative middle Cambrian rock units in the southern and eastern Georgina Basin are included within the Narpa Group.

The Barkly Group is widely distributed in the NT in AVON DOWNS, RANKEN, MOUNT DRUMMOND, FREW RIVER, ALROY, BRUNETTE DOWNS, WALHALLOW, southern BAUHINIA DOWNS, northeastern BONNEY WELL, eastern TENNANT CREEK and HELEN SPRINGS. It is also known from the subsurface in BEETALOO, TANUMBIRINI and HODGSON DOWNS. In Queensland, the group occurs in western URANDANGI, western MOUNT ISA, western CAMOOWEAL and southwestern LAWN HILL.

Constituent units include the Gum Ridge Formation, Top Springs Limestone and Anthony Lagoon Formation (all Barkly Sub-basin); and the Wonarah Formation, Ranken Limestone and Camooweal Dolostone (all Undilla Sub-basin).

The Barkly Group unconformably overlies the early middle Cambrian Thorntonia Limestone (Narpa Group) in the Undilla Sub-basin. It also unconformably overlies the early Cambrian Helen Springs Volcanics (Kalkarindji Province), or where this is absent, the Mesoproterozoic Renner Group (Tomkinson Province) and correlative South Nicholson Group (South Nicholson Basin). The group is conformably overlain by the late Cambrian Arrinthrunga Formation (Narpa Group), or where this is absent, is unconformably overlain by Mesozoic rocks. It is (in part) correlated with and passes laterally into the Narpa Group, and is also correlated with the lower Goulburn Group of the Arafura Basin; the Daly River Group of the Daly Basin; the Montejinni Limestone, Hooker Creek Formation, Lothari Hill Sandstone and Point Wakefield beds of the Wiso Basin; the Goose Hole Group of the Ord Basin; the Tarrara Formation, Hart Spring Sandstone, Skewthorpe Formation and Pretlove Sandstone of the Bonaparte Basin; and the Pertaoorrta Group of the Amadeus Basin (in part).

All Barkly Group rocks are middle Cambrian in age and are included within stratigraphic sequences 1 and 2 of Southgate and Shergold (1991). The oldest strata are Ordian, based on the fossiliferous Gum Ridge Formation (Öpik in Ivanac 1954, Kruse 1998) and Top Springs Limestone (JW Smith 1964, Plumb and Rhodes 1964, Kruse 1991), whereas the youngest strata are putative latest middle Cambrian, based on the late Cambrian age of the conformably overlying Arrinthrunga Formation.

Gum Ridge Formation

The Gum Ridge Formation (Öpik in Ivanac 1954) outcrops discontinuously as low, rubble-covered plateaux and rises along the eastern margin of the exposed Tennant Region from HELEN SPRINGS southward through TENNANT CREEK and BONNEY WELL into western FREW RIVER. It also extensively underlies the Barkly Sub-basin in ALROY and BRUNETTE DOWNS, where it onlaps the western flank of the Alexandria-Wonarah Basement High (Kruse 2008). Exposures are commonly pervasively ferruginised and/or silicified to chert, which typically occurs as subequant rubble on or beside topographic highs. The formation disconformably overlies the Helen Springs Volcanics (Kalkarindji Province), or where these are absent, Mesoproterozoic siliciclastic sedimentary rocks of the Renner Group (Tomkinson Province) and equivalent South Nicholson Group (South Nicholson Basin), or Palaeoproterozoic sedimentary and igneous rocks. It is overlain with apparent conformity by the Anthony Lagoon Formation, or in the vicinity of the Alexandria-Wonarah Basement High, by the Wonarah Formation. The Gum Ridge Formation is likely to be continuous with the Top Springs Limestone of the northern Georgina Basin beneath Cretaceous cover in the central WALHALLOW subsurface and it is correlated with the Tindall and Montejinni limestones, respectively of the interconnected Daly and Wiso basins.

The Gum Ridge Formation comprises commonly partially dolomitised, massive, ribbon, bioclast, lithoclast and minor oncoid limestone, and minor cryptomicrobial dololaminite and siliciclastic mudstone. A thin (8–10 m) basal siltstone occurs in HELEN SPRINGS and a thin (1 m) basal conglomerate in eastern BRUNETTE DOWNS. Limestones may be laminated, massive or nodular, and feature stylolites, solution seams, spheroidal concretions, mottling and bioturbation. Evaporite nodules, including cauliflower anhydrite, and solution-collapse breccias occur throughout the formation. Drillhole data indicate a consistent thickness of 141–151 m for the Gum Ridge Formation across the Barkly Sub-basin (Kruse 1996), thinning to around 51 m on the western flank of the Alexandria-Wonarah Basement High (Kruse 2008). The formation contains a diverse fossil assemblage of trilobites, brachiopods, hyoliths, molluscs and an archaeocopide (Kruse 1998) that is indicative of middle Cambrian stratigraphic sequence 1 (Ordian) of Southgate and Shergold (1991). The environment of deposition is interpreted to be a restricted marine shelf, subject to episodic peritidal influence (Kruse *et al* 2010).

Top Springs Limestone

The Top Springs Limestone (Plumb and Rhodes 1963, 1964) outcrops on flat to undulating plains in southern BAUHINIA DOWNS and northern WALHALLOW, where it forms scattered to substantial exposures, characterised by karstic pavements with lapies, solution basins, towers and dolines. The formation is disconformably sandwiched between the Neoproterozoic Bukalara Sandstone below and Cretaceous rocks of the onshore Carpentaria Basin above. However, as it is a lateral equivalent of the Gum Ridge Formation of the central Georgina Basin, it is likely to be continuous with that unit beneath Cretaceous cover, and may therefore be conformably overlain by the Anthony Lagoon Formation in the central WALHALLOW subsurface. The formation comprises partially dolomitised, mottled bioclast, peloid and oncoid limestone, minor brecciated limestone and microbial laminite, and rare fenestral limestone (Kruse in Pietsch *et al* 1991, Kruse *et al* 2010). All limestone types are prone to patchy or fabric-selective silicification. Evaporite lenses, nodules and veins (mainly of anhydrite), and associated collapse breccias occur throughout the formation. A maximum thickness of 92 m is attained in the stratotype section in cored drillhole DD86SC2 in central-northern WALHALLOW (Colliver and Bubner 1987, Pietsch *et al* 1991, **Figure 28.14**). The limestone contains a fossil assemblage of trilobites, brachiopods, molluscs, sponges and a hyolith (Kruse 1991), indicative of the middle Cambrian (Ordian) stratigraphic sequence 1 of Southgate and Shergold (1991). A restricted marine shelf environment of deposition has been interpreted for the formation (Kruse *et al* 2010).

Anthony Lagoon Formation

The virtually unfossiliferous Anthony Lagoon Formation (Kruse *et al* 2010 after Plumb and Rhodes 1963, 1964) is a heterolithic carbonate-siliciclastic unit that outcrops poorly over much of the central and northern Georgina Basin (Barkly Sub-basin), including southern WALHALLOW, BRUNETTE DOWNS, ALROY, northeastern TENNANT

CREEK and HELEN SPRINGS. To the northwest, Howard (1990) tracked the unit beneath the Carpentaria Basin at least as far as northern BEETALOO and questionably into southern TANUMBIRINI. Exposures are typically subdued and consist of rubble tracts on undulating plains and low rises, and occasional cobble and boulder fields; sandstone intervals are locally ridge-forming or occur as subcrop beneath low hills. The formation overlies the Gum Ridge Formation and possibly the Top Springs Limestone with apparent conformity, and possibly directly overlies the Mittiebah Sandstone (South Nicholson Basin) with angular unconformity. It is unconformably overlain by flat-lying Cretaceous rocks, or where these are absent, by the Miocene Brunette Limestone. Correlative units include, in the central Georgina Basin (Alexandria-Wonarah Basement High and western Undilla Sub-basin), the Wonarah Formation; in the eastern Undilla Sub-basin, the Inca Formation, Gowers Formation, Beetle Creek Formation, Currant Bush Limestone and Blazan Shale; and in the southern Georgina Basin, the lower Arthur Creek Formation (Kruse and Radke 2008).

The Anthony Lagoon Formation is between 50 m and a maximum of 244.2 m in thickness. Comparison of cored drillholes across the sub-basin (NTGS96/1 in HELEN SPRINGS, BN04DD01 in western BRUNETTE DOWNS, NTGS02/1 in eastern BRUNETTE DOWNS; Kruse 1996, 2003, **Figure 28.14**) establishes that the formation is primarily a distinctive maroon dolomitic–siliciclastic siltstone interbedded with pale grey dolostone (**Figure 28.22a**). Dolomitic sandstone-siltstone interbeds and beds of quartz sandstone (**Figure 28.22b**) are also present, and nodular and bedded evaporite and siliceous (chert) concretions are common. Carbonate rock types include dolomudstone/dolosparstone, intraclast and oncoid dolostone, sucrosic dolostone, ooid dolograinstone and microbial dololaminite. The silt source was clearly to the west at the time of deposition: in NTGS96/1, the formation is almost entirely of maroon siltstone, whereas in BN04DD01 siltstone and dolostone are in subequal proportions, and in NTGS02/1 dolostone predominates, with only thin interbeds of maroon siltstone at the bases of metre-scale cycles (Kruse 2003, 2008). The easterly extent of maroon sediment has been mapped by Howard (1971, 1986), using drill core and waterbore data, and the unit appears to pass laterally into the Wonarah Formation on or about the western flank of the Alexandria-Wonarah Basement High. A striking similarity between the Anthony Lagoon Formation in drillhole NTGS96/1 and the Jinduckin Formation of the Daly Basin invites correlation, and the latter unit, together with the overlying Oolloo Dolostone in that basin, is now regarded as middle Cambrian in age (see **Daly Basin**). The depositional environment for the formation is interpreted to have been peritidal: a mixed carbonate-siliciclastic tidal flat subject to recurring supratidal exposure (Hussey *et al* 2001). The age of the formation is middle Cambrian and it is referred to stratigraphic sequence 2 of Southgate and Shergold (1991), based on its stratigraphic position overlying the Gum Ridge Formation (sequence 1), coupled with its lateral transition into the fossiliferous Wonarah Formation (latest Ordian–Templetonian; sequence 2), which likewise overlies sequence 1 units (Kruse 2008).

Wonarah Formation

The Wonarah Formation (Kruse in Kruse and Radke 2008, after Öpik 1956b) outcrops as low hills and plateau caps in the central Georgina Basin (Undilla Sub-basin and Alexandria-Wonarah Basement High), in AVON DOWNS, RANKEN, MOUNT DRUMMOND, FREW RIVER, ALROY and BRUNETTE DOWNS in the NT. It also possibly occurs in the subsurface in western URANDANGI, western MOUNT ISA, western CAMOOWEAL and southwestern LAWN HILL in Queensland. It is the only middle Cambrian unit known to mantle the Alexandria-Wonarah Basement High. The formation disconformably overlies the Gum Ridge Formation and Thorntonia Limestone, or where this is absent, unconformably overlies the Helen Springs Volcanics (Kalkarindji Province), or where this is absent, unconformably overlies the Mesoproterozoic Renner Group (Tomkinson Province) and correlative South Nicholson Group (South Nicholson Basin). The formation is conformably overlain by the Ranken Limestone and Camooweal Dolostone, and appears to pass laterally westward into the Anthony Lagoon Formation of the Barkly Sub-basin on or about the western flank of the Alexandria-Wonarah Basement High. The basal 3 m of this formation in drillhole NTGS01/1 (**Figure 28.14**) is a distinctive dark grey, finely carbonaceous, marly planar laminite bearing

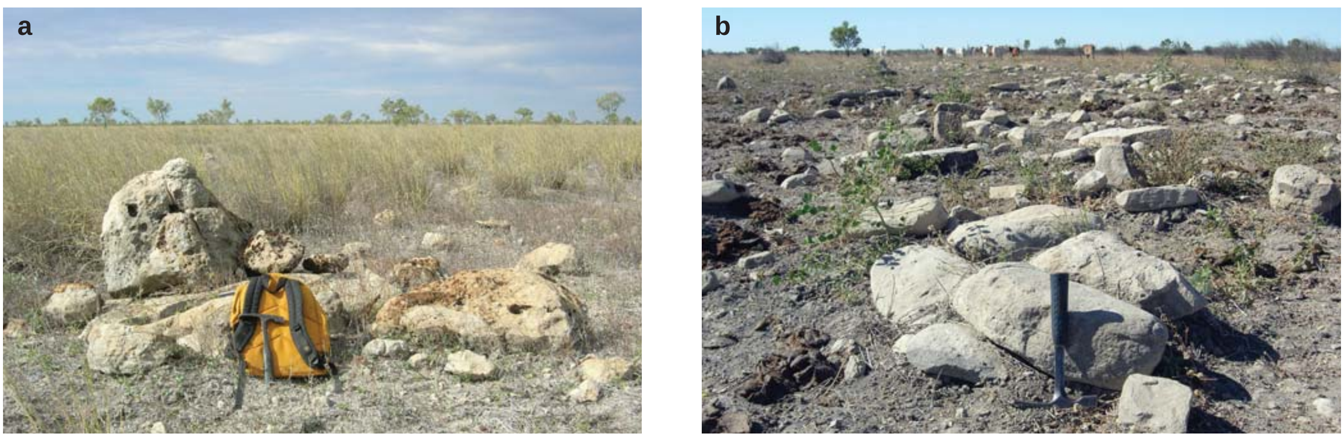


Figure 28.22. Anthony Lagoon Formation. (**a**) Boulders of light grey dolomudstone (BRUNETTE DOWNS, BRUNETTE 53K 576075mE 7934938mN, after Kruse *et al* 2010: figure 16). (**b**) Quartz sandstone boulder field (BRUNETTE DOWNS, ROCKHAMPTON DOWNS, 53K 551087mE 7920867mN, after Kruse *et al* 2010: figure 26).

Xystridura trilobites and draping an erosional surface of the Thorntonia Limestone. This interval confirms the lateral continuity of the formation with the more basinal lower Arthur Creek Formation of the southern Georgina Basin. Other correlative units include the Inca Formation, Gowers Formation, Beetle Creek Formation, Currant Bush Limestone and Blazan Shale of the Undilla Sub-basin (Kruse and Radke 2008, Kruse *et al* 2010).

The Wonarah Formation ranges in thickness from 118 m in BMR Cattle Creek-1 to greater than 191 m in NTGS00/1. It consists mostly of silty dolostone with calci/dolomudstone and siliciclastic mudstone interbeds (**Figure 28.23a**). These two principal lithotypes are intergradational, locally recrystallised to dolosparstone, and exhibit varying degrees of pressure solution 'boudinage' and possible bioturbation. Some dolostone intervals are stylobedded or stylonodular. Other lithotypes include local micaceous siltstone and minor intraclast and bioclast wacke- to grainstone. Early and late diagenetic dolomitic concretions, siliceous (chert) concretions and pyrite recur throughout the formation (Kruse and Radke 2008). Evaporites are locally present as nodular and vein-filling anhydrite or bedding-subparallel gypsum veins, as in basal beds of the formation in NTGS00/1 (Kruse *et al* 2010). At surface, carbonate rocks are typically extensively silicified (Rawlings *et al* 2008, Kruse and Radke 2008, **Figure 28.23b**). The Wonarah Formation has yielded a moderately diverse fauna [listed in Shergold *et al* (1985) and Kruse and Radke (2008)] that includes trilobites, bradoriides, brachiopods, hyoliths, molluscs and eocrinoids. These indicate a latest Ordian–?Floran (middle Cambrian) age (Gravestock and Shergold 2001, Laurie 2004), equivalent to early stratigraphic sequence 2 of Southgate and Shergold (1991). The depositional environment for the Wonarah Formation is interpreted as being subtidal platform marine (Kruse *et al* 2010).

Ranken Limestone

The Ranken Limestone (Öpik 1956a, b) forms scattered bouldery outcrops on grey-black clay-rich soil along the eastern flank of the Alexandria-Wonarah Basement High in the Undilla Sub-basin (central Georgina Basin), in northern AVON DOWNS, RANKEN and southern MOUNT DRUMMOND. The formation is conformable between the Wonarah Formation below and Camooweal Dolostone above, but is lenticular and also passes laterally into the Camooweal Dolostone. It is correlated with the Anthony Lagoon Formation of the Barkly Sub-basin; with the Age Creek Formation, Currant Bush Limestone,

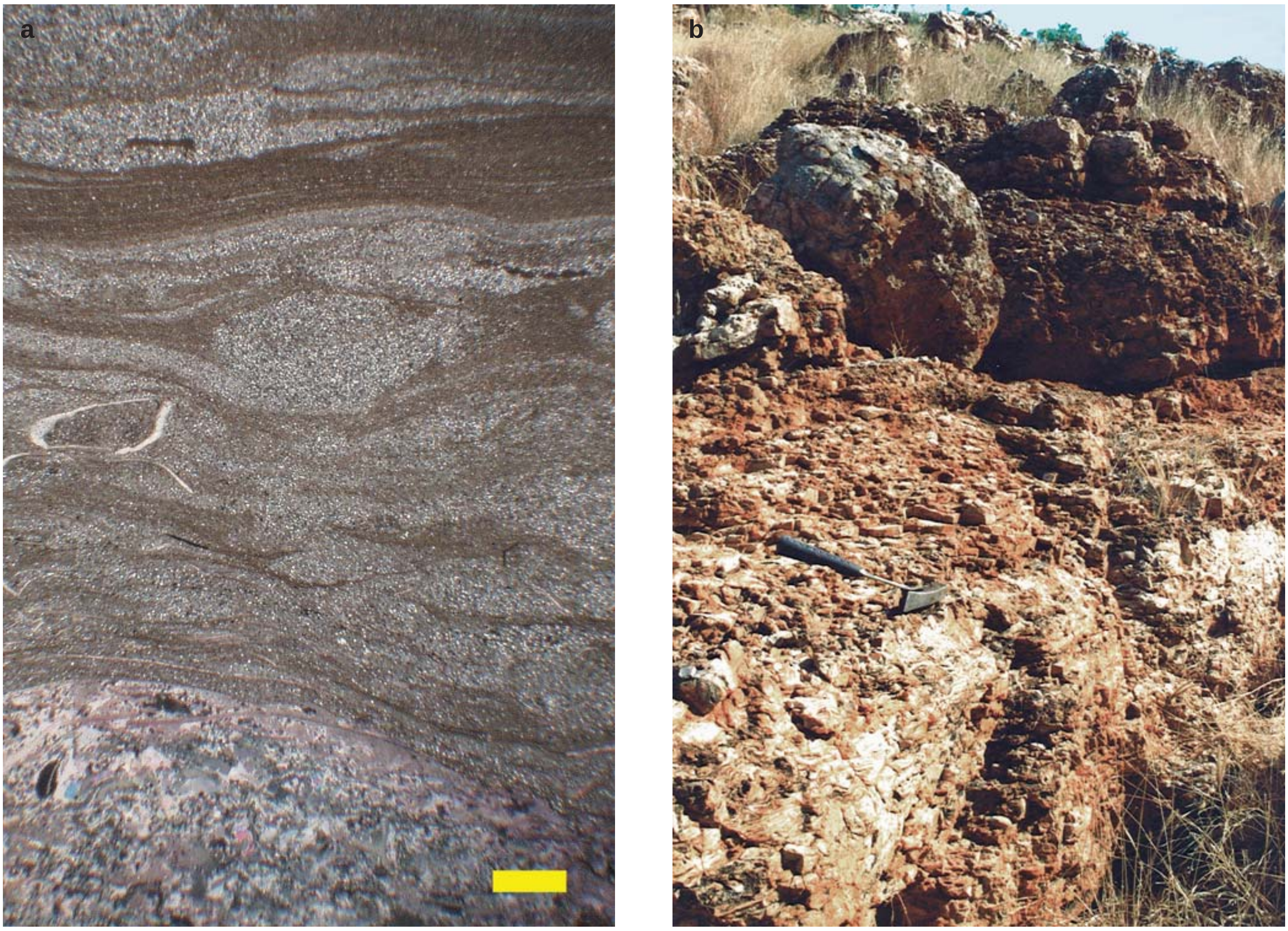


Figure 28.23. Wonarah Formation. (**a**) Light grey silty dolostone with pale laminations rich in angular to subangular, medium silt- to very fine sand-sized quartz, mica flakes and interstitial fine dolospar; interleaved with dark laminations rich in iron oxides ± clays, with finer silt-sized quartz and muscovite, and dolomicrospar. Bioclast rudstone (at bottom) of trilobites and hyoliths in coarse ferroan calcite spar cement. Scale bar = 2 mm (photomicrograph 00/1-37.3, stained with Alizarin red S and potassium ferricyanide, crossed nicols; RANKEN, RANKEN, 53K 691310mE 7802951mN, 37.3 m depth in drillhole NTGS00/1, after Kruse and Radke 2008, figure 8). (**b**) Outcrop of orange chertified mudstone capped by grey Cenozoic silcrete (AVON DOWNS, BARRY CAVES, 53K 678731mE 7782748mN, after Kruse and Radke 2008, figure 11).

V-Creek Limestone, Mail Change Limestone, Devoncourt Limestone and/or Roaring Siltstone of the Undilla Sub-basin in Queensland; and with the medial Arthur Creek Formation of the southern Georgina Basin (Kruse and Radke 2008).

Two principal lithofacies comprise the Ranken Limestone, which is at least 74 m thick in drillhole BMR GRG16 (Milligan 1963, **Figure 28.14**). The dominant lithofacies is a bioclast, bioclast-ooid and bioclast-intraclast rudstone, with bioclasts of hyoliths, trilobites and echinoderm plates, and occasional brachiopods and molluscs (**Figure 28.24a**). A subordinate low-energy lithofacies locally interdigitates with the rudstone and is a bioclast wacke/floatstone that features similar bioclasts in a calcimudstone matrix (**Figure 28.24b**). Other minor rock types are millimetre-scale interbeds of ribbon calcimudstone, flat-pebble conglomerate and calcimudstone with calcite-replaced evaporite nodules (Kruse and Radke 2008). The age of the formation is considered to be ?Floran to late Undillan or early Boomerangian (middle Cambrian), based on a poorly documented trilobite fauna (Öpik 1956b). The environment of deposition is interpreted to have been a marine ramp, where bioclast-rich debris accumulated under intermittent peritidal to low-energy marine conditions, subject to high-energy reworking. This was seaward of a high-energy shallow subtidal barrier represented by the lower interval of the Camooweal Dolostone. These deposits collectively denote a high-energy transition between the generally deeper (below wave-base) marine Wonarah Formation and the peritidal to epeiric back-barrier Camooweal Dolostone proper (Kruse and Radke 2008).

Camooweal Dolostone

The essentially unfossiliferous Camooweal Dolostone (Öpik 1954, 1956a) outcrops in the central and eastern Georgina Basin (Undilla Sub-basin) in AVON DOWNS, RANKEN and MOUNT DRUMMOND in the NT, and URANDANGI, MOUNT ISA, CAMOOWEAL and LAWN HILL in Queensland. It forms prominent hills to low rubbly outcrops, and is well exposed in dissected terrains, or expressed as disoriented boulders on clay-rich soil plains. Exposed Camooweal Dolostone commonly has been subjected to significant silicification. The formation is conformable above the Ranken Limestone, Wonarah Formation and Currant Bush Limestone, and is apparently conformable beneath the Arrinthrunga Formation (Rawlings *et al* 2008,

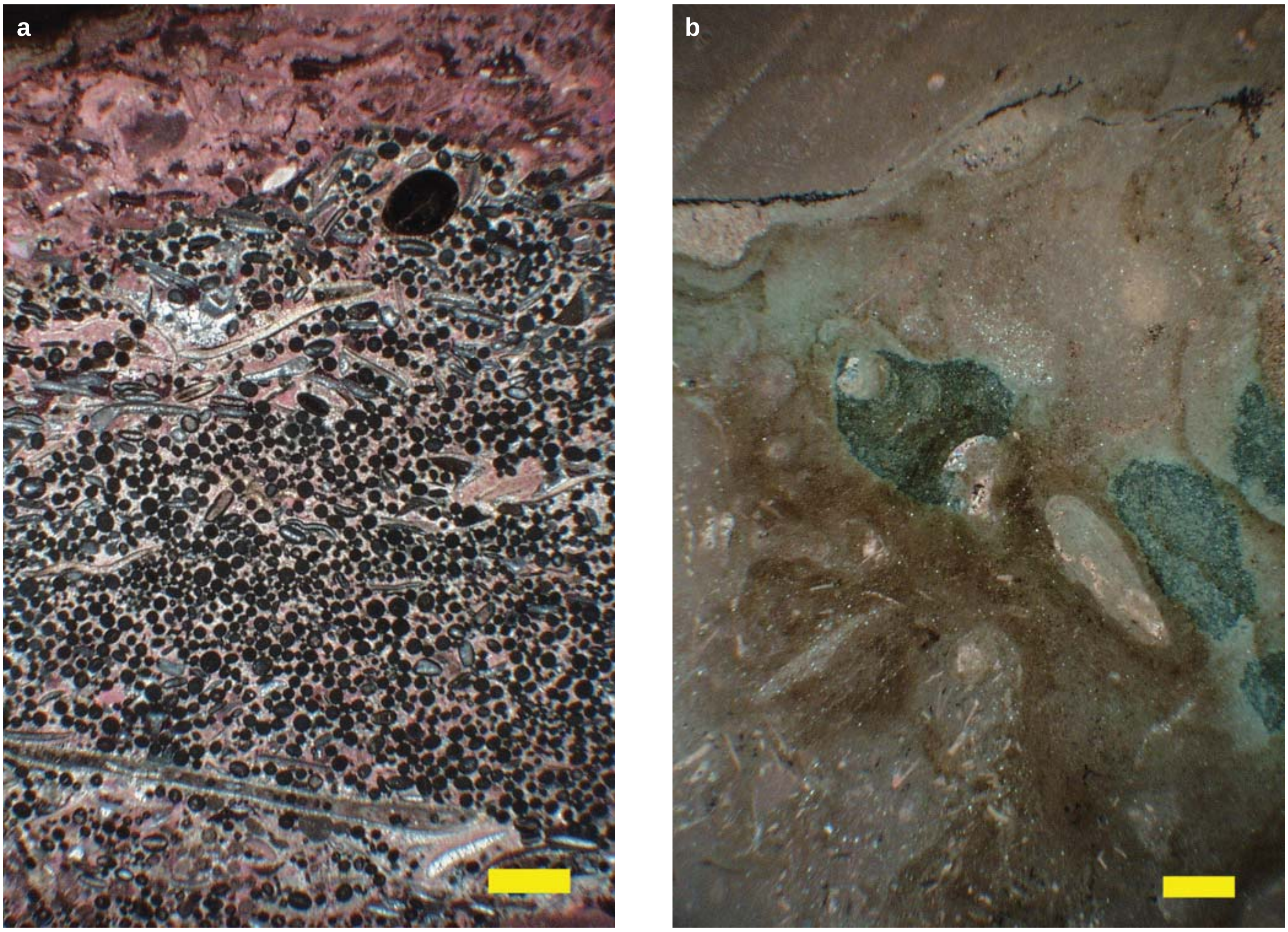


Figure 28.24. Ranken Limestone. (**a**) Light grey ooid-bioclast grainstone with grain-supported texture of ooids, trilobites and echinoderm plates; grains locally selectively silicified to chert + chalcedony ± megaquartz (black). Micrite envelopes around some bioclasts are also silicified. Scale bar = 2 mm (photomicrograph GRG16-90.0, stained with Alizarin red S and potassium ferricyanide, crossed nicols; RANKEN, Ranken, 53K 695550mE 7814006mN, 90.0 m depth in drillhole BMR GRG 16, after Kruse and Radke 2008, figure 12). (**b**) Light grey bioclast wackestone with tracts of trilobites, echinoderm plates, hyoliths, sponge spicules and minor angular to subrounded, medium silt- to very fine sand-sized detrital quartz in lime mud, now a microspar mosaic with interstitial iron oxides ± clays. Scale bar = 2 mm (photomicrograph RK001, stained with Alizarin red S and potassium ferricyanide, crossed nicols; RANKEN, Ranken, 53K 708543mE 7787880mN, after Kruse and Radke 2008, figure 13).

