The Permian–Triassic boundary in western Australia: evidence from the Bonaparte and Northern Perth basins—exploration implications

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ABSTRACT

Several sedimentary basins in western Australia contain petroleum reservoirs of Late Permian or older age that are overlain by thick shaly sequences (400–2,000 m) that have been assigned an Early Triassic age. The age of the base of the Triassic shales has been, and continues to be, contentious with strata variously ascribed to the latest Permian (Changhsingian Stage) or wholly within the earliest Triassic (Induan Stage). In the Perth Basin the Permian-Triassic boundary appears to be located somewhere in the Hovea Member of the Kockatea Shale. In the Bonaparte Basin, the boundary would appear to be either in the uppermost Penguin Formation or at the boundary between the Penguin and Mairmull formations.

The uncertainty of the boundary placement relates to the interpretation of the sedimentological, biostratigraphic and geochemical record in individual sections and basins. Major problems relate to the recognition, or even the presence of unconformities, complications related to the presence of reworked sediments and paleontological material (both conodonts and spore-pollen) and to the significance of geochemical shifts.

The age of the basal Kockatea Shale (northern Perth Basin) and the basal Mt Goodwin Sub-group (Bonaparte Basin) is reassessed using palaeontological data, augmented by carbon isotopic measurements and geochemical analyses, supported by wireline log correlations and seismic profiles. The stratigraphy of the latest Permian to Early Triassic succession in the Bonaparte Basin is also revised, as is the nomenclature for the Early Triassic Arranoo Member of the Kockatea Shale in the northern Perth Basin. The Mt Goodwin Sub-group (new rank) is composed of the latest Permian Penguin Formation overlain by the Early Triassic Mairmull, Ascalon and Fishburn formations (all new).

KEYWORDS
Permian-Triassic boundary, western Australia, northern Perth and Bonaparte basins, palaeontology, carbon isotopes, well log correlations, 2D and 3D seismic, redefined Mt Goodwin Sub-group and Penguin Formation, defined Mairmull, Ascalon, Fishburn formations (new), Arranoo Member, tectonics, eustacy, source rocks.

INTRODUCTION

The Early Triassic sedimentary succession is one of the most tightly age-controlled intervals in the Phanerozoic sedimentary record. Recent advances in the radio-isotopic methods of dating of ashfall tuff zircons are producing reproducible results with error bar constraints of +/- 0.2 Ma (Mundil et al, 2001; 2004; Mattinson, 2005; Galfetti et al, 2008). In China a biostratigraphically (ammonoids and conodonts) well-constrained succession from the Late Permian (Changhsingian) through to the Middle Anisian and containing literally hundreds of interbedded tuff horizons has been examined (Galfetti et al, 2008). Table 1 shows the revision of the age constraints in the Early Triassic from GTS 2004 (Gradstein et al, 2004) through to the Middle Anisian and containing literally hundreds of interbedded tuff horizons has been examined (Galfetti et al, 2008). The time constraints on this Early Triassic interval demonstrate that the duration of the Griesbachian Substage was only about 0.4 Ma, the Dienerian about 0.53 Ma, the Smithian about 0.73 Ma and the Spathian about 2.87 Ma. The short duration of
these time intervals may well contribute to our inability to recognise sediments of the early part of this interval in some regions of the Western Australia margin.

Marine Triassic rocks are widespread in the Bonaparte, Browse, Canning, northern Carnarvon and Perth basins (Fig. 1). Many petroleum exploration wells have penetrated Triassic strata and together with widespread seismic profiling in the search for oil and gas resources, enable a robust lithostratigraphy to be established. The Early Triassic sedimentary succession is predominantly composed of marine fine-grained clastic sediments and occasional interbedded carbonates, with total thickness ranging from 400–2,000 m, deposited over a time interval of 5.1 million years (Ogg et al., 2008). Most of the Early Triassic formations identified in the literature are based on lithostratigraphy, that is, correlated by electric log profiles and dominant rock types, with some biostratigraphy included by way of palynology. Unfortunately, most of the Australian Triassic spore-pollen zones are endemic to the region (Balme, 1969; 1990; Balme and Foster, 1996; Dolby and Balme, 1976; Helby et al., 1987) and correlations to better-dated strata elsewhere in the world is somewhat problematic. In some instances, particularly in the upper part of the Triassic, dinoflagellates can be correlated outside of the Australian region (e.g. Balme, 1969; 1990; Balme and Foster, 1996), and in even fewer instances conodonts and ammonoids prove useful in correlation (e.g. Nicoll and Foster, 1998; Nicoll, 2002; Skwarko and Kummel, 1974).

In the Perth Basin, the basal Triassic shales are seals to underlying Permian reservoirs (e.g. Cliff Head and Hovea fields) and also interpreted to be source rocks (Thomas and Barber, 2004), and minor oil and gas reservoirs are present in the regressive Early Triassic strata at the Dongara oil and gas field (Arranoo Member). In the Bonaparte Basin the basal Triassic shales form the ultimate seal for Permian reservoirs at the Prometheus, Rubicon, Fishburn, Petrel and Tern fields and include thin reservoir quality and gas-bearing sandstones at Blacktip–1 and Ascalon–1A (Ascalon Formation, see below).

The primary correlation is by wireline log curve matching between petroleum exploration wells, supported by conodont and palynological control in shallow marine to continental strata. Inter basinal correlations are made using the same methodology but more emphasis is placed on the matching of chronostratigraphic surfaces supported by the generally short-lived conodont faunas. In addition, carbon isotope profiles over the Permian-Triassic transition provide information on the base of the Triassic System by means of correlation to well-dated extra-Australian measured sections controlled by detailed palaeontology (Galfetti et al., 2008; Mundil et al., 2001, 2003).

**STRATIGRAPHIC NOMENCLATURE AND THE TRIASSIC/PERMIAN BOUNDARY**

**Bonaparte Basin**

The present lithostratigraphic nomenclature of Triassic rocks known from the subsurface across the Timor Sea, and
The Permian-Triassic boundary in west Australia: evidence from the Bonaparte and Northern Perth basins—exploration implications

outcrops in the southeastern Bonaparte Basin (Dickins et al., 1972; Mory, 1988, 1991), is illustrated in Figure 2. Correlation between wells relied on wireline log similarities.

The basal Triassic unit redefined by Mory (1988) was the Mt Goodwin Formation of the Kinmore Group, recognised regionally as a seismically bland package from the southeastern part of the Bonaparte Basin (e.g. Petrel field), westwards across the Londonderry High (e.g. Osprey–1 area) and onto the Ashmore Platform (e.g. Sahul Shoals–1 area). The Mt Goodwin Formation was originally defined by Helby (1974) from Petrel–1 well between 2,887 and 3,464 m, where it consists of a series of interbedded shales and siltstone with minor fine-grained sandstones.

