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Cainozoic sedimentary basins in the eastern Arunta Block, Alice Springs region, central Australia

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Tertiary sedimentary rocks, in places over 200 m thick, occupy a series of elongate basins within and partly surrounding the Arunta crystalline basement in the Alice Springs region, central Australia. The best-known sedimentary succession is that of the Hale Basin, where four distinctive members constitute the poorly indurated Early Tertiary Hale Formation. The oldest, the Ambalindum Sandstone Member, rests on deeply weathered basement. It is overlain by the Delaney Mudstone Member, olive-green mudstone and siltstone, deposited probably under quiet-water reducing conditions in a series of large lakes. At this time there was low input of terrigenous detritus from the nearby MacDonnell, Strangways and Harts Ranges. In places, these fine-grained sediments grade upwards and laterally into a lignite and oil shale unit, the Ulgnamba Lignite Member, probably reflecting local development of shoals and peripheral swamps. A mid to Late Eocene age is likely for this member. The Ulgnamba Lignite Member or, where it is absent, the Delaney Mudstone Member, passes abruptly upwards into the poorly sorted, coarse-grained Tug Sandstone Member. This unit is likely to have been deposited rapidly on piedmont slopes flanking the margins of the uplands. The abrupt change in sedimentary characteristics suggests either uplift in the nearby ranges or a change in climate, or both. In the Hale Basin and other Cainozoic basins, the uppermost part of the Cainozoic succession, the Waite Formation, generally consists of green and red, silty sandstone, containing ferruginous pisoliths and a few massive chalcedonic calcrete beds. Erosion, possibly in the Oligocene, partly removed the older Cainozoic sediments as well as ferricrete formed at the basin margins, and incorporated some of the detritus in the Waite Formation. Other Tertiary basins overlying the eastern part of the Arunta Block show a broad lithostratigraphic similarity to the Hale Basin. Palynological studies of carbonaceous sedimentary rocks and lignite in the Hale, Bundey and Ayers Rock Basins, combined with palaeomagnetic and stratigraphic data, suggest that sedimentation in these basins took place in two main phases—the first, largely in the Paleogene, may have begun in the Late Cretaceous; the other, in the Neogene, began in the Late Miocene or Early Pliocene after one or more breaks in deposition, which are likely to have occurred in the Oligocene. Although there are large gaps in the sedimentary succession, there are sufficient data to broadly relate the depositional sequence to the pattern of uplift and sagging in the Alice Springs region and, in a general way, equate these movements with tectonism within the Australian Plate. Palaeomagnetic dating, in some cases supported by palynology, has identified two main periods of intense chemical weathering in these central Australian basins. The younger, near the top of the Hale Formation, has a Late Eocene magnetic age. The older is represented by relict weathered profiles developed in the Arunta basement, and may be earliest Tertiary or older. In addition to these two main weathering periods, various oxidised, mottled or silicified rocks in several basins indicate other, lesser periods of interrupted sedimentation and weathering.

Introduction

The distribution and stratigraphy of central Australian Tertiary basins in general have been discussed by Perry et al. (1962), Hays (1967), and Mabbutt (1967), but since then they have received little attention in the geological literature, owing, in part, to their poor outcrop and to strong weathering overprints. Early investigations of specific basins tended to focus on groundwater (e.g. Woolley 1965a, b, 1966; Morton 1965; O'Sullivan 1973a, b; Jacobson et al. 1989; McDonald et al. 1988a, b), but lignite has been investigated in the Hale Basin, vertebrate fossils at Alcoota in the Waite Basin (Woodburne 1967), and uranium in the Ti-Tree Basin (O'Sullivan 1973; Hughes & O'Sullivan 1973).

This study reviews current understanding of Cainozoic sedimentary basins in the eastern part of the Arunta Block, with particular focus on the Hale, Ti-Tree, Waite, Bundey, and Aremra Basins, where stratigraphic drilling was carried out from 1973 to 1986 by the then Bureau of Mineral Resources (BMR; now the Australian Geological Survey Organisation, AGSO). The results provide a framework for reconstruction of the probable Cainozoic depositional, weathering, climatic and tectonic history of central Australia. Although there are still large gaps in our knowledge, the data have wide implications in the context of the palaeogeographic and tectonic evolution of the Australian Plate.

Drilling and reconnaissance geological mapping have shown that the basin sequences have been profoundly altered by weathering, with its associated mineralogical and chemical changes. The sedimentary sequence also contains contemporaneous siliceous and calcareous beds, as well as redeposited or recycled sediments, including former weathered and/or chemically precipitated rock types.

Besides drilling, the main stratigraphic information comes from geological reconnaissance in several Tertiary basins. The Waite Basin (Alcoota 1:250 000 Sheet area) was investigated by Yeates (1971). Parts of the Sixteen Mile, the Burt and the Ti-Tree Basins were drilled in 1973. Both the Aremra Basin (Illogwa Creek 1:250 000 Sheet area) and southwestern part of the Ti-Tree Basin (Alcoota 1:250 000 Sheet area) were investigated by BMR in 1979. The Hale River Basin was also drilled by BMR in 1979. Results from drilling in the Hale Basin by the Northern Territory Geological Survey (NTGS; Clarke, 1975) and by industry in the early 1980s are also incorporated.

Much of this investigation was carried out by B.R. Senior (Senior, 1972; Shaw et al., 1982). A multidisciplinary study of the sedimentation, age and weathering history of Cainozoic epicratonic basins commenced in BMR in 1979. This study included preliminary palaeomagnetic dating of ferruginous weathered profiles and palynological studies of a carbonaceous and lignitic succession from the Hale Basin, as well as further geological studies elsewhere in the region. Palynological work was carried out on lignite and carbonaceous rock types in drill core supplied by the Northern Territory Geological Survey from the Hale Basin east of The Garden homestead, (Truswell & Marchant, 1986). Ferruginised rocks were studied palaeomagnetically to establish the timing of weathering events in the Alice Springs region. This paper summarises the published palynological work, as well as

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interim results of the palaeomagnetic work already mentioned. It also attempts to synthesise the findings, up to 1994, of other BMR/AGSO research in the region.

Outline of Cainozoic geology

Tertiary rocks in the Alice Springs region occupy elongate intermontane basins (which, at least in some cases, are fault-controlled) and flanking palaeodrainages and piedmont deposits—some basins appear to have been initiated as early as the Late Cretaceous (Harris & Twidale 1991). In places, the succession is more than 200 m thick, but outcrops are rare and mostly deeply weathered. The Tertiary sequences are mantled by widespread unconsolidated Quaternary sediments, forming the flat or subdued depositional landscapes of the main river systems, including those of the Ti-Tree, Hanson, Plenty, Bundey, Illogwa, and Hale Rivers. Most of the riverine plains are partly bounded by steep, deeply dissected mountain ranges, some merging with lowlands of bedrock dotted with flat-topped residuals.

The Cainozoic sedimentary succession mostly overlies crystalline Proterozoic Arunta basement, but it also overlies parts of the Neoproterozoic to Palaeozoic Amadeus and Georgina Basins (Fig. 1). Much of the Tertiary sedimentary succession has been eroded from the northwestern, central and southeastern parts of the Amadeus Basin.

Evidence presented here suggests that, for the most part, sediment accumulated in two separate pulses, one in the Paleogene and the other in the Neogene. The first partly filled narrow depressions within mountain ranges of the Precambrian crystalline Arunta basement; examples are the Hale, Burt, Mount Wedge, and Whitcherry Basins. Deposition in the second pulse was in palaeodrainage depressions on the northern and eastern flanks of the uplands formed by the basement; depressions preserving this pulse include, for example, the Aremra, Bundey, Ti-Tree, Willowra, Ngalabaldjiri, and Yaloogarie Basins.

On the southernmost flanks of the uplands, which here include part of the Amadeus Basin, the Cainozoic history was very different. Piedmont fans formed on actively steepening slopes were dissected, both during and after deposition, to form a series of mesas (Fig. 1). The most active period of dissection started possibly in the late Pliocene with uplift in the MacDonnell Ranges (Shaw & Wells 1983). Only in the Ayers Rock Basin was deposition more-or-less continual (Jacobson et al. 1989). An idealised overview of how the mapped lithostratigraphic units relate to landforms is given in Figure 2.

The basement complex and the Tertiary sequences appear to have undergone more than one period of intense chemical weathering. According to Senior (1972), a trizonal weathered profile developed in crystalline Arunta rocks. This profile is up to 40 m thick and grades from a lowermost leached zone through an intermediate mottled zone to a ferruginous top. Erosion subsequently stripped the profile from most of the area, some of the detritus being incorporated into sediments accumulating within the intermontane basins. The Tertiary rocks were, in turn, weathered and crusts of silcrete, ferricrete, and thin ferruginous profiles developed in the Yaloogarie Basin (Stewart 1976), Hale Basin (this paper), and in the western Ti-Tree Basin (O'Sullivan 1973). Earlier, Mabbutt (1967) drew attention to the lateral variation from laterite at the centre to silcrete at the margins of the Hale Plain (Hale Basin), attributing this variation to a shallower, less-fluctuating former water table in the axial region, together with possible down-slope migration of iron.

Results from reconnaissance geological work indicate that ferruginous profiles on the Lower to Upper Jurassic Hooray Sandstone, along the northwest margin of the Eromanga Basin in the Illogwa Creek 1:250 000 Sheet area, were ferruginised possibly during the Late Cretaceous and Paleocene. In the Hale Basin and at three places in the Arunta basement rocks, recognition of a mid-Tertiary ferruginisation event is supported by palaeomagnetic work.

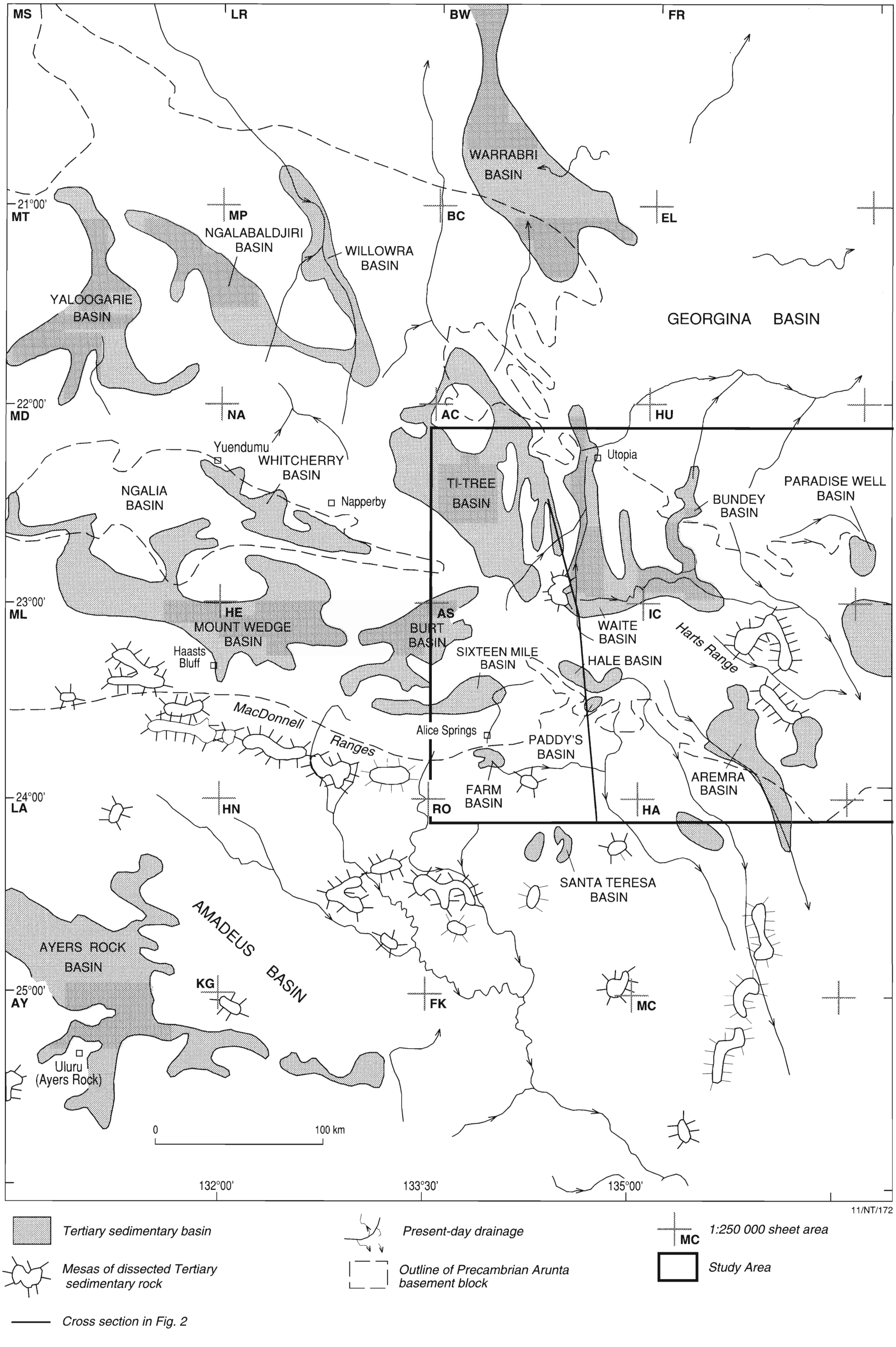
Because of the complex weathering history, which altered the mineralogical composition of much exposed rock, and the absence or destruction of fossils, age relations between individual Cainozoic rock units in the Alice Springs region remain uncertain. Nevertheless, some idea of the most likely stratigraphic framework is provided by palaeontological evidence from adjacent areas that appear to have a parallel history.

Palynological work between Ayers Rock and the Olgas suggests that deposition there may have begun as early as the Late Cretaceous, possibly even earlier. Lignites near the base of the 100 m thick succession were dated originally as Paleocene (Twidale & Harris 1977), but a recent reassessment, based on discovery of further diagnostic spore species, suggests that parts of the section are as old as the Maastrichtian Stage of the Late Cretaceous (Harris & Twidale 1991). Harris & Twidale (1991) concluded that there were at least three depositional phases in the area—a Late Cretaceous, a possible mid to Late Paleocene, and a Late Eocene phase.

Palynology indicates that carbonaceous clay in BMR Napperby 1, in a probable arm of the Whitcherry Basin (Fig. 1), is also of Eocene age (Kemp 1976). Carbonaceous sediments in the Ti-Tree Basin were described by Galloway & Kemp (1977) as possibly Miocene, but they could, on more recent data, be as old as Eocene. Vertebrate fossils indicate a Late Miocene or Early Pliocene age for the upper part of the Waite Formation near Alcoota station (Woodburne 1967). The palaeontological evidence, therefore, suggests that most of the sedimentary succession in the eastern Arunta region is Late Cretaceous to Miocene or Pliocene. From the Pliocene to the present day, sedimentation continued intermittently in local depressions.