Kruse and Radke 2008). Laterally, it interdigitates to the east with the Age Creek Formation in CAMOOWEAL (Shergold *et al* 1985, Southgate and Shergold 1991) and it also passes laterally westward into the Ranken Limestone along the eastern flank of the Alexandria-Wonarah Basement High. Other correlative units include the V-Creek Limestone, Mail Change Limestone, Devoncourt Limestone and/or Roaring Siltstone of the Undilla Sub-basin in Queensland; and the upper Arthur Creek Formation of the southern Georgina Basin, which is likewise overlain by the Arrinthrunga Formation. It is also possibly correlated with the Anthony Lagoon Formation of the Barkly Sub-basin (Kruse and Radke 2008).

The formation consists of dolostone [including dolosparstone (**Figure 28.25**) and minor peloid and ooid dolostone], dolomitic limestone with nodular chert, minor marl, and basal high-energy rocks, including locally cross-bedded intraclast, ooid and oncoid dolostone and quartz sandstone. This lower interval is 73 m thick in cored drillhole NTGS01/1 (**Figure 28.14**) and thickens westward to the eastern flank of the Alexandria-Wonarah Basement High, where it also includes high-energy bioclastic sediments of the Ranken Limestone. The bulk of the formation consists of planar to crinkly microbial dololaminite, variably recrystallised to dolosparstone and bearing early diagenetic spheroidal and lobate chert nodules. Thin bands of intercalated dolomudstone may be desiccation-cracked or horizontally bioturbated. Local cross-beds and intraformational conglomerates denote brief higher-energy episodes within this generally lower-energy succession (Rawlings *et al* 2008, Kruse and Radke 2008). The Camooweal Dolostone is notionally 240–300 m thick (Shergold *et al* 1976), but is usually less than 200 m thick in drill intersections (Kruse and Radke 2008). Most of the formation was deposited under peritidal conditions in a restricted to epeiric back-barrier environment. The basal high-energy interval was probably a peritidal to shallow subtidal barrier between the generally below-wave-base marine Wonarah Formation to the west and the back-barrier Camooweal Dolostone proper to the east (Rawlings *et al* 2008). The age of the formation is interpreted to be latest Floran or early Boomerangian to notionally early Mindyallan (middle Cambrian). The lower age limit is based on its stratigraphic position above the fossiliferous Ranken Limestone and Wonarah Formation; the upper age limit is based on apparent conformity with the overlying unfossiliferous, but notionally late Cambrian Arrinthrunga Formation (Rawlings *et al* 2008, Kruse and Radke 2008). Southgate and Shergold (1991) limited the formation to the highstand systems tract of their middle Cambrian stratigraphic sequence 2 (ie late Templetonian/Floran or younger).

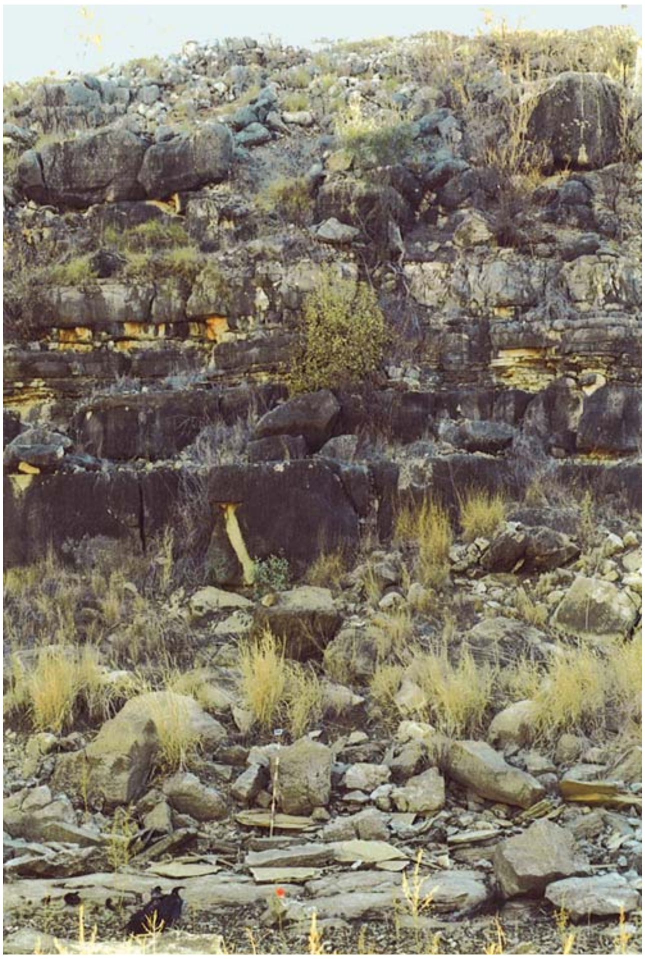


Figure 28.25. Camooweal Dolostone. Cliff section mainly of pale yellow dolosparstone with mid- to dark grey patina. Jacobs staff (at bottom) is 1.5 m long (RANKEN, GALLIPOLI, 53K 815016mE 7881750mN, after Kruse and Radke 2008, figure 23).

MEDIAL LATE CAMBRIAN–EARLY EARLY ORDOVICIAN

Cockroach Group

The Cockroach Group (Kruse in Dunster *et al* 2007) is widely distributed through the southern and eastern Georgina Basin in BARROW CREEK, ALCOOTA, ELKEDRA, HUCKITTA, SANDOVER RIVER, TOBERMOREY and HAY RIVER in the NT, and MOUNT WHELAN, GLENORMISTON, URANDANGI, BOULIA and DUCHESS in Queensland. The group is disconformable on various units of the Narpa Group and, in the NT, includes the Ninmaroo Formation and laterally interdigitating Tomahawk Formation. The depositional hiatus between these groups is represented in Queensland by the Chatsworth Limestone. Trilobites and conodonts in this formation indicate that the equivalent hiatus spans much of the Iverian and Payntonian stages of the late Cambrian/Furongian (Druce *et al* 1982, Shergold and Nicoll 1992). The Ninmaroo Formation denotes open to restricted marine and emergent evaporitic carbonate sedimentation on a broad epeiric platform extending into western Queensland. Deposition of this unit continued into the Warendan stage (equivalent to early part of international Tremadocian stage) of the Early Ordovician (Shergold and Nicoll 1992). Concomitantly, at least to end-Datsonian (end-Cambrian) time (Jones *et al* 1971, Shergold and Druce 1980), siliciclastic deposits of the Tomahawk Formation were introduced onto the platform from emergent land areas to the west, to interdigitate with the Ninmaroo Formation. The Swift Formation in Queensland is included in the group as it was regarded by Shergold *et al* (1976) and Druce *et al* (1982) to be a subaerial regolith discordant on the uppermost Ninmaroo Formation. The upper extent of the

Cockroach Group is therefore diachronous: late Warendan or Bendigonian (ie early Tremadocian or mid-Floian) atop Ninmaroo Formation–Swift Formation to the east, but latest late Cambrian (late Datsonian) atop Tomahawk Formation to the west (Shergold and Druce 1980, Jones *et al* 1971, Shergold and Nicoll 1992).

The Cockroach Group is conformably to locally disconformably overlain by the Kelly Creek Formation of the Toko Group, or where this is absent, is unconformably overlain by Mesozoic sedimentary rocks (Casey 1959, Shergold *et al* 1976, 1985). It is correlated with the Pacoota Sandstone 1–3 of the Amadeus Basin and possibly with the poorly dated Djagamara Formation of the Ngalia Basin (Webby *et al* 1981, Shergold *et al* 1985).

Ninmaroo Formation

The Ninmaroo Formation (Casey 1959 after Whitehouse 1936) forms extensive tracts of smoothly rounded hills to isolated low rises in southeastern SANDOVER RIVER, eastern TOBERMOREY and northeastern HAY RIVER in the NT, and south-central DUCHESS, central BOULIA (Burke River Structural Belt), northern MOUNT WHELAN, GLENORMISTON and southwestern URANDANGI in Queensland. Five formal constituent members are recognised in the type section in BOULIA (Shergold and Druce 1980), but these have not been identified in the NT (Kruse *et al* 2002a, b). The formation conformably overlies the Chatsworth Limestone in Queensland, or where this is absent, disconformably overlies the Arrinthrunga Formation (NT), or the Georgina or Mungerebar limestones (Queensland). It laterally interdigitates with the more westerly, sandstone-rich Tomahawk Formation, with the zone of interdigitation exposed in northern TOBERMOREY and southern SANDOVER RIVER (Kruse *et al* 2002a, b). The formation is conformably overlain by the Swift Formation in Queensland, or where this is absent, is conformably to locally disconformably overlain by the Kelly Creek Formation (Toko Group).

The Ninmaroo Formation consists of ooid, peloid, bioclast, intraclast, microbial and mixed-lithology limestone and dolostone (**Figure 28.26**), and minor quartz sandstone and conglomerate. Microbial carbonate rocks include microbial dololaminite, stromatolitic doloboundstone and stromatolitic biostromes. Sedimentary features include laminated and bioclast-rich beds, low-flow-regime parallel bedding, millimetre- to decimetre-scale low- to high-angle cross-beds (including bidirectional ripples), flat-pebble conglomerates, domical and columnar stromatolites, occasional ichnofossils, occasional synaeresis features and stylobeds (Kruse *et al* 2002a, b). Shoaling cycles have been described from within the Queensland succession (Radke 1980), but these have not been recognised in the NT. The thickness of the formation ranges from >58 m (incomplete) in Mulga-1 (SANDOVER RIVER) to >220 m (incomplete) in Owen-2 (TOBERMOREY), up to a maximum of 795 m in the type section. A diverse fossil fauna (listed by Dunster *et al* 2007) includes trilobites, conodonts, brachiopods, molluscs (including nautiloids, monoplacophorans, gastropods, a polyplacophoran and rostroconchs), echinoderms, calcimicrobes, domical, clavate and columnar stromatolites and ichnofossils, including horizontal trails or burrows and arthropod tracks. The conodonts indicate an age range for the formation from medial late Cambrian (mid-Payntonian) to earliest Early Ordovician (Warendan or early Tremadocian; Shergold and Nicoll 1992). The depositional environment is interpreted to have been a broad epeiric marine platform under normal open-marine to restricted and emergent evaporitic conditions, subject to recurring high-energy episodes (Radke 1980, 1981, in Druce *et al* 1982).

Tomahawk Formation

The Tomahawk Formation (Kruse in Dunster *et al* 2007, after KG Smith 1964) outcrops as contiguous tracts of hilly country, or isolated low to moderate hills, or prominent ridges. It flanks the Dulcie Range in eastern BARROW CREEK, northeastern ALCOOTA, southwestern ELKEDRA and northwestern HUCKITTA, and is extensive northward of the Tarlton Range in eastern HUCKITTA, southeastern ELKEDRA, western TOBERMOREY and southwestern SANDOVER RIVER. The formation is disconformable on the Arrinthrunga Formation and is conformably overlain by the Kelly Creek Formation. It laterally interdigitates with the more easterly, carbonate-rich Ninmaroo Formation in northern TOBERMOREY and southern SANDOVER RIVER (Kruse *et al* 2002a, b).

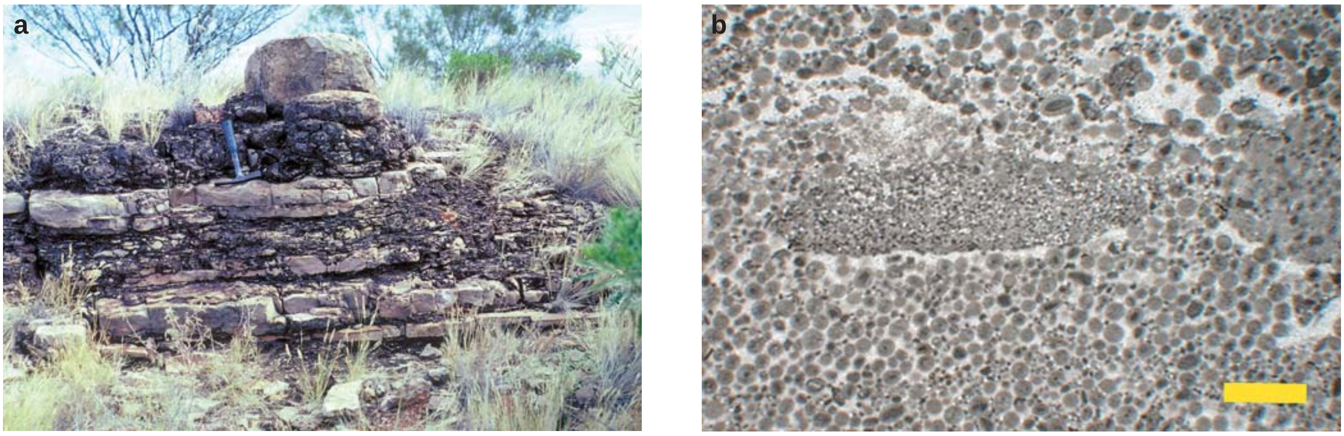


Figure 28.26. Ninmaroo Formation. (**a**) Outcrop of interbedded dolostone and dolomitic quartz sandstone. SANDOVER RIVER, GORDON CREEK, QR299707, after Kruse *et al* 2002b, figure 22). (**b**) Ooid dolograinstone with reworked ooid dolograinstone pebbles. Scale bar = 2 mm. Photomicrograph C75139, plane polarised light, SANDOVER RIVER, GORDON CREEK, 53K 713100mE 7579300mN, after Kruse *et al* 2002b, figure 20).

The Tomahawk Formation is dominated by fine to medium (to coarse), locally dolomitic, glauconite-bearing quartz sandstone (**Figure 28.27**) with minor quartz wacke, subarkose and sublithic sandstone, plus thin interbeds of conglomerate, micaceous siltstone and shale. The dominant sandstone bears horizontal planar lamination, cross-beds (including solitary and festoon sets and rare herringbone cross-beds), ripples, synaeresis features, mud pebble moulds, current markings, wrinkle marks and tabular sandstone intraclast beds (Kruse *et al* 2002a, b). Dolostone interbeds are also developed within the formation, particularly towards the top. These are westerly continuations of Ninmaroo Formation carbonate facies in the zone of interdigitation between these two units that have been included within the Tomahawk Formation. Dolostones are generally recrystallised to dolosparstone or dolomicrosparestone and original depositional textures are rarely preserved; finely laminated dolomudstone also occurs. The thickness of the formation is in the range 150–190 m; 149 m was intersected in the type section in NTGS Elkedra-6 (Kruse *et al* 2002a). A moderately diverse fossil assemblage (listed by Dunster *et al* 2007) of trilobites, conodonts, brachiopods, hyoliths, molluscs (including pelecypods, nautiloids, gastropods and rostroconchs), echinoderms, possible sponge spicules, columnar stromatolites and ichnofossils occurs within the formation. Trilobites and rostroconchs in the basal beds (Casey and Gilbert-Tomlinson 1956, Jones *et al* 1971, Pojeta *et al* 1977) indicate a medial late Cambrian (Iverian or Payntonian) age. Conodonts suggest a probably latest late Cambrian age (Shergold and Druce 1980, Jones

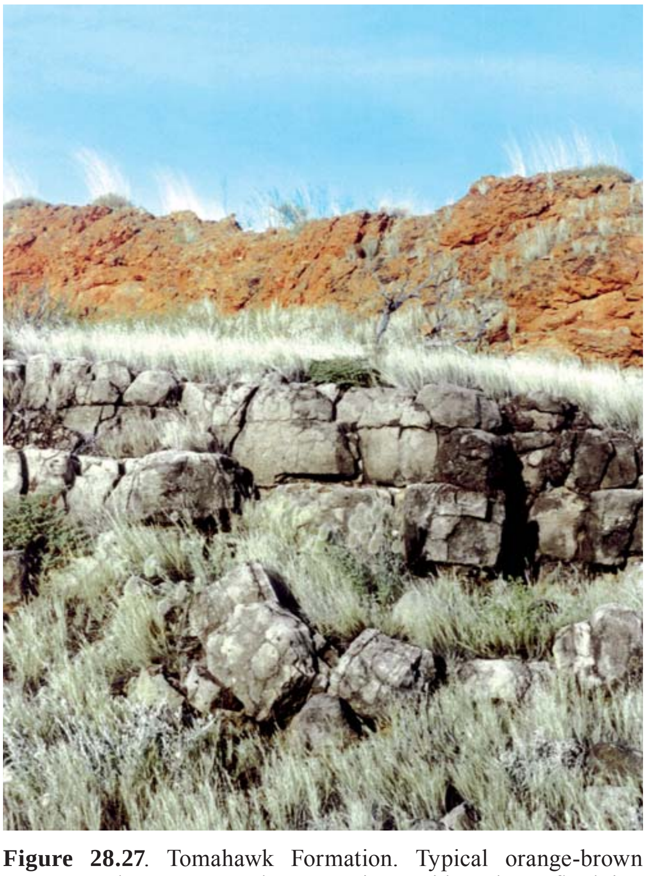


Figure 28.27. Tomahawk Formation. Typical orange-brown quartz sandstone exposed as prominent ridge above flat-lying yellow-grey dolostone interbed. Dolostone ledge is about 1 m high. SANDOVER RIVER, ARGADARGADA, 53K 679200mE 7574100mN, after Kruse *et al* 2002b, figure 13).

et al 1971, Shergold and Nicoll 1992) for the uppermost beds. A putative Early Ordovician fauna listed from the Tomahawk Formation by Laurie (2000) is stratigraphically below an uppermost Tomahawk Formation limestone bearing Datsonian conodonts. The Tomahawk Formation represents the episodic shedding of terrigenous sand from exposed Aileron or Davenport province basement rocks in the present west. It was deposited in littoral to sublittoral conditions extending for a considerable distance offshore on a broad marine platform within restricted to open-marine waters. It was locally subject to reversing tidal currents, but extended into moderately deep settings above storm wave base (Brakel in Kruse *et al* 2002a).

ORDOVICIAN

Toko Group

The Toko Group (Casey in Smith 1963a after Whitehouse 1936) forms scarps, plateaux and hills in the southern Georgina Basin in eastern BARROW CREEK, northeastern ALCOOTA, southwestern ELKEDRA, northern HUCKITTA, southern TOBERMORY and northeastern HAY RIVER in the NT, and western GLENORMISTON and MOUNT WHELAN in Queensland. Only the lower units of the group are exposed in more westerly areas, whereas the entire group is exposed to the east. The group conformably overlies the Tomahawk Formation and conformably to locally disconformably (Reynolds 1968, Jones *et al* 1971) overlies the Ninmaroo Formation (both Cockroach Group), or where these are absent, unconformably overlies the Georgina Limestone (Narpa Group). It is unconformably overlain by the Cravens Peak beds (Devonian) or where these are absent, by Mesozoic sedimentary rocks. Constituent units, in ascending stratigraphic order, include the Kelly Creek Formation, Coolibah Formation, Nora Formation, Carlo Sandstone, Mithaka Formation and Ethabuka Sandstone. These attain a combined maximum known thickness of 1678 m in AOD Ethabuka-1 (MOUNT WHELAN; Mulready 1975, modified by Draper 1980), although the upper part may have been eroded. The Toko Group spans the Early to Late Ordovician and is correlated with the Pacoota Sandstone 4, Horn Valley Siltstone, Stairway Sandstone, Stokes Siltstone and Carmichael Sandstone of the Amadeus Basin; possibly with the poorly dated Djagamara Formation and Kerridy Sandstone of the Ngalia Basin; Hanson River beds of the Wiso Basin (Webby *et al* 1981, Shergold *et al* 1985); and Florina Formation of the Daly Basin.

Kelly Creek Formation

The Kelly Creek Formation (Casey in Smith 1965) forms prominent hills, scarps and dissected plateaux within the Tarlton and Toko ranges in HUCKITTA, ELKEDRA, BARROW CREEK, ALCOOTA and TOBERMOREY in the NT, and southwestern GLENORMISTON and northwestern MOUNT WHELAN in Queensland. It also occurs in the subsurface in southwestern and south-central MOUNT WHELAN. The formation conformably overlies the Tomahawk Formation in the west and conformably to locally disconformably overlies the Ninmaroo Formation further to the east in GLENORMISTON and MOUNT WHELAN (Reynolds 1968, Jones *et al* 1971), or where this formation is absent, unconformably overlies the Georgina Limestone. It is conformably overlain by the Coolibah Formation, or where this is absent, by the Nora Formation.

The Kelly Creek Formation is a resistant unit that can be divided into informal lower and upper portions. The lower portion comprises calcareous and dolomitic quartz-lithic and quartz ± glauconite sandstone, intraclast-lithoclast-bioclast dolostone, siltstone, and minor conglomerate and coquinite. The upper portion consists of quartzose to sucrosic dolostone, dolomitic quartz sandstone, dolomudstone, quartzose dolomitic limestone and minor conglomerate. In general, the proportion of carbonate within the formation diminishes westward (Dunster *et al* 2007). Sedimentary structures include streaming lineations, thin flat-pebble intraclast, mud pebble and mud cobble intervals, symmetric to asymmetric linear, linguoid and interference ripples, low- to high-angle cross-beds (including bidirectional to herringbone types), bioclast-bearing granule beds, microbial lamination (in dolostone), local synaeresis features and ichnofossils (Kruse *et al* 2002a). The formation is 92 m thick in TOBERMOREY (Kruse *et al* 2002a), but thickens to the east to a maximum of 290 m in drillhole AOD Mirrica-1 in MOUNT WHELAN (Gausden 1980). A sparse fossil assemblage includes rare trilobites and brachiopods, molluscs including gastropods and endoceratid nautiloids, conodonts and ichnofossils (**Figure 28.28**). The conodont faunas suggest an age of early Early Ordovician (early Warendan to early Floian; Druce in Shergold 1979a, revised according to Shergold and Nicoll 1992). Jones *et al* (1971) also reported late late Cambrian (late Datsonian) conodonts for the basal Kelly Creek Formation, but it is likely that the sampled interval is a part of the underlying Ninmaroo Formation (Radke 1981, Shergold 1985, Nicholl *et al* 1992). A peritidal to unrestricted open-marine depositional environment has been interpreted for the formation (Shergold and Druce 1980).

Coolibah Formation

The Coolibah Formation (Casey in Smith 1965) is poorly exposed in low hills and ridges (Smith 1972) and contiguous terraced tracts around the Toko Syncline in TOBERMOREY and HAY RIVER in the NT, and GLENORMISTON and MOUNT WHELAN in Queensland. It conformably to disconformably overlies the Kelly Creek Formation and is conformably overlain by the Nora Formation, but as both the lower and upper contacts are diachronous (Stait and Druce 1993), the formation might also be partially equivalent to the uppermost and lowermost beds of these formations respectively. The Coolibah Formation consists of limestone (**Figure 28.29**), quartzose limestone, dolostone, marl and local lenticular chert, with a basal interval of sandstone, conglomerate or silicified microbial boundstone (Kruse *et al* 2002a). Its thickness ranges from as little as 7.5 m in the type area in southeastern TOBERMOREY (Stait and Druce 1993) up to 110 m in MOUNT WHELAN (Smith 1972). A varied fossil fauna of trilobites, an ostracode, conodonts, brachiopods, molluscs (nautiloids, pelecypods, gastropods, rostroconchs), sponges, algae, acritarchs, a cyanobacterium and fish is listed by Dunster *et al* (2007). Conodonts indicate a Lower Ordovician (mid- to late Floian) age for the formation (Stait and Druce 1993). The depositional environment is interpreted to have been intertidal to shallow-subtidal marine with fluctuating energy conditions (Shergold *et al* 1976).

Nora Formation

The Nora Formation (Casey in Smith 1963a) is a recessive unit, poorly exposed in plateau scarps that are generally covered by scree of the overlying cap rock of Carlo Sandstone. It outcrops along the eastern Dulcie Range in HUCKITTA, Tarlton Range in western TOBERMOREY, and Toko Range in eastern TOBERMOREY, northeastern HAY RIVER, western GLENORMISTON and western MOUNT WHELAN. The formation conformably overlies the Coolibah Formation and Kelly Creek Formation, and might also be partially equivalent to the uppermost beds of the former (Stait and Druce 1993). It is conformably overlain by the Carlo Sandstone, or where this is absent, is unconformably overlain by the Dulcie Sandstone. The Nora Formation consists of thinly bedded, micaceous and glauconitic siltstone, claystone, fine sandstone and minor dolostone, with a basal bioclast

Figure 28.28. Kelly Creek Formation. *Cruziana* and *Rusophycus* ichnofossils on sole of medium-grained quartz sandstone bed (TOBERMOREY, Tarlton, 53K 688600mE 7465800mN, after Kruse *et al* 2002a, figure 35).

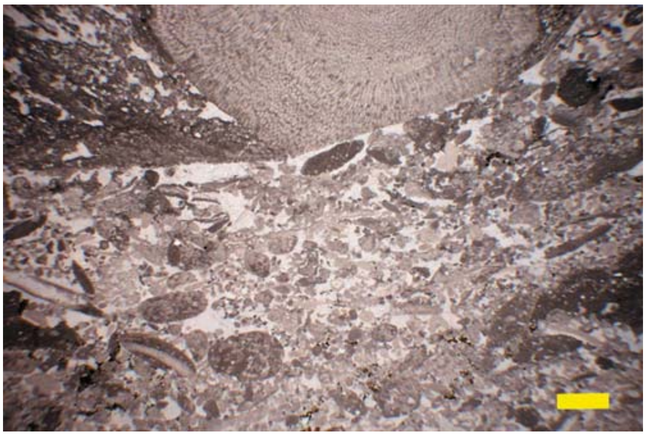


Figure 28.29. Coolibah Formation. Intraclast bioclast grainstone-rudstone of intraclasts, echinoderm ossicles and trilobites in coarse calcite spar. Intraclasts include reworked calcimudstone and bioclast grainstone with trilobites, echinoderm ossicles, bryozoans (top centre) and pelecypods or ostracodes. Scale bar = 2 mm (photomicrograph C75154, plane polarised light, TOBERMOREY, Toko, 53K 776500mE 7490600mN, after Kruse *et al* 2002a, figure 38).

grainstone-rudstone (**Figure 28.30**). Some siliciclastic units are rippled and cross-laminated (Shergold and Druce 1980). The formation is 42 m thick in TOBERMOREY, but thickens considerably to the southeast to reach a maximum thickness of 250 m in MOUNT WHELAN. The lower part of the unit is richly fossiliferous and contains trilobites, ostracodes, conodonts, brachiopods, molluscs (nautiloids, gastropods, rostroconchs, pelecypods), echinoderms, bryozoans, sponges, corals, fish remains, questionable foraminifers and ichnofossils (listed by Dunster *et al* 2007), consistent with a mid-late Arenig age (Shergold *et al* 1976; equivalent to Floian to Dapingian or early Darriwilian). The upper part of the formation contains fewer body fossils, but does contain some ichnofossils. Shergold *et al* (1976) and Shergold and Druce (1980) interpreted an intertidal to low-energy, shallow subtidal marine environment for the formation, with the coarser basal interval representing an offshore bar. In contrast, Draper (1977) interpreted an offshore, below-wave-base setting for the entire formation.