Defining the base of the Triassic—Bonaparte Basin

The base of the Triassic in the Bonaparte Basin has generally been considered to be at the base of the Mt Goodwin Formation (now Sub-group); however, in some wells there is a shaly section similar to the Mt Goodwin Sub-group between the undoubtedly Late Permian Tern Formation and the well-dated basal Triassic. This unit was called the Penguin Formation by Gorter (1998). Log correlations in the southern Bonaparte Basin (e.g. Fig. 3) show that there is an unconformable contact between Late Permian and Early Triassic strata in the region of Fishburn–1 and this unconformable relationship is supported by seismic profiles and is well illustrated by 3D seismic at Blacktip–1, where well-defined dendritic systems are incised into the top of the Tern Formation (Fig. 4). The two Permian limestones sequences seen in Petrel–2 in Figure 3 are readily correlated on seismic profiles across the Bonaparte Basin and the erosion of the Late Permian Dombey Limestone is evident at Fishburn–1. In this well there is a shaly interval between the eroded top of the Cape Hay Formation and the base of the dated Mairmull Formation (new name). This shaly sequence is assigned to the Penguin Formation, and contains the *P. microcorpus* Oppel Zone at Fishburn–1 (Fig. 5). The major change in the carbon isotopic profile is seen to occur at the base of the *P. microcorpus* Oppel Zone in Fishburn–1, but the most negative values lie at the base of the *L. pellucidus* Oppel Zone (Fig. 5).

If the top of the Permian is defined as lying between the *L. pellucidus* Oppel–Zone and the *P. microcorpus* Oppel–Zone, then the most likely positioning of the basal Triassic is at the lightest carbon isotopic horizon, i.e. the top of the Penguin Formation. The base of the Penguin Formation is a clearly defined unconformity with the Tern Formation and Dombey Formations absent by erosion. The base of the Penguin Formation was cored in Tern–5. In the core the base of the Penguin Formation lies below a granite pebble lag described from about 2,545.2 m in the core above the Tern Formation (Fig. 6). Palynological information from just above the pebble lag indicated the lower *P. microcorpus* Oppel Zone is present in a nearshore depositional environment (Purcell, 2008). The granite pebble horizon suggests long distance transport from granitic terrain to the south.

The major isotopic break in Tern–3 (data from Morante, 1996) also occurs below the base of the *P. microcorpus* Oppel Zone (Fig. 7). The isotopic shift in Tern–3 is saw-toothed in pattern, with more negative isotopic values increasing up section (Fig. 7). Helby (1983, in the Tern–3 well completion report) placed the base of the Triassic at

![Figure 2. Stratigraphy of the Timor Sea region and Bonaparte Basin (modified from Gorter, 2008 unpublished poster).](image-url)
Figure 3. Correlation section between Fishburn–1, Tern–3 and Petrel–2 across the Permian-Triassic transition. Note the unconformable contact at Fishburn–1 is also supported by the seismic and well log correlation to offset wells, with the Dombey and Tern formations both eroded at the well site.
The Permian-Triassic boundary in west Australia: evidence from the Bonaparte and Northern Perth basins—exploration implications

Detailed examination of the Permian-Triassic transition in Tern–3 shows a sharp boundary between the Tern Formation and the overlying Penguin Formation indicated by the gamma ray (GR) curve (Fig. 8). Also shown in Figure 8 are the palynofacies percentages of opaque organic matter, plant debris and acritarchs (after Helby, 1983, in Tern–3 well completion report). It is clear that over the transition interval marked by the P. microcorpus Oppel Zone that the decreasing amount of opaque organic debris parallels the upward negative shift of the carbon isotopic curve (Fig. 8). Note that the carbon isotopic values were derived from digitising a figure from Morante (1996) whereas the other curves are derived from digital data in the Tern–3 well completion report; there may be a slight discrepancy in depth between these measurements.

In Petrel–4 the boundary is not so clearly demarcated because the isotopic break occurs above the 9½" casing (data from Morante, 1996), with the cuttings-based isotopic values below the casing shoe having heavier isotopic values. These cuttings-derived values are not as isotopically heavy as from the cored Cape Hay Formation section below the Dombey Formation limestone marker (with the notable exception of the sample from 3,600 m where over 93.5% of the kerogen is from acanthomorph acritarchs) (Fig. 9).

The evidence from the southern Bonaparte Basin shows that the major unconformity lies between the P. microcorpus Oppel Zone and older Late Permian strata. The unconformity is supported by 2D and 3D seismic data, well log correlations and palynology. The carbon isotopic profiles show a negative inflexion at the base of the Penguin Formation above relatively monotonous heavy isotopic values through the Permian (except where complicated by very negative measurements equated to marine incursions). The base of the Triassic is marked by the most negative carbon isotope values and the incoming of the L. pellucidus Zone.

Northern Perth Basin

The basal Triassic stratigraphic subdivisions of the Perth Basin were established by Playford et al (1976) and the summary published by Cockbain (1990) is essentially unchanged by subsequent publications, other than the recognition of the Hovea Member at the base of the Kockatea Shale (Thomas and Barber, 2004) and the reinterpretation that at least some of the sandstone bodies—like the Dongara Sandstone—are of Late Permian age. Nonetheless, there is considerable debate about the nature of the Permian-
Triassic transition (Fig. 10) and the precise placement of the boundary. Thomas and Barber (2004) contended that deposition was essentially continuous across the Permian-Triassic boundary and Metcalfe et al (2008) suggested that the lack of Early Triassic (Induan) conodont faunas from any locality in Western Australia probably indicates a depositional break in the boundary interval.

In establishing the Hovea Member of the Kockatea Shale, Thomas and Barber (2004) extended the base of the Kockatea Shale into the Late Permian. They placed the base of the Kockatea Shale into the upper part of the Wuchiapingian Stage and included both the D. parvithola to P. microcorpus Oppel Zones in the Permian. There may be some question regarding the recognition of the D. parvithola Oppel Zone in the base of the Hovea Member, but the interpretation of a P. microcorpus Oppel Zone in the base of the Hovea Member is more certain (Thomas et al, 2004).

The Arranoo Member is the interbedded fine-grained sandstone and siltstone facies in the upper Kockatea Shale in onshore wells in the Dongara gas field area (Gilchrist and Holloway, 1983; Mory and Iasky, 1996: Crostella and Backhouse, 2000), and is overlain by a regressive unit, the Woodada Formation (Mory and Iasky, 1996). The Arranoo Member contains the K. saeptatus Oppel Zone.

The Kockatea Shale crops out in the northernmost Perth Basin around the Northampton Complex and as far north as
The Permian-Triassic boundary in west Australia: evidence from the Bonaparte and Northern Perth basins—exploration implications

**Figure 7.** Carbon isotopic profile across the Permian-Triassic transition in Tern–3 (isotopic data digitised from Morante, 1996). Note the maximum negative shift at the base of the Mairmull Formation below the \textit{P. microcorpus} Oppel Zone (based on core data).

**Figure 8.** Details of the Permian-Triassic transition in Tern–3, showing the sharp boundary between the Tern Formation and the overlying Penguin Formation (left hand column), the carbon isotopic profile (after Morante, 1996), and the palynology in the right hand column (from Helby, 1983, in Tern–3 well completion report). Also shown are palynofacies percentages of opaque organic matter, plant debris, and acritarchs (after Helby, 1983, in Tern–3 well completion report).
Figure 9. Carbon isotopic profile across the Permian-Triassic transition in Petrel–4 (isotopic data from Morante, 1996; Foster et al., 1997) indicating no marked negative shift at the base of the Penguin Formation in this well, possibly because of complications resulting from the placement of the 9¾” casing. Note the highly negative marine spike in the Permian section caused by the abundance of spinose acritarchs and the marked negative isotope excursion at the base of the Mairmull Formation.