The sequence of poorly to moderately lithified sedimentary rocks (conglomerate, sandstone, siltstone, mudstone, lignite, oil shale, and calcarenitic chalcedonic limestone) and weathered profiles of Cainozoic age in the Hale Basin northeast of Alice Springs is shown in Table 1. This composite reference section, established from surface mapping and drilling, forms the basis of the regional

Figure 1. Inferred outline of Tertiary basins, showing their relation to the underlying Arunta basement (non-standard projection). The 1:250 000 map sheets are abbreviated as follows: AC—Alcoota, AS—Alice Springs, AY—Ayers Rock, BC—Barrow Creek, BW—Bonney Well, EL—Elkedra, FK—Finke, FR—Frew River, HA—Hale River, HN—Henbury, HE—Hermannsburg, HU—Huckitta, IL—Illogwa Creek, KG—Kulgera, LA—Lake Amadeus, MC—McDills, MD—Mount Doreen, ML—Mount Liebig, MP—Mount Peake, MS—Mount Solitaire, MT—Mount Theo, NA—Napperby, RO—Rodinga.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Tertiary sedimentary basin
Present-day drainage
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Mesas of dissected Tertiary
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Outline of Precambrian Arunta
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Study Area
Cross section in Fig. 2

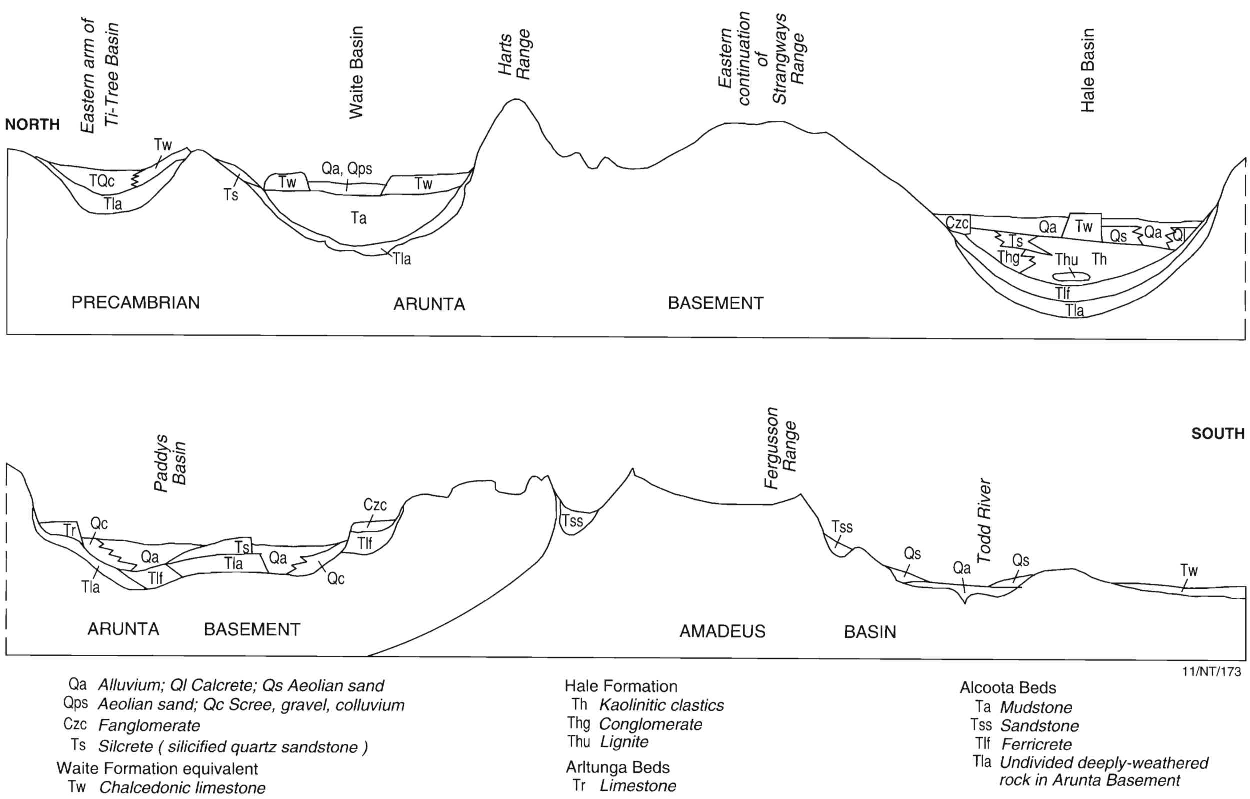

Figure 2. Diagrammatic N–S cross-section of the Hale Basin and regions bordering the eastern MacDonnell Ranges, showing the relationship between the surficial geological units and the topography.

stratigraphic framework described here. It incorporates data from Lloyd (1968), Senior (1972), Shaw & Warren (1975), and Shaw et al. (1979a, b), and the results of more recent studies. The stratigraphic succession and ages of some units, and particularly of weathering events, have been updated in accordance with evidence discussed here.

Hale Basin

This basin lies about 80 km northeast of Alice Springs (Figs 1–3). It underlies the Hale Plain between Claraville and The Garden homesteads, and is one of a number of small, sediment-filled depressions on a deeply weathered surface of Proterozoic and early Palaeozoic rocks. The basin forms a complex arcuate depression about 45 km long and up to 13 km wide. Its southern margin may have been a fault which controlled initial subsidence in the Late Cretaceous or Early Paleocene. The full succession is developed in the more extensive western part of the basin, where the reference succession is located in BMR DDH Alice Springs SH 2; another section has been described from the NTGS DDH 1 (Figs 4 & 5). A thinner sequence is preserved in the east in the Claraville Sub-basin, which is separated from the main basin by a basement ridge. The surrounding basement rocks comprise largely metamorphic rocks and granites of the Arunta Block (Shaw & Wells 1983).

The basin is filled with mainly fluviatile and lacustrine clastics (Clarke 1975; Senior *in* Shaw et al. 1982; Shaw et al. 1984). The spatial and temporal distributions of the deposits have been determined from reconnaissance mapping (Shaw & Langworthy 1984; Shaw et al. 1984), the logging of chip samples left *in situ* by an exploration company (Fig. 5), and stratigraphic drilling by BMR in 1966 and NTGS in 1975 (Figs 3–5 for locations).

Stratigraphy

At the base of the succession, overlying the deeply weathered metamorphics of the basement complex (Tlf of the map units, Table 1; weathering event A in Figure 4), is the Hale Formation (Th) (Stewart et al. 1980a; Shaw et al. 1984), a unit of kaolinitic quartz sandstone, siltstone, and mudstone, which grades into coarser sediments at the basin margins. In the Hale Formation (Fig. 4; Table 1) the succession begins with the Ambalindum Sandstone Member (Thg), argillaceous, poorly sorted sandstone with intercalations of granule and pebble conglomerate. It is about 55 m thick in BMR DDH Alice Springs No. 2. Conformably overlying this unit in the main western part of the basin is the Ulgnamba Lignite Member (Thu), formally defined by Stewart et al. (1980b) as the unit of lignite and carbonaceous shale which is 4 m thick in its type section in BMR DDH Alice Springs SH 2. The lignite also crops out, in a very weathered state, in a mesa 3 km west-northwest of Claraville homestead. Locally, the lignite is accompanied by pockets of oil shale. In the Claraville Sub-basin, an olive-green unit of mudstone and siltstone lies immediately below a discontinuous, carbonaceous clay unit assigned to the Ulgnamba Lignite Member. The olive-green unit is informally referred to as the Delaney Mudstone Member (Thc) and appears to belong to the same episode of deposition as the lignite. Thus, the Ulgnamba Lignite Member is a facies variant of the upper part of the Delaney Mudstone Member.

In the eastern Claraville Sub-basin, the Delaney Mudstone Member rests in places on weathered (yellow) sandstone (weathering event B in Figs 4 & 5), presumed to be the Ambalindum Sandstone Member (Fig. 5). The Delaney Mudstone Member (Thc) occurs as lenses in several of the drill holes penetrating the Hale Plain; it becomes

Table 1. Summary of stratigraphy.

Rock unit	*Lithology*	*Thickness*	*Tectonic events*	*Environment, fossils and age*
Qa	Fine and coarse clay-quartzose sand, silt and minor gravel, lacking a marked soil profile		Possible uplift in the area of the Harts, Strangways and MacDonnell Ranges or rejuvenation due to subsidence within the Lake Eyre Basin	Channels date from latest pluvial period—either Holocene or latest Pleistocene.
Ql	Calcrete; hard calcareous cements within formerly porous sediments			Humid oxidising conditions succeeded by aridity and aeolian activity. Cementation of porous surface sediments and colluvium forming calcareous crusts.
Qs, Qps	Quartzose sand (Qs); with fixed dunes (Qps)		Region tectonically stable	Development of broad sand plains with minor dune fields.
Qc	Colluvium, eluvium, scree			
Qr	Shallow red, oxidised, clayey and sandy oxidised soil ("Red earth"), clayey, oxidised silty-sand			Soil produced by repeated phases of alluviation and burial. Mixed with sheet sands (Qs) suggesting that the unit began forming in the late Pliocene (Litchfield 1969).
Czg	Redistributed ferricrete and quartz gravel	20 m		Transported ferruginous clastics derived from deeply weathered profiles.
Czc	Fanglomerate	20 m	Movement on some faults	Alluvial fan deposits flanking uplands.
Tw Waite Formation and equivalents	Greenish grey siltstone and chalcedonic limestone in type area.	20 m	Region tectonically stable	Argillaceous sediments and chemical precipitates in very quiet lacustrine environments. Age is Late Miocene–Early Pliocene (Woodburne 1967).
Arltunga beds Tr	Arenaceous limestone, silicified limestone, pebbly sandstone	4 m	Probable mild uplift and warping of some fault-bounded blocks	Coarse clastics grading to minor lake sediments. Probably equivalent to Tw (above) or, less likely, Th (below). Preceded by widespread hiatus.
Ts, Tl (overprint of Tlf, Tla)	Silcrete (strongly silicified quartzose sedimentary or felsic igneous rocks), Weathering Event C		Region tectonically stable	Groundwater silica sourced from felsic igneous rocks in regions of restricted drainage (e.g. margin of Hale and Paddys Plain Basins). Late Eocene age for Weathering Event C determined palaeomagnetically.
Hale Formation Th, (Thr, Thu, Thc, Thg)	Kaolinitic quartzose sandstone, siltstone and mudstone, minor conglomerate and lignite	195 m in Sixteen Mile Bore (Nth of Alice Springs)	Probable mild uplift and warping of some fault-bounded blocks	Lakes and swamps succeeded by river sediments grading laterally to coarse, poorly sorted clastics along intermontane margins. Probably equivalent to unit Ta of the Waite and Aremra Basins.
Tug Sandstone Member Thr	Brown sand and minor silt (subsurface)	30 m in NTGS DDH-1		
Ulgnamba Lignite Member, Thu	Grey carbonaceous clay, lignite	10 m in NTGS DDH-1		Marsh or swamp habitat. Lignite is probably mid-Late Eocene (Truswell & Marchant 1986).
Delaney Mudstone Member, Thc	Olive green mudstone and siltstone, locally developed mottled Weathering Event B	Equiv. unit 72 m in BMR Alcoota 20		Weathering Event B
Ambalindum Sandstone Member, Thg	Poorly sorted boulder conglomerate at basin margin in outcrop; Silty sand and sand in subsurface	55 m in DDH BMR Alice SH2		High energy fluviatile deposits
Tlf	Ferricrete (Weathering Event A extensive, Weathering Event C overprint)		See below	See below
Tla	Undivided weathered profile with ferruginous, mottled and leached zones, in places grading down into unweathered rocks. Well developed on coarsely crystalline igneous rocks. Weathering Event A.	±20 m	Region tectonically stable, widespread weathering.	Deep weathering under humid conditions. Seasonal precipitation, and fluctuating water-table, forming a trizonal weathered profile. Palaeomagnetic evidence from the Eromanga Basin suggests a Maastrichtian to Early Eocene weathering event (Idnurm & Senior 1978).

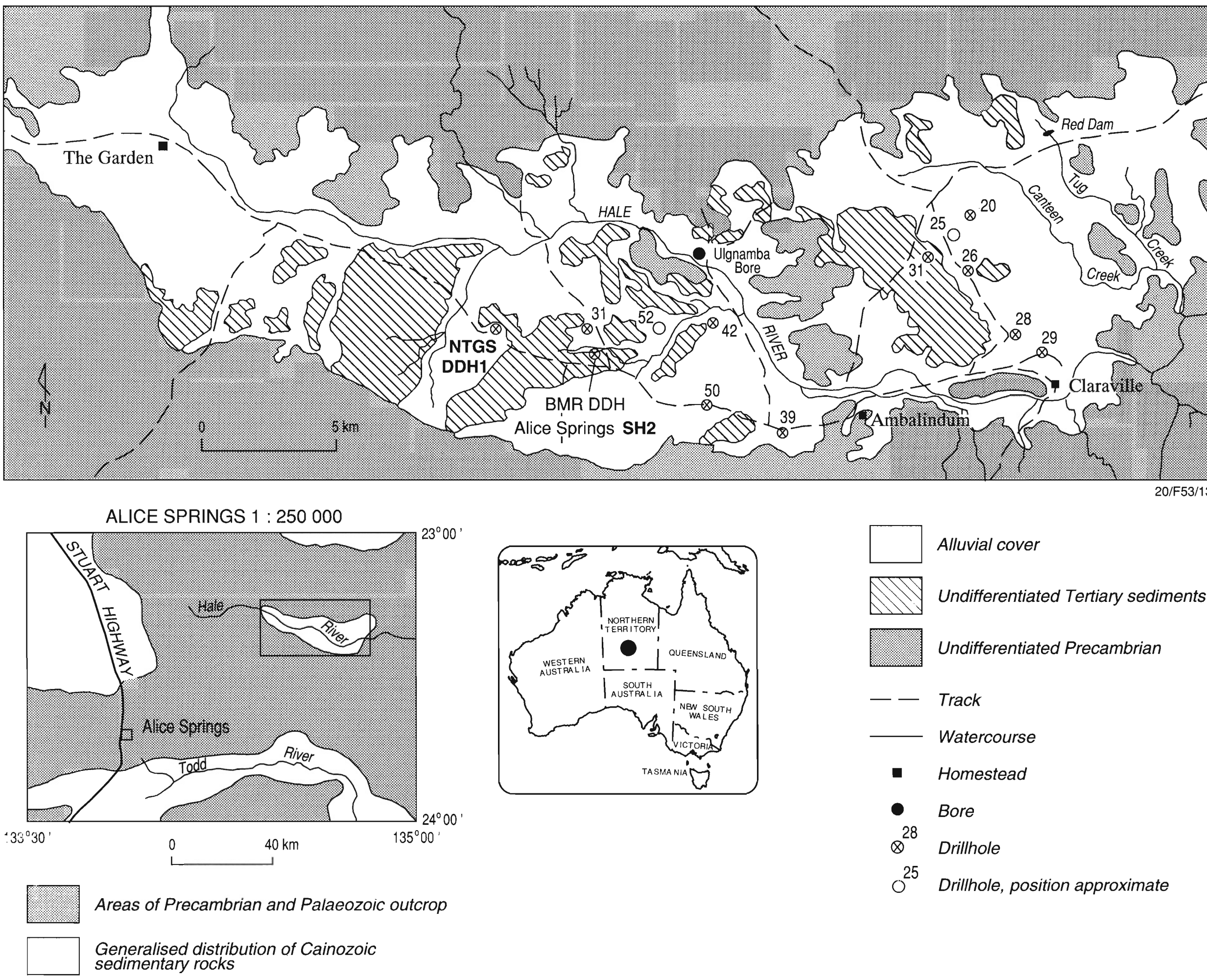

Figure 3. Sketch map of the Hale Basin, showing the location of NTGS DDH1, BMR DDH Alice Springs SH2 and a series of company drill holes.

sandier westwards so that in the region of BMR DDH Alice Springs SH2 it equates with a sandstone above a thin conglomerate (Fig. 5).