Carlo Sandstone

The Carlo Sandstone (Casey in Smith 1963a) is a resistant sandstone unit that caps the Tarlton and Toko ranges in TOBERMOREY, HAY RIVER, GLENORMISTON and MOUNT WHELAN. It conformably and gradationally overlies the Nora Formation, and is conformably and gradationally overlain by the Mithaka Formation, or where this is absent, is unconformably overlain by the Cravens Peak beds. The formation consists of medium to thick beds of fine to medium quartz sandstone, and minor feldspathic sandstone and siltstone. Characteristic current features include streaming lineations, flute casts, thick cross-bed sets and ripples. A prominent clay-pellet bed forms the base of the formation. The Carlo Sandstone is 22 m thick in southwestern TOBERMOREY (Kruse *et al* 2002a), but thickens considerably to the southeast to reach a maximum thickness of 174 m (or 190 m; Draper 1977) in Ethabuka-1 in MOUNT WHELAN (Mulready 1975). Body fossils (listed by Dunster *et al* 2007) are sparse and are mainly found toward the base and top of the formation; they include molluscs (nautiloids, rostroconchs, gastropods, pelecypods), brachiopods, conodonts and fish. In contrast, ichnofossils are relatively common and diverse throughout (**Figure 28.31**). An Middle-Late Ordovician (Darriwilian to Sandbian) age is indicated for the Carlo Sandstone from its conformable position beneath the Mithaka Formation, which contains a relatively well dated Late Ordovician conodont fauna (Kuhn and Barnes 2005). Shergold *et al* (1976) interpreted a shallow littoral depositional environment for the formation in a shoaling or barrier island setting. Draper (1977) subsequently developed a high-energy barrier depositional model with barrier island, flat and bay subfacies.

Figure 28.30. Nora Formation. Basal ferruginous echinoderm grainstone-rudstone bed with echinoderm plates and minor gastropods, nautiloids, trilobites and possible brachiopod fragments. Scale bar = 2 mm (photomicrograph C75155, plane polarised light, TOBERMOREY, Toko, 53K 776500mE 7490600mN, after Kruse *et al* 2002a, figure 39).

Mithaka Formation

The recessive Mithaka Formation (Casey in Smith 1963a) is poorly exposed in the Tarlton and Toko ranges in TOBERMOREY, HAY RIVER, GLENORMISTON and MOUNT WHELAN. It conformably and gradationally overlies the Carlo Sandstone and is conformably and gradationally overlain by the Ethabuka Sandstone, or where this is absent, is unconformably overlain by the Cravens Peak beds. The formation consists of thinly bedded gypsiferous shale, calcareous siltstone, minor calcareous, glauconitic and micaceous quartz sandstone, and minor coquinite and granule conglomerate. The formation ranges in thickness from 20 m up to 120 m in the Tarlton and Toko ranges respectively (Smith 1965, 1972), and reaches a maximum thickness of 156 m in drillhole Mirrica-1 (MOUNT WHELAN; Gausden 1980). It contains a mostly undescribed fossil fauna (listed by Dunster *et al* 2007) of trilobites, ostracodes, conodonts, brachiopods, molluscs (nautiloids, gastropods, pelecypods), bryozoans, sponges, receptaculitaleans, probable echinoderms, conodonts, fish, a chitinozoan and ichnofossils. Conodonts indicate a Late Ordovician (late Gisbornian, equivalent to Sandbian and/or Katian) age (Kuhn and Barnes 2005). The depositional environment was probably a low-energy marine lagoon with limited tidal range, inshore of a high-energy barrier of Carlo Sandstone (Draper 1977), or alternatively, a more open shallow subtidal setting is possible (Kuhn and Barnes 2005).

Ethabuka Sandstone

The Ethabuka Sandstone (Draper 1980 after Mulready 1975) forms prominent ridges and uplands in the Toko Range in TOBERMOREY, HAY RIVER, GLENORMISTON and

Figure 28.31. Carlo Sandstone. Arthropod scratch marks on sole of medium quartz sandstone bed. Pen is 13.5 cm long (TOBERMOREY, Tarlton, 53K 683900mE 7496300mN, after Kruse *et al* 2002a, figure 40).

MOUNT WHELAN. It conformably and gradationally overlies the Mithaka Formation and is unconformably overlain by the Cravens Peak beds, or where these are absent, by the Jurassic Hooray Sandstone (Eromanga Basin, Queensland). The formation is 1147 m thick in the type section in drillhole Ethabuka-1 in MOUNT WHELAN in Queensland (Mulready 1975, Draper 1980), where it has been subdivided into four informal subunits. In the NT, only about 35 m of the lowest subunit is exposed within the axial Toko Syncline as an escarpment around the junction of TOBERMOREY, HAY RIVER and GLENORMISTON (Shergold *et al* 1976). There, the formation consists of sublabile to quartzic sandstone with minor siltstone and claystone interbeds, and rare conglomerate. The thinly to medium-bedded sandstone bears clay pellets, cross-laminations, asymmetric linguoid and interference ripples, load casts, parting and streaming lineations, flute casts and other current structures, and minor phosphate pellet conglomerate, flaser bedding and ichnofossils (Kruse *et al* 2002a). An undescribed fossil fauna comprises trilobites, brachiopods, molluscs (nautiloids, gastropods, pelecypods) and ichnofossils. The age of the formation is probably medial Late Ordovician from its conformable stratigraphic position above the Mithaka Formation, which has yielded a late Gisbornian (Sandbian and/or Katian) conodont fauna (Kuhn and Barnes 2005). The depositional environment is interpreted (Draper 1977, 1980) to have been a high-energy shallow-marine barrier, but with bioturbated intervals also indicating subordinate lower-energy subtidal conditions. Haines *et al* (2001) considered that this unit was possibly generated as a result of the Rodingan Event (Wells *et al* 1970) in the Late Ordovician, regarded as the earliest episode of the 450–300 Ma Alice Springs Orogeny. This event evidently terminated Ordovician sedimentation in the basin.

DEVONIAN

After deposition of the Ordovician Toko Group, no further sedimentation took place in the Georgina Basin until the mid-Devonian, when the Pertnjara–Brewer events of the Alice Springs Orogeny instigated deposition of synorogenic siliciclastic sediments of the Dulcie Sandstone in the Dulcie Syncline, and the Cravens Peak beds in the Toko Syncline of the southern Georgina Basin. These units are the youngest sedimentary deposits within the basin.

Dulcie Sandstone

The Dulcie Sandstone (KG Smith 1964 after Joklik 1955) outcrops in the Dulcie Syncline in western HUCKITTA, southwestern ELKEDRA, northeastern ALCOOTA and southeastern BARROW CREEK. It forms prominent cliff-forming caps and scarps atop the southeastern and central Dulcie Range, with outcrops becoming lower and more discontinuous in the northwestern Dulcie Range. The formation is a correlative of the Cravens Peak beds of the southeastern Georgina Basin, and unconformably overlies the Nora Formation, or where this is absent, the Kelly Creek Formation. There is no overlying unit. The Dulcie Sandstone ranges in thickness from about 450 m up to a maximum of 650 m, and consists of prominently cross-bedded, medium- to thickly bedded quartz sandstone, with rare beds of silty calcareous sandstone and pebble conglomerate (Freeman 1986). It contains an Early–Middle Devonian (Pragian–early Eifelian) fish fauna (Young and Goujet 2003) and rare ichnofossils (Freeman 1986). Hills (1959) interpreted a continental aeolian and braided fluviatile depositional environment for the formation.

Cravens Peak beds

Strata of the Cravens Peak beds (Reynolds in Smith 1965) are distributed around the Toko Syncline along the Toomba and Toko ranges in HAY RIVER, MOUNT WHELAN, GLENORMISTON and southeastern TOBERMOREY. The unit is well exposed as strike ridges or steep cuestas along the Toomba Range, particularly in Queensland, but is generally less well exposed elsewhere as low, rubble-covered rises or low dip slopes (Reynolds 1968, Smith 1972). The formation is a correlative of the Dulcie Sandstone of the southwestern Georgina Basin, and unconformably overlies the Ethabuka Sandstone, or where this is absent, the Mithaka Formation or Carlo Sandstone. It is unconformably overlain by Mesozoic sedimentary rocks of the Eromanga Basin. The unit is at least 280 m thick (Shergold 1985) and is informally divided into a lower interval of calcareous siltstone, calcareous sandstone, limestone and minor conglomerate, and an upper interval of cross-bedded, fine- to medium-grained quartz sandstone with clay pellets, and conglomerate. It contains a fossil assemblage (listed by Dunster *et al* 2007) of ostracodes, fish, a plant and stromatolites; the fish fauna indicates an Early–Middle Devonian (Pragian–early Eifelian) age (Young and Goujet 2003). The depositional environment is interpreted to have been initially shallow subtidal to marginal/shoreface marine, passing via offshore sandbar and beach facies into non-marine braided fluviatile settings (Hills 1959, Draper in Turner *et al* 1981).

STRUCTURE

Most deformation visible in outcrop of the Georgina Basin is related to folding and faulting that occurred during the Late Ordovician to Carboniferous Alice Springs Orogeny. However, most of the significant faults in the southern Georgina Basin were initiated in Neoproterozoic time as normal faults marginal to large-scale northwest-trending intracontinental rifts; these were subsequently reactivated as high-angle reverse faults in the Palaeozoic (Zhao *et al* 1994, Greene 2003, 2010). In the central and northern Georgina Basin, much of the succession is little deformed and is flat-lying to gently folded.

Tectonic setting

Neoproterozoic

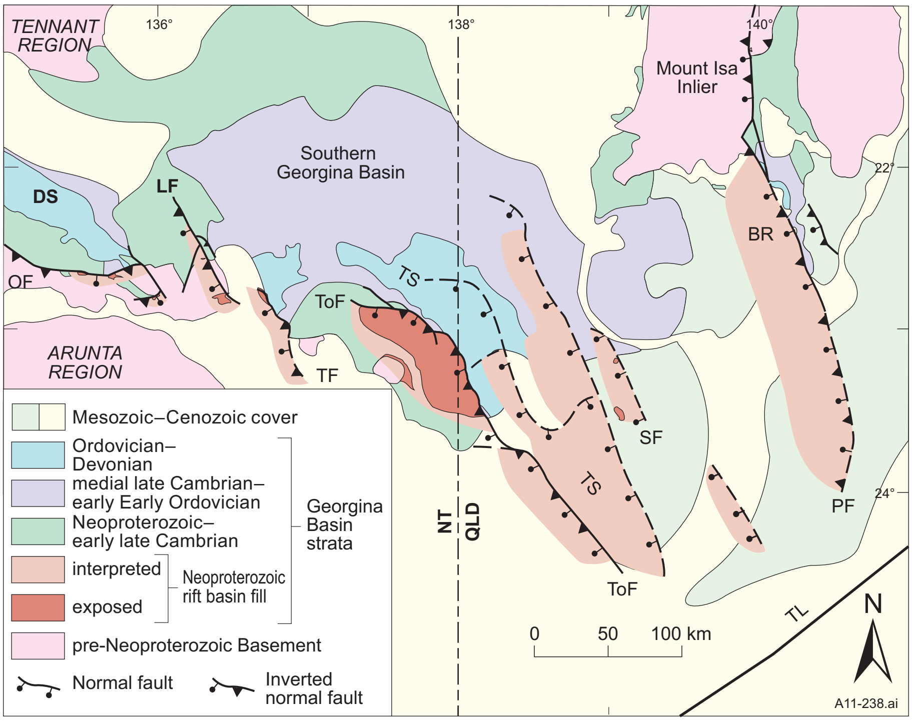
Neoproterozoic deposits of the Plenty Group in the southern Georgina Basin form the distal edge of a regionally widespread, southwestward-thickening, shallow-marine siliciclastic succession that was deposited on a low-relief basement surface as a part of Supersequence 1 of a broad intracratonic sag basin (Centralian A Superbasin; Walter *et al* 1980, see **Centralian Superbasin**). Walter *et al* (1995) noted that these sedimentary rocks thin out against basement highs in the southern part of the basin. Overlying Neoproterozoic successions were deposited in a series of northwest-striking rift basins that underlie Palaeozoic strata of the basin (**Figure 28.32**). Rift basin successions indicate two major periods of extension (Greene 2010): a major rift-forming episode coeval with deposition of the late Cryogenian Supersequence 2 and a second episode of extension coeval with deposition of the Ediacaran Supersequence 3. Deposits of the late Ediacaran Supersequence 4 and the lower portion of the early Cambrian Shadow Group (pre-Red Heart Dolostone) are interpreted as having been deposited in a distal foreland-sag setting, related to the 580–530 Ma late Neoproterozoic Petermann Orogeny, which mainly affected the Musgrave Province to the southwest (Dunster *et al* 2007).

The Neoproterozoic succession has been subjected to at least four tectonic movements of varying intensities (**Figure 28.6**). The mid-Cryogenian *Areyonga Movement*, which resulted in folding and faulting of Supersequence 1 rocks elsewhere in the Centralian A Superbasin (eg Wells *et al* 1970, Apak *et al* 2002), corresponds to a lengthy hiatus of possibly as much as 100 million years in the southern Georgina Basin prior to deposition of Supersequence 2 (Aroota Group). The late Cryogenian *Rinkabeena Movement* (Wells and Moss 1983), which equates to a disconformity in the Ngalia Basin succession, was extended to the corresponding disconformity between the Aroota Group (Supersequence 2) and Keepera Group (Supersequence 3) by Walter (1980). Walter further invoked the *Toomba Movement* to account for a local angular unconformity between elements of the Keepera and Mopunga groups, accompanied by a thick wedge of arkose (Gnallan-a-Gea Arkose). This movement was probably synchronous with the Souths Range Movement of the Amadeus Basin. Walter's (1980) *Huckitta Movement* was coined to denote a period of local uplift and erosion spanning the Precambrian–Cambrian boundary (Mopunga Group–Shadow Group contact). The hiatus is interpreted as a distal expression of the Petermann Orogeny.

Palaeozoic

Overlying Cambrian–Ordovician strata were deposited on a relatively stable, broad marine platform, forming part of the Centralian B Superbasin (see **Centralian Superbasin**), prior to termination of sedimentation by uplift associated with the earliest phases (Rodingan Event) of the 450–300 Ma Alice Springs Orogeny in the Late Ordovician. In the middle and late Cambrian, exposure and karstification of the Thorntonia Limestone, deposition of the Steamboat Sandstone and Eurowie Sandstone Member, and a hiatus between the Arrinthrunga and Tomahawk formations all reflect localised relative uplift related to the Cambro–Ordovician *Delamerian Orogeny* that deformed and metamorphosed areas to the east and south of the Georgina Basin, notably in the southern Adelaide Fold Belt. The late Early and Middle Ordovician (480–460 Ma) *Larapinta Event* (**Figure 28.6**) was an intense but very localised tectonic episode that reflects metamorphism and deformation of the Irindina Province, to the south of the Georgina Basin, at depths of 30–35 km and temperatures of ca 800°C (Mawby *et al* 1999, Hand *et al* 1999, Buick *et al* 2001). Buick *et al* (2005) interpreted this event as being the result of the opening and subsequent closure of a pull-apart basin (Irindina Province) in a dextral strike-slip fault system, probably associated with development of the northwest-trending Larapintine Seaway, which possibly connected the Canning, Amadeus, Georgina and Warburton basins to the proto-Pacific Ocean (Webby 1978, Haines and Wingate 2007). Deformation associated with the Larapinta Event was sharply partitioned across the bounding shear zones and did not significantly affect rocks in the Georgina Basin (Scrimgeour and Raith 2001), which accumulated coeval rocks of the Toko Group. Nevertheless, Dunster *et al* (2007) interpreted syndepositional normal faulting and elevated heat flow in what is now the Toko and Dulcie synclines at about this time.

A series of major Late Ordovician to Carboniferous (450–300 Ma) tectonic events, collectively known as the



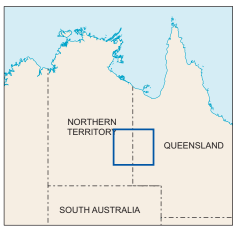


Figure 28.32. Simplified geological map of southern Georgina Basin showing interpreted Neoproterozoic rift basins, some under cover. Many normal faults marginal to rift basins were later reactivated as reverse faults. Abbreviations: BR – Burke River Structural Belt; DS – Dulcie Syncline; LF – Lucy Creek Fault; OF – Oomoolmilla Fault; PF – Pilgrim Fault; SF – Sun Hill Fault; TF – Tarlton Fault; ToF – Toomba Fault; TL – approximate location of Neoproterozoic continental margin; TS – Toko Syncline (redrawn and slightly modified after Greene 2010: figure 6).

Alice Springs Orogeny, produced intense deformation, including major thrust faulting, on the southern margin of the Georgina Basin and was responsible for much of the present structure. Haines *et al* (2001) recognised three constituent orogenic events: the Rodingan Event in the Late Ordovician, Pertnjara-Brewer events in the mid-Devonian and Mount Eclipse Event in the mid-late Carboniferous; these correlate with pulses of synorogenic sedimentation in the Amadeus, Gnalia and Georgina basins. The 450–440 Ma *Rodingan Event* was mostly confined to parts of the eastern and central Arunta Region, and was related to exhumation of the deeply buried Irindina Province and its juxtaposition against the surrounding Palaeoproterozoic Aileron Province (Scrimgeour and Raith 2001). The most intense deformation visible in the southern Georgina Basin is attributed to the 390–375 Ma *Pertnjara-Brewer events*, which formed the present structural margin of the southern Georgina Basin when basement was thrust over Cryogenian–Ordovician rocks. Pre-existing normal faults bounding Neoproterozoic rift basins were selectively reactivated at this time and are now expressed as high-angle reverse faults that inverted the pre-existing rift basins (Greene 2003, 2010). Deformation was mostly brittle in style and was related to predominantly north–south to northeast–southwest crustal shortening. Synorogenic foreland deposition of the Devonian Dulcie Sandstone and Cravens Peak beds accompanied these movements (Dunster *et al* 2007). Only minor reactivation of older Alice Springs Orogeny structures is inferred for the 330–320 Ma *Eclipse Event* in the southern Georgina Basin.

Faults

Major named faults within the southern Georgina Basin are listed by Dunster *et al* (2007); significant faults in the NT portion of the basin are shown in **Figure 28.4**. Most major faults are long-lasting Neoproterozoic or earlier structures that were reactivated at various times during the Phanerozoic (**Figure 28.32**). They are typically associated with monoclinal folds and have steep to overturned bedding in the footwall immediately adjacent to the fault. According to Greene (2003, 2010), many of the major faults in the southern part of the basin were probably generated on the then Australian continental margin at the time of breakup of the Rodinian Supercontinent during the Neoproterozoic, although it is possible that some are reactivated earlier Proterozoic structures (Warren 1981). They are interpreted to have been a series of Neoproterozoic south- to southwest-dipping normal faults bounding northwest-striking rift segments and offset by northeast-striking transform faults. These normal faults were then reactivated as high-angle reverse faults during the largely compressional Alice Springs Orogeny, in particular during the Pertnjara-Brewer (395–375 Ma) and Eclipse (340–310 Ma) events. Most reverse fault displacement occurred during the Pertnjara-Brewer orogenic phase, creating the present southern basin margin. Cenozoic activity has also been noted on some faults, including the Wilora and Taylor faults in BARROW CREEK, which formed active fault scarps with associated extensive fanglomerate, marginal to Cenozoic graben or half-graben basins (Haines *et al* 1991).

The northern margin of the Georgina Basin in eastern MOUNT DRUMMOND is an apparent faulted contact with the South Nicholson Basin, along the east-northeast-trending Little Range Fault on the southern flank of the Carrara Range. Associated subparallel faults in the adjacent Lancewood Creek area have probably affected Narpa Group rocks (McMahon 1969). In central-western RANKEN, faults interpreted from aeromagnetic data may be partly or wholly responsible for the poor expression of the Alexandria-Wonarah Basement High and apparent lateral offset of the lithostratigraphic succession in that area (Kruse and Radke 2008). Radiometric, digital terrain model and Landsat images provide an indication of conjugate east-northeasterly and northwesterly–north-northwesterly lineament trends in parts of the central region, reflected to a degree in drainage orientations. Along the northern basin margin, a dominant northwesterly to westerly joint orientation is evident in the exposed Bukalara Sandstone.

There are few direct indications of syndepositional fault activity at the time of Palaeozoic sedimentation within the basin. One candidate is a possible growth fault tentatively identified on Pacific Oil and Gas seismic line 89–208 near drillhole Hunt-1 (**Figure 28.14**). Though poor reflection quality lowers confidence in the interpretation, reflectors correlated with the upper Arthur Creek Formation apparently thicken westward into a fault on this line (Dunster *et al* 2007).

Several of the more significant and better documented major faults of the southern Georgina Basin are briefly described below.

Oomoolmilla Fault Zone

The Oomoolmilla Fault (Freeman 1986) is about 25 km in length, strikes 70°E and dips approximately 70° south. It is a prominent, northeast-striking, steeply south-dipping reverse fault that juxtaposes Proterozoic crystalline basement to the south with Cambrian to Devonian sedimentary rocks of the Georgina Basin to the north. The fault has had a minimum vertical displacement of 1400 m (Greene 2010), but may have had a maximum total displacement of some 3500 m (Freeman 1986). It has experienced a component of sinistral motion (Dunster *et al* 2007) and was interpreted by Greene (2010) as a step or transfer fault within the otherwise northwest-trending regional fault system of the southern Georgina basin. The hangingwall of the fault contains Neoproterozoic sedimentary rocks (Mount Cornish Formation, Oorabra Arkose) assigned to supersequences 2 and 3 of the Centralian A Superbasin succession. These thin away from the fault and have been interpreted as rift basin fill deposited in localised half grabens (Freeman 1986, Walter and Veevers 2000, Dunster *et al* 2007). The Oomoolmilla Fault therefore probably originated as a southeast-down, rift-bounding normal fault that was reactivated as the present southeast-up reverse fault during the Alice Springs Orogeny (Greene 2010).

Lucy Creek Fault Zone

The Lucy Creek and Mount Playford faults are related northwest-striking, steeply west-dipping, west-side-up reverse faults in the Huckitta region. The Lucy Creek Fault is greater than 75 km in length and has had a minimum vertical displacement of about 700 m, with an actual displacement possibly exceeding 1000 m. A thin wedge of Neoproterozoic rift basin fill (Mount Cornish Formation, Oorabra Arkose) is exposed in the hangingwall, and is overlain by Cambro-Ordovician rocks (Freeman 1986). The shorter Mount Playford Fault appears to curve into and terminate against the Lucy Creek Fault in a ‘J-hook’ relationship, as is characteristic of younger-against-older fault terminations (Greene 2010). It has possibly experienced about 1600 m of vertical displacement. Greene (2010) presented a model in which the Lucy Creek Fault is interpreted as an early (Neoproterozoic) west-side-down, normal rift-margin fault, later reactivated as a west-side-up reverse fault during the later stages of the Alice Springs Orogeny. The Mount Playford Fault developed at this later time as a lower-angle, footwall shortcut fault that acted to decrease resistance to horizontal shortening.

Tarlton Fault Zone
The Tarlton Fault Zone is a northwest-striking, 40 km-long fault zone that juxtaposes Proterozoic crystalline basement to the west with flat-lying Ordovician strata of the southeastern Georgina Basin to the east (Kruse *et al* 2002a). It is located approximately 25 km southeast of the Lucy Creek Fault and appears to be a left-stepping en echelon extension of that fault. Greene (2010) interpreted this structure to be a west-dipping reverse fault, not an east-dipping normal fault as previously thought (Kruse *et al* 2002a, Dunster *et al* 2007), and estimated more than 3300 m of total west-side-up stratigraphic offset on two fault strands. The hangingwall of the Tarlton Fault exposes Neoproterozoic rift basin fill (Black Stump Arkose and Wonnadinna Dolostone of Supersequence 3), indicating that a pre-existing west-side-down Neoproterozoic normal fault has been reactivated as a Palaeozoic west-side-up reverse fault (Greene 2010), possibly with some transcurrent movement (Dunster *et al* 2007). Further slight movement on the Tarlton Fault may have occurred as recently as the early Eocene–late Oligocene (Warren 1981). Relatively more rapid erosion of felsic crystalline basement in the uplifted hangingwall block has resulted in topographic inversion, so that structurally lower Palaeozoic footwall rocks now form a fault line scarp that stands topographically high relative to the Proterozoic basement (Greene 2003).

Toomba Fault Zone
The Toomba Fault Zone (Kruse *et al* 2002a) is a major northwest-striking structure that forms about 200 km of the present southwestern margin of the Georgina Basin. It is a high-angle reverse fault with a 40–70° west dip and west-side-up vertical displacement of up to 6.5 km, that may have also experienced some dextral strike-slip movement during the Alice Springs Orogeny (Harrison 1979). This complex fault zone juxtaposes Proterozoic crystalline basement of the Arunta Region and overlying Neoproterozoic sedimentary rocks with Palaeozoic strata preserved in the prominent footwall Toko Syncline. It consists of left-stepping en echelon segments that die out northward into monoclinal folds (Simpson *et al* 1985), as displacement is transferred between segments. A substantial thickness of up to 1000 m of Neoproterozoic rift basin fill (Yardida Tillite, Black Stump Arkose) is exposed in the hangingwall of the fault zone indicating two periods of Neoproterozoic rifting and basin formation, corresponding to the time of deposition of supersequences 2 and 3 of the Centralian A Superbasin succession. Reactivation as a west-side-up reverse fault displaced mid-Devonian synorogenic sedimentary rocks (Cravens Peak beds) that form the western limb of the Toko Syncline, indicating that major reverse movements occurred during the later phases of the Alice Springs Orogeny. The present structurally complex fault zone may have resulted partly from reactivation of a pre-existing, segmented normal fault system and partly from formation of new footwall cutoff faults during Palaeozoic contractional deformation (Greene 2010).

Subsurface faults underlying Toko Syncline
From seismic, aeromagnetic and gravity data, Greene (2010) has interpreted the presence of two separate Neoproterozoic rift basins underlying the Toko Syncline, mostly in Queensland (**Figure 28.32**). These are bounded to the east by prominent west-dipping reflectors in seismic profiles (Harrison 1979, Lechler and Greene 2006) that were interpreted by Greene (2010) to be Neoproterozoic normal faults that were not significantly reactivated during the Alice Springs Orogeny.