Figure 10. Stratigraphy of the northern Perth Basin (from Gorter et al., 2008).
Kalbarri in the southern Carnarvon Basin (Mory and Iasky, 1996). Ammonoids indicate that the base of the Kockatea Shale in the subsurface in BMR Beagle Ridge–10 is Early Triassic (Griesbachian), and Smithian at the top (Dickins and McTavish, 1963; Balme, 1990; Gorter et al, 1995; Foster et al, 1997). North of Beagle Ridge–10, at Mt Minchin, ammonoids from the lower part of the formation are of Smithian (late Early Triassic) age demonstrating that the Kockatea Shale is time transgressive onto the Northampton Block (Playford et al, 1976). Outcrop in the north of the basin is generally sparse and weathered, and detailed measured sections are non existent—the type section is 12 m thick according to Mory and Iasky (1996)—so that well logs and drill cuttings are the major source of lithostratigraphic and biostratigraphic information.

The Kockatea Shale is the only Triassic formation in the northern Perth Basin with established ties to international biostratigraphy including conodonts and ammonoids, but most of the non-marine Triassic in the basin relies on long ranging spores and pollens for age dating. The Kockatea Shale contains the *K. saeptatus* Oppel Zone, sometimes sub-divided into the *P. samoilovichii* zone and the basal *L. pellucidus* zone. Conodonts from the basal limestone are usually dated as Smithian by the *N. dieneri–N. pakistanensis* zones. Carbon isotopic profiles have been established for the Permian-Triassic transition in Woodada–2 (Gorter et al, 1995; Foster et al, 1997), several Dongara area wells (Andrew et al, 1999; Morante et al, 1999), and Hovea–3 (Thomas and Barber, 2004; Thomas et al, 2004). Morante et al (1994) and Morante (1996) provided some additional information on BMR Beagle Ridge–10A, but unfortunately insufficient to enable a vertical profile to be drawn.

The Dongara oil and gas field is the largest hydrocarbon pool in the northern Perth Basin. Reservoirs include several named Permian sandstones that are sealed, and sourced by the overlying Early Triassic Kockatea Shale. At Dongara–1 the basal part of the Kockatea Shale includes an inertinitic interval overlain by a sapropel-rich unit called the Hovea Member (Thomas et al, 2004). The exact age of the inertinitic unit is still in dispute (see above) but the sapropelic interval in the upper part of the Hovea Member is clearly near-basal Triassic in age as it contains distinctive bivalves, conodonts and ammonoids that are of the same age as well-dated Early Triassic sections elsewhere in Gondwana. The sapropelic interval and the overlying Kockatea Shale proper contain the *K. saeptatus* Oppel Zone (Fig. 11). The informally named limestone marker, which overlies the sapropelic unit, dated by the occurrence in several wells of the *N. pakistanensis* conodont fauna (e.g. Corybas–1 in Metcalfe et al, 2008), is included in the Hovea Member by Thomas et al (2004).

### Defining the base of the Triassic—Perth Basin

Detailed palaeontological and organic geochemical information derived from cores from Dongara–4 is illustrated in Figure 12. The Rock-Eval T<sub>max</sub>, hydrogen index (HI) and production index (PI) measurements are from in-house Eni data measured by Geotech (West, 2000). The GR (API) and sonic (DT) logs are from digitised electric log data from the Western Australian Department of Mines and Petroleum website. The SC GR (API) is a gamma ray log run over slabbed core by CoreLab in 1998 for British-Borneo (now Eni). The ranges of the various fossils in the core are from Dr Peter Jones (Australian National University, pers. comm.), for the ostracod *Carinaknightina discarnarita*; RSN (new conodont identifications), and McTavish (1973) for the *N. dieneri* zone conodonts. The identification of *Claraia* sp was by Dr Mac Dickins (deceased, ex Bureau of Mineral Resources, pers. comm.) and JDG (in house identifications). The position of the limestone marker is derived from the sonic log correlation to nearby wells and cuttings described from the Dongara–4 mud log. Cores were matched to the top hole logs via the core gamma log for cores 1 to 3, and are matched at the top of core 4 based on the rounded pebble lag (Backhouse, 1996) and the gamma ray curve. The interpreted trends for the latest Permian (blue box) and Early Triassic (pink box) carbon isotopes follows the Hovea–3 data (Thomas and Barber, 2004; Thomas et al, 2004) as shown in Figure 11.

The Dongara–4 Rock-Eval data derived from the cored section (cores 1 to 3) show the contained organic matter is immature (also shown by vitrinite reflectivity values of <0.6%; West, 2000) and the conodont colour alteration index of 1. The carbon isotopic values through the undoubted Permian section are closely comparable to the Permian section of Hovea–3 (as in Fig. 11), but in Dongara–4 the undoubted Triassic interval shows a marked scatter of isotopic values from measurements closely comparable to undoubted Permian values (Fig. 12) to values similar to those from the undoubted Triassic section in Hovea–3. The undoubted Triassic samples with the heaviest carbon isotopic composition in Dongara–4 appear to contain recognisable megaspores (Dr Clinton Foster, Geoscience Australia, pers. comm.). Megaspores are particularly noted from the inertinitic member at Corybas–1 (Metcalfe et al, 2008).

Gorter et al (1995) noted possible reworking of the Permian strata with heavier isotopic measurements in Woodada–2, and Foster et al (1997) attributed the heavy isotopic values in the same core to reworking. The Dongara–4 data do not disprove the Hovea–3 interpretation, but the absence of any heavy isotopic values in the Hovea–3 Triassic is surprising—perhaps the Hovea location was far enough from the eroding Permian outcrop that reworked Permian organic detritus was not deposited (or it was deposited during the height of the transgression so that no hinterland was exposed).

Metcalfe et al (2008, fig. 2) illustrated a section through Corybas–1 to Hovea–3/ST1 that could support the interpretation here of an unconformity at the top Permian or the top of the inertinitic unit at Hovea–3. A poorly preserved occurrence of the Late Permian conodont *Clarkina jolfensis* at the base of the sapropelic interval may indicate a continuous section, but equally it could be reworked. Unfortunately at the time of writing there is no palynological information from this well. Log correlation between Hovea–3/ST1, Dongara–4 and Corybas–1 (Fig. 13) implies that the single specimen of *C. jolfensis* may be reworked.
The very fine-grained sandstones of the informally named Indoon member in Indoon–1 (Fig. 14) can be correlated from Indoon–1 to East Lake Logue–1 and into some of the Woodada gas field wells, but sandstones are absent in other field wells like Woodada–2, where the stratigraphic equivalent may be represented by calcareous shales deposited on the pre-existing, pre-Triassic topographic high (e.g. Gorter and Davies, 1999, fig. 13). In the Dongara area the Indoon member may merge with the Arranoo Member (both occur in a section containing the *K. saeptatus* Oppel Zone), but further work is required to validate this.

**DISCUSSION**

Gorter (1994) interpreted regressive-transgressive events in the Triassic strata of the offshore Carnarvon Basin (Fig. 1) by correlating palynological zones with the sea level curve of Haq et al (1988). These transgressive and regressive events are correlated to sea level events deduced for the Triassic succession in Tethys as determined by Hardenbol et al (1998) in Figure 2. The Induan 1 and 2 sea level events are here equated with a sea level fall at the base of the Ascalon Formation (new name) between sequences 1 and 2 of Gorter (1994), and the sea level fall between sequences 2 and 3 is correlated with the Olenkian 3 event of Hardenbol et al (1998). In the Early and Middle Triassic, Ogg (in Gradstein et al, 2004) noted major regressions in the Induan (In1), middle Olenkian (Ol1) and near the top of the Olenkian (Ol4) and the late Ladinian (Lad3). In Ogg et al (2008) this was changed to limit the major regressions to the Late Permian (late Changhsingian (end Perm)), the late Olenkian (Ol4) and the late Ladinian (Lad 3). The Ol4 event of Ogg et al (2008) probably coincides with the Olenkian 3 event of Hardenbol et al (1998), but given the widespread nature of the regressive event at the base Ascalon Formation in the Bonaparte Basin, probably reflected in the incoming of the Indoon member in the northern Perth Basin, it is surprising that it is not recognised by Ogg et al (2008). In Ogg et al (2008) peak transgressive events are shown to have occurred in the mid to late Olenkian (*Neospadodus pingdingshanensis* Zone) and at about the Anisian–Ladinian boundary level (top *Nevadites secedens* Zone).