Above the lignite, the uppermost part of the Hale Formation has been referred to informally as the 'Arltunga Member', a unit mapped in the Paddys Basin several kilometres to the south. This is a succession of poorly consolidated, fine-grained brown silty sandstone, with minor sandy siltstone, and clay interbeds. There is some confusion about its nomenclature, as the name Arltunga beds has been used for calcarenitic limestones which may be more appropriately grouped with either the Hale Formation (Senior *in* Shaw et al. 1979a) or the overlying Waite Formation equivalents (Shaw & Wells 1983; Shaw et al. 1984). For this reason, it is placed in a new unit, the Tug Sandstone Member (Tht).

The Hale Formation appears to record deposition in a progressively flooding and slowly subsiding basin (Clarke 1975). The basal sandstones reflect a relatively high-energy fluvial environment, whereas the Ulgnamba Lignite Member records a marsh or swamp habitat and the Tug Sandstone Member probably a phase of relatively low-energy fluviolacustrine sedimentation. As noted earlier, such specific palaeoenvironmental interpretations need to be confirmed by more detailed future studies—for example, little information on sedimentary structures is at present available.

Formation of silcrete (Ts) in former porous and permeable quartzose sandstone, presumably by groundwater movements, and another interval of deep weathering (weathering event C in Figs 4 & 5) affected the Tug Sandstone Member and the adjoining basement. This weathering preceded deposition of a fine-grained clastic unit equated with the Waite Formation (Tw). In the surrounding basement, the ferruginous weathering unit, now placed in Tl, had been previously assigned to Tlf (Shaw et al. 1984). The Waite Formation was originally defined in the Waite Basin to the northeast (Shaw et al. 1982), where Woodburne (1967) described a Late Miocene to Early Pliocene vertebrate fossil assemblage.

Age of the Ulgnamba Lignite Member (Thu)

Dating the relatively thin successions in the Cainozoic basins of inland Australia continues to be a major problem. The difficulties of setting up a time framework within these basins were outlined by Truswell & Harris (1982): the sequences are entirely non-marine, and frequently deeply weathered; there are no intercalated volcanics that would allow radiometric dating; and the sequences are for the most part too thin to permit the use of magnetic reversal stratigraphy as a dating tool. In addition, they are remote from key palynological reference sections for Australia, which have been defined in the southeast.

In the Hale River Basin, the Hale Formation is both underlain and overlain by deeply weathered profiles. The climatic event that produced a trizonal weathered profile in the basement Arunta rocks on which the Cainozoic sequences rest is likely to have occurred in the Late Cretaceous and/or Paleocene, based on a comparison with the chronology of weathered profile development in the Eromanga Basin of southwest Queensland. The second, younger, weathering event, which affected the top of the Hale Formation, was suggested by Senior (in Shaw et al. 1979b) to be Late Oligocene to Early Miocene, on the assumption that this event correlated with the younger of the two weathering events in the Eromanga Basin (see Senior et al. 1978). However, preliminary palaeomagnetic results from the Hale Basin indicate Late Eocene as the most likely age for the weathering (see **Discussion** below), suggesting Late Eocene as the probable younger age limit for the Hale Formation and its included Ulgnamba Lignite Member. The outcropping ferruginised or deeply weathered basement rocks sampled north of the Hale Basin similarly record a Late Eocene age of magnetisation.

Truswell & Marchant (1986) described palynomorphs from the Ulgnamba Lignite Member, at 42.2 m depth in the borehole DDH-1, drilled by the Northern Territory Geological Survey. The assemblage was correlated with the middle *Nothofagidites asperus* Zone of the Gippsland

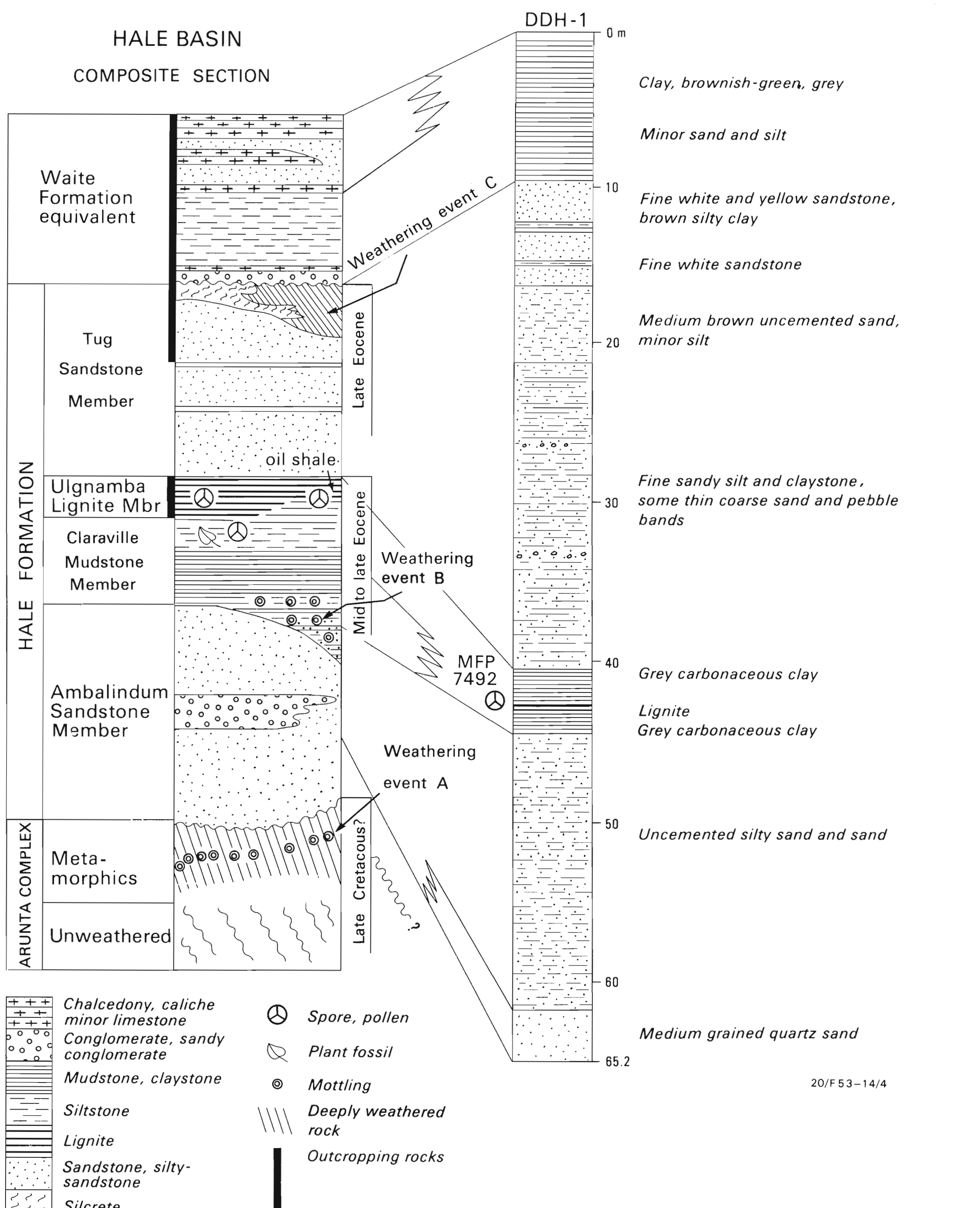

Figure 4. Stratigraphic column for NTGS DDH1, showing correlation with a generalised section of the Hale Basin, which is based in part on the succession intersected in BMR DDH Alice Springs SH2.

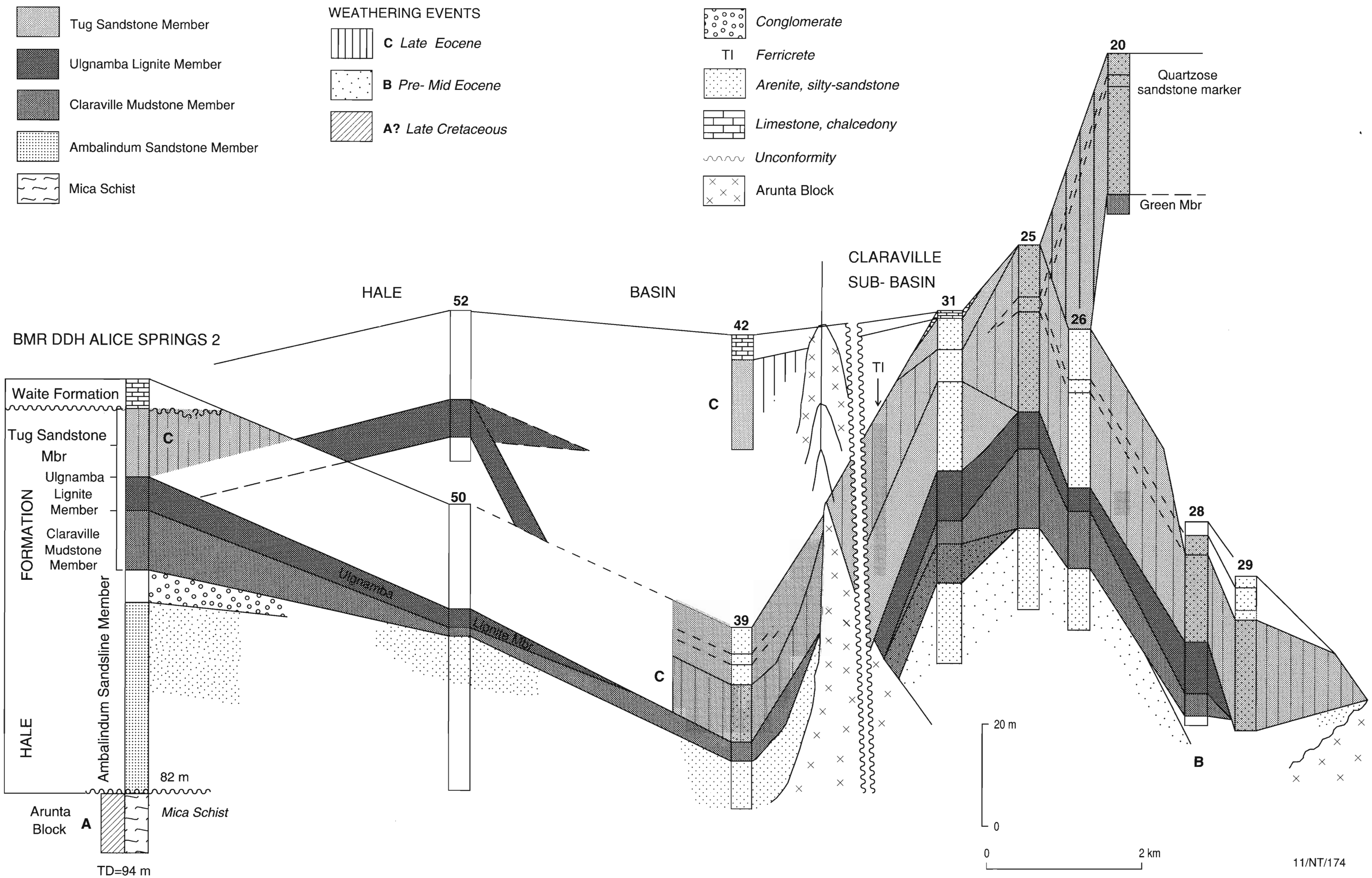

Figure 5. Panel diagram showing members of the Hale Formation and their relationship to weathering events within the eastern part of the Hale Basin and the Claraville Sub-basin; based on selected company scout holes as numbered in Fig. 3. Note, Claraville homestead is located at the eastern (RHS) apex of the diagram (see Fig. 3).

Basin, which, in its type area, spans the Middle to Late Eocene boundary. The correlation rests on relatively small numbers of index species, namely, on the presence of *Nothofagidites falcatus, Santalumidites cainozoicus,* and *Proteacidites confragosus,* so that precise relationships are difficult to determine. Assuming that the time ranges of species are similar in central and southeastern Australia, then a Middle to Late Eocene age is implied, consistent with the palaeomagnetic results.

Ti-Tree Basin

The Ti-Tree Basin lies mainly in the northwestern Alcoota Sheet area, and also overlaps the Napperby and Barrow Creek Sheet areas (Fig. 6), covering possibly as much as 1000 km^2. Exposure of the basin deposits is limited to low, sandy soil-mantled rises, and most of the succession is known only from drill holes and from lithological logs of water bores. The basin is thought to be thickest in the east, where it is crossed by both the Woodforde River and the Stuart Highway, south of the Ti-Tree roadhouse (Fig. 6).

Previous investigations

The groundwater potential of the basin was investigated by Edworthy (1966) and McDonald (1988a, b), and the recharge mechanism and groundwater age have been assessed by Calf et al. (1991). The uranium potential of the basin was examined by O'Sullivan (1973) and Hughes & O'Sullivan (1973).

Distribution and stratigraphy

Hanson River region. This northeasternmost part of the basin, south of the Ti-Tree roadside village has been investigated by industry drilling (O'Sullivan 1973). The succession is shown schematically in Figure 9. Depth to basement in six stratigraphic holes drilled by CRA Exploration Pty Ltd, ranged from 146 to 319 m. Weathered rocks were intersected at the base of the succession in two of the holes. In the deeper holes, up to 130 m of white siltstone and claystone rests on basement and is overlain by lenticular units of lignite and carbonaceous claystone. The carbonaceous units, or where they are absent, the 'white beds', are overlain by greenish-grey siltstone and silty sandstone. These pass, in turn, upwards into their weathered and oxidised equivalents. The uppermost 60 m or so is commonly dominated by reddish-brown sandy siltstone, whereas the lower 60 m or so is, in places, characterised by multicoloured (pale-grey, brownish-grey, white or yellow) siltstone or mudstone, and includes minor coarse sandstone and gritty sandstone layers. In one hole, a second weathered sequence was intersected within a greenish-grey siltstone unit, which lacked carbonaceous intervals. The greenish siltstone unit and the associated carbonaceous lenses were absent in two holes.