Sun Hill and Pilgrim faults
The Sun Hill and Pilgrim faults are prominent steeply west-dipping structures in the southern Georgina Basin to the east of the Toko Syncline in Queensland that feature Neoproterozoic rift basin sedimentary rocks in the hangingwall. Both of these were interpreted by Greene (2010) as being similar to the Toomba, Tarlton, and Lucy Creek faults to the west in that they were originally west-dipping normal faults flanking Neoproterozoic rift basins that were reactivated in the Palaeozoic as west-side-up reverse faults.

Folds

The Toko and Dulcie synclines have wavelengths of tens of kilometres and dominate the broad-scale structure of the southern Georgina Basin. These are the only structures of sufficient amplitude to preserve any Devonian section. The fold axes of both are parallel to the adjacent faulted basin margin, which appears to have acted as a rigid buttress against which folding has occurred. The Dulcie Syncline is somewhat asymmetric in a gross sense, its southern limb steepening against the southern margin of the basin. There is some indication from gravity and magnetic modelling of basin thicknesses that they are amplifications of preexisting basin depocentres. Other folds in the southern Georgina Basin are of much smaller amplitude and are harder to identify from outcrop geology, to the extent that they are not apparent at the basin scale (Dunster *et al* 2007).

The central Georgina Basin is typically masked by a pervasive regolith, and the northern region is largely concealed beneath the onshore Carpentaria Basin. Nevertheless, the succession appears to be generally flat-lying to gently folded. The Lake Nash Anticline is a prominent isolated fold in the Camooweal Dolostone in southeastern AVON DOWNS, in the Undilla Sub-Basin. The structure plunges to the south and is open to the north. It may be a distal expression of the Alice Springs Orogeny, or a draped structure (Smith 1972). Mesoscale folding is also interpreted in jointed and regolith-mantled Wonarah Formation on the Alexandria-Wonarah Basement High, around the AVON DOWNS–RANKEN–FREW RIVER–ALROY conjunction. A south-plunging anticline at Barry Caves is the best substantiated of these folds (Kruse and Radke 2008).

MINERAL RESOURCES

The Palaeozoic successions of both the NT and Queensland portions of the Georgina Basin contain base metals mines, prospects, occurrences and anomalies that can be assigned to several styles of Cu and Pb-Zn mineralisation, including Mississippi Valley-type (MVT), stratiform sediment-hosted and sandstone-hosted. The basin is also very prospective for phosphate over large areas of its central and northern parts and hosts several substantial deposits, including Wonarah in the NT. The southern Georgina Basin is widely regarded as one of the more prospective areas for onshore petroleum in the NT, but substantial oil/gas pools are yet to be identified and the basin remains underexplored. Other prospective commodities within the Georgina Basin include diamonds, manganese and uranium. Neoproterozoic and/or Palaeozoic successions of the southern Georgina Basin have also been explored for gold and platinum group elements, but without success.

Base metals

The Neoproterozoic succession of the southern Georgina Basin is prospective for base metals and contains a number of known prospects. Pb-Zn-anomalous Cambrian and cupriferous Neoproterozoic rocks in the southern Georgina Basin have been the subject of company exploration for over 30 years, although exploration has been sporadic, at best, during the last two decades. Draper (1978) provided an overview of all Pb-Zn prospects in the basin.

Base metals occurrences in the Neoproterozoic of the central–northern Georgina Basin are few. A thin, shallow black shale at the Buchanan Dam phosphate deposit (ALROY) was unsuccessfully drilled for base metals by CRA (Alexander and Chalmers 1982). In southern AVON DOWNS, partially cored drillhole Scarr-1 (**Figure 28.14**) was drilled to 321 m depth to test a 2 mgal gravity and 480 nT magnetic anomaly for possible carbonate-hosted base metals mineralisation. Visible sulfides were lacking in carbonaceous dololaminite in the interval 293–321 m depth (ie lower Arthur Creek Formation), and precious metal assays were very low (Graham 1988).

Lead isotope data for galena from the Box Hole prospect and Mount Skinner areas (Dunster *et al* 2007) are consistent with other samples from both the Queensland and NT portions of the Georgina Basin (G Denton, CSIRO, *in litt* 2001); they indicate that all Pb has been derived from a common source during a single basin-wide mineralising event. There is not yet a unique solution for the timing of mineralisation relative to source rock Pb composition, but Proterozoic-age Pb and a mineralisation age corresponding to the later phases of the Alice Springs Orogeny are considered most likely.

Mount Skinner area

The Mount Skinner area (**Figure 28.33**), located about 170 km north-northeast of Alice Springs and 40 km east of the Alice Springs–Darwin railway in ALCOOTA, has been targeted for syngenetic exhalative sediment-hosted base metals (Ashley in Chuck 1982), Zambian-style stratiform Cu (Utah 1970) and stratabound Cu mineralisation (Menzies and Louwrens 1995). Previous exploration (Youles 1965, Halliday 1965, 1966, Shaw and Warren 1975) demonstrated that visible surface copper mineralisation, consisting of malachite-stained rocks and float, extends for several kilometres along strike. Core drilling (Mount Skinner-1 to -4, **Figure 28.33**) by the Mines and Water Resources Branch of the Northern Territory Administration (Grainger 1968a) demonstrated that anomalous Cu continues downdip into fresh rock, but failed to find any economic grades. The highest Cu assay was 6500 ppm for a 0.3 m interval at about 203 m depth in Mount Skinner-3. In addition, this hole unexpectedly intersected two intervals of elevated Pb and Zn that seemingly occur independently of Cu. One 1.5 m-thick interval reputedly averaged 6700 ppm Pb including 2% Pb for the sample from 131.7–132 m depth; the other had up to 950 ppm Zn over 0.3 m at 313.0–313.3 m depth (Grainger 1968b, Shaw and Warren 1975). Centamin NL drillholes (CMS1 to 4, **Figure 28.33**) proved the existence of a prospective interval below the Central Mount Stuart Formation as then understood (Cotton 1972, Chuck 1982, 1983).

Dunster *et al* (2007) better defined the stratigraphic succession and confirmed the presence of stratiform copper mineralisation in the Neoproterozoic Tops Member (**Figure 28.12**) of the Central Mount Stuart Formation and epigenetic base metals mineralisation in the Elyuah Formation. Visible galena, pyrite, chalcopyrite and fluorite were described in core from drillhole CMS4 to the east of Mount Skinner at a depth of 247–260 m. Core logging and geochemistry conducted during the same study confirmed elevated copper, lead, zinc and barium levels, and revealed previously unrecognised lead-zinc mineralisation at depth. The Pb mineralisation event may be younger than the Cu mineralisation event. Ore mineral textures and lead isotope data for galena in the Elyuah Formation confirm the involvement of hydrothermal processes.

Based on this NTGS work, Uramet Minerals Ltd targeted Zambian-style stratiform Cu and Jinding-style sediment-hosted Pb-Zn. In 2007, they undertook a 440 line-km airborne VTEM survey in the Mount Skinner area. Aeromagnetic and gravity data, soil and rock chip sampling, auger drilling and trenching confirmed the NTGS interpretation of mapped faults, but did not identify any anomalies suggestive of a massive sulfide source. The overburden is highly conductive and may obscure responses due to deeper sources (Penna 2010b).

Box Hole-Turkey Creek

Box Hole-Turkey Creek Pb-Zn prospect (and abandoned mine) is located at 53K 579515mE 7530175mN in

HUCKITTA. Galena, barite and minor sphalerite are hosted in stromatolitic late Cambrian carbonate rocks of the Arrinthrunga Formation. Stratabound surface mineralisation with similarities to MVT mineralisation can be mapped discontinuously for 6.5 km along strike (**Figure 28.34**). The mineralised interval lies immediately above the constituent Eurowie Sandstone Member and stratigraphically just below a stromatolitic interval several metres thick (**Figure 28.35a–b**).

Box Hole mineralisation is best exposed in and around Kings Workings, where galena cubes up to 4 cm across occur in a grey silicified carbonate (**Figure 28.35c**). At surface, the host limestone is pervasively dolomitised and variably silicified along strike and upsection. This latter alteration is not stratigraphically controlled at metre scale and does not persist into the subsurface. The Arrinthrunga Formation in the vicinity of Box Hole is gently folded about northwesterly and north-northwesterly fold axes with amplitudes of up to 100 m and wavelengths of 500–2000 m (Ypma 1984). Surface dips are typically less than 15°. The mineralised interval is exposed in

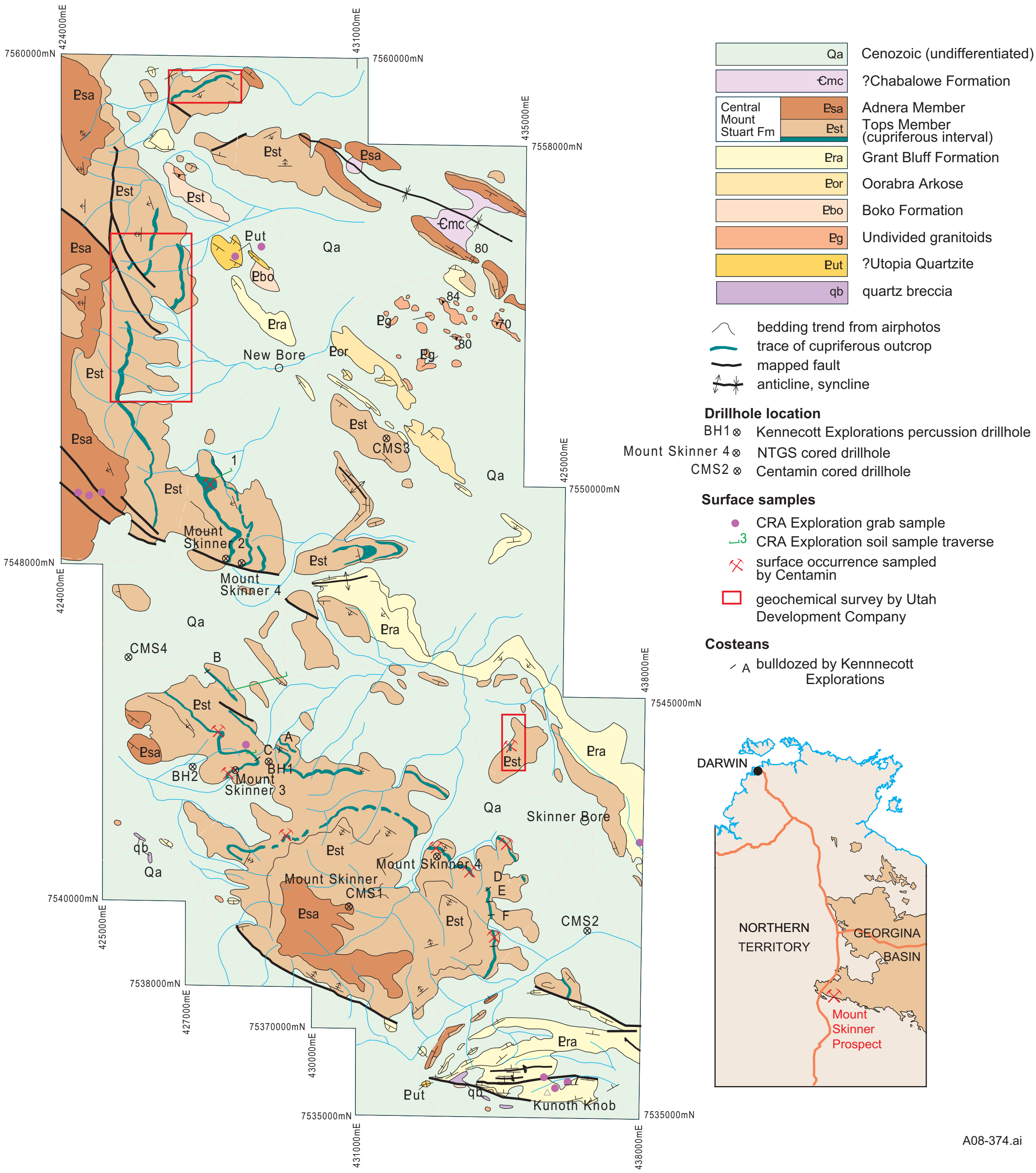


Figure 28.33. Mount Skinner geological sketch map showing cupriferous outcrop, drillhole locations and surface sampling (compiled from company reports and Haines 2004).

two north-trending synclines (**Figure 28.34b**). Kings Workings and associated ore-grade mineralisation are on the eastern limb of the southern syncline (Marshall 1989). The stratigraphic equivalent in the north contains visible galena only on the western limb. In addition, a throughgoing regional fault is interpreted to splay to the north and transect both synclines. In the southern syncline, this fault is inferred to dip east and would offset or delimit the westerly dipping mineralised interval. The mineralised interval on the western limb of the northern syncline is cut by numerous small faults, some of which may be near bedding-parallel.

Visible ore-grade mineralisation occurs as isolated galena cubes up to several centimetres in size in silicified stromatolitic carbonate with associated crosscutting barite veins (**Figure 28.35d–e**); as isolated and clumped millimetre-scale galena cubes that are largely independent of the host fabric; as galena infill to breccia in silicified

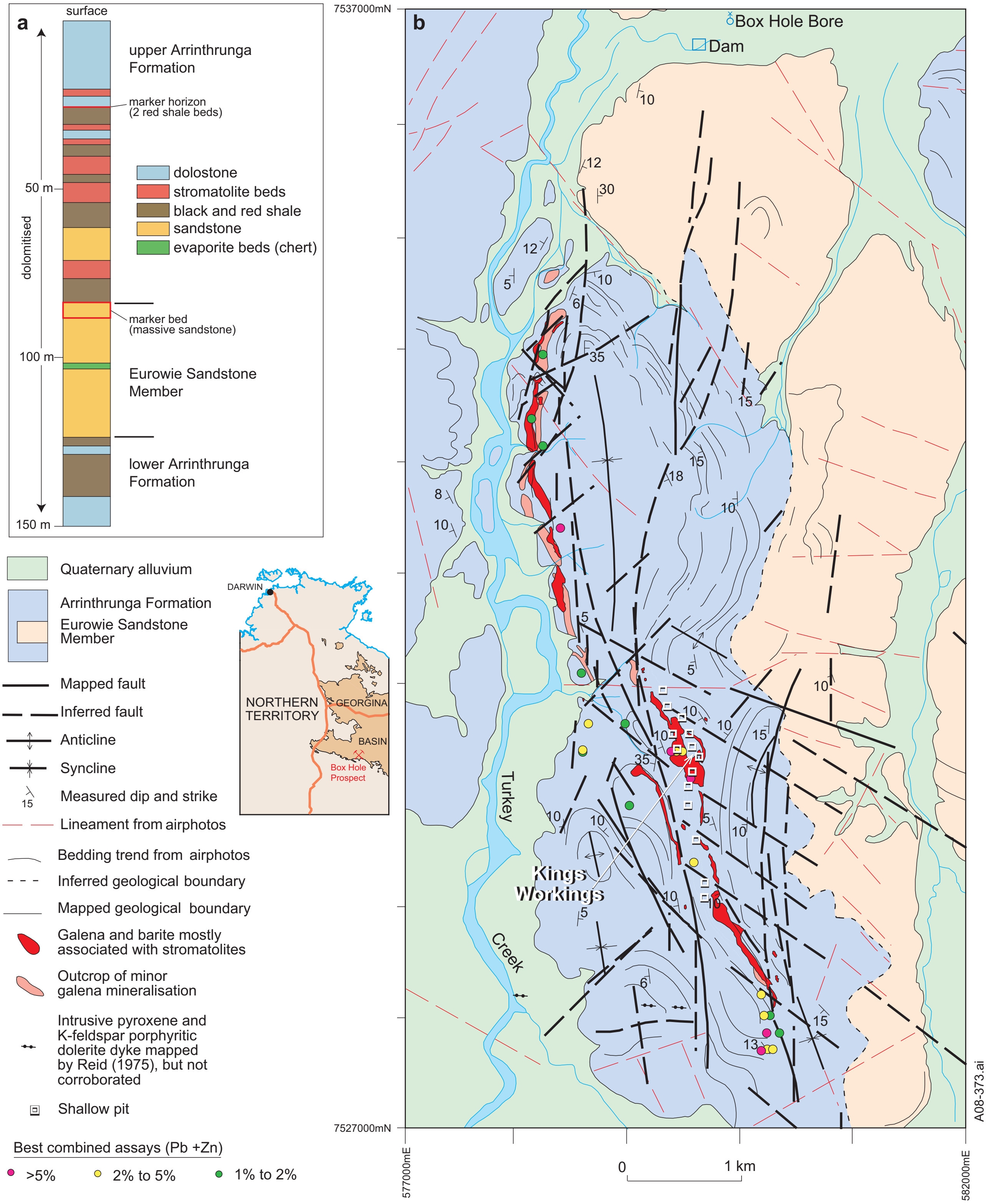


Figure 28.34. Box Hole prospect. (**a**) Stratigraphic column (reproduced with permission from Penna 2009a). (**b**) Mapped surface geology (after Dunster *et al* 2007, Uramet Minerals 2008).

stromatolitic carbonate; and as galena in sedimentary infill of interstices in stromatolitic dolostone (**Figure 28.35a**).

Uramet Minerals Ltd undertook ground gravity and IP surveys over Box Hole in 2008 in an attempt to identify the presence of disseminated metal sulfide bodies at depth. The company also RAB drilled 94 holes for a total of 4155 m in order to test a number of possible base metals targets. The broadest zinc intercept was 12 m at 2.8% Zn (and 0.67% Pb) from 17 m depth, including 1 m at 14.7% Zn from 24 m depth. The best lead intercept was 2 m at 3.98% Pb (and

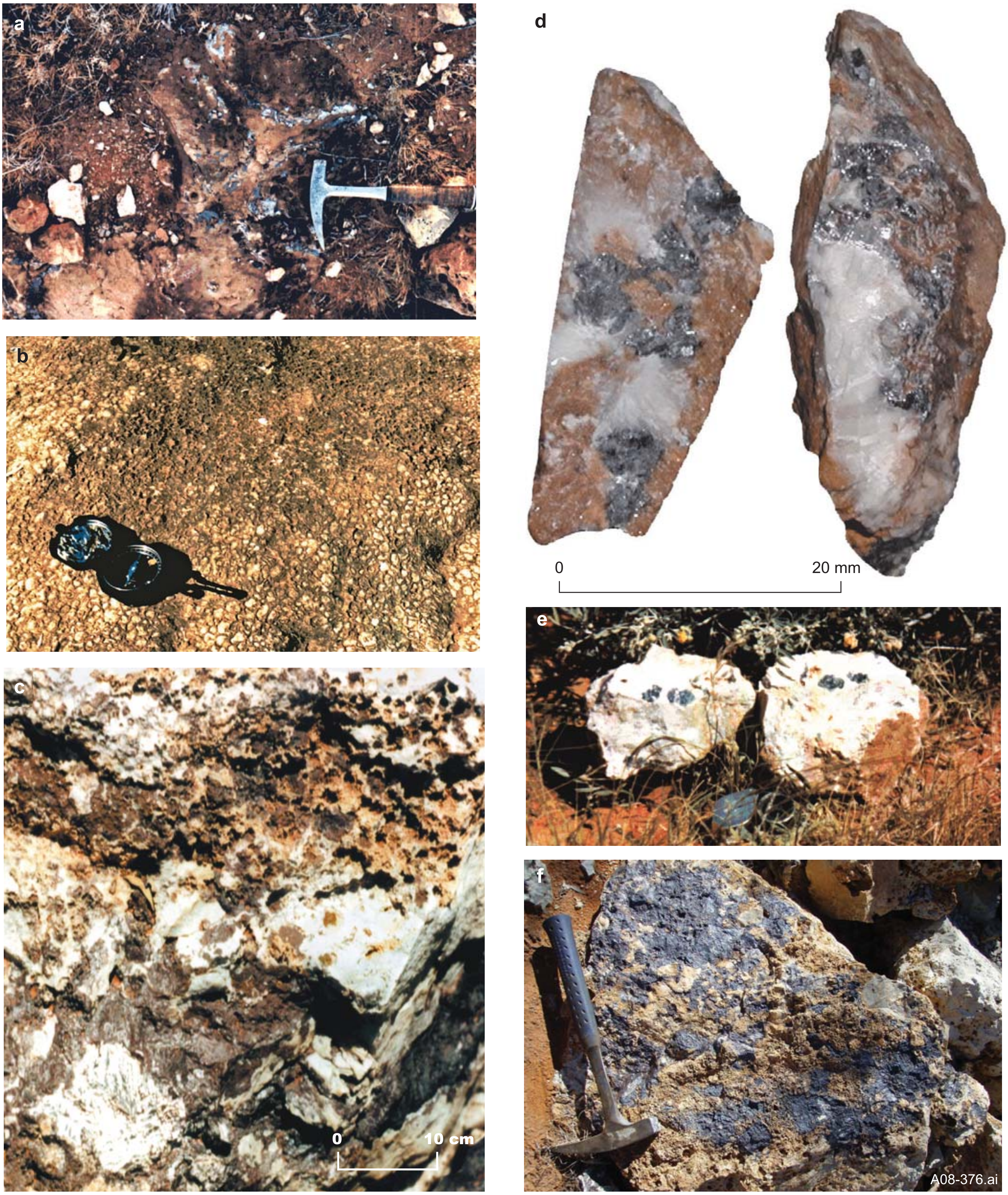


Figure 28.35. Box Hole mineralisation and host facies (after Dunster *et al* 2007). (**a**) Galena between domical stromatolites, southernmost mineralisation, Box Hole (from Ypma 1983). (**b**) Detail of surface texture on a stromatolitic mound, up-section from mineralised interval near Kings Workings (from Ypma 1983). (**c**) Host rock showing voids formed after galena has weathered out. (**d**) Detail of small samples of coarse barite and galena from near Kings Workings. (**e**) Cubic galena in massive barite from northernmost outcrop of mineralisation (800 m north of core shed). Hand lens (bottom) for scale (from Ypma 1983). (**f**) Galena (leach sulfide) mineralisation at Box Hole prospect (photo W Taylor, Uramet Minerals Ltd).

2.8% Zn) including 1 m at 5.39% Pb and 3.4% Zn (Uramet Minerals Ltd, ASX Announcement, 30 September 2008).

Marqua–Boat Hill area

Like Box Hole, the Marqua area has been the subject of systematic company exploration for over 30 years. This structurally complex southern margin of the Georgina Basin in TOBERMOREY–HAY RIVER contains several Cambrian formations that are anomalous in Zn and Pb over kilometres of strike length. Minor visible galena, sphalerite and pyrite have been reported at the surface and below the depth of weathering in the Red Heart Dolostone and Thorntonia Limestone. Boat Hill Pb-Zn prospect (53K 773744mE 7466000mN), the only named prospect (**Figure 28.36**), has returned up to 1.15% Zn over 2 m in channel chip samples and the best cored intercepts to date are about 2% Zn over 0.5 m. The highest reported Pb is 1.8% over 2 m from percussion drill samples (McGeough 1992). From petrological studies of selected mineralised samples, Croxford (in McGeough 1992) concluded that the mineralisation is MVT and occurred as several episodes. At least three generations of pyrite are accompanied or postdated by sphalerite and hydrocarbons (**Figure 28.37**). Galena was apparently the last ore mineral to form, filling vugs in saddle dolomite (**Figure28.38**). In the 2000s, Uramet Minerals Ltd undertook a helicopter-borne electromagnetic (VTEM) survey, regional reconnaissance work including mapping and surface geochemistry, and aircore, RC and diamond drilling as part of joint phosphate–base metals exploration of the Marqua area, but no economic mineralisation was found (Penna 2010a).

Elkedra Diamonds NL unsuccessfully explored the Marqua–Boat Hill area for Kupferschiefer-style Cu mineralisation and for epithermal Au in carbonate rocks and structural traps (Elkedra Diamonds NL, press release to ASX, 25 September 2003). The Marqua area has also been unsuccessfully explored for Zechstein-style shale-hosted platinum group elements (Virtue 1988). As part of a BMR core drilling program in the area, Shergold (1985) documented evidence of hydrothermal activity and invoked a Carlin-style Au model for future exploration, which was unsuccessfully pursued by Mount Isa Mines Ltd (McGeough 1992, McGeough and Shalley 1992).

Trackrider

Trackrider Pb prospect in the Ooratippra area (**Figure 28.39**) of southernmost ELKEDRA contains surface galena and minor pyrite centred on 53K 628900mE 7569000mN. Sporadic exploration over 40 years has targeted Olympic Dam-type and MVT mineralisation. The host rocks are vuggy, siliceous and manganiferous dolostone of the late Cambrian Arrinthrunga Formation, just below the contact with the overlying Tomahawk Formation. This disconformity is marked by a ferruginised zone of haematite and goethite with manganiferous encrustations that contain percent levels of Pb and <1200 ppm Zn in outcrop and near the surface, but appears to lack any significant sulfides at depth (eg Sturmfels 1960). Scavenging and concentration in the weathering profile are responsible for the highest observed concentrations of ore minerals. Mn- and Fe-rich calcrete can contain as much as 5000 ppm Pb, without showing any Pb sulfide even at the microscopic scale. However, elsewhere, the same calcrete does contain distinct galena crystals, some of which are being leached to oxide under the present weathering regime. Unlike the better known occurrences in the Georgina Basin, visible galena at Trackrider Prospect is not obviously associated with existing porosity in the host rock, barite gangue or possible feeder faults. It is conceivable that mineralisation is located at the Arrinthrunga Formation–Tomahawk Formation contact as a result of mineralising fluids passing along the disconformity. This scenario is similar to a model previously proposed for the Tomahawk Prospect in Queensland, but metal anomalism would be expected to continue into the subsurface and this has yet to be demonstrated at Trackrider. Although the available

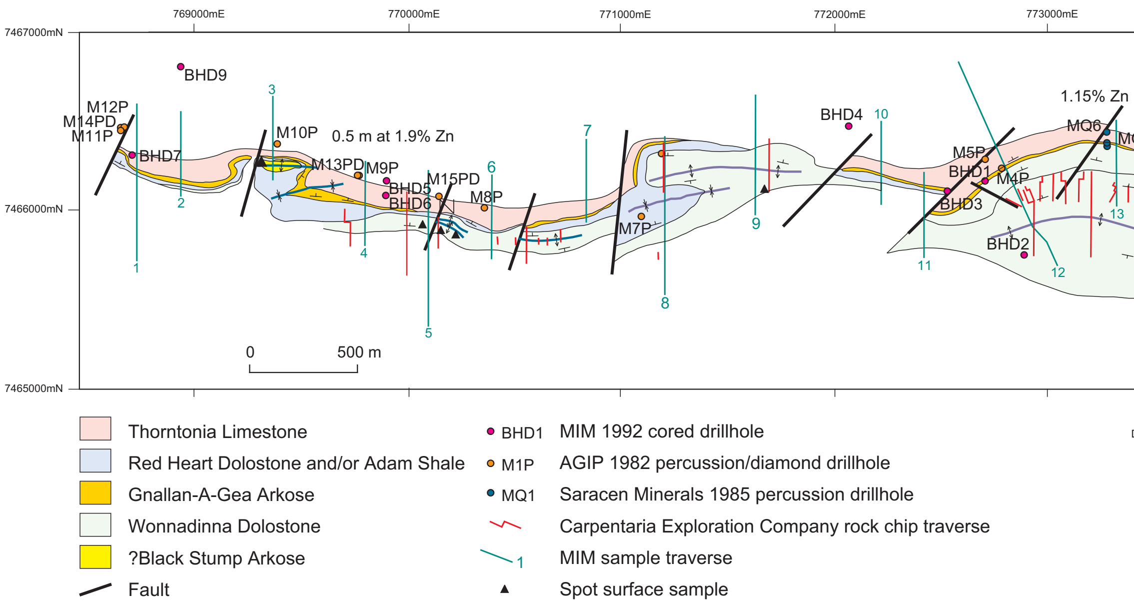


Figure 28.36. Boat Hill surface geological map, compiled from numerous company reports and airphoto interpretation (after Dunster *et al* 2007).