**Isotope stratigraphy**

High-resolution carbon isotope measurements from many stratigraphic sections in south China have demon-
The Permian-Triassic boundary in west Australia: evidence from the Bonaparte and Northern Perth basins—exploration implications

...strated that the pronounced carbon isotopic excursion at the Permian-Triassic boundary is not an isolated event but merely the first in a series of large fluctuations that continued throughout the Early Triassic before ending abruptly early in the Middle Triassic. Composite carbon isotopic curves (δ13Ccarb‰) for the well-dated Meishan locality and other sites in China (e.g. Krull et al, 2004, fig. 8; Payne and Kump, 2007; Galfetti et al, 2007, 2008), show that the lightest carbon isotopic content (i.e. the most negative values) occurs in bed 25 at Meishan in the upper Changsingian. In marine sections, such as at Meishan, the negative carbon isotopic excursion and the Permian-Triassic boundary may be separated by a few centimetres whereas in non-marine sections several tens or even hundreds of metres may separate these events, and the boundary can not be placed with any certainty within the transitional palynoflora or vertebrate fauna (Metcalfe et al, in press). The Permian-Triassic boundary in the Bonaparte and northern Perth basins lies within a siliciclastic-dominated succession that, on the present palaeontological dating, appear to have been deposited rather rapidly—consistent with a stretched carbon isotopic profile (e.g. in Fishburn–1, Fig. 5 and Tern–3, Fig. 7). The abrupt break in the carbon isotopic curve shown by Hovea–3 (Fig. 11) is consistent with extremely rapid sedimentation over the inertinitic and sapropelic interval boundary or a sedimentary hiatus.

Payne and Kump (2007, fig. 1), demonstrated that at least four marked swings in isotopic values occur in the Early Triassic in the Great Bank of the Nanpanjiang Basin (e.g. Lehrmann et al, 2003), an isolated Permo-Triassic carbonate build-up at Guizhou in southern China (Fig. 15). Ogg et al (2008) have shown preliminary revised stage and substage boundary ages (our Table 1) and these have been further revised by Galfetti et al (2008) and used to redraft Figure 15 contrasting carbon isotopic curves from Guizhou (Payne and Kump, 2007) and Guangxi (Galfetti et al, 2007). Galfetti et al (2007, fig. 2) indicate the most negative isotopic excursion in the Early to Middle Triassic occurs in the early Smithian at the base of the Flemingites nrisiradiatus beds in the Jinya/Waili composite measured section in northwestern Guangxi in southern China, approximately equivalent to the N. dieneri-N. waageni con-

Figure 12. Dongara–4 Rock-Eval Tmax, hydrogen index (HI) and production index (PI) from in house data by Geotech (West, 2000). GR (API) and DT logs are from digitised data in DoIR website files. SC GR (API) is a gamma ray log run over slabbed core by CoreLab in 1998 for British-Borneo (now Eni). The ranges of the various fossils in the core are after Peter Jones (pers. comm., for the Carinaknightina discarinata); Robert Nicoll (pers. comm.) and McTavish (1973) for the N. dieneri zone conodonts; Claraia sp from Mac Dickins (pers. comm.) and Gorter (in house); and the limestone marker from sonic log correlation to nearby wells and cuttings described in the Dongara–4 mud log. Cores are matched to the down hole logs via the core gamma log for cores 1 to 3, and are matched at the top of core 4 based on the reported rounded pebble lag (Backhouse, 1996) and the gamma ray curve. The carbon isotopic compositions are from Morante (1996) and Morante et al (1999). The trends for the latest Permian (blue box) and Early Triassic (pink box) carbon isotopes follows Hovea–3 data (Thomas and Barber, 2004;Thomas et al, 2004) as shown in Figure 11.
Figure 13. Wireline log correlation between Hovea–3/ST1, Dongara–4 and Corybas–1 across the Permian-Triassic boundary. This correlation indicates that the Hovea–3 boundary is likely to be erosional and the onlap of the Triassic over the Hovea–3 area occurred later than at Dongara–4 and Corybas–1.
odont zones (composite δ13Corg‰ curve reproduced in Fig. 15). Foster et al. (1997) had earlier demonstrated that the carbon isotopic content of kerogen in the Triassic could be artificially heavy because of the reworking of Permian woody material with heavy isotopic values. In this isolated bank, influx of recycled Permian wood is unlikely and the isotopic swings must be caused by other means, perhaps sea level fluctuations (see Haq et al. (1988) and Hardenbol et al. (1998) for eustatic variations in the Early Triassic), or the episodic and catastrophic release of methane from hydrates (e.g. Hesselbo et al., 2000; de Wit et al., 2002; Retallack and Krull, 2006).

Australian carbon isotopic curves from δ13Corg‰ over the Late Permian to Early Triassic transition (based on data from Morante, 1995, etc.) have been published by Morante et al. (1994) and Morante (1996) for Tern-3, Foster at al. (1997) for Petrel-4, and Morante (1996) and Retallack and Krull (2006) for Fishburn-1 (see Fig. 5). While carbon isotopic curves based on the carbon isotope values from organic-derived carbon (total organic components, δ13Corg‰) are not strictly comparable to carbon isotopic values derived from carbonate minerals (δ13Ccarb‰) (e.g. Kump and Arthur, 1999; Retallack and Krull, 2006, fig. 5; Arthur, 2008), as both presumably reflect the isotopic composition of the global atmosphere, it is assumed that the negative-positive shifts in both measures move in tandem, as shown by de Wit et al. (2002) across the palynologically defined Permian-Triassic boundary from five basins in the interior of the former Gondwana Supercontinent. In addition, as pointed out by Giddings and Wallace (2009), δ13Ccarb‰ values derived from basinal carbonate facies are generally lighter than proximal facies with changes.

Figure 14. Shallowing event (Indoon member) in the Kockatea Shale at Indoon-1 recognised from the gamma ray and sonic log profiles and by a decrease in the spino acritarch content of the palynofacies (from Indoon-1 well completion report). The correlation between Indoon-1 in the northern Perth Basin and Petrel-4 in the southeastern Bonaparte Basin shows close similarities in formation architecture, supported by palynological information and carbon isotopic measurements across the Permian-Triassic boundary.
of 8–11‰ in age equivalent facies. Similar gradients can occur in proximal siliciclastic facies, where much of the contained organic matter may be derived from land plants resulting in heavier carbon isotopic values, compared to distal settings where the organic matter is more likely to have been derived from marine organisms, with lighter isotopic values.