The age of this succession is inferred on the basis of correlation with the nearby Whitcherry Basin (Fig. 1). Similar carbonaceous sediments to those in the Ti-Tree Basin were intersected in an arm of the Whitcherry Basin at a depth of 136–139 m in BMR Napperby No. 1 located 13.5 km southwest of Napperby homestead (Fig. 1). These carbonaceous sedimentary rocks contain a Middle to Late Eocene microflora (Kemp 1976). If these correlations are correct, they suggest that the weathered profile at the base of the succession in the northwestern part of the Ti-Tree Basin may be older than Middle Eocene. The second profile, recognised locally in the greenish-grey siltstone, may correlate with weathering event B of the Hale Basin (Fig. 4).

Bushy Park region. In the southwestern part of the Ti-Tree Basin (in the southwestern Alcoota Sheet area), the Cainozoic succession reaches more than 194 m thick, as recorded in BMR SH 2 (Fig. 6). Reduced successions were intersected in other stratigraphic holes, such as BMR Alcoota Nos 2, 18 and 19. In the nearby BMR Alcoota No. 20, a 25 m thick sequence—comprising calcareous siltstone, green claystone, minor granule conglomerate, and rare limestone—was found to overlie silicified sandstone basement at a depth of about 184 m. The overlying 70 m thick olive-green or white mudstone includes 12 m of grey, green and brown siltstone and sandstone in its upper part. Plant fossil fragments were recorded infrequently in this interval. This mudstone is correlated with unit Ta in the Waite Basin (Fig. 7; see below) and with the Delaney Mudstone Member of the Hale Formation in the Hale Basin (Fig. 7; see above). The remaining interval of about 87 m is assigned to TQt (see below) and consists of variously oxidised red and brown silty sandstone, minor siltstone, and pebbly silty sandstone. It is overprinted by ferruginous weathering.

This upper unit, TQt, can be divided in the southeastern Ti-Tree Basin region, into four sub-units (TQt_{1-4}), three of which ($TQt_{1,2,3}$) are represented in Alcoota No. 20. These sub-units (and the correlative units Ta_{4-5}) are as follows:

- The lowest (TQt_1), up to 30–40 m thick, is dominated by siltstone and minor silty sandstone. A similar lutite was intersected in BMR Alcoota 3 in the Waite Basin (see below and Fig. 6). The lower, more silty part of TQt in the southeastern Ti-Tree Basin may correlate with the multicoloured siltstone and, in places, mudstone and coarse angular sandstone lenses, intersected in drill holes in the northwestern part of the Ti-Tree Basin (e.g. hole TT4 in O'Sullivan 1973). TQt_1, the lower part of TQt, may also correlate, in part, with the Waite Formation (see above), as well as Ta_4. The lowest part of this unit in BMR Alcoota 20 includes grey siltstone and white sandstone, lithological types reminiscent of the 'clean' sandstones in Ta_4 in the Aremra Basin (see below).
- The next unit (TQt_2) is commonly sand dominated, and is up to about 25 m thick. It may be multicoloured in places rather than red-brown. It commonly includes high proportions of silt and clay, and rarely includes calcareous elements and conglomeratic intervals with white mica and basement clasts. It may correlate with the multicoloured siltstone and, in places, mudstone, sandstone and coarse angular sandstone, intersected in drill holes in the northwestern part of the Ti-Tree Basin (e.g. hole TT4 in O'Sullivan 1973). This lower part of TQt may also correlate, in part, with the Waite Formation (see above) and the lower part of Ta_5.
- The upper unit (TQt_3) is about 20 m thick and commonly dominated by brown or red-brown, poorly sorted sandstone. It may correlate with the upper unit of reddish sandy siltstone and sandstone of the northwestern part of the basin (O'Sullivan 1973) as well as the upper part of Ta_5 in the Aremra Basin (see below), characterised by red-brown silty sandstone. In BMR Alcoota 20 it has a strong ferruginous overprint.

- Unit TQt consists of calcrete and brown silty sandstone. Chalcedonic cappings and strong ferruginisation, which are characteristic of the Waite Formation (see below and also McDonald 1988a, b) are absent. The lack of these weathering imprints indicates that the upper part of TQt most likely postdates the Waite Formation of the Waite Basin.

Allungra Creek region. Drilling by Northern Territory Power and Water Authority (McDonald 1988a) in this central-northern part of the basin (Fig. 6) delineated an 80 m thick unit of poorly consolidated, oxidised silty sandstone. McDonald considered this to be TQt and interpreted it as a fluviatile deposit. In the deeper part of the basin it grades downwards into grey-green mudrock (Ta_2) of possible lacustrine origin (McDonald 1988a). TQt is not readily subdivided as it shows wide lithological variation within a complex drainage system. The unit is commonly calcareous and, locally, appears to interfinger with chalcedonic, calcarenitic limestone of the Waite Formation type (Tw).

Palaeogeography

The palaeodrainage system within the western Ti-Tree Basin (Hanson Plain of Shaw et al. 1979b; Shaw & Warren 1975) is considered to have formed at about the same time as the 'Waite Surface' (see below) and to have continued to evolve during the Pleistocene and into the early Holocene. TQt may span a stratigraphic interval ranging from the Tug Sandstone Member of the Hale Formation to the Waite Formation (Tw), i.e. from Late Eocene to Late Miocene or younger, and in places possibly through to that of the oxidised alluvial unit Qr. In places, marginal tilting appears to have occurred at some stage, resulting in erosion of Tw before deposition of the last phase of TQt (see McDonald 1988a). The complex drainage system, outlined by calcrete deposits, then shifted slightly to a new location and continued to evolve as a coalescing northerly flowing palaeodrainage system. In the Pleistocene, the depositional basin (the Hanson Plain) became covered by ferruginous 'red earth' soil (Qr), then by aeolian sand, which contains subdued dune landforms. Wet interludes, in this otherwise arid period, produced

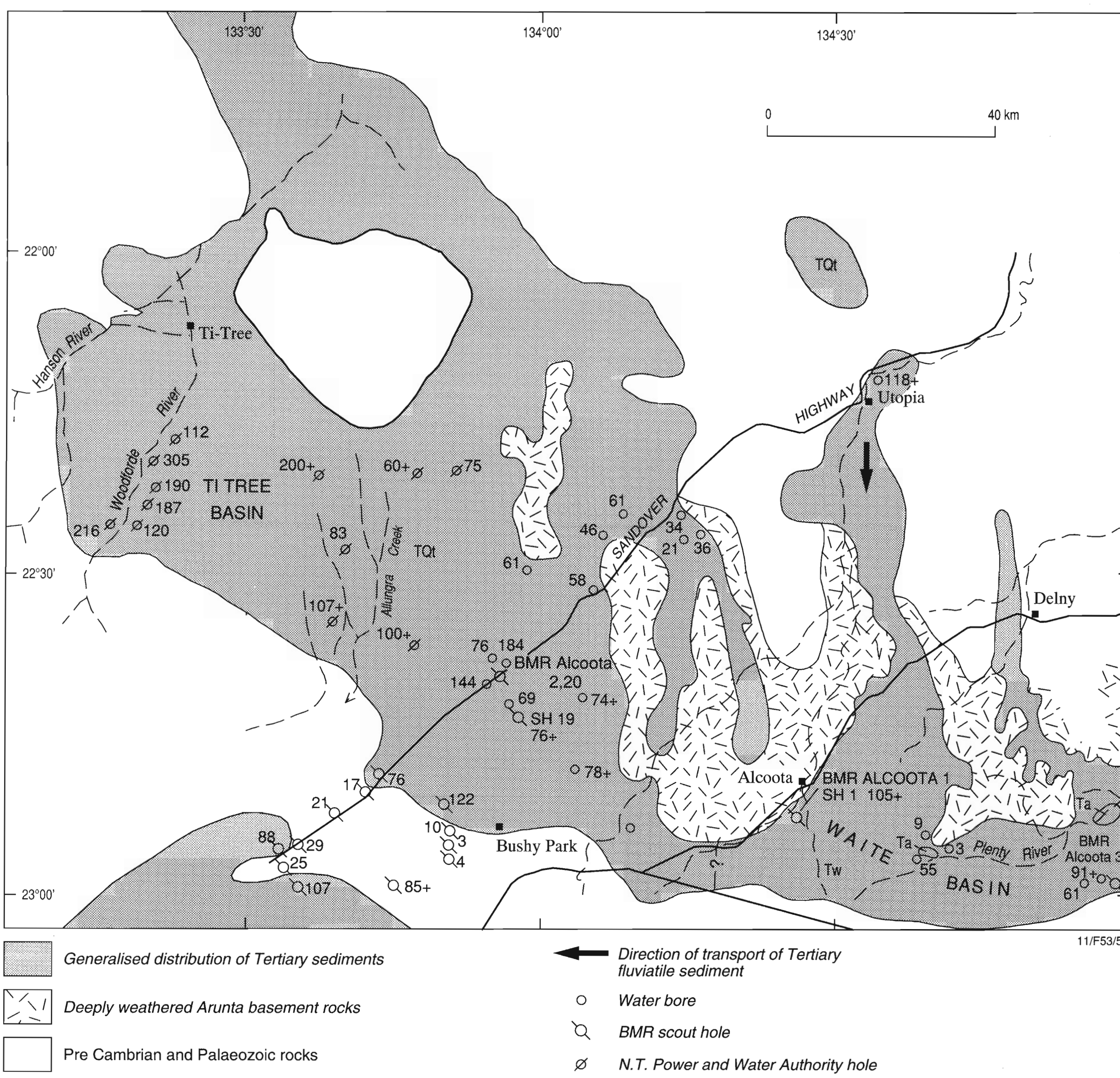

Figure 6. Distribution of deeply weathered rocks and Cainozoic sediments, Ti-Tree and Waite Basins, showing the location of selected drill holes and estimated depths to basement.

north-flowing drainage channels with deposition of alluvium. Since then, these drainage channels have been largely abandoned, to be replaced by the present Hanson drainage system.

Waite Basin

The Waite or Plenty River Basin is an east–west depression north of the Harts Range, covering possibly 1200 km^2 (Figs 1, 6 & 7). It contains up to 180 m of Tertiary lacustrine and fluviatile sedimentary rocks, referred to informally as the Alcoota beds (Ta). These rocks are similar to those in the subsurface at the eastern part of the Ti-Tree Basin, but, to a limited extent, have been uplifted and dissected. The outcropping and dissected sequence in the western part of the Waite Basin belongs to the younger Late Miocene to Early Pliocene Waite Formation (Woodburne 1967).

Uplift within the MacDonnell, Strangways, and Harts Ranges—together with probable subsidence to the north (i.e. northern part of the Alcoota Sheet area)—terminated much of the southeasterly drainage in the western part of the Waite Basin, possibly in the Pliocene. As a result, the Sandover and Bundey River systems developed on new, largely north-dipping, slopes. The eastern part of the Plenty River system continued eastwards in the direction of the earlier river system that deposited the Waite Basin succession.

The Alcoota beds (Ta) (Map units Ta, Waite Formation Tw, and minor TQt) 'Alcoota beds' is an informal name applied to Tertiary units, largely preserved in subcrop in the Alcoota Sheet area. (Only about 15 per cent of the total thickness of Tertiary sedimentary units is exposed.) The Alcoota beds have a composite thickness of about 250 m, as inferred from stratigraphic drill holes, BMR Alcoota SH1, 2 and 3. Of this, the basal mudstone and siltstone sequence (Ta) is represented by less than 5 m of outcrop in the Plenty River valley. The Waite Formation (Tw), a sub-unit of the Alcoota beds, crops out extensively in escarpments around flat-topped landforms in a belt roughly peripheral to the margins of the Waite Basin (Woodburne 1967) in the southeast quadrant of the Alcoota Sheet area.

Near the margins of the Waite Basin, the Waite Formation unconformably overlies a partly truncated weathered profile developed in crystalline rock (Fig. 6). It seems likely that the onset of deposition of the Waite Formation related to former low-lying zones within the Arunta Block, where surface drainage and groundwater conditions were conducive to development and preservation of this profile. Further downwarping of this weathered surface, combined with some erosion and dispersion of weathered materials, replicated the position of the developing Waite Basin. The youngest sediments, originally mapped as TQt and included in the Alcoota beds, are represented at the surface by only a few metres of fine quartz sandstone, chalcedonic calcarenitic limestone, and greenish-grey siltstone (Fig. 6). TQt is restricted to the Ti-Tree Basin (see above) and, hence, is excluded from the Alcoota beds. It correlates in part with the Waite Formation, but includes younger elements and probably also older elements.

The lithology of the Alcoota beds in subcrop differs appreciably from that of the majority of outcrops, but for ease of mapping (see Shaw & Warren 1975) the name 'Alcoota beds' was applied informally to the entire succession. The formally defined Waite Formation (Woodburne 1967) becomes the middle unit within this framework. The lower limit of the Alcoota beds is unknown: the only two drill holes in the basin, BMR Alcoota 2 and 20, failed to reach the basement.

The lithology and possible correlation between units in the Alcoota beds are shown in Figure 7. The coarse-grained sediments in BMR Alcoota No. 3 are thought to be a facies equivalent of the Waite Formation and to have been derived locally from the nearby Harts Range.

These thick Tertiary sediments, discovered during drilling in 1971 in the Alcoota Sheet area, may have potential for hosting uranium. They are derived from nearby crystalline basement, where felsic plutonic source rocks are abundant and include rocks with significant U values. The sediments appear to have been deposited in fluviatile and lacustrine environments and show a variety of red, white and green zones, the result of alternating periods of oxidation and reduction. Such conditions are known to favour uranium precipitation.

Gamma-ray logs were run in BMR Alcoota 2 and in three abandoned water bores on Annitowa station (previously Woodgreen station). Two of the holes indicate small and apparently anomalous zones of relatively high radioactivity. In BMR Alcoota 2 (Fig. 7), the small anomaly, recorded from a sandy conglomerate bed in the interval 90–100 m, may reflect very low concentrations of uranium in groundwater (Senior 1972). The second anomaly, obtained in the bore Woodgreen 1, is 10.5 m thick and, according to the driller's log, lies in a median position between a red micaceous sandstone and a green and grey medium-grained sandstone (fig. 7 in Senior 1972). However, subsequent investigation of the Tertiary sediments in the Ti-Tree Basin in the northwest of the Alcoota 1:250 000 Sheet area revealed only low U contents, the maximum reported being 23 ppm. Here, calcrete assigned to TQt, intersected in shallow bores, was 6–12 m thick, forming an irregular channel-like body, closely linked with basement morphology (cf. O'Sullivan 1973).

Unit Ta

BMR Alcoota SH1 & 2 drill holes penetrated a massive mudstone and siltstone unit below the Waite Formation to a total depth of 194 m (Senior 1972, fig. 5). The upper part of these argillaceous deposits is weathered, mottled and stained by red iron oxide. The red coloration is especially evident in BMR Alcoota SH1. However, in both holes the unit includes a zone of slightly leached white mudstone and siltstone, which in BMR Alcoota SH2 grades into a basal sequence of green and grey, unaltered mudstone. These rocks are almost devoid of bedding except for a few faint laminations. This may reflect deposition in a quiet-water lacustrine environment.