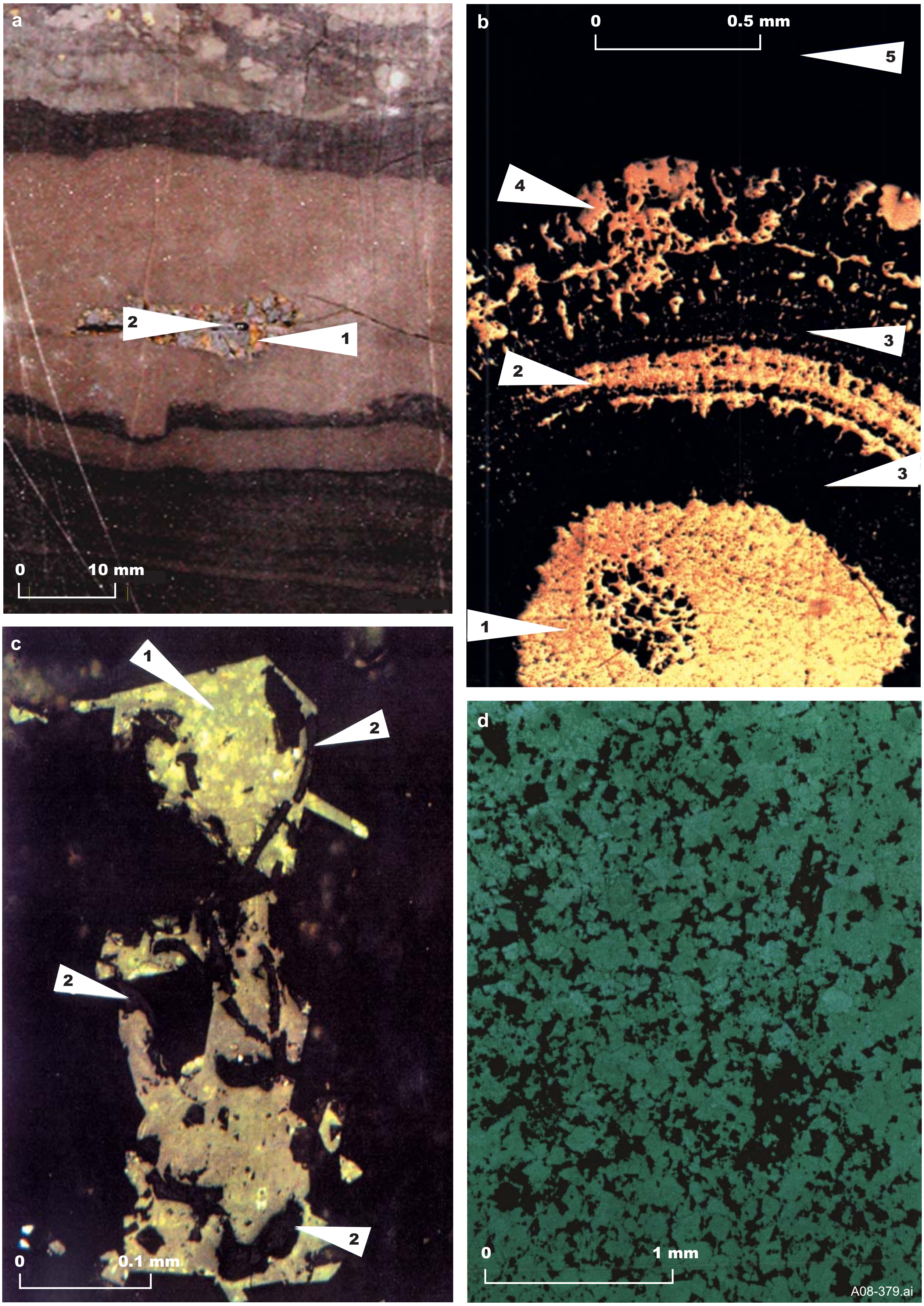


Figure 28.37. Ore textures at Boat Hill Prospect. (**a**) Honey-coloured low-iron sphalerite (1) and galena (2) in core of lower Thorntonia Limestone from drillhole BHD9. Quarter core over this interval (530.90–531.36 m depth) assayed 1.05% Zn and 770 ppm Pb (from Kruse *et al* 2002a). (**b**) Colloform-texture: pyrite core (1), intermediate pyrite zone (2), sphalerite (3), outer zone of marcasite (4), host dolomite (5). 531.07–531.2 m depth in drillhole BHD9. Polished thin section in reflected plane-polarised light. (**c**) Colloform sphalerite (1) and platy organic matter (2) interrelated in vug fill in medial Thorntonia Limestone. 513.36 m depth in drillhole BHD9. Polished thin section in reflected plane-polarised light (from Kruse *et al* 2002a). (**d**) Low-iron sphalerite (black) interstitial to subhedral and euhedral phosphatic dolomite crystals. 513.36 m depth in drillhole BHD9. Transmitted plane-polarised light with green filter (from Croxford in McGeough 1992).

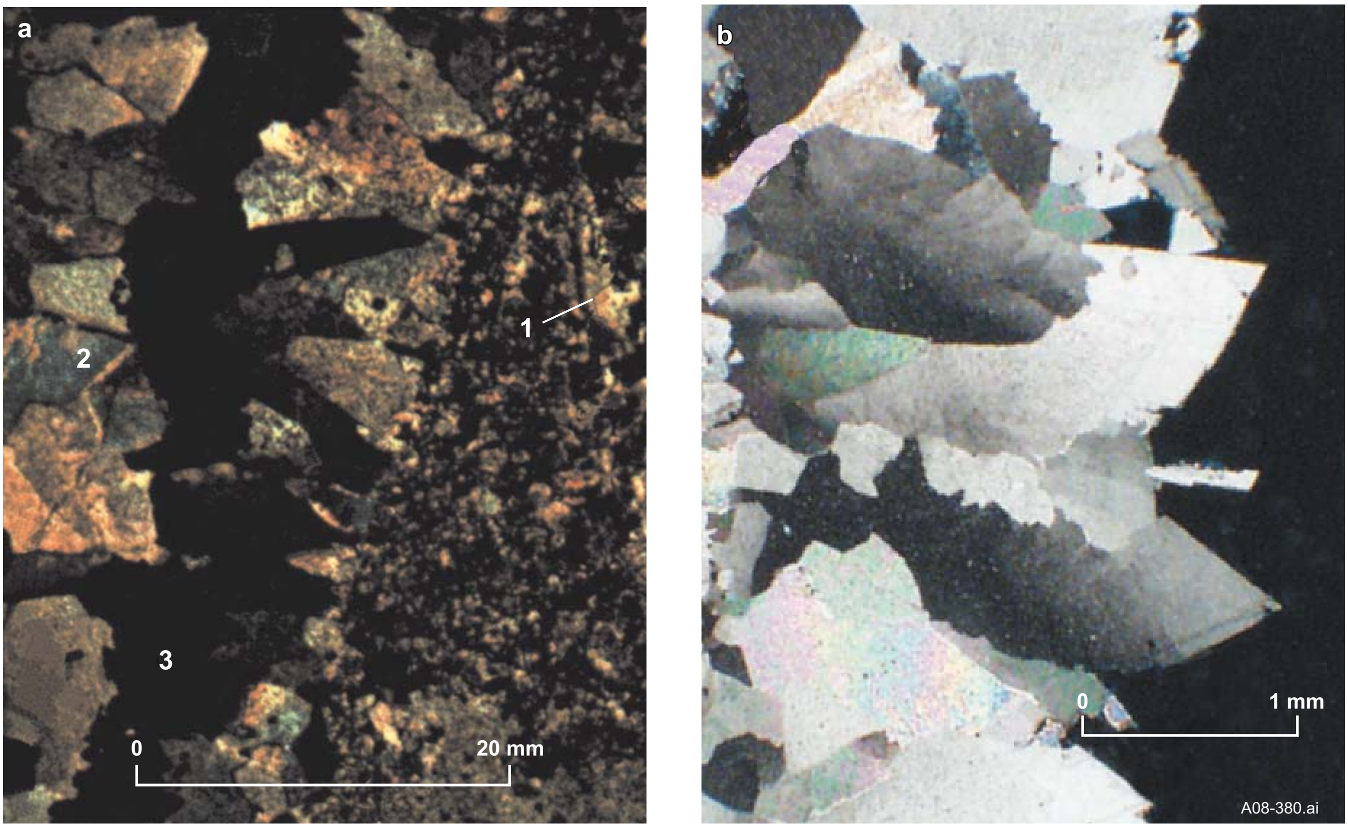


Figure 28.38. Saddle dolomite from Boat Hill Prospect. (**a**) Red Heart Dolostone, 304.83–305.00 m depth in cored drillhole BHD4. Fossil fragments (1) are visible in host dolomite. Vug fill consists of coarsely crystalline saddle dolomite (2) with final core of opaque sphalerite (3) and minor galena. Crossed nicols (from Croxford in McGeough 1992). (**b**) Upper Thorntonia Limestone, 558.2 m depth in cored drillhole NTGS99/1. Note curved crystal faces of coarse saddle dolomite lining a cavity in bioclast dolograinstone (after Dunster *et al* 2007).

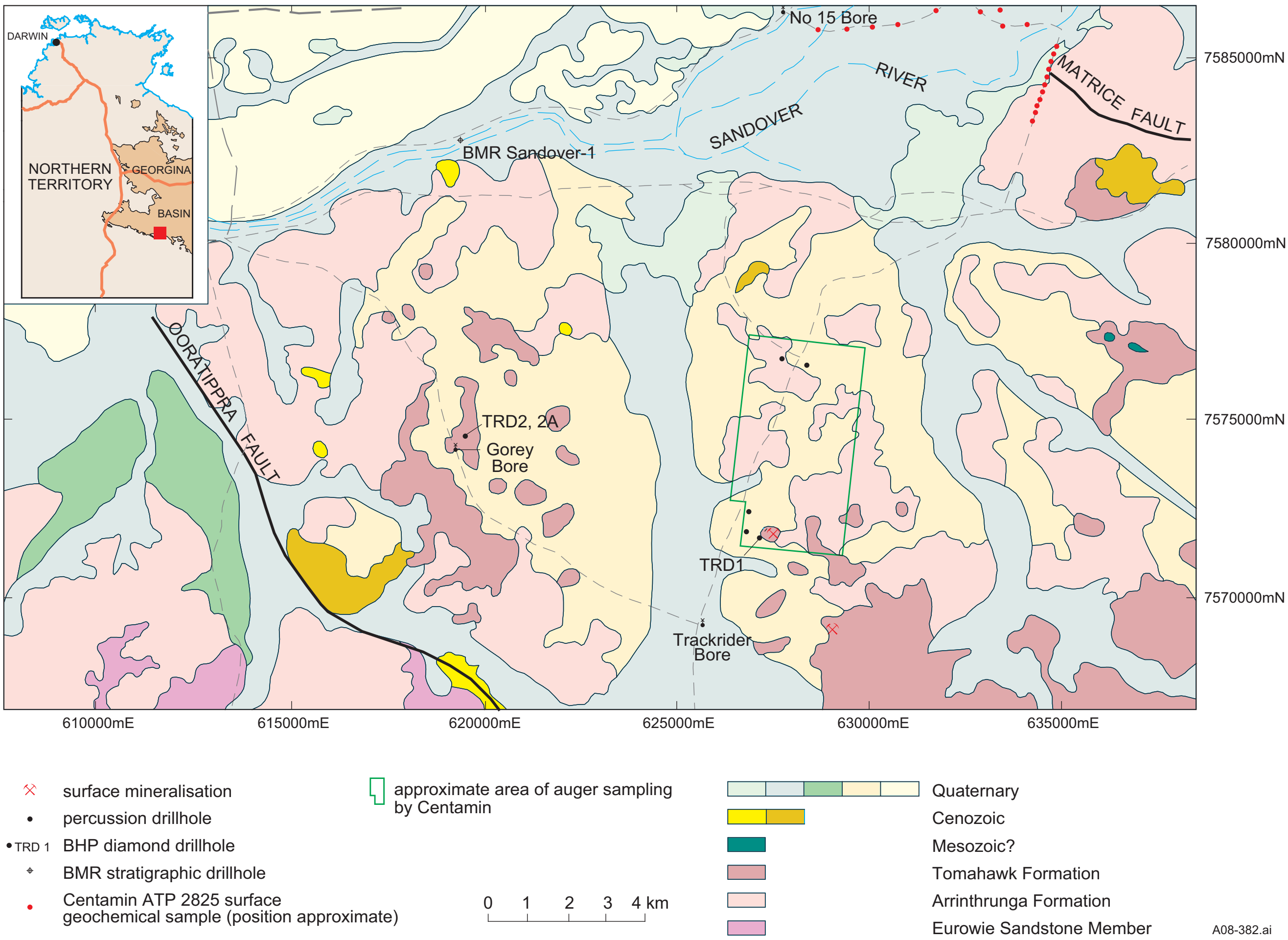


Figure 28.39. Geological map of Ooratippra area showing Trackrider Prospect, based on numerous company reports and published 1:250 000 ELKEDRA geological map (after Dunster *et al* 2007).

evidence thus far confirms only surficial concentrations at Trackrider Prospect itself, confirmation of >1100 ppm Zn at depth in the Arthur Creek Formation in the area does suggest hydrothermal processes. Furthermore, the very existence of visible galena and sphalerite at the prospect means that there is a sufficient source of Pb and Zn in the area to be concentrated by whatever mechanism (Dunster *et al* 2007).

A gravity and magnetic high (Ooratippra Geophysical Anomaly), defined by the BMR (Barlow 1965, 1966) and covering 1200 km^2, may also have some association with mineralisation at Trackrider (eg Kostlin 1970, 1971).

Phosphate

The Georgina Basin is a world-class phosphate province with numerous deposits in both the NT and Queensland.

Wonarah area

Phosphate exploration in the central Georgina Basin was initiated by BMR in the early 1960s, as high-grade Oceania island phosphates became depleted. The substantial Wonarah deposit (**Figures 28.40**, **28.41**) was identified by

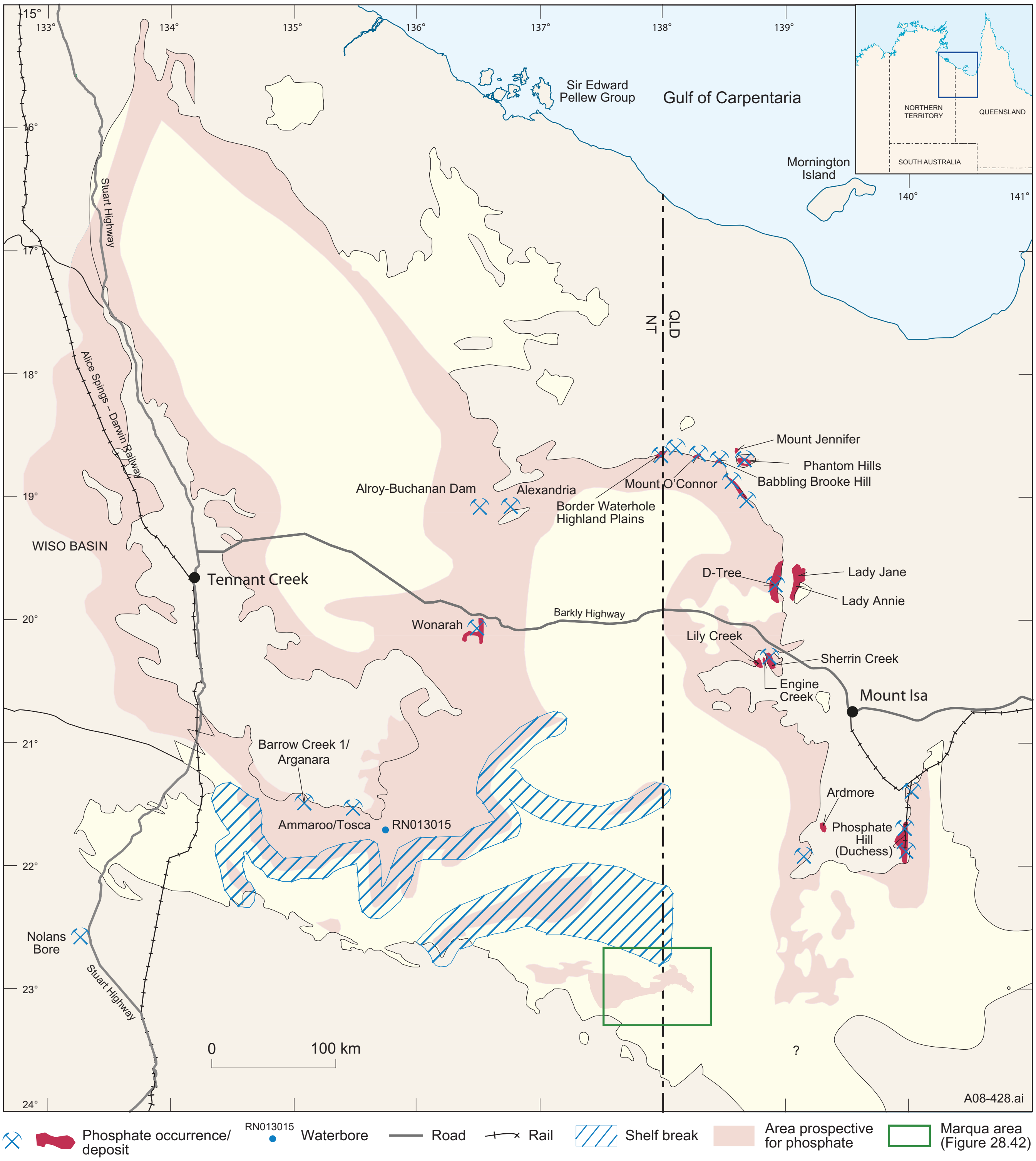


Figure 28.40. Phosphate deposits, occurrences and prospective areas in Georgina Basin (after Dunster *et al* 2007). Prospective areas in southern Georgina Basin near Queensland border after Uramet Minerals Ltd media release dated 8 May 2008.

IMC Development Corporation in 1967 in the southeastern corner of ALROY, using regional mapping, geophysics and open-hole drilling (Howard 1971, 1972), which located ore-grade phosphorite at depths in the range 12–59 m (Howard 1989). Howard (1989) characterised the deposit as two successive phosphorite beds comprising phosphatic mudstone, silty mudstone and grainstone (of reworked mudstone clasts). IMC relinquished the Wonarah deposit in 1971, after an unfavourable preliminary feasibility study (Howard and Perrino 1976). A transport distance of 260 km to the nearest railway was a major drawback.

A Rio Tinto–Australian Kimberley Diamonds (AKD) joint venture explored for large-tonnage phosphorite in the Wonarah area during 1999–2002, employing photointerpretation, geological mapping, rock chip sampling, ground gravity surveys and the drilling of RC and some diamond drillholes. An ore-grade (>15% P_2O_5) 'phosphorite horizon' was delineated, almost directly overlying the early Cambrian Helen Springs Volcanics, in a decametre-scale stratigraphic interval attributed to the upper Gum Ridge Formation (Lilley 2002). However, the presence of the Gum Ridge Formation is not confirmed in this area on the Alexandria-Wonarah Basement High, and the phosphorite interval may represent basal Wonarah Formation. The phosphatic interval in some areas is too deep to be economic (eg Sas 2003), but an accessible inferred resource of 72 Mt at 23% P_2O_5 (AKD Ltd, ASX Announcement, 24 January 2002) was delineated at the RANKEN–AVON DOWNS–FREW RIVER–ALROY conjunction, beneath 15–77 m of overburden.

As a result of significant rock phosphate price increases in the mid 2000s, the Wonarah deposit was reevaluated as a potential long-term mining operation by the current tenement holders, Minemakers Ltd. After several drilling campaigns commencing in 2008, Minemakers determined that mineralisation is controlled by palaeohighs and that there are at least two substantial phosphate deposits in the Wonarah area. Mineralisation previously delineated by Rio Tinto-AKD is now included within the *Main Zone* deposit, whereas mineralisation outcropping over a 2 km strike length about 15 km to the southwest is termed the *Arruwurra* deposit. The Minemakers project is now Australia's largest undeveloped rock phosphate project. Indicated and Inferred Resource estimates for the entire volume of the modelled phosphatic units total 1258 Mt at 12% P_2O_5. This includes 620 Mt at 18% P_2O_5 at a 10% P_2O_5 cutoff (MineMakers 2010). Minemakers is also looking to value-add by producing superphosphoric acid directly from unbeneficiated Wonarah phosphate ore (Minemakers 2011).

Alexandria, Alroy and Buchanan Dam

The small *Alexandria* deposit in northwestern RANKEN (**Figure 28.40**) was identified at the same time as Wonarah (Perrino 1970). According to Howard (1972), this is a shoestring deposit, 300 m wide and possibly 24 km long, of variable thickness (1.5–6 m) and at a depth of 12–53 m. It is a low-grade phosphatic mudstone with an average of 10–16% P_2O_5 in individual drillholes. One of the best intercepts was 6.1 m at 15.6% P_2O_5 from 48.8 m depth (Phosphate Australia 2011). Driessen (in Shergold and Southgate 1986) listed a pre-JORC inferred resource of 15 Mt at 10% P_2O_5.

A sustained program of scout drilling by Continental Oil Corporation and others beginning in 1968 identified

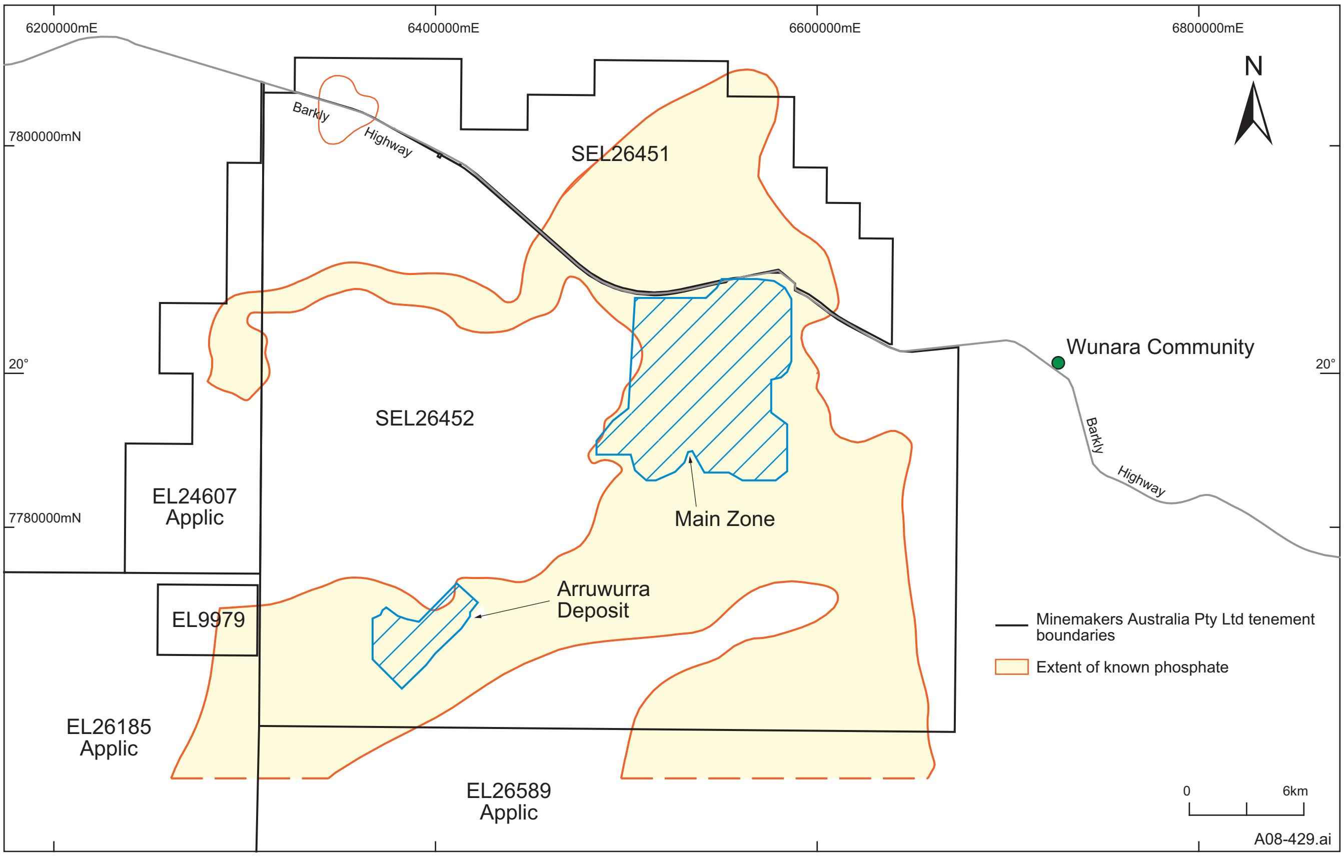


Figure 28.41. Phosphate deposits, extent of known phosphate mineralisation and tenement boundaries at Wonarah as of February 2010 (Minemakers 2010).

two areas of phosphate in ALROY (Campbell 1968, Forrest 1970, Kennedy 1971, Hackett 1977). The *Alroy* deposit has a highest single assay of 32.6% P_2O_5 and Kennedy (1971) estimated a pre-JORC inferred resource of 5.1 Mt at 20% P_2O_5. *Buchanan Dam* has a best intercept of 6.1 m at 25.0% P_2O_5 from 12.2 m depth (Phosphate Australia 2011) and the pre-JORC estimated inferred resource was 7.9 Mt at 20% P_2O_5 (Kennedy 1971).

None of these small deposits are well understood. The Alexandria deposit may be either in Ranken Limestone or more likely, Wonarah Formation. Alroy and Buchanan Dam are apparently in Wonarah Formation.

Highland Plains

The Highland Plains deposit, which straddles the NT–Queensland border in southeastern MOUNT DRUMMOND (**Figure 28.40**), is hosted by the Border Waterhole Formation. McMahon (1969) delineated two major tabular phosphatic intervals in the lower part of the formation. The lower of these (thickness 1.5–17 m) is at the formation base. Some 7–17 m stratigraphically above this, the upper interval, which is 1.5–11 m thick, grades 16–30% P_2O_5. The current tenement holders, Phosphate Australia Ltd, have reported a JORC-compliant Inferred Resource of 56 Mt at 16% P_2O_5 with a lower cutoff of 10% P_2O_5. This includes the Western Mine Target Zone that has an Inferred Resource of 14 Mt at 20% with a lower cutoff of 15% P_2O_5. They also reported low levels of Fe, Al and Mn, and a low ratio of CaO to P_2O_5 (Phosphate Australia 2011).