The Early Triassic Kockatea Shale in the northern Perth Basin has a distinctive log facies and contains the *K. saepatus* Oppel Zone. The last appearance of the species *K. saepatus* is at the top of the *B. buurensis-S. milleri* conodont zone, i.e. it is no younger than topmost Smithian (Ogg and Nicoll, 2007) in the Arctic. The lower part of the formation contains the *N. dieneri* to *N. pakistanensis* conodonts in and below a limy interval (i.e. the limestone marker) seen in most northern Perth Basin wells. The overlap of conodont ranges reported from Corybas–1 by Metcalfe et al (2008) indicates an early Smithian age for this carbonate interval. Both species have their last appearance near the top of the *B. buurensis-S. milleri* conodont zone, i.e. latest Smithian.

These early Smithian limestones lie below a slightly sandy interval, seen in the Indoon–1 and Woodada field wells, in the *K. saepatus* Oppel Zone that is interpreted to be the equivalent of the Ascalon Formation in the

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**Figure 15.** Composite carbon isotopic ($\delta^{13}C$‰) compositional changes measured across the Permian-Triassic boundary in an isolated deep marine carbonate bank at Guizhou in southern China (after Payne and Krump, 2007, fig. 1) should be relatively free from reworked terrestrial input which may bias the isotopic measurements. Also shown for comparison is the composite carbon isotopic ($\delta^{13}C_{\text{carb}}$‰) curve from northwestern Guangxi (Galfetti et al, 2007). Both curves are fitted to the Galfetti et al (2008) timescale at the substage boundaries.
Timor Sea wells (e.g. Fig. 14). In Fishburn–1, the Ascalon Formation, while itself not analysed for carbon isotopic composition, appears to be part of a continuum of carbon isotopic values. Values are initially increasingly negative, then switch upward through the Mairim Formation to increasingly positive values below the Ascalon Formation (Fig. 5). Above the Ascalon Formation in the Fishburn Formation (new name), the isotopic values again become increasingly negative upwards through the formation to be the lightest values in the well, immediately below the unconformity at the base of the Jurassic. If the entire sedimentary section across the Permo-Triassic boundary is present in the Bonaparte Basin wells shown in Figure 3, and assuming the sampling interval is narrow enough to record all possible perturbations in carbon isotopic values, the lightest carbon isotopic value can be correlated with bed 25 at Meishan, and is located in the latest Permian, or at a younger light isotopic inflexion, for example near the Griesbachian-Dienerian boundary. If the former correlation is correct, the incoming of *L. pellucidus* occurs in the latest Permian, or if the latter in the latest Griesbachian or earliest Dienerian (cf. Figs 5 and 15).

**Unconformities**

The most negative carbon isotope values equate to the lower part of the Kockatea Shale in the northern Perth Basin and the lowermost Mairmull Formation or topmost part of the preserved Fishburn Formation in the Bonaparte Basin (Fig. 16a). The sharp break to the negative at about 1,981 m in the Hovea–3 core is of a comparable magnitude. The lack of any slope between the negative Smithian values and the positive Permian values suggest that section is missing in the cored section at Hovea–3 and is entirely consistent with the Late Permian age of the *P. microcorpus* Oppel Zone in the positive isotopic interval, and the highly negative isotopic part of the *K. saeptatus* Oppel Zone interval. Similar conclusions can be drawn from a comparison of the carbon isotopic curves and palynology between Hovea–3 and Tern–3 (Fig. 16b).

Support for absence of the earliest Triassic in western Australian basins is forthcoming from the fossil record: there are no unequivocally Griesbachian conodonts, ammonites or shelly fossils known from any basin on the western Australian margin. This is not to say that older Triassic strata may not be present in unlined basin areas. The oldest Triassic rocks on the western Australian margin, based on isotopic curve matching, are most likely in the Bonaparte Basin where the latest Griesbachian *P. microcorpus* Oppel Zone occurs in the Penguin Formation, which from well log correlations (Fig. 3) and seismic data is unconformable on the Tern Formation. Furthermore, in Tern–5 the base of the Penguin Formation with the lower *P. microcorpus* Oppel Zone (Purcell, 2008) is a granite pebble lag overlying the Tern Formation (Fig. 6). In the Blacktip–1 region, 3D seismic data indicates channelling of the top of the Tern Formation (Fig. 17). In the Perth Basin, there is no conclusive evidence from dipmeter or seismic data for an erosional break between the sapropelic and inertitic intervals of the Hovea Member in either Hovea–3 or Corybas–1, but in other wells such as Cliff Head–4, there is a clearly defined unconformity between the sapropelic interval and the older Permian based on palynology (Purcell, 2006). In this well the contact is shale-on-shale and there is no obvious evidence of the unconformity such as facies change, weathering, angularity or lag, but there is a colour change and a marked palynological break (Early Triassic over Artinskian). A similar shale-on-shale contact with no discernible evidence of hiatus apart from palynology change and a negative carbon isotopic excursion occurs in Woodada–2 (Gorter et al, 1995; Foster et al, 1997).

From a comparison of the isotopic curves (e.g. Payne and Kump (2007) and Galfetti et al (2007) in Fig. 16), it can be argued that the base of the Kockatea Shale (i.e. above the *P. microcorpus* Oppel Zone) is no older than latest Griesbachian and there is a substantial time gap in the order of a million years—with or without significant erosion—between the inertinitic interval of the Hovea Member and the sapropelic interval at the base of the Kockatea Shale. This is clearly demonstrated at Dongara–4 (Fig. 12) where the unconformity occurs between the sapropelic lowermost Kockatea Shale (upper Hovea Member of Thomas et al, 2004, fig. 2) and the underlying inertinitic part of the Hovea Member (Fig. 11).

Throughout the Bonaparte Basin, the base of the Ascalon Formation demonstrates a widespread downward shift in facies probably coinciding with the Induan 1/2 lowstand (Fig. 2). The sandy lithofacies in the proximal parts of the Bonaparte Basin shales out distally until there is very little sandstone present in the system. The Indoon and Arranoo members in the northern Perth Basin may be a similar, coeval lowstand deposit.

**Depositional rates and palaeoclimate**

In passing, the new constraints on the ages of the lower shaly units of the earliest Triassic suggests that the several hundred metres of the Mt Goodwin Sub-group were deposited in basin depocentres in as little as 1–1.5 million years (averaged from Table 1), during which time there was also a marine regression and regional erosion at the base of the Ascalon Formation. This implies a depositional rate of >500 m/million years for depocentres where seismic information suggests up to 2 km of Mt Goodwin Sub-group accumulation (after compaction)—a phenomenal depositional rate for what is essentially a shallow marine to paralic siltstone unit—and implies a vast supply of fine-grained detritus in the hinterland that was transported into the shallow sea. There are no known fossil river systems of basal Triassic or latest Permian age in the hinterland of the Bonaparte Basin that may have distributed this weathered material, leaving open the possibility that much of the finer detritus was dispersed by wind. Possibly the weathered detritus was from far afield, for example from a later Permian cool temperature desert that was located on the craton away from the preserved Late Permian marine strata (e.g. the Hyland Bay Sub-group contains cool water limestones and was, in the Bonaparte Basin area at
Figure 16a and b. Comparisons between the carbon isotopic composition of kerogens in Hovea–3 (data from Thomas et al, 2004) and Fishburn–1 (Fig. 16a) and Hovea–3 and Tern–3 (Fig. 16b) (data from Morante et al, 1994; Morante, 1996). If the carbon isotopic values are directly comparable, the preserved P. microcorpus Oppel Zone isotopic values (i.e. < -24‰ δ¹³C) in Hovea–3 equates to the lower P. microcorpus Oppel Zone in Tern–3, supporting the suggestion that most of the P. microcorpus Oppel Zone is eroded at Hovea–3.