Waite Formation (Tw)

The type section of the Waite Formation is a small mesa on the north side of Waite Creek, 6 km southwest of Alcoota homestead and 15 km northeast of Mud Tank Bore. Only about 440 m of the upper part of the formation crop out; the full thickness is not known.

In outcrop, the Waite Formation consists of interbedded chalcedonic calcarenitic limestone, sandstone, siltstone, and minor sandy conglomerate. Beds of cream or white chalcedonic calcarenitic limestone form the hard resistant

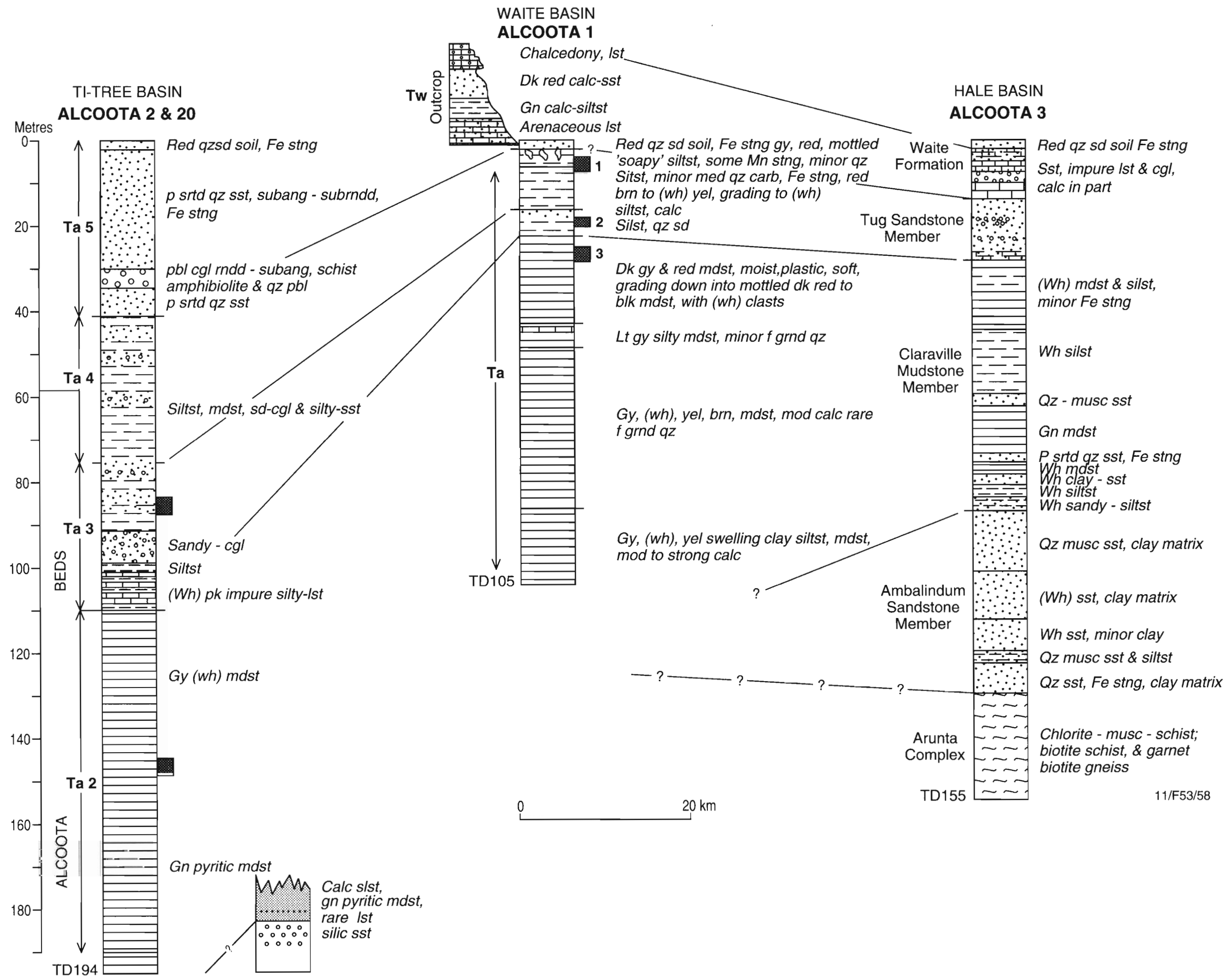

Figure 7. Correlation between drill holes in the Ti-Tree and Waite Basins, and possible correlation with the units of the Hale Basin.

summit caps on many low plateaus and mesas. In places, chalcedonic silica is dominant and there is a lack of clastic detritus, which indicates that they formed by chemical precipitation of silica and are contemporaneous with interbedded clastic deposits of the Waite Formation. Some of the siliceous beds have a sedimentary fabric, owing to penecontemporaneous replacement of calcium by silica. A sample of chalcedonic limestone, analysed by x-ray fluorescence, consisted dominantly of SiO_2 (96.7%) with minor iron oxides (0.77%), CaO (0.35%), and P_2O_5 (0.25%).

In most outcrops, the grain size of clastics in the Waite Formation increases upwards. In the Alcoota Sheet area, Woodburne (1967) attributed this to a change from a lacustrine to a fluviatile environment of deposition. Core from BMR Alcoota SH1 drill hole tends to confirm an initial lacustrine environment, because the subsurface sediments are dominantly argillaceous and include abundant mudstone, siltstone, and claystone. The sedimentary sequence may well equate with deposition within a regressive lake.

Vertebrate fossils in the outcropping lacustrine part of the sequence were described as being of Late Miocene or Early Pliocene age (Woodburne 1967). Subsequently, in an overview of the stratigraphic relationships of Australia's fossil mammal faunas, Woodburne et al. (1985) tentatively placed the Alcoota fauna in the Late Miocene on the basis of evolutionary relationships, equating it with faunas of the Cheltenhamian Stage in southeastern Australia.

The prolific iron staining observed from near the top of BMR Alcoota SH1 ("grey-red mottled 'soapy' siltstone" (Fig. 7): the result of contemporaneous weathering) suggests correlation with weathering event C which affected the Tug Sandstone Member in the Hale Basin. Sediments from cuttings in the interval 102–105 m in BMR Alcoota SH1 (Ta) were palynologically barren.

The distribution of Tertiary sediments (Figs 1 & 6) shows two north-trending extensions of the Waite Basin. On the westernmost extension, at a site 10 km south of Utopia homestead, coarse-grained sediments contain pebble to small boulder-sized clasts. The linear distribution and coarse clastic composition of these deposits, coupled with decrease in grain-size southwards, indicate a northerly source for the detritus. This is the reverse of the present-day drainage direction. If the vertebrate fossils present in the upper part of the Waite Formation are Late Miocene, then the Waite Basin must have been dissected after this date.

Deeply weathered rocks—Ti-Tree and Waite Basins (includes older units Tla and Tlf and younger unit Tl)

In the region surrounding the Ti-Tree and Waite Basins, a well-developed profile is formed in the Arunta igneous and metamorphic basement rocks, and in lacustrine and fluviatile Tertiary sediments referred to as the Alcoota beds (see above; mainly in the Alcoota 1:250 000 Sheet area). Deep chemical weathering has altered the upper 40 m of exposed crystalline rocks, forming a trizonal profile, comprising a lowermost leached zone, an intermediate mottled zone, and a ferruginous upper zone. In subcrop, it underlies some of the Cainozoic sediments, as seen from drill cuttings. In outcrop, only the Waite Formation rests unconformably on the weathered profile developed in Arunta basement rocks.

The trizonal weathered profile has been most extensively studied in the Alcoota Sheet area (Senior 1972), where it is widely preserved. A mid-Tertiary age was initially assigned (Senior 1972) on the assumption, proposed by Woolnough (1927), that such profiles formed during a continent-wide phase of chemical weathering. Subsequent stratigraphic and palaeomagnetic studies of thick, deeply weathered profiles in western Queensland indicated two major weathering episodes (Senior et al. 1978; Senior & Mabbutt 1979). The older of these is either Late Cretaceous or early Tertiary (Morney profile) and the younger is middle Tertiary (Canaway profile). The Canaway profile overprinted the partly eroded Morney profile over extensive areas of the Eromanga and Surat Basins. Within the current study area, palaeomagnetic studies at three sites have identified only a mid-Tertiary, probably Late Eocene, magnetic age of ferruginisation.

Drilling has shown that the Arunta basement rocks underlying the Hale Basin (weathering event A in Fig. 4) and the Aremra Basin are deeply weathered. The probable Middle to Late Eocene Ulgnamba Lignite Member is sandwiched between strongly oxidised rocks, which appear to represent either contemporaneous weathering and/or input of former weathered detritus. It seems possible, therefore, that the Arunta basement profile in these drill holes (equivalent to weathering event A in Figs 4 & 5) may be equivalent, at least in part, to the Morney profile of the Eromanga Basin (i.e. Late Cretaceous and/or Paleocene). From palynological evidence, deposition may have begun in central Australia in the Late Cretaceous, or possibly earlier, implying that the deep weathering of Arunta basement is Cretaceous or older. A third weathering profile (weathering event C in Figs 4 & 5) appears to affect the Tug Sandstone Member exposed at Red Ochre Dam (see map accompanying Shaw et al. 1984).

As noted above, a pilot palaeomagnetic study of weathered profiles indicates a possible Late Eocene magnetic age for outcropping profiles in the Hale Basin area, in agreement with results from the northern margin of the Waite Basin. The estimate is based on 44 samples collected from seven localities (Senior et al. in press). Thermal demagnetisation, using 13–18 steps, gives a palaeomagnetic pole at lat. 113.0° E, long. 65.8° S (radius A_{95} of 95% confidence circle 3.9°), coincident with the Late Eocene pole on the Australian apparent polar wander path (Idnurm 1994). Late Eocene is, therefore, the most likely age, but Early Eocene or Late Oligocene cannot be ruled out with 95% confidence. The confidence circle for the pole does not enclose the pole of the Canaway profile of southwest Queensland, suggesting a possible shift in timing of a single mid-Tertiary weathering event or two separate events, one in each region. (It should also be noted that the confidence circle does not enclose the older Morney profile pole.)

A period of erosion (possibly in the Oligocene, cf. Kamp 1991; see Table 2) removed part of the Eocene and older profiles, and detritus was incorporated into the Waite Formation (see Table 1 and below). In some depressions, such as in the southeastern part of Alcoota 1:250 000 Sheet area (see Senior 1972; fig. 4), an almost complete weathering profile is preserved below the Waite Formation. The trizonal character of this profile implies that it largely corresponds to weathering event A (largely mapped as units Tl, Tla—see Table 1), but that it has been overprinted by weathering event C (mapped as units Tl, Ts). The fact that the deep trizonal profile normally predates the initiation of Tertiary deposition has been established from surface mapping in the Hale Basin. The less-well-developed mottling and ferruginisation of sediments, probably equivalents of the Tug Sandstone Member, immediately underlying the Waite Formation (Fig. 7) are correlated with weathering event C from the Hale Basin.

The leached or clay-rich zone at the base of the exposed profile, developed in Arunta Block rocks, grades from relatively unweathered parent rock upwards into a zone dominated by white kaolinitic clay minerals. It is generally possible to identify the gross lithology of the parent rock in the basal to middle part of this zone. In this zone, textural features of the host rock are preserved, together with quartz veins and remnants of large phenocrysts, such as quartz and muscovite.

The kaolinitic zone grades up into a multicoloured or mottled zone, up to 10 m thick. This zone contains patches stained pink, purple, brown or yellow by iron oxides, contrasting markedly with the white clay-rich matrix. Individual stained patches or mottles vary from small nodules to structureless masses. Iron-oxide staining and enrichment increase upwards through the mottled zone. Kaolinite and quartz are dominant, with subordinate amounts of hematite and goethite (see Senior 1972, table 1). The texture of the parent rock cannot be recognised at the top of the mottled zone, even though there is a tendency for this type of profile to have developed within formerly strongly textured, coarsely crystalline gneissic or granitic rock types.

Overlying the mottled zone is a ferruginous zone up to 8 m thick. This, the most strongly indurated part of the profile, forms prominent vertical escarpments with generally a columnar structure. Goethite and hematite are the dominant iron minerals. The rock is generally fine-grained and massive, except for an irregular mosaic of fine fractures. Numerous vertical and subhorizontal joints give the zone a pronounced columnar structure similar to that developed in some soil profiles as a result of volume changes. In places, the upper 3 or 4 m of the ferruginous zone is reworked by pedogenic processes and consists of a re-cemented layer of fragments and pisolites. The latter are up to 1 cm in diameter and have a simple structure of concentric shells of iron oxides of contrasting colour. This material has locally slumped down vertical fractures into the underlying ferruginous zone, thereby forming 'pipe-like' infillings. Some pisolites are strongly

Table 2. Tentative interpretation of tectonic and palaeogeographic setting.