Marqua area

In the Marqua area (**Figure 28.42**), about 400 km east of Alice Springs, high-grade phosphorite mineralisation has been reported from several prospects within the middle Cambrian Thorntonia Limestone. Mineralisation at the *Foss Hill* prospect consists of four phosphorite intervals, separated by chert bands and claystone. The phosphorite intervals include average grades of 12 m at 28.2% P_2O_5, 8 m at 14.1% P_2O_5, 8 m at 19.2% P_2O_5 and 29 m at 34.2% P_2O_5, with the highest reported assay for an individual sample being 39.4% P_2O_5. Other prospects in this area have returned peak P_2O_5 values (Uramet Minerals Ltd, media release, 21 August 2008) of 37.3% (*Coquina Creek*), 23.1% (*Library Ridge*), 36.3% (*White Hill*) and 19.9% (*Mauritania/Red Heart*).

Ammaroo / Barrow Creek area

The Thorntonia Limestone and lower Arthur Creek Formation are phosphatic near *Ammaroo* in ELKEDRA. Early drillhole intercepts were 0.9 m at 30% P_2O_5 at 26 m depth (Morrison 1968, Howard 1990). More recent drilling has returned 2 m at 18.8%; 2 m at 15.2%; 8 m at 13.1%; 2 m at 22.8%; 5 m at 14.8%; 2 m at 17.7%; 10 m at 17.3% and 6 m at 14.8%. (**http://aragonresources.com.au/projects.html accessed 01/10/2010**). The average depth to the top of the mineralisation is 31.4 m, making it amenable to an open cut mining scenario. This area is about 110 km east of the Alice Springs–Darwin railway line.

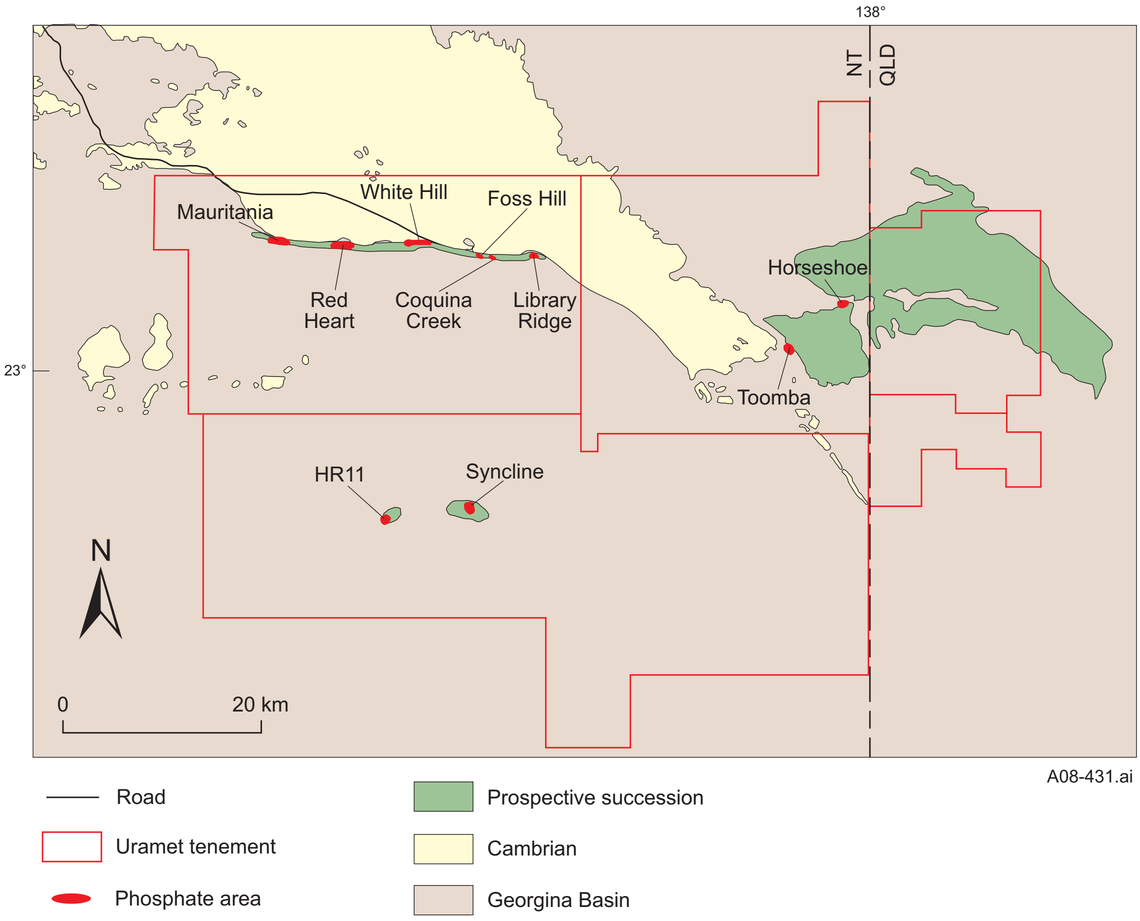


Figure 28.42. Phosphate occurrences and prospective areas in southeastern Georgina Basin. Marqua area incorporates east–west-trending prospects in northeastern tenement (redrawn from Uramet Minerals Ltd website: **http://www.uramet.com.au/?page=projects&section=37**; accessed December 2008). Location shown in **Figure 28.40**.

An area of phosphate west-northwest of Ammaroo includes the *Barrow Creek 1* and *Arganara* prospects (formerly Ammaroo Area 1). First-pass drill results at Barrow Creek 1 included 3 m at 30.2% P_2O_5 from 4 m depth in hole APAC 114, 3 m at 31.2% P_2O_5 from 14 m depth in APAC 119, and 5 m at 25.3% P_2O_5 from 24 m depth in APAC 111. Near-surface mineralisation extends over 2.5 km in a north–south direction and over 2 km east–west (Aragon Resources Ltd Press Release, 7 December 2010). Barrow Creek 1 is one of the shallowest phosphate deposits in the NT, is within 100 km of the Alice Springs–Darwin railway line and is currently held by Rum Jungle Resources Ltd. The adjacent Arganara prospect is held by NuPower Resources Ltd.

Some 60 km east of Ammaroo, phosphate mineralisation in the range 2.3–16.9% P_2O_5 was intersected over the depth range 30–75 m in waterbore RN013015 (**Figure 28.14**) near Ooratippra on the Sandover Highway. This phosphate is hosted within fine and cherty siltstone/sandstone of the Arthur Creek Formation (Khan *et al* 2007).

Gypsum

In 1985, Northern Cement Pty Ltd identified economic gypsum in grey-black clay-rich soil at 6 Mile Waterhole (RANKEN) on the south bank of the Playford River, 10 km west-southwest of Alexandria homestead. A 1986–1989 drilling program outlined a deposit up to 2.4 km long and 0.5–1.5 km wide, with a thickness of up to 3 m but averaging around 1.75 m. This deposit was estimated to contain at least one million cubic metres of gypsum (Nixon 1988c, 1989a, b).

Gypsum was also discovered at 18 Mile Waterhole in adjacent ALROY (Nixon 1988c). Four smaller, uneconomic gypsum occurrences were additionally mapped by Nixon (1990) on the Playford River west of Alexandria homestead (northwestern RANKEN).

Three further occurrences were recognised by Nixon (1988a) in the Brunette Creek–Lake Sylvester area of BRUNETTE DOWNS. One such site was auger drilled, but results were disappointing (Nixon 1988b).

Diamonds

The Georgina Basin was targeted for diamond exploration during the mid-1980s and early 2000s. Regional diamond exploration programs by CRA Exploration Ltd, Ashton Mining Ltd, Stockdale Prospecting Ltd, Aberfoyle Resources Ltd and Australian Diamond Exploration NL covered much of the central and northern Georgina Basin during the mid-1980s. These companies variously employed airborne and ground magnetic-radiometric surveys, photointerpretation, Landsat thematic mapping, density drainage gravel, soil and loam sampling, and shallow drilling (eg Allnutt and Bubner 1985, Ashton 1986). Drillholes targeting circular magnetic anomalies in RANKEN–AVON DOWNS intersected magnetically susceptible maghemite-bearing sand and grit, interpreted as karst infill in Cambrian dolostone (Allnutt and Bubner 1986a, b), or sandstone breccia of regolithic character (Bubner 1987). Modelling of aeromagnetic targets in eastern HELEN SPRINGS indicated that none had the dipolar characteristics of kimberlite diatremes (Hwang 1994a–c).

Up until the early 2000s, several exploration programs had discovered microdiamonds and abundant diamond indicator minerals (eg picroilmenite, mantle-derived chromite) in the southern Georgina Basin. They had been unable to trace the source of these minerals partly because of reworking into, and liberation from Cenozoic palaeochannels and regolith (Dunster *et al* 2007). A second phase of exploration, initiated by Elkedra Diamonds NL in 2001, focused on the southern Georgina Basin. Their exploration model drew on an analogy with the eastern Siberian Platform and relied on the presence of the Altjawarra Domain (Altjawarra craton of Myers *et al* 1996), a region of thickened, stable crust with relatively low heat flow and low crustal temperatures inferred to underlie much of TOBERMOREY, SANDOVER RIVER and eastern HUCKITTA (Teasdale and Pryer 2002, Tompkins *et al* 2003, Dunster *et al* 2007, see **Basement**). It was hoped that Cambrian or younger diamond-bearing kimberlite pipes would be preserved in the Georgina Basin succession and would be identifiable as discrete magnetic anomalies. Exploration licences covering most of AVON DOWNS were relinquished in 2004, following disappointing results (eg Ingram and Tompkins 2004). Other companies active in this period were De Beers and Astro Diamond Mines NL.

Manganese

The southern and central Georgina Basin contains numerous widespread, apparently surficial manganese occurrences. Surficial manganocrete and pisolitic manganiferous lag are known from outcrop and subcrop of the Ninmaroo, Tomahawk and Kelly Creek formations.

In western TOBERMOREY, two apparently stratabound occurrences, Lucy Creek 2 and Halfway Dam, initially gave encouraging high surface assays. Elkedra Diamonds NL reported three samples assaying 51%, 48% and 46% Mn and low levels of iron, phosphorus, silica and alumina from Lucy Creek 2 (53K 670300mE 7522200mN) in the Tomahawk Formation (Elkedra Diamonds NL, press release to ASX, 25 September 2002). Elevated levels of trace metals, replacement ore textures and close proximity to basement suggested a low-temperature hydrothermal origin similar to that of manganese deposits of the Tomkinson Province in the northern Tennant Region (see Ferenczi 2001, Scriven and Munson 2007). However, follow-up drilling results indicated that the volume of ore-grade material was insufficient to be economic and Elkedra Diamonds withdrew (Leadbeatter 2005). Lucy Creek 2 is now held by Auvex Resources Ltd-South Boulder Mines NL, who have confirmed the grade and extent of outcrop of surface manganese and ferro-manganese.

At Halfway Dam prospect (53K 702000mE 7507500mN), manganiferous material appears to be hosted in dolomitic quartz sandstone and dolostone at or near the base of the Kelly Creek Formation. Although relatively high Mn values of up to 69% were returned from some surface rock chip samples, no economic deposits were identified in the area (Leadbeatter and Tompkins 2004).

Other possibly locally significant assay results include rock chip samples from CWN-90 (in Tomahawk Formation) and Loc44 (in Ninmaroo Formation) which returned up to

42% and 29% Mn, respectively (Elkedra Diamonds NL, press release to ASX, 25 September 2002).

Uranium

Several companies have explored for uranium in the Georgina Basin but without appreciable success to date. A summary of the early history of uranium exploration, particularly in the southern part of the Georgina Basin, is given by Dunster *et al* (2007). Exploration programs have used models variously referred to as sediment-hosted, roll-front and unconformity-related. All three styles of mineralisation have been targeted at or near the unconformity between Arunta Region basement and overlying sedimentary rocks of the southern Georgina Basin. Other exploration models have included sediment-hosted uranium mineralisation in the Devonian Dulcie Sandstone, roll-front uranium mineralisation in the Marqua area in TOBERMOREY, unconformity-related uranium mineralisation at the top of the Mount Baldwin Formation in the northern Jervois Range and uranium in association with phosphate in the eastern Georgina Basin.

Uramet Minerals Ltd examined radiometric anomalies and conceptually targeted uranium mineralisation at the unconformity between Cenozoic lacustrine limestone and underlying Cambrian limestone, siliciclastic sedimentary rocks and basalt. At *Corella Lake*, several uranium anomalies detected by an airborne radiometric survey were found to correspond with broad, low mounds of chert nodules typical of the middle Cambrian Anthony Lagoon Formation and small areas of surficial ferruginisation. Soil sampling in 2008 used a single-channel scintillometer to find hot spots. Samples were subsequently analysed in the field using a Niton portable XRF analyser and by Genalysis Laboratory Services of Perth. Niton and laboratory assays showed moderate Th and K, but low U. The apparent discrepancy between the U-channel anomalies on the airborne radiometrics and the geochemical results remains unresolved and Uramet surrendered the EL in 2009 (Penna 2009b).

Most current uranium exploration activity in the Georgina Basin area is focused on mineralisation in overlying Cenozoic strata (see **Cenozoic geology and regolith**).

Petroleum

The southern Georgina Basin is among the most prospective onshore areas in the NT for both conventional and unconventional oil and gas, but exploration is still at the frontier stage, with only limited seismic data available. Key publications include Draper *et al* (1978), SIBGEO (1991a, b, 1992), Questa (1994), Ambrose (2000, 2002) and Ambrose *et al* (2001a, b); these are summarised by Dunster *et al* (2007).

Petroleum systems

The Georgina Basin contains elements of the Neoproterozoic Centralian petroleum supersystem of Bradshaw *et al* (1994) and, in particular, the prospective early Palaeozoic Larapintine supersystem of Bradshaw (1993) and Draper (2000).

Neoproterozoic strata have not been systematically evaluated for petroleum and there are no known hydrocarbon shows in rocks of this age. Their petroleum potential is therefore virtually unknown, although correlative Neoproterozoic rocks in other basins (eg Amadeus Basin) do contain petroleum shows. The Larapintine supersystem comprises three recognised petroleum systems in the southern Georgina Basin (Boreham and Ambrose 2007): Thorntonia(!) Petroleum System, Arthur Creek(!) Petroleum System and Hagen(!) Petroleum System[2]. The dominant reservoir-seal couplet in the Thorntonia(!) Petroleum System is the Thorntonia Limestone/basal Arthur Creek Formation black shale[3]. This is a regional system, but hydrothermal alteration may have reduced reservoir quality in some areas. The main targets in the Arthur Creek(!) Petroleum System are intraformational reservoir–seal couplets within the middle–upper Arthur Creek Formation. The Hagen(!) Petroleum System includes basal grainstones sealed by anhydrite on the western basin margin and is volumetrically the least important of the three.

Source rocks

There are few total organic carbon (TOC) analyses of Neoproterozoic rocks in the Georgina Basin. Shergold (1979b) reported 0.31–0.90% from three samples of a shale within the Yardida Tillite in BMR Hay River-10.

Potential Cambrian source rocks occur in the Thorntonia Limestone (maximum 8.6%, average 1.46% TOC) and Arthur Creek Formation. In particular, TOCs of selected samples of pyritic carbonaceous black shale in the lower Arthur Creek Formation are in the range 0.11–14.2% and average 3.3%, constituting a world-class prospective petroleum source rock. Thin shales in the Arrinthrunga Formation and the Hagen Member of the Chabalowe Formation are also viable source rocks, averaging over 1% TOC. Hydrocarbon yields in the Thorntonia Limestone and Arthur Creek Formation are generally high. Values range up to 50.7 kg/t and 35.8 kg/t respectively, although these may in part reflect migrated oil. Biomarker geochemistry indicates that each formation has generated genetically distinct oil. A Soviet study (SIBGEO 1991a, b, 1992) calculated that, overall, 40 x 10^9 t of oil have migrated (not just generated) in the southern Georgina Basin. Source rocks in the lower Arthur Creek Formation alone in the NT portion of the basin may have generated in excess of 10 x 10^9 t of oil.

Reservoirs and seals

Neoproterozoic siliciclastic rocks, intersected in Baldwin-1, NTGS Elkedra-3, Exoil Huckitta-1, NTGS Huckitta-1, Hunt-1, MacIntyre-1 and exploration drillholes at base metals prospects, have limited reservoir potential, because most porosity has been occluded by a silica cement (Dunster *et al* 2007). Ambrose *et al* (2001a) concluded that fracturing was the best prospect for reservoir quality improvement in Neoproterozoic siliciclastic rocks. Numerous argillaceous interbeds provide adequate intraformational seals.

[2] At the end of a petroleum system's name, the level of certainty is indicated by (!) for known, (.) for hypothetical, and (?) for speculative.
[3] Also colloquially referred to as 'hot shale', eg Ambrose *et al* (2001a).

In the Cambrian succession of the southern Georgina Basin, some of the best visible porosity occurs in fractured and vuggy dolostone. Potential reservoirs exist in the Red Heart Dolostone, medial and upper Thorntonia Limestone (**Figure 28.43**), upper Arthur Creek Formation [in drillhole MacIntyre-1 (**Figure 28.14**), this formation has measured permeabilities of 1.2 Darcies] and Hagen Member of the Chabalowe Formation. Dolomitic sandstone seen in Owen-2 exhibited core porosities of 10–15% and permeabilities of 15–95 mD. Potential reservoirs in the Arthur Creek Formation include tempestites, debris flows, middle-ramp submarine channels, oolitic shoals, near-shoreline quartz sandstones and valley-fill incision channels (Ambrose 2006, Boreham and Ambrose 2007). There are also potential reservoirs in the Early Ordovician Kelly Creek Formation, which flowed gas at about 240 000 cfd from Ethabuka-1 in Queensland. The overlying Ordovician Carlo Sandstone/Mithaka Formation is another potential reservoir/seal couplet.

Regional seals are provided by Arthur Creek Formation shale and other intraformational rocks with >1000 psi capillary pressure for 10% Hg saturation, and locally by anhydrite. Red beds in the upper Chabalowe Formation above the upper Arthur Creek Formation are also potential regional seals (Central Petroleum Ltd, ASX Announcement 30 April 2009).

Thermal maturity

Thermal maturity was documented by Dunster *et al* (2007). Middle Cambrian source rocks grade from immature in the north to overmature near the present southern margin of the basin. In addition, gas-prone to overmature rocks occur in a northwest-trending zone from the basin margin to the vicinity of Discovery Bore (ELKEDRA).

Prospectivity

Prospective areas within the southern Georgina Basin in the NT were conceptually subdivided by Ambrose *et al* (2001a) and Dunster *et al* (2007). Potential oil targets identified by Ambrose *et al* (2001a) included the Dulcie Trough, where postulated target depths are less than 1000 m, and the NT–Queensland border area, around drillholes Owen-2 and Todd-1 (**Figure 28.14**), where target depths were considered to be less than 1500 m. The Toko Trough was interpreted as being gas prone with target depths of >2000 m. Ambrose *et al* (2001a) considered the most promising stratigraphic intervals to be the juxtaposition of rubbly Thorntonia Limestone reservoir with source rocks in the medial Thorntonia Limestone and overlying lower Arthur Creek Formation; and intercalated source shale, reservoir dolograinstone and anhydrite seal in the Hagen Member of the Chabalowe Formation. Conceptual structural targets invoked by Dunster *et al* (2007) included proximity to early-mature troughs, the presence of structures associated with Ordovician faults, a lack of deformation during later phases of the Alice Springs Orogeny, and suitable reservoir–seal combinations at drillable depths. This study highlighted an area of Red Heart Dolostone ideally situated to be charged from the Dulcie and Marqua troughs. Dunster *et al* (2007) identified the Thorntonia Limestone and Arthur Creek Formation as containing potential reservoirs in a structurally favourable setting overlying the basement Altjawarra domain. Conceptual stratigraphic traps included an updip pinchout of the Red Heart Dolostone in HUCKITTA and the wedging out of the Thorntonia Limestone on the southern basin margin. They considered that siliciclastic wedges, which are developed downflank of palaeohighs, may enhance the reservoir potential of the Mount Baldwin Formation and its equivalents in the same area.

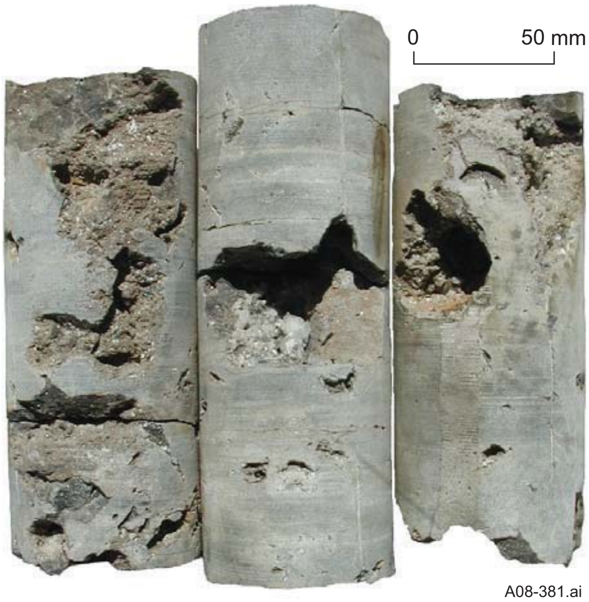


Figure 28.43. Vuggy porosity in core from Thorntonia Limestone at (from left to right) 959.6 m, 962.5 m and 962.7 m depth in Ross-1.

Questa (1994) considered the petroleum prospectivity of the relatively thin and unstructured central-northern Georgina Basin succession to be minimal. However, high-quality source rocks occur in the underlying McArthur Basin succession to the northeast and there is some evidence that hydrocarbons were generated and migrated/remigrated from these source rocks during the Palaeozoic (see **McArthur Basin – Petroleum**). It is therefore possible that parts of the northern Georgina Basin have received a hydrocarbon charge, although there has only been limited petroleum exploration activity in the region to date. In the Undilla Sub-basin, petroleum exploration well Lake Nash-1 was drilled in the axis of the Lake Nash Anticline (AVON DOWNS, **Figure 28.14**) by Amalgamated Petroleum NL in 1962. Viscous tar or asphalt and occasional oil drops were detected throughout 'Unit C' of Mines Administration (1963), interpreted as Thorntonia Limestone by Kruse and Radke (2008). Two petroleum wells were also drilled in the Barkly Sub-basin in 1964: Papuan Apinaipi Petroleum Company Ltd drilled Brunette Downs-1 to basement (Mines Administration 1964), and Barkley Oil Company Pty Ltd drilled Frewena-1 as a stratigraphic evaluation of the region (Pemberton and Webb 1965). Neither well encountered hydrocarbon shows and none of the above wells was continuously cored.

A dry gas flow in AOD drillhole Ethabuka-1 in Queensland remains the most significant show of any kind in the basin to date (Radke and Duff 1980), although widespread and locally abundant hydrocarbon shows have been reported from other wells drilled (Ambrose *et al* 2001a). Ethabuka-1 is also the only well of 23 drilled in the southern Georgina Basin to have tested a valid structural trap defined by seismic. Widespread shows have also been reported from the Red Heart Dolostone, Thorntonia Limestone (**Figure 28.44**), Arthur Creek Formation, Chabalowe Formation and Arrinthrunga Formation in the NT portion of the southern Georgina Basin. Collectively, these attest to the overall prospectivity, but untested nature of the basin.

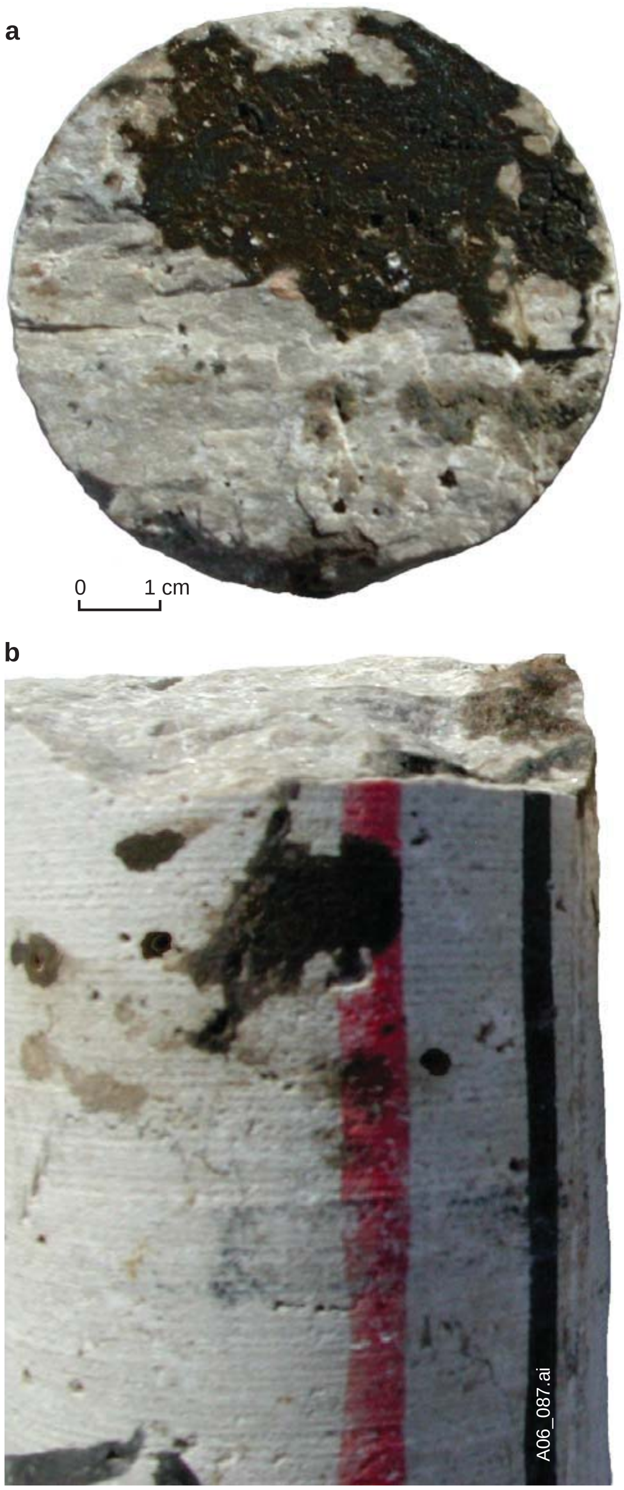


Figure 28.44. (**a**, **b**). Oil shows in Thorntonia Limestone (934.77 m depth in Ross-1, 53K 656524mE 7585548mN).