Swamping of normal marine conditions in the Bonaparte Basin during the Early Triassic by rapid deposition of re-worked and weathered Permian glacial and post-glacial (and older) sediments, may explain the impoverished fauna and lack of Early Triassic source facies in the Bonaparte Basin. An extensive survey of the open file geochemical data base in this region shows no enrichment of organic matter in the basal beds of the Mairmull or Penguin Formations comparable to that documented from the Hovea Member sapropelic interval in the northern Perth Basin (Thomas and Barber, 2004). While both the sapropelic interval of the Hovea Member and the Mairmull Formation contain the K. saeptatus Oppel Zone, Early Triassic strata in the northern Perth Basin contain marine organisms, including ammonoids, conodonts, several bivalves, spinose acritarchs and foraminifera that together suggest a more saline environment than indicated by the impoverished fauna described from the Early Triassic in the southern Bonaparte Basin (lingulid brachiopods, spinose acritarchs, conchostracans and non-diagnostic shelly remains). In addition, the occurrence of the limestone marker and nodular carbonate concretions in the lower Kockatea Shale supports a more open marine circulation in comparison to the basal Mairmull Formation where limestones and carbonate nodules are mostly lacking.

Chumakov and Zharkov (2003, and references therein) discussed evidence for high latitude cold conditions in southeastern Australia south of about 70° during the Late Permian (Tatarian = Capitanian) and noted that at the ‘very end of the Late Permian, climate here was sometimes close to the subarctic one’ (Chumakov and Zharkov, 2003, p. 362). Archbold and Shi (1995) and Nicoll and Metcalfe (1998, fig. 2) from brachiopod and conodont faunas also interpreted a period of cooling during the Tatarian of the southern Carnarvon and Canning basins. According to palaeogeographic maps available for the latest Permian (255 Ma, latest Wuchiapingian) on the Scotese website, the northern Perth Basin lay at about 60°S indicating a cool to possibly cold climate. There is good evidence for the existence of younger than Sakmarian ice caps or valley glaciers in the vicinity of the northern Perth Basin. According to Eyles et al (2006), the thick transgressive shales of

![Figure 17](image.png)

**Figure 17.** Flattening on the top Ascalon Formation (A1 reservoir) at Blacktip–1 based on the Blacktip 3D seismic survey shows that the section between the top of the Ascalon and to a depth of about 16 ms (i.e. about 30 m) into the formation, the depositional architecture includes meandering channels.
the late Early Permian (Artinskian-Kungurian) Carynginia Formation contain ice-rafted debris reflecting renewed subsidence but continuing seasonally cool climates with coarse debris ice rafted into a marine embayment. Just (2003) interpreted a cool, shallow ramp origin for the carbonates of the Beekeeper Formation (Fig. 14), which contains microfossils indicative of Wordian-Wuchiapingian age (David Haig, University of Western Australia, pers. comm. 2009), about 254–268 Ma. The overlying Wagina Sandstone contains coal and so is probably of latest Permian age (deposited before the earliest Triassic coal gap, Retallack and Krull, 2006), probably from the Capitanian to the Wuchiapingian. Tupper et al (1994) interpreted a cool but not cold environment of deposition. Given the circumstantial evidence for cool to cold climate around the northern Perth Basin during the later Permian it would be expected that a large amount of glacially derived and weathered material may have been available on the craton to fill any nearby depocentre.

In a major review of zircon provenances, Veevers et al (2005) concluded that there was uplift along the Darling Fault to the east of the northern Perth Basin at about 255 Ma (approximately the Wuchiapingian-Changhsingian boundary), with drainage to the southeast and east away from the subsiding northern Perth Basin. Thus, the input of craton-derived material to the latest Permian strata of the northern Perth Basin was limited—the Hovea Member inertinitic interval may have been deposited at this time. With transgression in the earliest Triassic and the amelioration of the climate (Fig. 1), the sapropelic interval of the Hovea Member was laid down in a marine environment relatively free of influx of weathered material from the uplifted rift shoulders.

The economic implications of depositing such a large thickness of shale in such a short period of time needs to be addressed. Note that the present measured thicknesses of these shaly units from wells and seismic data is after compaction and dewatering. Intuitively, this rapid deposition should push any underlying source rocks rapidly through the oil generation window implying that in the depocentres at least, oil generation probably initiated during the Triassic possibly prior to trap formation related to the Middle Triassic to Early Jurassic Fitzroy Movement (Colwell and Kennard, 1996).

CONCLUSIONS

This study has shown that a combination of palaeontology, carbon isotopic curves, wireline log correlations and seismic profiles allows inter-basinal correlation of lithofacies across the Permian-Triassic boundary in two basins at opposite ends of Western Australia—the Bonaparte and northern Perth basins.

We conclude that the main latest Permian unconformity in the Perth Basin lies above the P. microcorpus Oppel Zone, and in the Bonaparte Basin, the main unconformity lies below the P. microcorpus Oppel Zone, unless the P. microcorpus Oppel Zone is time transgressive.

Implications from this conclusion include:

- The tectonic history of the Permian-Triassic boundary differs between the Bonaparte and northern Perth basins;
- The apparent correlation of the Ascalon Formation and the Indoos member lowstand units in the lower part of the K. saeptatus Oppel Zone implies a possible eustatic connection between the northern Perth and Bonaparte basins; and,
- The different tectonic history may partly explain the lack of an equivalent to the excellent oil and gas source in the sapropelic unit of the basal Kockatea Shale (upper part of the Hovea Member) of the northern Perth Basin in the Bonaparte Basin.

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APPENDIX: REVISED STRATIGRAPHIC NOMENCLATURE

The stratigraphy of the Permo-Triassic Kinmore Group (Mory, 1988, 1991) is revised with the elevation of the Mt Goodwin Formation to sub-group rank and the recognition of four subdivisions—three new—to the sub-group.

Mt Goodwin Sub-group (new)

The Mt Goodwin Formation, the upper unit of the Kinmore Group of Mory (1988) was informally sub-divided into the Lower and Upper units (Gorter, 1998; Gorter et al, 1998). As the Ascalon Formation is here proposed for a mappable unit in the Mt Goodwin Formation overlying an unconformity, the unit is raised to Sub-group status in the Kinmore Group. The Kinmore Group is thus made up of a lower Fossil Head Formation, the middle Hyland Bay Sub-group and an upper Mt Goodwin Sub-group. The Mt Goodwin Sub-group is composed of four units: the Penguin Formation (base), the Mairmull Formation, the Ascalon Formation and the Fishburn Formation (top). The base of the Mt Goodwin Sub-group (i.e. the base of the Penguin Formation) is defined as an unconformity overlying older Permian strata. The top of the Mt Goodwin Sub-group (i.e. the top of the Fishburn Formation) is an erosional surface below the Osprey Formation in the eastern Bonaparte Basin, and the Sahul Group in the western Bonaparte and northern Browse basins.

Correlations are made using wireline log signatures, palynology and limited micropalaeontology supplemented by seismic profiles. Carbon isotopic values from Fishburn–1, Petrel–4 and Tern–3 have been used to constrain the Base Triassic-Top Permian contact.

Penguin Formation (additional information)

Definition and type section—The formation was formally defined by Gorter (1998) for a medium grey to dark grey-brown claystone in Tern–3 between (2,400–2,449 m).