Period approx.	*Age[1] (Ma) ~ base*	*Units*	*Plate-wide[3,4] tectonism*	*Central Australian tectonism*	*Lat.[4] C. Aust °S, °shift*	*Plate-wide palaeo-geography[2, 7]*	*Suggested central Australian depositional environment*	*Tentative central Australian climate*
Holocene	0.01	Qa, Qs, Ql	Craton stable	Stable	24, 0	Present-day conditions	Present-day drainage and deposition	Present-day dry conditions
Pleistocene–latest Pliocene	~ 2	Qps, Qa, Qs	Craton stable	Stable	24+, 0	Waxing & waning of ice caps	Sand plains, minor dune fields	Dry, sporadic pluvial period
Late Pliocene	~ 3	Qr, TQt_4 Czc, Czg	Localised uplift, ?compressional tectonism	Upward doming of ranges, drainage reversal of Sandover River	24+, 0	Rejuvenation of drainage	Oxidised soil development, sheet sand	Wetter conditions, followed by increasing aridity
Early Pliocene–Late Miocene	~ 3–20	Tw, Tr, TQt_{1-3}, Ta_{4-5}	Craton stable	Switch in sites of sedimentation	25+, –1	Lowering of sea level & expansion of ice cap	Restricted drainage, lakes including salt lakes	Moderate temperatures, seasonal rain
Early Miocene to Oligocene	~ 20–35	Hiatus	Beginning of N Aust. collision[5]	Widespread uplift	≥43, –19	Sea level rise at ~ 20 Ma after episode of widespread weathering (Canaway Profile eq.)	Widespread hiatus	?Drier
Late Eocene	~ 35–45	Tl, Ts	Plate rearranngement. Inversion and wrenching of early structures at plate margins. Uplift of parts of continent	Reduced rates of subsidence, break in sedimentation in Claraville sub-basin	46, –22	Beginning of expansion of Antarctic ice cap and sea level fall	End of widespread deep weathering, especially east of ranges	Uncertain
Late to mid-Eocene	~ 45$^{\pm}$	Tht, Ta_3,Tss	Pacific plate rearrangement[6]	Limited upward doming of ranges, minor tilting east of ranges	48, –24	Humid, temperate climate over much of the continent	River sediments, sheet outwash, coelescing piedmonts	Warm, moist
Mid - Eocene	~ 50$^{\pm}$	Thu, Thc, Ta_2,Tss	Start of rapid spreading away from Antarctica, end Tasman Sea spreading, start spreading Coral Sea, subsidence in Murray Basin and in Eromanga Basins after break	Renewed localised subsidence after local break	≥50, –26	Moist, increased circulation of warmer seas, presence of lakes, peat swamps and forest	Localised lakes and peat swamps, forest on slopes.	Warm, moist, possibly with dry phases
Early Eocene - Paleocene	~ 55–65	Thg, Ta_1, Tss	Continued spreading between Australia and Antarctica, subsidence in Eromanga Basin	Narrow intermontane basins, rapid local subsidence	54, –30	Main present-day river systems established, major disturbance of ocean currents, negligible ice cap	Coarse river deposits, forest and peat swamps very locally	Warm, moist, possibly with some dry episodes
Earliest (?) Paleocene - Late Cretaceous	~ 70–90	Tlf, Tla	Start of Tasman Sea rifting, and continued spreading between Australia and Antartica	Broad uplift over much of continent, more marked in the Eastern Highlands	58, –34	Subaerial erosion (Morney Profile eq.) of much of Australia and Antartica	Widespread deep weathering (age uncertain)	Warm, moist, possibly seasonal rain

References: 1) Harland & others 1990, **2)** BMR Palaeogeographic Group 1990, **3)** Etheridge et al. 1991, **4)** Veevers et al. 1991, **5)** Kamp 1991, **6)** Wells 1989, **7)** Truswell & Harris 1982.

magnetic, probably due to some near-surface process whereby goethite and hematite are converted to maghemite. The morphology of the ferruginous zone is very similar to that of the upper crust-forming portion of the Canaway profile of western Queensland and may have formed by analogous processes. As previously mentioned, the timing of the weathering events, as determined palaeomagnetically (Idnurm & Senior 1978), indicates that weathering began earlier (Late Eocene) in the Alice Springs region, compared to a Late Oligocene or Early Miocene age for the Canaway profile.

X-ray diffraction and X-ray fluorescence studies (Senior 1972) have shown that the profile developed through *in situ* rock decomposition, liberation of alkali and alkaline earth metals (K, Na, Ca, Mg) as well as leaching of silica, accompanied by concentration of iron and aluminium oxides in addition to hydroxides. In general, iron oxide concentrations increase upwards, reaching 40 per cent or more in the ferruginous zone. The abundances of SiO_2 in the leached and mottled zones are similar, but in the ferruginous zone SiO_2 is markedly reduced.

Bundey Basin

The name 'Bundey Basin' is applied to a sedimentary fill up to 40 m thick, intersected in water bores along the Bundey River in the Huckitta 1:250 000 Sheet area (Fig. 1). These deposits consist of siltstone and claystone with interbedded sandstone and conglomerate beds. Drilling by the Northern Territory Geological Survey in 1982 intersected chalcedonic limestone at shallow depths and most of the rocks in the water bores may be regarded as Waite Formation equivalents or unit TQt (Freeman 1986). However, cored hole NTGS HUC11, on the Huckitta 1:250 000 Sheet Area, intersected partly carbonaceous siltstone, then sandstone and siltstone to a total depth of 127 m. This thickness exceeds that of other Cainozoic sedimentary rocks in the Bundey Creek region. Preliminary palynological determination (Truswell 1987; Freeman 1986) suggested that the carbonaceous siltstone accumulated in the Paleocene. However, the carbonaceous claystone contains many undescribed pollen types, including forms morphologically similar to species that Harris & Twidale (1991) now consider to be Late Cretaceous, described from lignitic sedimentary rocks above the basement between Ayers Rock and the Olgas, and the material from HUC11 could well be just as old.

Aremra Basin

The Aremra Basin, in the southwestern part of the Illogwa Creek 1:250 000 Sheet area (Figs 1 & 8), is known only from the subsurface; it is named after Aremra Creek. The basin appears to extend from just west of Gidyea Bore southwards, for 80 km or more, along the eastern margin to ranges of metamorphic rocks bordering Illogwa Creek. Structurally, it comprises flat-lying beds that occupy a southeast-trending depression centred on the present-day position of Aremra Creek.

The succession in the Aremra Basin, referred to as unit Ta, is similar to that in the Ti-Tree and Waite Basins (Alcoota and Napperby 1:250 000 Sheet areas). Ta rests unconformably on schists and gneisses of the Arunta Block (BMR Illogwa Creek 2), except in the southeast, where it probably rests unconformably on the Hooray Sandstone, a Late Jurassic and Early Cretaceous unit within the Eromanga Basin succession. Ta is overlain, probably conformably, by Waite Formation equivalents (Tw) and by unconsolidated Quaternary deposits.

The oldest lithological components in the basin are claystone and interbedded sandstone. The massive nature of the claystone suggests quiet-water deposition; there is a lack of terrigenous detritus from the nearby ranges. These rocks pass abruptly upwards into poorly sorted clastics deposited as a series of coalescing piedmont fans. The clastics are intensely weathered and contain abundant iron oxide pisoliths. The succession is capped by a thin veneer of chalcedonic calcarenitic limestone (Tw), which is more extensive in the east, where it caps weathered metamorphic rocks. As this basin provides an additional key reference section for Cainozoic stratigraphy in the Alice Springs region, it is described in some detail below. A generalised stratigraphy is given in Figure 9.

Deep-weathering profiles in the Aremra Basin region. (Tl, Tla, Tlf, Illogwa Creek Sheet area)

As mapped, Tl is a composite unit, incorporating several weathering events. These profiles are most extensively developed north and west of the Aremra Basin (Fig. 8). They are best preserved along the interfluve between Huckitta and Atula Creeks, forming scattered exposures in the flatter eastern two-thirds of Illogwa Creek 1:250 000 Sheet area, away from the higher ranges.

The most widespread and probably oldest weathered profile (Tla, Tlf) is up to 30 m thick and trizonal, comprising a lowermost kaolinised zone, an intermediate mottled zone, and a ferruginous top. It is correlated with an identical profile in the Alcoota 1:250 000 Sheet area (see above and Senior 1972), suggesting former continuity between these two regions. Decomposed, soft kaolinitic metamorphics of the Arunta Block, which may have been affected by the same weathering event, were intersected below the unnamed Cainozoic sediments (Ta) in BMR Illogwa Creek 1 and 2. The marked ferruginisation that is widely developed on the Mesozoic Hooray Sandstone is also correlated with this deep weathering profile (Senior in Shaw et al. 1982).

In addition, several younger periods of intensive oxidation leading to weathered profile development are recorded within unit Ta in the Aremra Basin, indicating that intense weathering continued during deposition. Of these profiles, the one associated with the strongest oxidisation (affecting subunit Ta_3, see below) is correlated with Tl. The formerly extensive Tl weathering profiles were buried in the Miocene or Early Pliocene by lacustrine and fluvial sediments of the Waite Formation. The tops of mesas of Waite Formation equivalents (Tw) and the underlying weathered profile, dip gently southwards, diminishing in relief until they become concealed by Quaternary and recent aeolian sands around the northwest edge of the Simpson Desert.

The revision of weathering chronology on rocks sampled for palaeomagnetic study and described above, suggests a Late Eocene date for the main period of ferruginisation.

Unnamed Cainozoic sedimentary rocks and sediments (Ta) (after Senior in Shaw et al. 1982)

These consist of soft, red and green siltstone, claystone, and friable lithic sandstone, with lesser amounts of quartzose sandstone and conglomerate. Carbonaceous

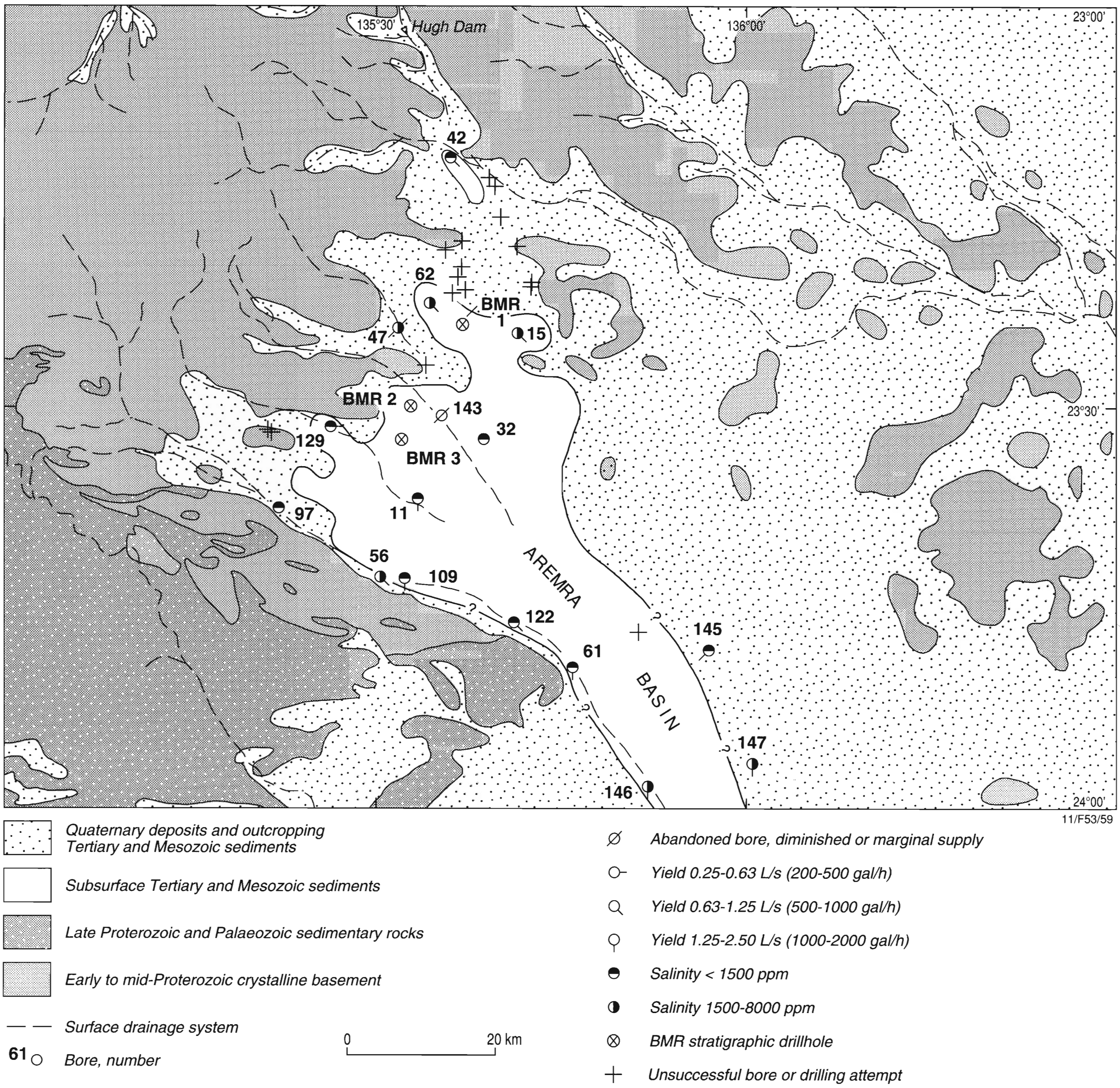

Figure 8. Sketch map of Cainozoic sediments in the Illogwa 1:250 000 Sheet area, showing the approximate outline of the Aremra Basin and details of drilling for groundwater.

matter, gypsum, and ironstone are present locally. Calcareous lenses and pedoliths occur at shallow depths. The unit is up to 250 m thick in drill holes. It grades upwards into either Waite Formation equivalents (Tw) or unconsolidated aeolian and alluvial Quaternary sediments (Qs, Qa, Qr).

The succession is divided into five units on the basis of drilling results from 18 holes by Agip Nucleare (1977, 1979), and cores from three holes by BMR (Fig. 9) and one by the Northern Territory Mines Department. From the base upwards these are:

- Unit 1 (Ta_1) is up to 20 m thick, but commonly much thinner. It consists mainly of iron-oxide-enriched sedimentary rocks, minor silcrete developed in quartz sandstone, and minor white or greenish claystone. The rocks comprise ferruginised red-brown and yellowish claystone interbedded with reddish quartzose sandstone. A lacustrine environment with fluviatile incursions is inferred from the variety of rock types, possibly reflecting a humid climate with dry intervals resulting in oxidation and silicification.
- Unit 2 (Ta_2) is dominated by an olive and green claystone with interbeds of quartzose sandstone and minor red-brown siltstone. Gypsum and carbonaceous fragments are present locally. Ta_2 is up to 144 m thick and grades upwards, through a mottled zone, into unit 3. Lacustrine and pediment distributary fan and plain accumulations are the likely depositional environments. Periods of desiccation resulted in the formation of gypsum. The presence of carbonaceous material and oil shale suggests that vegetation and abundant aquatic organisms were present in marginal swamplands.
- Unit 3 (Ta_3) comprises oxidised red-brown silty and clayey sandstone intercalated with minor layers of quartzose sandstone. These clastics contain fragments of ironstone derived from weathered profiles and rare