There is also considerable potential for unconventional basin-centred gas and oil plays over large areas of the basin (Tiem *et al* 2011), and the Arthur Creek Formation in particular is currently being investigated as a potential oil shale or tight gas reservoir. The high TOC in the Arthur Creek Formation basal black shale indicates that it is a very rich oil source that compares favourably to the Bakken oil shale in the Williston Basin of Canada and United States. The unconventional potential comprises gas or oil in fractured shale and other tight reservoirs, including fractured/vuggy silty dolostone of the upper Arthur Creek Formation and fractured silty shale of the lower Arthur Creek Formation (Central Petroleum Ltd, ASX Announcement 30 April 2009).

Based on a conservative assumption that up to 1.5% of migrated oil may have been trapped in fractures, Central Petroleum estimated that its tenements could contain as much as 650 Mmbbl Undiscovered Oil Initially In Place (UOIIP) in addition to 50 TCF (trillion cubic feet) of Undiscovered Gas Initially In Place (UGIIP). In the deeper Toko Syncline, Central Petroleum estimated that widespread thermal cracking of oil pools and gas accumulations could have generated up to 69 TCF of gas (Central Petroleum Ltd, ASX Announcement 30 April 2009). According to Ryder Scott (2010), the unrisked UOIIP for both conventional and unconventional reservoirs in the Georgina Basin tenements of PetroFrontier Corporation is estimated to be in the range 195 935–372 961 Mmbbl; the unrisked recoverable oil resource is estimated to be in the range 14 326–40 911 Mmbbl.

REFERENCES

Ahmad M and Scrimgeour IR, 2006. *Geological map of the Northern Territory. 1:2 500 000 scale*. Northern Territory Geological Survey, Darwin.

Alexander KR and Chalmers JB, 1982. Buchanan Dam EL 3536, N.T. Georgina Basin. Annual and final report, 1982. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1983-0151.

Allnutt SL and Bubner GJ, 1985. EL 4585, Mikado, NT. EL 4586, Lorne Creek, NT. EL 4587, James River, NT. EL 4588, Scrubby Creek, NT. Final report period ending 16 August, 1985. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1985-0270.

Allnutt SL and Bubner GJ, 1986a. EL 4596, Scarr EL 4597, Burramurra EL 4598, Bluebush Swamp EL 4608, Blenheim Hill. Annual report for the period ending 2nd September, 1986. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1986-0254.

Allnutt SL and Bubner GJ, 1986b. EL 4591 – Soudan, N.T. EL 4592 – Avon Downs, N.T. EL 4593 – Shakespeare Creek. EL 4594 – Happy Creek. Final report for the period to 26th June, 1986. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1986-0256.

Ambrose GJ, 2000. The Georgina and Pedirka Basins revisited: in Wood GR (compiler) *'Second Sprigg Symposium – Frontier Basins, Frontier Ideas, Adelaide, 29–30 June 2000'*. *Geological Society of Australia, Abstracts*, 64–67.

Ambrose GJ, 2002. New ideas on the petroleum potential of the southern Georgina Basin: in Cowie M (editor) *'Unlocking reserves using new ideas'. PESA (Queensland) Symposium, Brisbane, 11 September 2002*, 75–81.

Ambrose G, 2006. The Amadeus Basin: in *'Northern Territory of Australia, onshore hydrocarbon potential, 2006'. Northern Territory Geological Survey, Record* 2006-003.

Ambrose GJ, Kruse PD and Putnam PE, 2001a. Geology and hydrocarbon potential of the southern Georgina Basin, Australia. *APPEA Journal* 41, 139–163.

Ambrose GJ, Kruse PD and Putnam PE, 2001b. Exploration in a Middle Cambrian carbonate succession, Georgina Basin, Australia. *'AAPG Convention, Denver, Colorado, 3–6 June 2001.' American Association of Petroleum Geologists. Extended Abstracts.*

Apak, SN, Ghori, KAR, Carlsen, GM, and Stevens, MK, 2002, Basin development with implications for petroleum trap styles of the Neoproterozoic Officer Basin, Western Australia: in Keep M and Moss SJ (editors) *The sedimentary basins of Western Australia 3. Proceedings of the Petroleum Exploration Society of Australia (PESA) Symposium, Perth, Western Australia, 2002*, 913–928.

Ashton, 1986. Final report EL 4530 25th January 1985 to 7th January 1986. Ashton Mining Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1986-0111.

Barlow BC, 1965. Georgina Basin reconnaissance gravity survey, NT and Qld 1959. *Bureau of Mineral Resources, Australia, Record* 1965/96.

Barlow BC, 1966. Georgina Basin reconnaissance gravity surveys using helicopters, Northern Territory and Queensland 1960–1961. *Bureau of Mineral Resources, Australia, Record* 1966/147.

Boreham CJ and Ambrose GJ, 2007. Cambrian petroleum systems in the southern Georgina Basin, Northern Territory, Australia: in Munson TJ and Ambrose GJ (editors) *'Proceedings of the Central Australian Basins Symposium (CABS), Alice Springs, Northern Territory, 16–18 August, 2005'. Northern Territory Geological Survey, Special Publication* 2, 254–281.

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

Bradshaw MT, Bradshaw J, Murray A, Needham DJ, Spencer L, Summons R, Wilmot J and Winn S, 1994. Petroleum systems in west Australian basins: in Purcell PG and Purcell RR (editors) *'The sedimentary basins of Western Australia'. Proceedings of the PESA Symposium, Perth, 1994*, 93–118.

Bubner GJ, 1987. EL 4608 Blenheim Hill, NT. Annual report, year ending 2nd September 1987. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1987-0211.

Buick IS, Miller JA, Williams IS and Cartwright I, 2001. Ordovician high-grade metamorphism of a newly recognised late Neoproterozoic terrane in the northern Harts Range, central Australia. *Journal of Metamorphic Geology* 19, 373–394.

Buick IS, Hand M, Williams IS, Mawby J, Miller JA and Nicol RS, 2005. Detrital zircon provenance constraints on the evolution of the Harts Range Metamorphic Complex (central Australia): links to the Centralian Superbasin. *Journal of the Geological Society of London* 162, 777–787.

Calver CR, Black LP, Everard JL and Seymour DB, 2004. U–Pb zircon age constraints on late Neoproterozoic glaciation in Tasmania. *Geology* 32, 893–896.

Campbell MD, 1968. Progress report No 1 phosphate search, Authorities to Prospect Nos 1874 and 2081, Northern Territory, Australia. Continental Oil Company of Australia Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1968-0016.

Carter EK, Brooks JH and Walker KR, 1961. The Precambrian mineral belt of north-western Queensland. *Bureau of Mineral Resources, Australia, Bulletin* 51.

Carter EK and Öpik AA, 1961. *Lawn Hill – 4-mile geological series. Explanatory notes No. 21.* Bureau of Mineral Resources, Australia, Canberra.

Casey JN, 1959. New names in Queensland stratigraphy (part 5). North-west Queensland. *Australasian Oil and Gas Journal* 5(12), 31–36.

Casey JN and Gilbert-Tomlinson J, 1956. Cambrian geology of the Huckitta-Marqua region, Northern Territory. *XX International Geological Congress, Mexico* 2, 55–74. [Reprinted 1957 *Bureau of Mineral Resources, Australia, Bulletin* 49, 55–74].

Chuck RG, 1982. Annual report for EL 2654 Mount Skinner, NT for the period 24/1/81–23/1/82. Alcoa of Australia Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1982-0183.

Chuck RG, 1983. Base metal exploration in EL 2654, Mount Skinner, central Australia, final report. Alcoa of Australia Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1983-0125.

Colliver IC and Bubner GJ, 1987. Spear Creek MCs N980-983. Final report (period to 18 November 1986). CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1987-0002.

Condon MA, 1958. Geological notes, inspection trip, 1958. *Bureau of Mineral Resources, Australia, Record* 1958/106.

Cotton JS, 1972. Mount Skinner area, report on diamond drilling programme, June 1971 to January 1972. Centamin NL: in Base metal exploration in EL 2654, Mount Skinner, central Australia, final report. Alcoa of Australia Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1983-0125.

Cross A, Claoué-Long JC, Scrimgeour IR, Ahmad M and Kruse PD, 2005. Summary of results. Joint NTGS-GA geochronology project. Rum Jungle, basement to southern Georgina Basin and eastern Arunta Region 2001–2003. *Northern Territory Geological Survey, Record* 2005-006.

David TWE, 1932. *Explanatory notes to accompany a new geological map of the Commonwealth of Australia.* Commonwealth Council for Scientific and Industrial Research, Australasian Medical Publishing Co Ltd, Sydney.

Debrenne F, Zhuravlev AYu and Rozanov AYu, 1989. *'Pravil'nye arkheotsiaty [Regular archaeocyaths]'. Trudy Paleontologicheskogo Instituta, Akademiya Nauk SSSR* 233.

Debrenne F, Rozanov A and Zhuravlev A, 1990. *Regular Archaeocyaths. Morphology. Systematics. Biostratigraphy. Palaeoecology. Biological affinities.* Cahiers de Paléontologie, Editions du CNRS, Paris.

de Keyser F, 1969. The phosphate-bearing Cambrian formations in the Lawn Hill and Lady Annie districts, northwestern Queensland. *Bureau of Mineral Resources, Australia, Record* 1969/147.

de Keyser F, and Cook PJ, 1972. Geology of the Middle Cambrian phosphorites and associated sediments of northwestern Queensland. *Bureau of Mineral Resources, Australia, Bulletin* 138.

Denaro TJ and Dhnaram C (compilers), 2009. *Queensland Minerals 2009. A summary of major mineral resources mines and prospects.* Queensland Department of Mines and Energy.

Donnellan N, 2008. *Mount Peake and Lander River, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SF 53-05, SF 53-01.* Northern Territory Geological Survey, Darwin.

Draper JJ, 1977. Environment of deposition of the Carlo Sandstone, Georgina Basin, Queensland and Northern Territory. *BMR Journal of Australian Geology and Geophysics* 2, 97–110.

Draper JJ, 1978. Lead and zinc in carbonate rocks – prospects in the Georgina Basin, Northern Territory and Queensland. *BMR Journal of Australian Geology and Geophysics* 3, 261.

Draper JJ, 1980. Ethabuka Sandstone, a new Ordovician unit in the Georgina Basin, and a redefinition of the Toko Group. *Queensland Government Mining Journal* 81, 469–475.

Draper JJ, 2000. Petroleum supersystems in Queensland: a key to undiscovered petroleum resources. *Queensland Oil and Gas* 6(4), 42–47.

Draper JJ, Shergold JH and Heighway KA, 1978. A review of petroleum exploration and prospects in the Georgina Basin. *Bureau of Mineral Resources, Australia, Record* 1978/10.

Druce EC, Shergold JH and Radke BM, 1982. A reassessment of the Cambrian–Ordovician boundary section at Black Mountain, western Queensland, Australia: in Bassett MG and Dean WT (editors) *'The Cambrian–Ordovician boundary: sections, fossil distributions, and correlations'. National Museum of Wales, Geological Series* 3, 193–209.

Dunn PR, 1963. *Hodgson Downs, Northern Territory (First Edition). 1:250 000 geological map series and explanatory notes, SD 53-14.* Bureau of Mineral Resources, Australia, Canberra.

Dunster JN, Kruse PD, Duffett ML and Ambrose GJ, 2007. Geology and resource potential of the southern Georgina Basin. *Northern Territory Geological Survey, Digital Information Package* DIP007.

Elkedra, 2001. *Prospectus: diamonds the right commodity.* Elkedra Diamonds NL, Perth.

Eyre B, 1994. Early Cambrian alluvial fan-deltas in the Georgina Basin, Australia. *Australian Journal of Earth Sciences* 41, 27–36.

Ferenczi PA, 2001. Iron ore, manganese and bauxite deposits of the Northern Territory. *Northern Territory Geological Survey Report* 13.

Forrest R, 1970. Northern Territory phosphate 1970 drilling program. Prospecting Authority 1874 (Alroy area). Picklands Mather and Company International. *Northern Territory Geological Survey, Open File Company Report* CR1970-0079.

Freeman MJ, 1986. *Huckitta, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SF 53-11.* Northern Territory Geological Survey, Darwin.

Gausden J, 1980. Mirrica No. 1 AP160P Queensland well completion report. Alliance Oil Development Australia NL. *Queensland Department of Natural Resources and Mines, Open File Company Report* 8295.

Geyer G and Shergold J, 2000. The quest for internationally recognized divisions of Cambrian time. *Episodes* 23, 188–195.

Glass LM, 2002. *Petrogenesis and geochronology of the north Australian Kalkarinji low-Ti Continental Flood Basalt Province.* PhD thesis, Research School of Earth Sciences, Australian National University, Canberra.

Glass LM and Phillips D, 2006. The Kalkarindji Continental Flood Basalt Province. A new Cambrian Large Igneous Province in Australia with possible links to mass extinction. *Geology* 34, 461–464.

Graham BJ, 1988. EL 4596 Scarr, N.T. Annual report period ending 2 September, 1988. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1988-0341.

Grainger DJ, 1968a. The investigation of copper mineralisation in the Mount Skinner area. *Northern Territory Geological Survey, Technical Report* GS1968-0016.

Grainger DJ, 1968b. Copper mineralisation in the Mount Skinner area. *Northern Territory Geological Survey, Technical Report* GS1968-0017.

Gravestock DI and Shergold JH, 2001. Australian Early and Middle Cambrian sequence biostratigraphy with implications for species diversity and correlation: in Zhuravlev AYu and Riding R (editors) *The ecology of the Cambrian radiation.* Columbia University Press, New York, 107–136.

Greene DC, 2003. Laramide-style basement block faulting and fault inversion during the mid-Paleozoic intraplate Alice Springs Orogeny, Huckitta region, Northern Territory, central Australia. *Geological Society of America, Abstracts with Programs* 34(7), 344.

Greene DC, 2010. Neoproterozoic rifting in the southern Georgina Basin, central Australia: implications for reconstructing Australia in Rodinia. *Tectonics* 29, TC5010, doi:10.1029/2009TC002543.

Grey K, 2005. Ediacaran palynology of Australia. *Memoirs of the Association of Australasian Palaeontologists* 31.

Grey K, 2008. Biostratigraphic correlation of Neoproterozoic glacial successions in Australia: in Gallagher SJ and Wallace MW (editors) *'Selwyn Symposium 2008. Neoproterozoic extreme climates and the origin of early metazoan life'. Geological Society of Australia, Extended Abstracts* 91, 5–11.

Hackett DON, 1977. Exploration Licence 1081, Alroy, Alexandria, annual report 1976. ICI Australia Ltd–Australian Fertilizers Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1977-0038.

Haines PW, 1990. Late Proterozoic and Early Cambrian clastic facies relationships, southwestern Georgina Basin, Northern Territory. *Geological Society of Australia, Abstracts* 25, 60.

Haines PW, 1998. *Chuaria* Walcott, 1899 in the lower Wessel Group, Arafura Basin, northern Australia. *Alcheringa* 22, 1–8.

Haines PW, 2004. *Woodgreen, Northern Territory (Second Edition). 1:100 000 scale geological map series, 5753.* Northern Territory Geological Survey, Darwin.

Haines PW, Bagas L, Wyche S, Simons B and Morris DG, 1991. *Barrow Creek, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SF 53-06*. Northern Territory Geological Survey, Darwin.

Haines PW, Hand M and Sandiford M, 2001. Palaeozoic synorogenic sedimentation in central and northern Australia: a review of distribution and timing with implications for the evolution of intracontinental orogens. *Australian Journal of Earth Sciences* 48, 911–928.

Haines PW, Pietsch BA, Rawlings DJ and Madigan TL, 1993. *Mount Young, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SD 53-15.* Northern Territory Geological Survey, Darwin.

Haines PW, Scrimgeour IR and Duffett, 2007. *Woodgreen, Northern Territory (Second Edition). 1:100 000 geological map series explanatory notes, 5753.* Northern Territory Geological Survey, Darwin.

Haines PW and Wingate MTD, 2007. Contrasting depositional histories, detrital zircon provenance and hydrocarbon systems: did the Larapintine Seaway link the Canning and Amadeus basins during the Ordovician?: in Munson TJ and Ambrose GJ (editors) *'Proceedings of the Central Australian Basins Symposium (CABS), Alice Springs, Northern Territory, 16–18 August, 2005'. Northern Territory Geological Survey, Special Publication* 2, 36–51.

Halliday AL, 1965. Report on As to P No 1345 and 1359 for the three monthly period ending 9 September. Kennecott Explorations (Australia) Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1965-0012.

Halliday AL, 1966. Final report on A to P No 1556, Mount Skinner, NT. Kennecott Explorations (Australia) Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1966-0015.

Hand M, Mawby J, Kinny P and Foden, J, 1999. U-Pb ages from the Harts Range, central Australia: evidence for early Ordovician extension and constraints on Carboniferous metamorphism. *Journal of the Geological Society, London* 156, 715–730.

Harrison PL, 1979. Recent seismic studies upgrade the petroleum prospects of the Toko Syncline, Georgina Basin. *APEA Journal* 19(1), 30–42.

Henderson RA and MacKinnon DI, 1981. New Cambrian inarticulate Brachiopoda from Australasia and the age of the Tasman Formation. *Alcheringa* 5, 289–309.

Henderson RA and Southgate PN, 1978. Middle Cambrian stratigraphy and sedimentology of the eastern Georgina Basin: in Rubenach M (editor) *Excursions handbook, 3rd Australian Geological Convention, Townsville*. Geological Society of Australia, Townsville, 85–110.

Hills ES, 1959. Record of *Bothriolepis* and *Phyllolepis* (Upper Devonian) from the Northern Territory of Australia. *Journal of the Royal Society of New South Wales* 92, 174.

Howard PF, 1971. Discovery of phosphorite in northern Australia. *American Institute of Mining Engineers, Transactions* 250, 269–273.

Howard PF, 1972. Exploration for phosphorite in Australia – a case history. *Economic Geology* 67, 1180–1192.

Howard PF, 1986. Proterozoic and Cambrian phosphorites – regional review: Australia: in Cook PJ and Shergold JH (editors) *Phosphate deposits of the world. Volume 1. Proterozoic and Cambrian phosphorites.* Cambridge University Press, Cambridge, 20–41.

Howard PF, 1989. The Wonarah phosphate deposit, Georgina Basin, Australia: in Notholt AJG, Sheldon RP and Davidson DF (editors) *Phosphate deposits of the world. Volume 2. World phosphate resources.* Cambridge University Press, Cambridge, 545–550.

Howard PF, 1990. The distribution of phosphatic facies in the Georgina, Wiso and Daly River Basins, Northern Australia: in Notholt AJG and Jarvis I (editors) *'Phosphorite research and development'. Geological Society Special Publication* 52, 261–272.

Howard PF and Perrino FA, 1976. Wonarah phosphate deposit, Georgina Basin, Northern Territory: in Knight CL (editor) *'Economic geology of Australia and Papua New Guinea. 4. Industrial minerals and rocks'. Australasian Institute of Mining and Metallurgy, Monograph Series* 8, 273–277.

Hussey KJ, Beier PR, Crispe AJ, Donnellan N and Kruse PD, 2001. *Helen Springs, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SE 53-10.* Northern Territory Geological Survey, Darwin.

Hwang PH, 1994a. Helen Springs area (SE 53-10) Exploration Licence 8562 (Attack Creek), combined first and final report for period ending 24 October 1994. Stockdale Prospecting Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1994-0804.

Hwang PH, 1994b. Helen Springs area (SE 53-10) Exploration Licence 8563 (Tarrabool), combined first and final report for period ending 24 October 1994. Stockdale Prospecting Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1994-0805.

Hwang PH, 1994c. Helen Springs area (SE 53-10) Exploration Licence 8559 (Coolunjie), combined first and final report for period ending 24 October 1994. Stockdale Prospecting Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1994-0806.

Ingram J-A and Tompkins LA, 2004. Altjawarra Craton Diamond Project. Final relinquishment report for EL 23265 (Barkly's Chance). Elkedra Diamonds NL. *Northern Territory Geological Survey, Open File Company Report* CR2003-0373.

Ivanac JF, 1954. The geology and mineral deposits of the Tennant Creek goldfield, Northern Territory. *Bureau of Mineral Resources, Australia, Bulletin* 22.

Jackson MJ, Muir MD and Plumb KA, 1987. Geology of the southern McArthur Basin, Northern Territory. *Bureau of Mineral Resources, Australia, Bulletin* 220.

Jell PA, 1975. Australian Middle Cambrian eodiscids with a review of the superfamily. *Palaeontographica A* 150, 1–97.

Jell PA, 1977. *Penarosa netenta*, a new Middle Cambrian trilobite from northwestern Queensland. *Memoirs of the Queensland Museum* 18, 119–123.

Jell PA, 1978. *Asthenopsis* Whitehouse, 1939 (Trilobita, Middle Cambrian) in northern Australia. *Memoirs of the Queensland Museum* 18, 219–231.

Joklik GF, 1955. The geology and mica-fields of the Harts Range, central Australia. *Bureau of Mineral Resources, Australia, Bulletin* 26.

Jones PJ and McKenzie KG, 1980. Queensland Middle Cambrian Bradoriida (Crustacea): new taxa, palaeobiogeography and biological affinities. *Alcheringa* 4, 203–225.

Jones PJ, Shergold JH and Druce EC, 1971. Late Cambrian and Early Ordovician stages in western Queensland. *Journal of the Geological Society of Australia* 18, 1–32.

Kennard JM, 1981. The Arrinthrunga Formation: Upper Cambrian epeiric carbonates in the Georgina Basin, central Australia. *Bureau of Mineral Resources, Australia, Bulletin* 211.

Kennard JM, 1991. Lower Cambrian archaeocyathan buildups, Todd River Dolomite, northeast Amadeus Basin, central Australia: sedimentology and diagenesis. *Bureau of Mineral Resources, Australia, Bulletin* 236, 195–225.

Kennedy TJ, 1971. Authority to Prospect number 1874, Alroy area, Northern Territory. Report on 1971 drilling programme. Minoil Services Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1971-0012.

Khan M, Ferenczi PA, Ahmad M and Kruse PD, 2007. Phosphate testing of waterbores and diamond drillcore in the Georgina, Wiso and Daly basins, Northern Territory. *Northern Territory Geological Survey, Record* 2007-003.

Kostlin EC, 1970. Geochemical stream and soil sampling in AP2372 and AP2392, Huckitta, NT. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1971-0140A.

Kostlin EC, 1971. As to P 2372 and 2392, Huckitta, NT. Supplementary Report dated 7th May 1971. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1971-0140B.

Kruse PD, 1990. Cambrian palaeontology of the Daly Basin. *Northern Territory Geological Survey, Report* 7.

Kruse PD, 1991. Cambrian fauna of the Top Springs Limestone, Georgina Basin. *The Beagle, Records of the Northern Territory Museum of Arts and Sciences* 8, 169–188.

Kruse PD, 1996. Helen Springs stratigraphic drilling 1996 – NTGS96/1 Nilly Waterhole. *Northern Territory Geological Survey, Technical Report* GS1996-004.

Kruse PD, 1998. Cambrian palaeontology of the eastern Wiso and western Georgina Basins. *Northern Territory Geological Survey, Report* 9.

Kruse PD, 2003. Georgina Basin stratigraphic drilling and petrography, 1999–2002. *Northern Territory Geological Survey, Record* 2003-005.

Kruse PD, 2008. Georgina Basin stratigraphic drilling 2002–2006 and petrography 2000–2007. *Northern Territory Geological Survey, Record* 2008-001.

Kruse PD, Brakel AT, Dunster JN and Duffett ML, 2002a. *Tobermory, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SF 53-12.* Northern Territory Geological Survey, Darwin and Geoscience Australia, Canberra.

Kruse PD, Mohammed LC, Dunster JN and Duffett ML, 2002b. *Sandover River, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SF 53-08.* Northern Territory Geological Survey, Darwin.

Kruse PD, Laurie JR and Webby BD, 2004. Cambrian geology and palaeontology of the Ord Basin. *Memoirs of the Association of Australasian Palaeontologists* 30, 1–58 [jointly published as *Northern Territory Geological Survey, Record* 2004-006, 1–58].

Kruse PD, Maier RC and Khan M, 2010. *Walhallow-Brunette Downs-Alroy-Frew River, Northern Territory. 1:250 000 geological map series explanatory notes, SE 53-07, SE 53-11, SE 53-15, SF 53-03.* Northern Territory Geological Survey, Darwin.

Kruse PD and Mohammed LC, 2005. *Geology of the southern Georgina Basin, Northern Territory (First Edition). 1:500 000 geological special map.* Northern Territory Geological Survey, Darwin.

Kruse PD and Radke BM, 2008. *Ranken-Avon Downs, Northern Territory. 1:250 000 geological map series explanatory notes, SE 53-16, SF 53-04.* Northern Territory Geological Survey, Darwin.

Kruse PD and West PW, 1980. Archaeocyatha of the Amadeus and Georgina Basins. *BMR Journal of Australian Geology and Geophysics* 5, 165–181.

Kuhn TS and Barnes CR, 2005. Ordovician conodonts from the Mithaka Formation (Georgina Basin, Australia). Regional and paleobiogeographical implications. *Geologica Acta* 3, 317–337.

Laurie JR, 1986. Phosphatic fauna of the Early Cambrian Todd River Dolomite, Amadeus Basin, central Australia. *Alcheringa* 10, 431–454.

Laurie JR, 2000. Macrofossils from the Tomahawk beds, Georgina Basin, Tobermory 1:250,000 sheet area, Northern Territory. *Australian Geological Survey Organisation, Professional Opinion* 2000/34.

Laurie JR, 2004. Macrofossils from surface outcrop on Avon Downs and Ranken 1:250 000 map sheet areas and core from NTGS 01/1 and BMR GRG 16 drillholes. *Geoscience Australia, Professional Opinion* 2004/01.

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.

Laurie JR and Shergold JH, 1985. Phosphatic organisms and the correlation of Early Cambrian carbonate formations in central Australia. *BMR Journal of Australian Geology and Geophysics* 9, 83–89.

Leadbeatter J, 2005. Altjawarra Craton diamond project. Final technical report, EL22534 Lucy Creek East. Reporting period: 17/10/2002–15/06/2005. Elkedra Diamonds NL. *Northern Territory Geological Survey, Open File Company Report* CR2005-0680.

Leadbeatter J and Tompkins LA, 2004. Altjawarra Craton diamond project. Final relinquishment report for EL22529 (Tarlton). Elkedra Diamonds NL. *Northern Territory Geological Survey, Open File Company Report* CR2004-0609.

Lechler AR and Greene DC, 2006. Fault reactivation during intracontinental deformation: the Toko Syncline and Toomba Fault, Georgina Basin, central Australia. *Geological Society of America, Abstract Programs* 38(5), 11.

Lilley GJ, 2002. Partial relinquishment report for the period ending 2nd July 2002, for EL 22167 Wonarah 5 and EL 22168 Wonarah 6, Frew River SF 53-03, Avon Downs SE 53-04, Northern Territory. Rio Tinto Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR2002-0259.

Lindsay JF, Kruse PD, Green OR, Hawkins E, Brasier MD, Cartlidge J and Corfield RM, 2005. The Neoproterozoic–Cambrian record in Australia: a stable isotope study. *Precambrian Research* 143, 113–13.