Age—The Penguin Formation contains the P. microcorpus Oppel Zone, considered by Helby et al (1987) to be latest Permian probably Changsianian.

Depositional environment—In cores from Tern–4 and 5 and sidewall cores from Tern–3, the finely laminated shales contain low percentages of spinose acritarchs, particularly in the lower part (Tern–3, Fig. 5), and exhibit little, if any, bioturbation. The lithology and palynofacies indicate an oxygen-poor depositional environment. Jeff Wood (Santos, pers. com., 2007) suggested a lacustrinal facies.

Stratigraphic relationships—Unconformably overlies the Late Permian Hyland Bay Sub-group at Fishburn–1, and appears to conformably underlie the Mairmull Formation (Fig. 5).

Distribution and thickness—The Penguin Formation is present throughout the southern Bonaparte Basin. It may be absent at Troubadour–1 and appears to be missing at Kelp Deep–1 on the Sahul Platform (Gorter and Davies, 1999, fig. 5), where the Mt Goodwin Sub-group onlaps the Troubadour High.

Synonyms—The unit was previously included in the Mt Goodwin Formation based on its lithological similarity. Helby (1983) in the Tern–3 well completion report called the P. microcorpus-bearing interval the A and B shales and suggested an affinity with the Hyland Bay Formation.

Mairmull Formation (new name)

Definition and type section—The Mairmull Formation, named after Mairmull Creek near the Triassic outcrop of Mt Goodwin southeast of Wadeye, Northern Territory, where the unit unconformably overlies the Late Permian Hyland Bay Sub-group (of Gorter, 1998), and is unconformable below the Ascalon Formation (new name, see below). The unit consists predominantly of claystone and siltstone and coarser sediments are rare. The type section is designated in Fishburn–1 between 2,121 m and 2,320 m (Fig. 5).

Age—Early Triassic based on its position in the Kraeuselisporites saeptatus Oppel Zone of Dolby and Balme (1976). In the Perth Basin the K. saeptatus Oppel Zone is associated with the N. dieneri to N. waageni conodont zones suggesting correlation with the Dienerian to late Smithian sub stages. The transition between the Permian and the Triassic may be marked by the largest negative shift in carbon isotopic values as seen in Fishburn–1 and Tern–3 (Figs 5 and 7).

Depositional environment—The Mairmull Formation was deposited in shallow water conditions as shown by the occurrence of Lingula and conchostracans in Petrel–1, the presence of spinose acritarchs, and the greenish and sometimes reddish colouration of the sediment. While the gamma ray log profile is generally monotonous, in several wells the lower beds are slightly more radioactive than the upper part of the formation, and there is a gradual increase in the proportion of thin sandstone beds in the uppermost interval below the base of the Ascalon Formation. The carbon isotopic profile at Fishburn–1 mirrors the gamma ray profile suggesting an initial transgressive portion of the formation shown by increasing upward negative isotopic values followed by a sustained upward trend to heavier carbon isotope values (Fig. 5). While unproven in this well, the changes in the isotopic composition probably reflect the proportion of spinose acritarchs present in the formation, the larger percentage in the transgressive strata and a lessening proportion of these saline indicators in the interpreted regressive part of the unit (e.g. see Gorter et al, 1995; Foster et al, 1997).

Stratigraphic relationships—Where the Penguin Formation is absent, the Mairmull Formation overlies unconformably the Late Permian Hyland Bay Sub-group. The Mairmull Formation unconformably underlies the Ascalon Formation.

Distribution and thickness—The Mairmull Formation is present throughout the Bonaparte Basin. It may be absent at Troubadour–1 on the Sahul Platform where the Mt Goodwin Sub-group onlaps the Troubadour High. The formation is recognised in Echuca Shoal–1 in the eastern Browse Basin where it is intruded or contains basaltic volcanics.
Synonyms—The only synonym for the Mairmull Formation is the Lower Mt Goodwin Formation of Gorter, 1998; Gorter et al (1998), now superseded.

Ascalon Formation (new name)

Definition and type section—The Ascalon Formation is a prominent, widespread, sandstone/siltstone unit roughly located in the middle of the Early Triassic Mt Goodwin Sub-group in the southern part of the Bonaparte Basin. In Ascalon–IA, the formation is described from cuttings as very fine to fine-grained very well sorted sandstone, with traces of silt and clay minerals, carbonaceous specks and poor to fair visual and inferred intergranular porosity. The logs suggest the unit is tight, but a total gas show of 11.31% associated with a drilling break and the appearance of unconsolidated or less cemented sandstone in the cuttings, and a resistivity increase, all indicate some permeability.

The Ascalon Formation is the previously unnamed silty sandstone encountered in wells usually at the base of the upper part of the Mt Goodwin Sub-group shales (Gorter et al, 1998) in the Kraeuselisporites saeptatus palynological zone. Gorter et al (1998) showed that these intra-Mt Goodwin Sub-group sandstones lay unconformably upon the Mairmull Formation and constituted the lowstand section of the Fishburn Formation. The A1 gas reservoir at Blacktip gas field is this unit where it is characterised by a prominent amplitude anomaly. Similar amplitude anomalies in the Ascalon Formation were mapped by Gorter et al (1998, their figure 7). There is no strong amplitude anomaly associated with the gas-bearing sandstone at Ascalon–IA.

The type section is in Ascalon 1A between 4,072.5 m and 4,105 m (Fig. 18).

Age—Early Triassic (Early to Middle Scythian) based on its position within the Kraeuselisporites saeptatus Oppel Zone of Dolby and Balme (1976) in all wells where it is recognised. In wells where the K. saeptatus Oppel Zone is subdivided, the unit lies in the Protohaploxypinus samoilovichii Oppel Zone, which Helby et al (1987) regard as almost entirely equivalent to the K. saeptatus Zone. Both these palynological zones occur in the Kockatea Shale in the Perth Basin (Gorter, 1994) where they are associated with the N. dieneri to N. waageni conodont zones suggesting correlation with the Dienerian to late Smithian sub stages.

Depositional environment—Transitional paralic to shallow marine, probably a sea level lowstand. The Ascalon Formation is interpreted to overlie a Type 1 sequence boundary in the Mt Goodwin Formation and is regional in extent. It forms the lowstand deposits of the Upper Mt Goodwin Formation (Fishburn Formation) succession. The depositional environment of the sandstone is debatable.

Figure 18. Type section of the Ascalon Formation in Ascalon–1A. Palynology based on cuttings.
with Mobil in the Ascalon–1A well completion report (p. 43) referring to a turbidite sand, apparently mistakenly accepting the Pattillo and Nichols (1990) contention of turbidite sandstones near the base of the Mt Goodwin Formation (based on the erroneous attribution of sandstones in the section derived from the gamma-ray logs in several wells—the gamma ray low counts are from casing shoes. Since a marginal marine depositional environment for the Mt Goodwin Sub-group is inferred from the sediments and the enclosed microflora, a turbidite origin for the Ascalon Formation is unlikely.

**Stratigraphic relationships**—Unconformably overlies the Mairmull Formation, conformably and transitionally underlies the Fishburn Formation. Seismic interpretation of the Blacktip 3D seismic survey shows that the Ascalon Formation in the region of the Blacktip–1 well is composed of a series of anastomising channels, many of which appear to be meandering (Fig. 17). The latter suggests a low relief delta plain depositional environment.