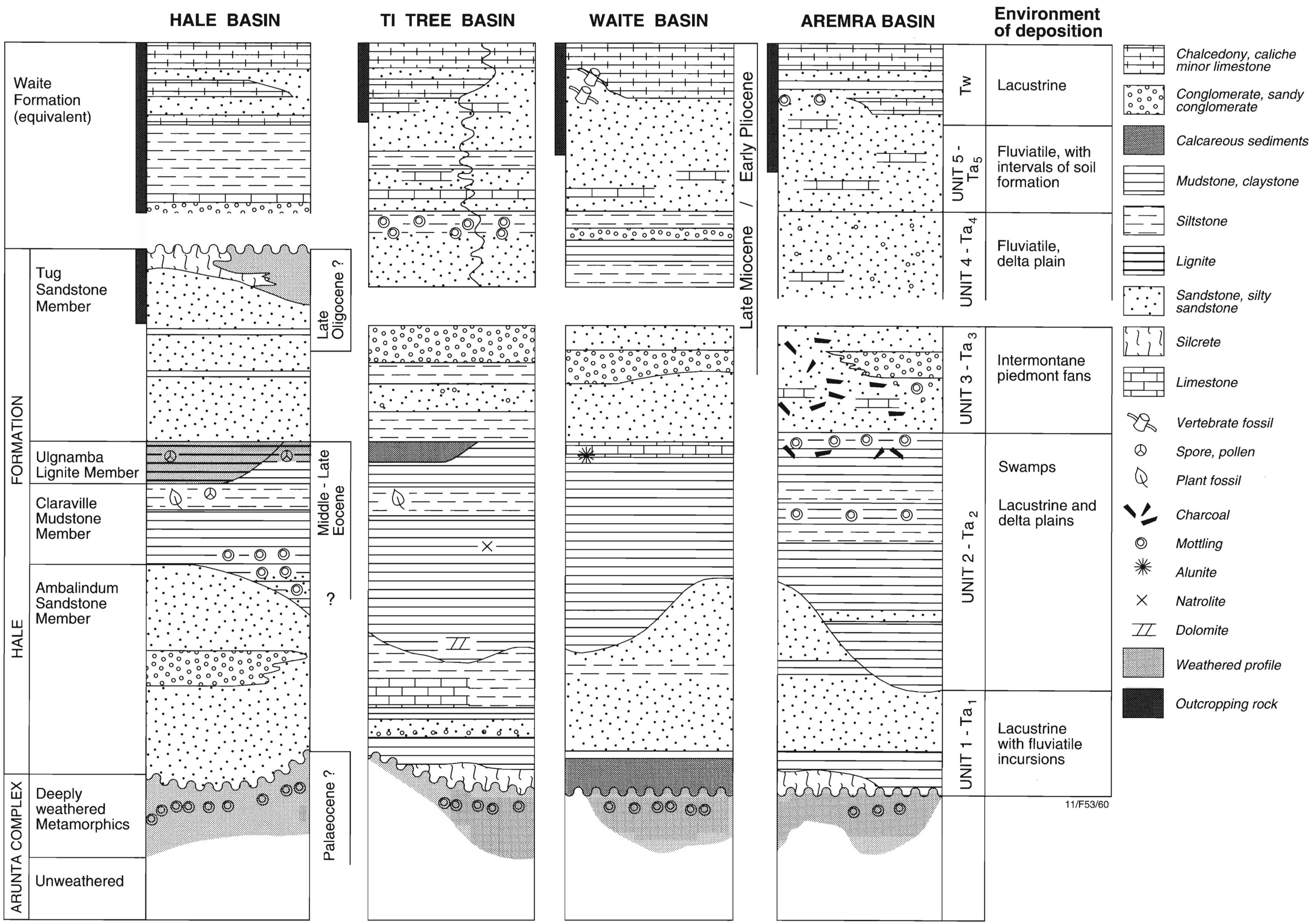

Figure 9. Diagrammatic correlation model for Tertiary units overlying the eastern part of the Arunta Block.

carbonaceous matter. The unit varies in thickness from less than 20 m (IR6 & IR9) to more than 100 m (IR11 & IR12). A prominent coarse quartz sandstone, 10–15 m thick, is widespread, generally at depths of 50–60 m. Rapid filling in intermontane piedmont fans is suggested by the poorly sorted nature of the sedimentary sequence. This would be consistent with an arid climate and sparse vegetation on the Harts, Strangways and MacDonnell Ranges, and rapid erosion in highland source regions. However, such a sedimentary facies would also equate with pluvial conditions in a humid climate. Concurrent tectonic movement is suggested by the tilted peneplain remnants forming concordant summit levels in the western hill country of the Illogwa Creek 1:250 000 Sheet area.

- Unit 4 (Ta_4) is widely distributed and consists of up to about 20 m of medium, coarse, or very coarse quartz–lithic sandstone. The sandstone is generally clean but in places may have a matrix of brown clay. Dominantly fluviatile deposition in a tributary and/or distributary drainage system is inferred by the widespread and generally matrix-free nature of the sandstones. These sediments appear to become increasingly fine-grained towards the axis of the basins, as is indicated by the dominantly fine clastic and lutitic sequence encountered at 10–40 m in BMR DDH 1. Stringers of coarse sandstone and conglomerate indicate periodic fluvial incursions in channel-like watercourses.
- Unit 5 (Ta_5), the uppermost unit, consists of intensely oxidised, red-brown silty sandstone with thin calcareous layers and nodules of probable pedogenic origin. Plant fragments were noted at a depth of 18 m in BMR Illogwa Creek 3. Ta_5 varies in thickness between 4 and 15 m. Lower energy fluviatile conditions are implied by the siltstone–sandstone facies. Lengthy periods of non-deposition, soil formation, and precipitation of calcareous materials are suggested by the oxidised nature of the sediments and the calcareous layers. The intensely oxidised nature of the sediments and precipitation of chalcedony may reflect seasonal rainfall under a dominantly arid climate.

Unit Ta is correlated with deposits, also mapped as Ta, in the Waite Basin and elsewhere (see above). For example, Ta_1 contains a minor silcrete at the base of the succession in the Aremra Basin and may equate with the very resistant silcrete (possibly Late Cretaceous in age) encountered below a thick green claystone–siltstone succession in BMR Alcoota 20 (i.e. in the Ti-Tree Basin, Alcoota Sheet area; Fig. 7; Shaw et al. 1979b). In addition, Ta_1 of the Aremra Basin has equivalents elsewhere in the region. For example, similar green claystones and siltstones lie stratigraphically below Mid–Late Eocene lignite and carbonaceous siltstone in the Hale Basin in the Alice Springs 1:250 000 Sheet area and in the southwestern part of the Ti-Tree Basin in the Alcoota 1:250 000 Sheet area (see above).

An early Tertiary or slightly older age is implied for the onset of deposition of Ta_1 following silcrete formation. The green claystone and siltstone unit (Ta_2) is considered to be Eocene, which is the age inferred for the lithologically similar Delaney Mudstone Member (Thc) below the Mid–Late Eocene lignite in the Hale Basin (see above; Truswell & Marchant 1986). Weathered elements in Ta_3 may correlate with weathering event C in the Hale Basin (Fig. 4), where palaeomagnetic data give Late Eocene as the most likely magnetic age. Although Tw appears to conformably overlie these units (Ta_{1-5}) it is possible they may be equivalent to or, in the case of Ta_5, slightly younger than Tw, as they occupy a stratigraphically lower position in the more depressed part of the basin. Thus, deposition of Ta_4 to Ta_5 may overlap in time with the deposition of the Waite Formation, which is Late Miocene or Early Pliocene.

Waite Formation equivalents (Tw)

The Waite Formation equivalents (Tw) consist of red and green silty sandstone with irregular calcareous nodules, travertine, calcarenitic and some pelletoidal limestone, and massive chalcedony. Up to 35 m of the unit is exposed on the rim of the Aremra Basin in the Illogwa Creek 1:250 000 Sheet area. Drill holes show that this formation grades downwards into unnamed poorly sorted sandstones and mudstones more than 200 m thick (Ta).

Tw forms extensive plateaus, mesas and rounded pinnacle-like hills. Its characteristic pale tones on aerial photographs are due to the presence of pale grey to whitish chalcedony layers, which are prevalent in the upper part of this formation. Upstanding landforms have flat summits and prominent bounding escarpments formed by beds of resistant chalcedony. Summit levels slope gently southwards, reflecting regional down-warping towards the broad Cretaceous and Cainozoic depression of the Lake Eyre Basin.

Beds within the unit are flat-lying. They consist of interbedded, reddish or greenish silty sandstone, sandstone, siltstone, and minor sandy conglomerate. Reworked clasts of ferruginous pisoliths and angular, conglomeratic, ferruginous fragments occur near the base, particularly where the formation overlies the weathered profile in Arunta basement rocks. In some places, chalcedonic layers are interbedded with fine sandstone, siltstone and mudstone lenses. The multiplicity of chalcedonic layers and the lack of clastic detritus indicate that they were formed by the precipitation of silica, possibly in shallow alkaline lakes or within groundwater discharge areas.

The unit is thought to represent an extensive sedimentary succession deposited in rivers and lakes (cf. Woodburne 1967). It overlies deeply weathered Arunta basement rocks in many areas, notably north of the Aremra Basin, north and east of Hugh Dam (Fig. 8). Elsewhere, Tw grades down into unnamed Tertiary sedimentary rocks (Ta).

Tw contains calcified plant debris. It is correlated with the Waite Formation, which is probably Late Miocene at its type section in the Alcoota region (Woodburne 1967).

Discussion

Stratigraphic framework

Although there is gross lithological similarity between the successions in the basins of the Alice Springs area, detailed correlation has been hampered by the weathering of many rock types and the lack of fossils. The lithological distribution in subcrop suggests that the Ti-Tree, Waite, and Aremra Basins were formerly interconnected. The Hale Basin evolved as a separate, isolated feature; it is used as a key reference section because of the better stratigraphic control established there. Dating within the basins is hampered by the poor recovery of palynomorphs from the largely weathered sediments, with only a few

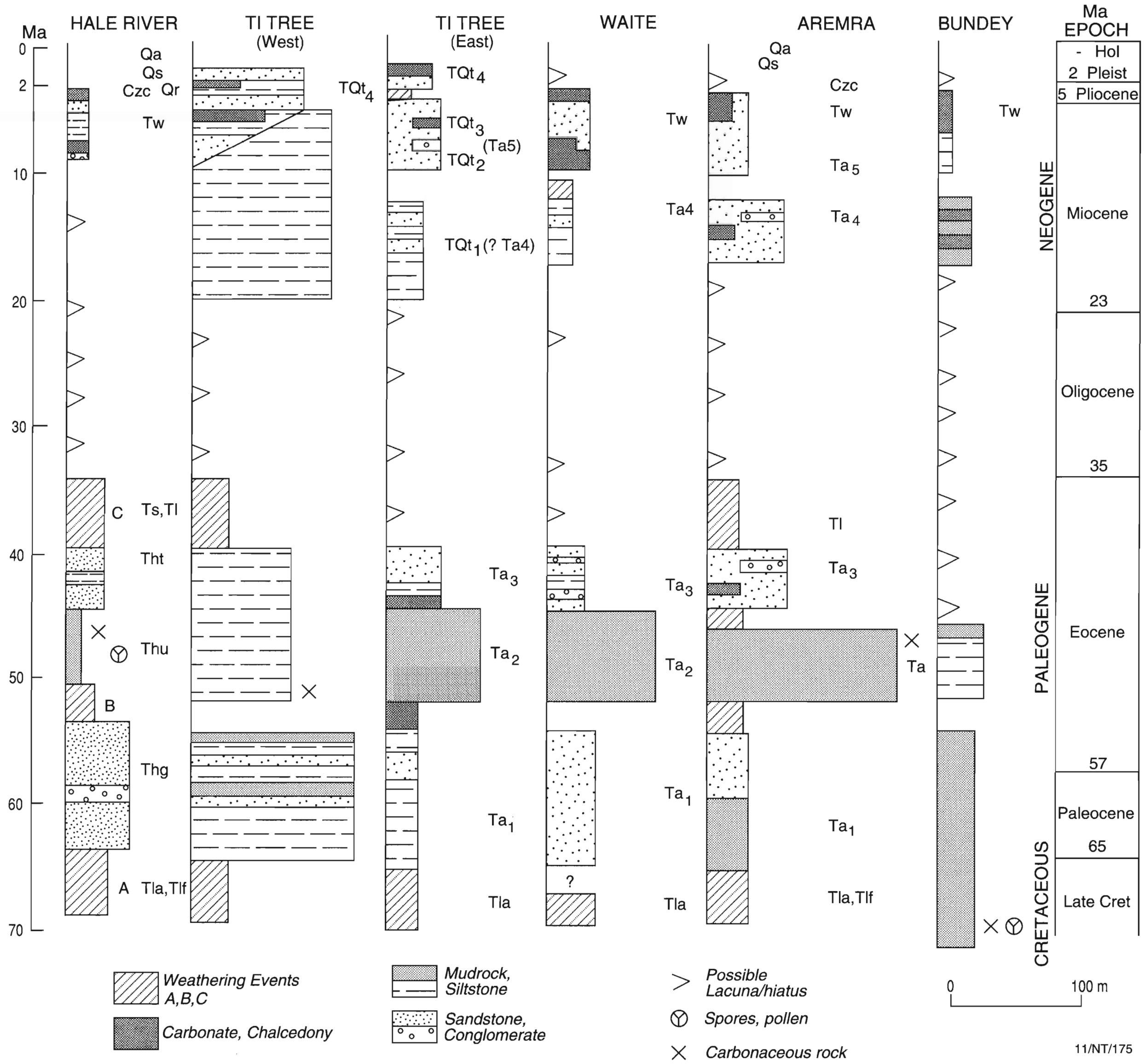

Figure 10. Interpretative time/depth plots for Cainozoic sedimentary units within the main basins overlying the eastern part of the Arunta Block. The timescale (Ma) is that of Harland et al. (1990).

sites yielding spores and pollen.

Although the Hale Basin evolved separately, it has a succession broadly comparable to the basins lying north and east of the Strangways and Harts Ranges (Fig. 1). Of particular interest is an olive-green mudstone unit present in most of the basins. In the Hale Basin, this mudstone grades upwards into a lignite-bearing carbonaceous succession; both the lignite and mudstone contain a rich flora of probable Mid to Late Eocene age. Widely distributed olive-green mudstone units in many of the basins (Fig. 9) possibly correlate with the mudstone in the Hale Basin and suggest the presence of a series of interconnected lakes and swamps during the Mid to Late Eocene.

Younger rocks in these basins consist of oxidised, coarse-grained, poorly sorted sandstone (e.g. Ta_3, Tht), which may have been rapidly deposited in coalescing piedmonts. The weathered profile in these sediments in the Hale Basin records the same Late Eocene magnetic age as weathered profiles preserved on topographically high residuals of Arunta basement. Tectonism and a hiatus in sedimentation may have preceded the deposition of younger sediments because the sites of deposition shifted in some regions. Late Miocene to Early Pliocene fossils reflect a diverse fauna of primitive marsupials, crocodiles, ringtail possums and other vertebrates and invertebrates, suggesting a change to lacustrine environments, probably with vegetated margins, during which interbedded red and green clayey siltstone, sandstone and lacustrine carbonate accumulated (e.g. Tw, TQt). These rocks are now protected from rapid erosion by resistant cappings of chalcedony, and thereby form low plateaus bounded by steep scarps. Sub-surface sedimentary rocks (units Ta_4, Ta_5) comprise some probable pedogenic ferruginous and calcareous layers and may be either equivalent to these lake deposits (i.e. Tw) or represent a longer period characterised by restricted intermittent deposition punctuated by episodes of exposure and erosion.

Figure 10 represents an evolutionary model for the depositional episodes, plotted in terms of current understanding of correlations, inferred age, and rates of deposition. It shows time versus thickness diagrams for the Tertiary segment of basin deposition. The plot is based on the lithological correlations shown in Figure 9, on presumed breaks in the sedimentary record, corresponding to periods of deep weathering in the Hale Basin (Figs 4 & 5), and, to a lesser extent, on possible correlation with weathering profiles dated palaeomagnetically in the Eromanga Basin (Idnurm & Senior 1978). The time slices adopted are consistent with the international time-scale of Harland et al. (1990), but boundaries are poorly constrained.