Marshall NJ, 1989. Final and relinquishment report EL 5545 Randall's Peak, EL 5557 Hann Range/Mount Byrne, EL 5558 Mount Finniss, EL 5559 Turkey Creek, EL 5560 Mount Eaglebeak, EL 4326 Winnecke. Range Resources Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1989-0356.

Mawby J, Hand M and Foden J, 1999. Sm-Nd evidence for high-grade Ordovician metamorphism in the Arunta Block, central Australia. *Journal of Metamorphic Geology* 17, 653–668.

McGeough M, 1992. Exploration licence No. 7299 "Tobermory" Northern Territory: final report. MIM Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1992-0506.

McGeough M and Shalley M, 1992. Exploration licence No 7299 "Tobermory" NT. First annual report: year ended 3rd April, 1992. MIM Exploration Pty Ltd, Technical Report No. 1923. *Northern Territory Geological Survey, Open File Company Report* CR1992-0235.

McKenzie KG and Jones PJ, 1979. Partially preserved soft anatomy of a Middle Cambrian bradoriid (Ostracoda) from Queensland. *Search* 10, 444–445.

McMahon KH, 1969. Northern Territory Joint Venture. Phase II final report on operations for Area No 7 of AP 1733, "Carrara Range". Australian Geophysical Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1969-0002.

Menzies DC and Louwrens DJ, 1995. EL8016 Mount Gwynne, NT, EL8017 Mollie Bluff, NT, final report for period ending 27-04-1995. CRA Exploration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1995-0562.

Milligan EN, 1963. The Bureau of Mineral Resources Georgina Basin core drilling programme. *Bureau of Mineral Resources, Australia, Record* 1963/86.

Mines Administration, 1963. Amalgamated Petroleum Lake Nash No 1 – Oil Permit 53, Northern Territory. Well completion report. Mines Administration Pty Ltd. *Northern Territory Geological Survey, Open File Petroleum Report* PR1963-0018.

Mines Administration, 1964. P.A.P. Brunette Downs No.1 well, Northern Territory. Mines Administration Pty Ltd. Papuan Apinaipi Petroleum Company Ltd. *Northern Territory Geological Survey, Open File Petroleum Report* PR1964-0004.

Minemakers 2010. *Resource update. Wonarah rock phosphate project.* Minemakers Ltd, ASX Announcement, 10 February 2010.

Minemakers 2011. Development projects. Wonarah rock phosphate. Wonarah 2011 drilling results. **http://www.minemakers.com.au/projects-development-wonarah.php** (accessed 16/02/2011).

Morrison ME, 1968. Progress report on phosphate exploration to October 31, 1968, Ammaroo, NT. Vam Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1968-0051.

Mulready J, 1975. Well completion report, Ethabuka No 1, ATP 160P, Queensland. Alliance Petroleum Australia. *Queensland Department of Natural Resources and Mines, Open File Company Report* 5119.

Myers JS, Shaw RD and Tyler IM, 1996. Tectonic evolution of Proterozoic Australia. *Tectonics* 15, 1431–1446.

Nicoll RS, Nielsen AT, Laurie JR and Shergold JH, 1992. Preliminary correlation of latest Cambrian to Early Ordovician sea level events in Australia and Scandinavia: in Webby BD and Laurie JR (editors) *Global perspectives on Ordovician geology*. Balkema, Rotterdam, 381–394.

Nixon LG, 1988a. Annual report for period ending 16/6/1987 on Exploration Licence 4935, Brunette Creek, Brunette Downs station NT. LGB Nixon and Associates. *Northern Territory Geological Survey, Open File Company Report* CR1988-0002.

Nixon LG, 1988b. Relinquishment report on EL 4935 and final report on EL 4935. Northern Cement Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1988-0231.

Nixon LG, 1988c. Relinquished area report on Exploration Licence 4968 Alexandria station NT. Northern Cement Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1988-0240.

Nixon LG, 1989a. Annual report for period ending 27.6.89 on Exploration Licence No 4968 Alexandria station, Northern Territory. Northern Cement Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1989-0616.

Nixon LG, 1989b. Relinquished area report for Exploration Licence No 4968 Alexandria station, NT. Northern Cement Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1989-0617.

Nixon LG, 1990. Surrender report Exploration Licence No 4968 Alexandria station, Northern Territory. Northern

Cement Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1990-0551.

Noakes LC, 1956. Upper Proterozoic and sub-Cambrian rocks in Australia. *XX International Geological Congress, Mexico* 2, 213–238. [Reprinted 1957 *Bureau of Mineral Resources, Australia, Bulletin* 49, 213–238].

Noakes LC, Carter EK and Öpik AA, 1959. *Urandangi – 4-mile geological series (Second Edition). Explanatory notes No. 1.* Bureau of Mineral Resources, Australia, Canberra.

Noakes LC and Traves DM, 1954. Outline of the geology of the Barkly Region: in *'Survey of the Barkly Region, Northern Territory and Queensland, 1947–48'. CSIRO Land Research Series* 3, 34–41.

Offe LA, 1978. *Mount Peake, Northern Territory (First Edition). 1:250 000 geological series explanatory notes, SF 53-05.* Bureau of Mineral Resources, Australia, Canberra.

Öpik AA, 1954. Cambrian stratigraphy of the Camooweal region (progress report). *Bureau of Mineral Resources, Australia, Record* 1954/31.

Öpik AA, 1956a. Cambrian geology of Queensland. *XX International Geological Congress, Mexico* 2, 1–24. [Reprinted 1957 in *Bureau of Mineral Resources, Australia, Bulletin* 49, 1–24].

Öpik AA, 1956b. Cambrian geology of the Northern Territory. *XX International Geological Congress, Mexico* 2, 25–54. [Reprinted 1957 in *Bureau of Mineral Resources, Australia, Bulletin* 49, 25–54].

Öpik AA 1960. Cambrian and Ordovician geology [of Queensland]. *Journal of the Geological Society of Australia* 7, 89–109.

Öpik AA, 1970. Nepeid trilobites of the Middle Cambrian of northern Australia. *Bureau of Mineral Resources, Australia, Bulletin* 113.

Öpik AA, 1979. Middle Cambrian agnostids: systematics and biostratigraphy. *Bureau of Mineral Resources, Australia, Bulletin* 172.

Öpik AA, 1982. Dolichometopid trilobites of Queensland, Northern Territory, and New South Wales. *Bureau of Mineral Resources, Australia, Bulletin* 175.

Pemberton RL and Webb EA, 1965. Completion report Frewena No 1 well Oil Permit 73 (2), Northern Territory. *Northern Territory Geological Survey, Open File Petroleum Report* PR1965-0029.

Penna P, 2009a. Annual Report for EL 22537 – Box Hole base metal project. Uramet Minerals Ltd. *Northern Territory Geological Survey, Closed File Company Report* CR2009-0461 (used with permission).

Penna P, 2009b. Final Report EL 25992 – Corella Lake uranium project. Reporting period: 29 October 2007 to 28 October 2009. Uramet Minerals Ltd. *Northern Territory Geological Survey, Open File Company Report* CR2009-0830.

Penna P, 2010a. Final Report, SEL 24769 – Marqua, Marqua project. Reporting period: 09.08.2006–08.08.2010. Uramet Minerals Ltd. *Northern Territory Geological Survey, Open File Company Report* CR2010-0557.

Penna P, 2010b. EL 25574 – Final report. Reporting period: 30.07.2007–29.07.2010. Uramet Minerals Ltd. *Northern Territory Geological Survey, Open File Company Report* CR2010-0661.

Perrino FA, 1970. Progress report on Prospecting Authorities 1766, 1897, 2159, 2160, 2161 and 2199 in the Alexandria region. IMC Development Corporation. *Northern Territory Geological Survey, Open File Company Report* CR1970-0038.

Phosphate Australia 2011. Advanced stage: Highland Plains phosphate project. **http://www.phosphateaustralia.com.au/projects/highland/** (accessed 16/02/2011).

Pietsch BA, Rawlings DJ, Creaser PM, Kruse PD, Ahmad M, Ferenczi PA and Findhammer TLR, 1991. *Bauhinia Downs, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SE 53-13.* Northern Territory Geological Survey, Darwin.

Plumb KA and Rhodes JM, 1963. Explanatory notes on the Wallhallow 1:250 000 geological sheet series SE 53-07, Northern Territory. *Bureau of Mineral Resources, Australia, Record* 1963/116.

Plumb KA and Rhodes JM, 1964. *Wallhallow, Northern Territory (First Edition). 1:250 000 geological map series explanatory notes, SE 53-07.* Bureau of Mineral Resources, Australia, Canberra.

Plumb KA, Shergold, JH and Stefanski MZ, 1976. Significance of Middle Cambrian trilobites from Elcho Island, Northern Territory. *BMR Journal of Australian Geology and Geophysics* 1, 51–55.

Pojeta J Jr, Gilbert-Tomlinson J and Shergold JH, 1977. Cambrian and Ordovician rostroconch molluscs from northern Australia. *Bureau of Mineral Resources, Australia, Bulletin* 171.

Preiss WV, Walter MR, Coats RP, and Wells AT, 1978. Lithologic correlations of Adelaidean glaciogenic rocks in parts of the Amadeus, Ngalia and Georgina basins. *BMR Journal of Australian Geology and Geophysics* 3, 45–53.

Pryer L and Loutit T, 2005. *OZ SEEBASE™ structural GIS 2005 version 1.* FrogTech Pty Ltd, Canberra.

Questa, 1994. *Georgina Basin*. Northern Territory Geological Survey, Petroleum Basin Study. Questa Australia Pty Ltd.

Radke BM, 1980. Epeiric carbonate sedimentation of the Ninmaroo Formation (Upper Cambrian-Lower Ordovician), Georgina Basin. *BMR Journal of Australian Geology and Geophysics* 5, 183–200.

Radke BM, 1981. Lithostratigraphy of the Ninmaroo Formation (Upper Cambrian-Lower Ordovician), Georgina Basin, Queensland and Northern Territory. *Bureau of Mineral Resources, Australia, Report* 181; *BMR Microform* MF153.

Radke BM and Duff P, 1980. A potential reservoir in the Georgina Basin: the lower Ordovician Kelly Creek Formation. *BMR Journal of Australian Geology and Geophysics* 5, 160–163.

Rawlings DJ, 2004. *Robinson River, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SE 53-04.* Northern Territory Geological Survey, Darwin.

Rawlings DJ, Haines PW, Madigan TLA, Pietsch BA, Sweet IP, Plumb KA and Krassay AA, 1997. *Arnhem Bay–Gove, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SD 53-03, 04.* Northern

Territory Geological Survey, Darwin and Australian Geological Survey Organisation, Canberra.

Rawlings DJ, Sweet IP and Kruse PD, 2008. *Mount Drummond, Northern Territory. 1:250 000 geological map series explanatory notes, SE 53-12*. Northern Territory Geological Survey, Darwin.

Reynolds MA, 1965. *Glenormiston, Queensland (First Edition). 1:250 000 geological series explanatory notes, SF 54-09*. Bureau of Mineral Resources, Australia, Canberra.

Reynolds MA, 1968. *Mount Whelan, Queensland (First Edition). 1:250 000 geological series explanatory notes, SF 54-13*. Bureau of Mineral Resources, Australia, Canberra.

Reynolds MA and Pritchard PW, 1964. The geology of the Glenormiston 1:250,000 sheet area. *Bureau of Mineral Resources, Australia, Record* 1964/28.

Rogers JK and Keevers RE, 1976. Lady Annie-Lady Jane phosphate deposits, Georgina Basin, Queensland: in Knight CL (editor) *'Economic geology of Australia and Papua New Guinea 4. Industrial minerals and rocks'. Australasian Institute of Mining and Metallurgy, Monograph Series* 8, 251–265.

Runnegar BN and Jell PA, 1976. Australian Middle Cambrian molluscs and their bearing on early molluscan evolution. *Alcheringa* 1, 109–138.

Ryder Scott, 2010. *Evaluation of the hydrocarbon resource potential pertaining to certain acreage interests in the southern Georgina Basin, Northern Territory, Australia, as of November 1, 2010*. Report prepared by Ryder Scott Company Petroleum Consultants for Australian Energy Corporation.

Saltzman MR, Cowan CA, Runkel AC, Runnegar B, Stewart MC and Palmer AR, 2004. The Late Cambrian SPICE ($\delta^{13}C$) event and the Sauk II-Sauk III regression: new evidence from Laurentian basins in Utah, Iowa, and Newfoundland. *Journal of Sedimentary Research* 74, 366–377.

Saltzman MR, Young SA, Kump LR, Gill BC, Lyons TW and Runnegar B, 2011. Pulse of atmospheric oxygen during the late Cambrian. *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* 108, 3876–3881.

Sas ZA, 2003. Partial relinquishment report for the period ending 6th February 2003 for EL 9976, Wonarah. Frew River SF 53-03, Avon Downs SE 53-04, Alroy SE 53-15, Ranken SE 53-16, Northern Territory. AKD Ltd. *Northern Territory Geological Survey, Open File Company Report* CR2003-0183.

Scrimgeour IR and Raith JG, 2001. Tectonic and thermal events in the northeastern Arunta Province. *Northern Territory Geological Survey, Report* 12.

Scriven NH and Munson TJ, 2007. Manganese in the sand and spinifex, Bootu Creek area, Northern Territory: in Munson TJ and Ambrose GJ (editors) *'Proceedings of the Central Australian Basins Symposium (CABS), Alice Springs, Northern Territory, 16–18 August, 2005'. Northern Territory Geological Survey, Special Publication* 2, 60–70.

Shaw RD and Warren RG, 1975. *Alcoota, Northern Territory (First Edition). 1:250 000 geological series explanatory notes, SF 53-10*. Bureau of Mineral Resources, Australia, Canberra.

Southgate PN, 1986. The Gowers Formation and Bronco Stromatolith Bed, two new stratigraphic units in the Undilla portion of the Georgina Basin. *Queensland Government Mining Journal* October, 407–411.

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.

Shergold JH (editor), 1979a. Georgina research, December quarter, 1978. *Bureau of Mineral Resources, Australia, Record* 1979/17.

Shergold JH (editor), 1979b. Georgina research, March quarter, 1979. *Bureau of Mineral Resources, Australia, Record* 1979/39.

Shergold JH, 1985. Notes to accompany the Hay River-Mount Whelan Special 1:250 000 geological sheet, southern Georgina Basin. *Bureau of Mineral Resources, Australia, Report* 251.

Shergold JH, 1997. Explanatory notes for the Cambrian correlation chart: in Kaesler RL (editor) *Treatise on invertebrate paleontology, Part O Arthropoda 1, Trilobita, Revised. Volume 1: Introduction, Order Agnostida, Order Redlichiida*. Geological Society of America, Inc and University of Kansas, Boulder and Lawrence, 303–311.

Shergold JH and Druce EC, 1980. Upper Proterozoic and Lower Palaeozoic rocks of the Georgina Basin: in Henderson RA and Stephenson PJ (editors) *The geology and geophysics of northeastern Australia*. Geological Society of Australia, Queensland Division, Brisbane, 149–174.

Shergold JH, Druce EC, Radke BM and Draper JJ, 1976. Cambrian and Ordovician stratigraphy of the eastern portion of the Georgina Basin, Queensland and eastern Northern Territory. *XXV International Geological Congress, Sydney, Excursion Guide* 4C.

Shergold JH, Jago JB, Cooper RA and Laurie JR, 1985. The Cambrian system in Australia, Antarctica and New Zealand. *International Union of Geological Sciences, Publication* 19.

Shergold JH and Nicoll RS, 1992. Revised Cambrian–Ordovician boundary biostratigraphy, Black Mountain, western Queensland: in Webby BD and Laurie JR (editors) *Global perspectives on Ordovician geology*. Balkema, Rotterdam, 81–92.

Shergold JH and Southgate PN, 1986. Middle Cambrian phosphatic and calcareous lithofacies along the eastern margin of the Georgina Basin, western Queensland. *Australasian Sedimentologists Group, Field Guide Series* 2. Geological Society of Australia, Sydney.

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

Shergold JH and Walter MR, 1979. BMR stratigraphic drilling in the Georgina Basin, 1977 and 1978. *Bureau of Mineral Resources, Australia, Record* 1979/36.

SIBGEO, 1991a. Provision of engineering type work for the determination of the quality and maturity of source rocks in the Georgina Basin. Report on contract 589/1423602/90023 by the Siberian Branch, USSR Academy of Sciences for Pacific Oil and Gas Pty Ltd. Volume 1 [1991], text [incomplete]; Volume 2 [1992], lithological-petrographic atlas (Georgina Basin); Volume 3 [1991], table of rock, kerogen, bitumoid and naphthide compositions [this volume incomplete, see also SIBGEO 1992, PR1993-002]. *Northern Territory Geological Survey, Open File Petroleum Report* PR1992-0107.

SIBGEO, 1991b. Provision of engineering type work for the determination of the quality and maturity of source rocks in the Georgina Basin. Report on contract 589/1423602/90023 by the Siberian Branch, USSR Academy of Sciences for Pacific Oil and Gas Pty Ltd. Volume 1 [1991], text; Volume 2 [1991], lithologic-petrographic atlas (Georgina Basin) graphical appendix; Volume 3 [1991], table of rock, kerogen, bitumoid and naphthide compositions; Volume 4 [1991], Appendix 19 plot of pyrolysis data vs TOC content and extract yield (Georgina Basin). *Northern Territory Geological Survey, Open File Petroleum Report* PR1993-006.

SIBGEO, 1992. Provision of engineering type work for the determination of the quality and maturity of source rocks in the Georgina Basin. Report on contract 589/1423602/90023 by the Siberian Branch, USSR Academy of Sciences for Pacific Oil and Gas Pty Ltd. Volume 1, text; Volume 2, plot of pyrolysis data vs TOC content and extract yield (Georgina Basin); Volume 3, table of rock, kerogen, bitumoid and naphthide compositions; Volume 4, Graphical Appendix. *Northern Territory Geological Survey, Open File Petroleum Report* PR1993-002.

Simpson CJ, Shergold JH, Radke BM, Walter MR, Wilford GE, Green D and Draper JJ, 1985. *Geology of the Hay River-Mount Whelan area, southern Georgina Basin (First Edition) 1:250,000-scale geological special map*. Geoscience Australia, Canberra and Geological Survey of Queensland, Brisbane.

Smith JW, 1964. *Bauhinia Downs, Northern Territory (First Edition). 1:250 000 geological map series explanatory notes, SE 53-03*. Bureau of Mineral Resources, Australia, Canberra.

Smith JW and Roberts HG, 1963. *Mount Drummond, Northern Territory (First Edition). 1:250 000 geological map series explanatory notes, SE 53-12*. Bureau of Mineral Resources, Australia, Canberra.

Smith KG, 1963a. *Hay River, Northern Territory (First Edition). 1:250 000 geological series explanatory notes, SF 53-16*. Bureau of Mineral Resources, Australia, Canberra.

Smith KG, 1963b. *Huckitta, Northern Territory (First Edition). 1:250 000 geological series explanatory notes, SF 53-11.* Bureau of Mineral Resources, Australia, Canberra.

Smith KG, 1964. Progress report on the geology of the Huckitta 1:250 000 sheet, Northern Territory. *Bureau of Mineral Resources, Australia, Report* 67.

Smith KG, 1965. *Tobermory, Northern Territory (First Edition). 1:250 000 geological series explanatory notes, SF 53-12*. Bureau of Mineral Resources, Australia, Canberra.

Smith KG, 1972. Stratigraphy of the Georgina Basin. *Bureau of Mineral Resources, Australia, Bulletin* 111.

Smith KG and Milligan EN, 1964. *Barrow Creek, Northern Territory (First Edition). 1:250 000 geological series explanatory notes, SF 53-06*. Bureau of Mineral Resources, Australia, Canberra.

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.

Stait K and Druce EC, 1993. Conodonts from the Lower Ordovician Coolibah Formation, Georgina Basin, central Australia. *BMR Journal of Australian Geology and Geophysics* 13, 293–322.

Stewart HWJ and Hoyling N, 1963. Morstone No. 1. Authority to Prospect 79 P – Queensland well completion report. Amalgamated Petroleum Exploration Pty Ltd. *Queensland Department of Natural Resources and Mines, Open File Company Report* 1173.

Stidolph PA, Bagas L, Donnellan N, Walley AM, Morris DG and Simons B, 1988. *Elkedra, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SF 53-07.* Northern Territory Geological Survey, Darwin.

Sturmfels EK, 1960. Mineralisation in the surroundings of the Turkey Creek lead–zinc prospect, NT. Report to Enterprise Exploration Company Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1960-0004.

Teasdale J and Pryer LL, 2002. Georgina SEEBASE™ Project (and GIS), April–May 2002. SRK Consulting Services report to Northern Territory Geological Survey. *Northern Territory Geological Survey, Record* 2002-004.

Tickell SJ, 2005. Groundwater resources of the Tindall Limestone. *Natural Resources Division, Northern Territory Department of Natural Resources, the Environment and the Arts, Technical Report* 34/2005.

Tiem VTA, Horsfield B and di Primo R, 2011. Gas shale potential of the Amadeus and Georgina Basins, Australia: preliminary insights. *Geoscience Australia, Record* 2011/10.

Tompkins LA, Taylor W and Cowan D, 2003. Diamond prospectivity of the Altjawarra Craton, Australia. *8th International Kimberlite Conference, Canada 2003, 22–27 June, Victoria, BC, Extended Abstracts*, 1–5.

Turner S, Jones PJ and Draper JJ, 1981. Early Devonian thelodonts (Agnatha) from the Toko Syncline, western Queensland, and a review of other Australian discoveries. *BMR Journal of Australian Geology and Geophysics* 6, 51–69.

Uramet Minerals, 2008. *Quarterly report to shareholders 31 December 2008*. Uramet Minerals Ltd.

Utah, 1970. First annual report for prospecting authority No 2430, NT, for the period ending November 25th, 1970. Utah Development Company. *Northern Territory Geological Survey, Open File Company Report* CR1970-0076.

Virtue RJ, 1988. Exploration Licence 5145 – "Marqua" (1:250 000 sheet SF 52-12 Tobermory). Report for 12 months 29 January 1987 to 28 January 1988. Saracen Minerals NL, Timbarra Mines NL, RT Gardiner and Associates. *Northern Territory Geological Survey, Open File Company Report* CR1988-0057.

Wakelin-King GJ, 1992. Randall No. 1 EP 10, Northern Territory well completion report. Pacific Oil and Gas Pty Ltd. *Northern Territory Geological Survey, Open File Petroleum Report* PR1992-0025.

Walley AM, 1987. *Frew River, Northern Territory (Second Edition). 1:250 000 geological series explanatory notes, SF 53-03.* Northern Territory Geological Survey, Darwin.

Walter MR, 1972. Stromatolites and the biostratigraphy of the Australian Precambrian and Cambrian. *Special Papers in Palaeontology* 11.

Walter MR, 1980. Adelaidean and Early Cambrian stratigraphy of the southwestern Georgina Basin: correlation chart and explanatory notes. *Bureau of Mineral Resources, Australia, Report* 214; *BMR Microform* MF92.

Walter MR, Elphinstone R and Heys GR, 1989. Proterozoic and Early Cambrian trace fossils from the Amadeus and Georgina Basins, central Australia. *Alcheringa* 13, 209–256.

Walter MR, Grey K, Williams I and Calver CR, 1994. Stratigraphy of the Neoproterozoic to early Palaeozoic Savory Basin, Western Australia, and correlation with the Amadeus and Officer Basins. *Australian Journal of Earth Sciences* 41, 533–546.

Walter MR, Shergold JH, Muir MD and Kruse PD, 1979. Early Cambrian and latest Proterozoic stratigraphy, Desert Syncline, southern Georgina Basin. *Journal of the Geological Society of Australia* 26, 305–312.

Walter MR and Veevers JJ, 1997. Australian Neoproterozoic palaeogeography, tectonics and supercontinental connections. *AGSO Journal of Australian Geology and Geophysics* 17, 73–92.

Walter MR and Veevers JJ, 2000. Neoproterozoic Australia: in Veevers JJ (editor) *Billion-year history of Australia and neighbours in Gondwanaland*. GEMOC Press, Sydney.

Walter MR, Veevers JJ, Calver CR and Grey K, 1995. Neoproterozoic stratigraphy of the Centralian Superbasin, Australia. *Precambrian Research* 73, 173–195.

Warren RG, 1981. Tectonic setting of the easternmost Arunta Block. *Bureau of Mineral Resources, Australia, Report* 221; *BMR Microform* MF154.

Webby BD, 1978. History of the Ordovician continental platform and shelf margin of Australia. *Journal of the Geological Society of Australia* 25, 41–63.

Webby BD, Vanden-Berg AHM, Cooper RA, Banks MR, Burrett CF, Henderson RA, Clarkson PD, Hughes CP, Laurie J, Stait B, Thomson MRA and Webers GF, 1981. The Ordovician system in Australia, New Zealand and Antarctica. Correlation chart and explanatory notes. *International Union of Geological Sciences, Publication* 6.

Wells AT, Forman DJ, Ranford LC and Cook PJ, 1970. Geology of the Amadeus Basin, central Australia. *Bureau of Mineral Resources, Australia, Bulletin* 100.

Wells AT and Moss FJ, 1983. The Ngalia Basin, Northern Territory: stratigraphy and structure. *Bureau of Mineral Resources, Australia, Bulletin* 212.

Whitehouse FW, 1936. The Cambrian faunas of north-eastern Australia. Part 1: Stratigraphical outline. Part 2: Trilobita (Miomera). *Memoirs of the Queensland Museum* 11, 59–112.

Whitehouse FW, 1939. The Cambrian faunas of north-eastern Australia. Part 3: the polymerid trilobites (with supplement No. 1). *Memoirs of the Queensland Museum* 11, 179–282.

Whitehouse FW, 1945. The Cambrian faunas of north-eastern Australia. Part 5: The trilobite genus *Dorypyge*. *Memoirs of the Queensland Museum* 12, 117–123.

Wyche S and Simons B, 1987. *Bonney Well, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SF 53-02.* Northern Territory Geological Survey, Darwin.

Youles IP, 1965. Copper mineralisation in the Central Mount Stuart beds at Mount Skinner, NT. *Northern Territory Mines Branch, NT Administration, Report* MBR/65/4.

Young DN, Duncan N, Camacho A, Ferenczi PA and Madigan TLA, 2002. *Ayers Rock, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SG 52-08.* Northern Territory Geological Survey, Darwin.

Young GC and Goujet D, 2003. Devonian fish remains from the Dulcie Sandstone and Cravens Peak Beds, Georgina Basin, central Australia. *Records of the Western Australian Museum, Supplement* 65.

Ypma PJ, 1983. Period 25-6-82 to 25-6-83 progress report on EL 3166 and EL 3214, Huckitta sheet SF 53-11, the Box Hole area. *Northern Territory Geological Survey, Open File Company Report* CR1983-0313.

Ypma PJ, 1984. The lead-zinc mineralisation at Box Hole Bore, Georgina Basin, Northern Territory: in *'Darwin conference, 1984'.* Australasian Institute of Mining and Metallurgy, Parkville, 339–345.

Zhao Jianxin, McCulloch MT and Korsch RJ, 1994. Characterisation of a plume-related ~800 Ma magmatic event and its implications for basin formation in central-southern Australia. *Earth and Planetary Science Letters* 121, 349–367.