**Distribution and thickness**—The Ascalon Formation is best developed in a sandstone facies along the southern margin of the Bonaparte Basin, and shales out towards the northwest (e.g. at Dillon Shoals–1 and Kelp Deep–1).

**Synonyms**—Intra-Mt Goodwin Sub-group sandstone of Gorter et al (1998). It is informally referred to as the A1 gas reservoir at Blacktip–1. It is not the Ascalon sandstones of Robinson and McInerney (2004). Robinson and McInerney (2004) considered that the Ascalon Formation of Gorter et al (1998) is older than their Ascalon sandstones. Perhaps they equated the Ascalon with the Osprey Formation sandstones, but stated that they only occur at Ascalon–1A, which is not the case. If they equated the Ascalon with the Crane Sandstone (Gorter et al, 2008), then they did not identify it in Crane–1, or other wells where it is well defined by logs and palynology.

**Fishburn Formation (new name)**

**Definition and type section**—The Fishburn Formation, named after Fishburn–1 in the southeastern Bonaparte Basin, is widespread in the Bonaparte Basin. The Fishburn Formation consists of grey and green claystones with minor siltstone and sandstone. The type section is designated to lie between 1,904.5 m and 2,084 m in Fishburn–1 (Fig. 5).

**Age**—The Fishburn Formation contains the *K. saeptatus* Oppel Zone (*P. samoиловичii* Oppel Zone). In Ascalon–1A the *T. playfordii* Oppel Zone occurs only in the uppermost beds, based on cuttings samples, so may be caved.

**Depositional environment**—The Fishburn Formation contains spinose acritarchs but in generally low abundance and low diversity, suggesting nearshore depositional environments. The carbon isotopic profile at Fishburn–1 implies a mostly transgressive character above the Ascalon Formation sandstones (Fig. 5). The gamma ray logs suggest initial transgression then an aggradational pattern with the incoming of thin sandstone beds in the upper part below the unconformity at the base of the Cape Londonderry Formation.

**Stratigraphic relationships**—The base of the Fishburn Formation is gradational over the Ascalon Formation and it is unconformable below the Cape Londonderry Formation in the east, and the Sahul Group in the west of the Bonaparte Basin.

**Distribution**—The Fishburn Formation is widespread in the Bonaparte Basin, but towards the southern margin it is truncated by erosional episodes related to later Triassic sea level falls or post-Triassic erosion.

**Synonyms**—The only synonym is the Upper Mt Goodwin Formation.

**Arranoo Member (renamed)**

The stratigraphic definition of the Arranoo Member is retained, but the unit is here-in renamed from the Arranoo Sandstone Member (as per the Geoscience Australia Stratigraphic Names Database) to the Arranoo Member of the Kockatea Shale. The Arranoo Member is not entirely a sandstone, but rather a finely laminated sequence of shale, siltstone and fine-grained sandstone, thus retaining the name Arranoo Sandstone Member is misleading. The lithological descriptor is not required as defined in the International Stratigraphic Guide, where the use of the unit term (Member) is preferred. The use of both the lithologic term and unit term in the name is discouraged.

Historic usage also supports the renaming, with Mory (1995), Mory and Iasky (1996), Rasmussen (1997), Crostella (2001), Bradshaw et al (2003), and Thomas and Barber (2004) all using the terminology Arranoo Member when describing this unit. Informal usage by WAPET in the 1980s (for example, Gilchrist and Holloway, 1983), wherein the unit was identified, also used the name Arranoo Member.
John Gorton is the new ventures manager for Eni Australia where he has been employed since 1992 (previously Hardy Petroleum and British Borneo). He graduated from the Australian National University in 1972 with a BSc (Hons), and was awarded a PhD from the University of New South Wales in 1992. After six years with the BMR (petroleum branch) he joined Esso Australia in 1978 and subsequently worked since 1980 with the petroleum exploration industry with various local and international companies, mainly on Australian basins. Member: PESA, AAPG, GSA.

Robert (Bob) Nicoll was educated in the USA and obtained his PhD from the University of Iowa in 1971. He worked for the Bureau of Mineral Resources/ Australian Geological Survey Organisation for 28 years and is a school visitor in the Research School of Earth Sciences of the Australian National University and is contracted to Geoscience Australia developing the Australian datapack for Time Scale Creator. His principal research interest involves all aspects of conodont biostratigraphy and palaeobiology from the Cambrian to the Triassic.

Ian Metcalfe obtained a BSc (Hons) in geology from Durham University, U.K. in 1971 and a PhD (conodont biostratigraphy) from Leeds University, U.K. in 1976. His academic career began as lecturer at the University of Malaya, Kuala Lumpur, Malaysia in 1977 where he taught palaeontology, micropalaeontology and petroleum geology and supervised postgraduates at the Institute of Advanced Studies working on petroleum geology projects in the Malay Basin and in Sabah and Sarawak. He has subsequently held academic positions as senior lecturer, associate professor and professor at the National University of Malaysia and University of New England, Australia. He was science coordinator for the International Ocean Drilling Program (ODP), Australian secretariat (1992–5) and secretary of the IUGS Subcommission on Carboniferous Stratigraphy (1996–2000). His research has largely centred on East and Southeast Asia and he was co-leader of IGCP Project 321, Gondwana dispersion & Asian accretion (1991–6) and 411, Geodynamics of Gondwanaland-derived terranes in East and Southeast Asia (1998–2002). He was Deputy Director of the UNE Asia Centre from 2001–8 and is editor of the Journal of Asian Earth Sciences. His international reputation is for the Palaeozoic and Mesozoic tectonic framework, evolution and palaeogeography of East and Southeast Asia (eastern Gondwana and the Tethys ocean basins), and for studies of the Permian Triassic boundary and end-Permian mass extinction in China and, more recently, in Australia.

Continued next page.
Robbert Willink commenced his career as a petroleum geologist with Shell in 1978 after graduating with a BSc (Hons) from the University of Tasmania and a PhD in geology from the Australian National University. After nine years with Shell that included international postings to the Sultanate of Oman and Turkey, he took up a lectureship in petroleum geology at the National Centre for Petroleum Geology and Geophysics in Adelaide. In 1988 he returned to industry to join Sagasco Resources Limited as exploration manager. In time, Sagasco was taken over by Boral which spun off Origin Energy Limited in 2000 as a separately listed entity on the ASX. Rob holds the position of executive general manager, Geoscience and Exploration New Ventures. Origin’s upstream portfolio of assets includes conventional exploration and production interests in the Cooper/Eromanga, Bowen/Surat, Perth, Otway and Bass basins in Australia and in the Taranaki Basin in New Zealand, frontier exploration interests in the Northland and Canterbury basins, offshore New Zealand, in the Lamu Basin, offshore Kenya and in the Song Hong Basin, offshore Vietnam. In addition, the company holds vast coal seam gas reserves in Queensland that it is currently developing in conjunction with ConocoPhillips.

Darren Ferdinando attended the University of Western Australia where he completed a BSc (Hons) in Geology in 1989 and later a PhD in 2004. He started his career as a geoscientist working for the Geological Survey of Western Australia and has since worked as a research geologist in DMP’s Petroleum Division and as a senior geologist with ARC Energy working on their Perth Basin assets. In late 2008 he joined Murphy Australia Oil as a senior staff geologist finding exploration opportunities in the Browse and Bonaparte basins. Member: PESA, AAPG, FESWA, ASEG and SEG.