The most rapid sedimentation appears to have been in the Palaeogene during deposition of the mudrock unit (Ta_2). Although the order-of-magnitude accumulation rate of 1–15 m/Ma is slow, it is nevertheless within the range of rates recorded in intracratonic basins (cf. Schwab 1986). In order to maintain consistent rates of sediment accumulation, a major break is needed between Paleogene and Neogene sedimentation phases. The apparent lack of a weathered profile equivalent to the Late Oligocene to Early Miocene Canaway profile in the Eromanga Basin in southwest Queensland, may mean that the Oligocene to Early Miocene was a period of active erosion and possibly uplift in central Australia. The plot provides a model for the stratigraphic framework to be tested and refined by future work.

Chronology of chemical weathering

At least two main periods of intense chemical weathering can be identified in the central Australian basins. The first is represented by a relict profile in the Hale Basin, developed near the top of the Hale Formation (weathering event C in Figs 4 & 5). This profile has a Late Eocene preliminary palaeomagnetic age, consistent with a Middle to Late Eocene palynological age for the underlying Ulgnamba Lignite Member (Truswell & Marchant 1986). Its possible age equivalents are found in other Cainozoic basins in central Australia. Examples include thickly weathered intervals in Cainozoic successions intersected by drilling in the Yaloogarie (Stewart 1976) and Ti-Tree Basins (O'Sullivan 1973). An exposed possible equivalent is in breakaways along the northern flanks of the MacDonnell Ranges (unit Tlf of Warren & Shaw 1993). Palaeomagnetic dates suggest ferruginisation of the Arunta basement rocks in the region north of the Hale Basin during the same period, implying that the basement there was exposed.

The second, older weathering period is represented by relict weathered profiles developed in the Arunta basement rocks. In the Bundey and Ayers Rock Basins, their maximum age, obtained by palynological evidence in overlying sediments (Truswell 1987), is either Palaeocene or Late Cretaceous (Harris & Twidale 1991). Similar weathered profiles are widespread in the Arunta basement where it is covered by Cainozoic sediments, including the Hale Basin (weathering event A in Figs 4 & 5). It is possible that basement weathering through central Australia may record the same earliest Tertiary or older event.

In addition to the two main weathering periods, variously oxidised, mottled, silicified, and partly calcified rocks in several of the basin successions indicate other lesser periods of interrupted sedimentation and intense weathering. Examples of such intervals are weathering event B in the Hale Basin (Figs 4 & 5), paleosols at several levels in unit Ta5 in the Aremra Basin, the chalcedonic top of Tw, and the markedly oxidised soils of Qr.

Some weathering events in central Australia may have extended to adjacent regions. In particular, the older period of weathering may be represented in the Eromanga Basin by the Morney profile, dated palaeomagnetically as Late Cretaceous/Early Tertiary (Idnurm & Senior 1978). The same chemical weathering may have ferruginised the Mesozoic Hooray Sandstone along the northwestern margin of the Eromanga Basin and its equivalent in the Hay River 1:250 000 Sheet area. Similarly, weathering event B in the Hale Basin may correlate with an early Middle Eocene hiatus in the Eromanga Basin. On the other hand, the prominent Late Eocene weathering profile in the Hale Basin region (weathering event C) seems to have no age equivalent in the Eromanga Basin: the Canaway profile, which resembles the trizonal Hale Basin profile, has a poorly defined but distinctly younger (approximately Oligocene) palaeomagnetic age. More dates are needed to test the central Australian, as well as inter-regional, tentative correlations.

Palaeoenvironmental and palaeoclimatic implications

Palynological investigations in the Hale Basin have provided both age control and climatic information. Pollen assemblages from the lignites and the underlying green mudstones contain, as very rare elements, pollen types confined to the Mid to Late Eocene interval in southern Australian coastal basins. Pollen assemblages at Hale River are dominated by *Nothofagus* (*Brassospora* spp.), the southern beech, and by pollen of a number of podocarpaceous (southern conifer) genera, suggesting that rainforest trees grew in the vicinity, under conditions of high humidity. Pollen of Casuarinaceae occurs in all assemblages and, assuming that these were non-rainforest species, there may have been some open forest vegetation, possibly on lake margin sites. The pollen cannot, however, be distinguished from rainforest members of the family. Pollen of aquatic plants, reeds and sedges, is locally common.

The pollen suite from the Ulgnamba Lignite bears some resemblance to suites of probable Middle Eocene age described from the Lake Eyre Basin (Sluiter 1991), for which quantitative estimates of palaeoclimates have been made. Some of the Lake Eyre assemblages are similar in that there is a high frequency of *Nothofagus* pollen and Casuarinaceae, but they differ in having a considerable abundance of pollen of Myrtaceae and Cunoniaceae. The two localities are similar in having significant quantities of pollen of aquatic taxa.

Sluiter (1991) used the climatic parameters controlling modern forest taxa as the basis for palaeoclimate estimates. The underlying assumption is that the ecophysiologic characteristics that determine the broad climatic responses of the vegetation are unlikely to have changed through time. On this basis, it was estimated that the mean annual temperature in the Eocene of central Australia was 17–18°C, and the mean annual precipitation around 1500 mm. While the Lake Eyre and Hale Basin microfloras differ in some respects, they were comparable enough to allow conjecture that similar conditions may have pertained in the Hale Basin in the Eocene. A tentative reconstruction of climatic conditions is outlined in Table 2.

Tectonic implications

On a continental scale, changes in the patterns of subsidence, including those in central Australia, appear to follow major phases of plate realignment and switches in the sites of sea-floor spreading (Table 2). The earliest recognised period of widespread deep weathering in central Australia may have begun in the Late Cretaceous and its termination may have been related to a broad uplift, affecting much of the continent. This uplift was greatest along the Eastern Highlands (see Veevers et al. 1991). Lister et al. (1986) suggested that this uplift of the Eastern Highlands was related to extension immediately prior to sea-floor spreading in the Tasman Sea. The central Australian intermontane basins may have been initiated at this stage or slightly later (i.e. units Ta_1, Thg; Table 2).

The succeeding phase of rapid Eocene infilling in the Cainozoic basins of central Australia (i.e. units Ta_2, Thu, Thc) appears to correspond to the rapid drift of Australia away from Antarctica (cf. Veevers et al. 1991). A major reorganisation of plate motions (Australian–Pacific plates) took place at about 43 Ma (i.e. in the late Mid-Eocene; see Wells 1989), and this event may correspond to minor tilting of piedmont fans (units Ta_3, Tht; see Table 2) as a result of limited doming of the ranges in central Australia. A period of more restricted deposition and widespread deep weathering followed in central Australia (units Tl, Ts and widespread overprinting of Tlf; Table 2). The end of widespread deep weathering is probably recorded by the Late Eocene magnetic date from the Hale Plain and surrounding region. More work is needed to clarify the timing, nature and correlation of these early Tertiary events.

In about the Oligocene, a widespread hiatus and a slight shift in the drainage systems in central Australia was accompanied by a switch in the sites of sedimentation (units Ta_4, TQt, then Tw; see Table 2). It is speculated that this period of apparent uplift of the central Australian ranges may be related to a rearrangement in the Pacific plate and the beginning of the northern Australian collision with Papua New Guinea at about 25–27 Ma (late Oligocene: see Kamp 1991; Etheridge et al. 1991). In this case, the hiatus may be the result of renewed, but slight, regional uplift and erosion of parts of the continent and may be related to compressional tectonism.

A similar, but later, compressional stress may explain the limited uplift of the central Australian ranges, which led to the major drainage reversal of the Sandover River. Tilting of the western MacDonnell Ranges, with some inferred uplift of the MacDonnell Ranges in the region of the Redbank Thrust Zone, probably took place in the latest Pliocene or earliest Pleistocene, as suggested by both the doming of earlier weathering profiles in the MacDonnell Ranges and, to a lesser extent, by the development of extensive fanglomerate deposits (e.g. unit Tuc, previously Czc as in Table 2). At this time, the duricrust capping the Late Devonian conglomerates, the Undandita Member (of the Brewer Conglomerate) appears to have been tilted along the western MacDonnell Ranges (Warren & Shaw 1993). The steep gradient to the Todd River and the beginning of dissection of the Sixteen Mile Basin (Fig. 1) may also date from this period. The inferred doming in the region of the MacDonnell Ranges seems to have been accompanied by subsidence in the region of the Lake Eyre Basin. The possibly Late Pliocene uplift of the MacDonnell Ranges was followed by a period of partial peneplanation and ferruginisation (unit Qr), which pre-dates the last phase of major erosion in the Holocene (units Qa, Qs, Ql, see Shaw & Wells 1983).

Implications for groundwater assessment

Some of the most productive aquifers within the Cainozoic sequences are commonly complex deeper channel sandstones, separated by claystone(and siltstone)-dominated aquicludes (e.g. unit TQt). They represent older drainage systems lying below the present drainage channels. Such aquifers have been investigated for their irrigation potential at Willowra (Morton 1965), and Kulgera (Woolley 1965a, b), the Farm-area Basin near Alice Springs (Woolley 1966; Quinlan & Woolley 1969), and Ti-Tree (McDonald 1988a, b). Groundwaters from these aquifers have variable low to high salt contents. Given the potential of this style of aquifer for recharge, these more permeable and porous upper parts of the Tertiary basins remain an important source for small to moderate renewable water supplies. Consequently, the identification and mapping of palaeodrainage systems within the Neogene fill remains an important target for future investigation.

The older Paleogene sedimentary rocks, lying at even greater depths (e.g. units Ta_2, Thu), tend to be dominated by claystone or mudstone, resulting in poor permeability. Similarly, deeply weathered bedrock generally yields only poor quality water, for which the quality and supply depend on the permeability of the weathered zone.

Future research

Stratigraphic studies need to be extended into the wider region, including the western Arunta Block, the Amadeus Basin and the Eromanga Basin. For example, similar basins overlying the western Arunta basement and the Palaeozoic and Late Proterozoic rocks of the Amadeus Basin should be more accurately delineated, using remote-sensing and techniques that estimate depths to magnetic basement. Further drilling is required in these western basins to see if basin development is similar to that in the eastern part of the Arunta Block. Analogous basins may also include the Horse Creek, Springvale, Marion, Austral Downs, and Noranside Basins, previously described by Paten (1964) in western Queensland. Comparison of sedimentary sequences throughout central Australia may enable a closer analysis of depositional environments and provide a basis for understanding continent-wide Cainozoic stratigraphic evolution.

Preliminary data reported here, together with geological mapping in the Hermannsburg 1:250 000 Sheet area (Warren & Shaw 1993), point to several future research topics concerning the Cainozoic geology of central Australia. These include:

- Detailed stratigraphic, lithologic, petrologic, and petrographic studies of the key successions to select sections suitable for developing models of past climatic regimes.
- A study of Cainozoic warping, as observed from tilted strata, and sediment distribution in relation to peneplain development. For example, the origin of intermontane basins with up to 300 m of sedimentary rocks implies some degree of extension. On the other hand, some compressional tectonism might be explained by the relationships between the exhumation history of peneplain surfaces along the MacDonnell Ranges and the growth and dissection of piedmont fans straddling the MacDonnell Ranges.

- A search for Permian and Mesozoic basins underlying the Cainozoic successions and assessment of their groundwater potential. Although only a thin Permian succession has been identified locally in the subsurface northeast of Haast Bluff (Truswell 1985), it is possible that a much thicker succession is preserved elsewhere. For example, it is likely that a considerable thickness, up to 300 m or more, of sedimentary rocks occurs along the BMR deep seismic line (J. Taylor, AGSO, personal communication, 1991).
- Reconstruction of the palaeogeography as the basis for an assessment of the presence of as yet unknown basin sequences. The extent and boundaries of the known basins are as yet incompletely understood.
- Recharge studies of the Tertiary basins to more accurately determine aquifer characteristics and potential yields of groundwater. For example, the Burt, Sixteen Mile, and Mount Wedge Basins (Fig. 1) deserve particular attention because of their proximity to Alice Springs. In the eastern Mount Wedge Basin, potential recharge is provided by the outwash and alluvial plains of the Derwent and Dashwood rivers. In the Burt Basin, potential for recharge is largely unknown and warrants a more detailed investigation.
- Regolith studies, including relationship of basins to landscape development.
- Further palaeomagnetic studies or implementation of $^{40}Ar/^{39}Ar$ weathered-rock dating techniques for improved age control. In addition, the use of oxygen and hydrogen isotopes should be explored for elucidating past climates, palaeolatitudes, and ages of weathering profiles.

Summary and conclusions

Analyses of Cainozoic sedimentary basin successions, supported by palynological and palaeomagnetic data, indicate two main episodes of deposition in several distinct basins.

- The first episode is represented by thick deposits that date from a Paleocene phase of basin infilling. Locally, as in the Ayers Rock Basin, an even earlier but less-widespread phase may have begun in the Late Cretaceous. Initial fluviatile sand deposition in several of the basins gave way, perhaps in the Middle Eocene, to widespread silt and mud accumulations in a series of interconnected lakes. Swamps and forests were prevalent at this time in regions such as that surrounding the Hale Basin. Then followed deposition of coarse lithic sands with derived weathered rock components, together with scattered woody debris and charcoal. Siliceous and calcareous rock types were chemically precipitated during this interval.
- The second episode of subsidence took place in the Late Miocene to Early Pliocene and was preceded by an extended period of hiatus, possibly spanning the Oligocene. This interval was characterised by deposition of sand, silt and clay, intercalated with calcareous and chalcedonic sediments, some of which appear to represent the products of weathering and groundwater processes.

Between these two episodes, the centres of deposition shifted, implying a change in the tectonic forces affecting the region. The Late Eocene magnetic date obtained for weathering event C is considered to record the time when weathering processes ceased over much of the region as a result of the implied tectonic rearrangement.

For a fuller understanding of the Cainozoic sedimentary sequences of central Australia, there is a particular need for better time control, through palynological and paleomagnetic studies, as well as other techniques. Dating of clay minerals (e.g. illite, cryptomelane–hollandite) by K-Ar methods shows considerable promise, although possible age modification of the clays by diagenesis and weathering will need to be considered. Stratigraphic studies of clay minerals, using semi-quantitative techniques, may also allow greater precision in correlating sedimentary units and weathering events.

Extension of these techniques to basins surrounding those in central Australia would greatly assist in piecing together the continent-wide Cainozoic successions, leading to an improved knowledge of tectonics and palaeoclimates. Because of the generally poor outcrop, improved drilling techniques leading to better sample recovery would be of considerable benefit. Wireline logging of drill holes is considered essential for improved correlation of both rock units and weathered profiles.

A full assessment of resources in the Cainozoic units warrants further investigations. There is potential for sedimentary uranium, although investigations to date have been largely disappointing. These Cainozoic deposits may well conceal economic mineral deposits in the basement rocks, but geochemical mineral exploration is hampered by the poorly understood effects of deep weathering on chemical dispersal. The presence of potentially commercial lignite and oil shale in basins of comparable age and sedimentary facies, such as the massive Stuart and Rundle deposits in Queensland, means central Australia remains prospective for similar resources.

These basins represent also potential sources of sustainable water supplies for use by small communities or for irrigated agriculture. However, their recharge characteristics remain largely unknown.

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