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Devonian–Carboniferous stratigraphy of Quail 1, Carnarvon Basin, Western Australia: regional implications for geohistory and hydrocarbon prospectivity

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The recovery of conodonts from cores in the onshore Carnarvon Basin petroleum exploration well Quail 1 has lead to a revision of the subsurface Devonian–Carboniferous stratigraphic interpretation in the basin. The Moogooree Limestone is absent in the well; instead, a major unconformity, representing a hiatus of at least 12 million years—the entire Tournaisian Series—separates the Frasnian Gneudna Formation and the Visean Yindagindy Formation. A significant part of the Late Devonian Famennian Stage may also be missing. This suggests that the Wandagee–Yanrey Ridge may be as old as Late Devonian. The Quail Formation is here recognised as a lateral equivalent of the outcropping Harris Sandstone, as originally defined. The Austin Formation is recognised as the base of the Lyons Group. Evaluation of conodont thermal maturation data indicates a former high heat flow in the southern and central parts of the basin, and suggests that some of the Early to Middle Palaeozoic section is overmature for hydrocarbons. The high heat flow may have been related to Jurassic volcanism, represented by the alkali picrites of the Wandagee Province.

Introduction

The onshore Carnarvon Basin of Western Australia (Fig. 1) is predominantly a Palaeozoic basin with Late Cambrian to Permian sediments (Hocking et al. 1987; Gorter et al. 1994). A thin Mesozoic cover expands offshore to form the economically dominant part of this hydrocarbon-rich basin (Hocking 1988). Early studies based on outcrop investigations (Condon 1965, 1967, 1968) and more recent investigations integrating outcrop and subsurface data (Hocking et al. 1987) have suggested that Late Devonian through Permian sedimentation was essentially continuous, except for short breaks in the Carboniferous (Early Tournaisian and Namurian) and Permian (Early Artinskian). New palaeontological studies now demonstrate that in part of the basin, on and near the Wandagee–Yanrey Ridge, the Tournaisian break may be more pronounced and probably extends down into the Late Devonian (Famennian).

Previous interpretations of the Devonian–Carboniferous stratigraphy (Fig. 2) in the onshore Carnarvon Basin petroleum exploration well Quail 1 (Pearson 1964; Hocking et al. 1987; Bentley 1988) suggested a major unconformity between the Munabia Sandstone and the Moogooree Limestone, and also between the Quail Formation and the Harris Sandstone/Lyons Group. Bentley (1988) also suggested that the Quail Formation rests unconformably on the Moogooree Formation in part of the basin.

New conodont information from Quail 1 indicates that the Gneudna Formation and a thin (31 m) sandstone unit, probably the Munabia Sandstone, are overlain by the Yindagindy Formation, rather than the Moogooree Limestone, which rests unconformably on the sandstone. Thus, in this well, the Quail Formation demonstrably rests on the Yindagindy Formation. Miospores recovered in the interval 2146–2562 m in Kybra 1 (Purcell & Ingram 1988) suggest a similar stratigraphic relationship with the Quail Formation overlying Yindagindy Formation. However, in outcrop, the Yindagindy Formation is overlain by the Harris Sandstone (Condon 1965). This study thus raises the possibility that the Quail Formation is laterally equivalent to the Harris Sandstone *sensu* Condon (1965, 1967), as both units rest conformably on the Yindagindy Formation. Recognition of the magnitude of the Early Carboniferous unconformity and the changed stratigraphic relationships have a significant effect on the interpretation of Carnarvon Basin geohistory.

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Conodont faunas, miospores and age determination

Conodont faunas were recovered from two of three cores in Quail 1, examined for conodonts and other phosphatic fossils (Table 1). Five conodont elements were recovered from core 14 (2637.2–2638.41 m) and twenty-eight from core 15 (2793.6–2796.34 m). Core 13 (2468.9–2470.73 m) contained no conodonts or other age diagnostic fauna. Miospore data are available for cores 12, 15 and 16 (Powis 1985).

Core 14 (Fig. 3) contains a very limited fauna with elements of *Cavusgnathus unicornis* and *Hindeodus cristulus*. In North America (Collinson et al. 1971), both species appear in the upper part of the St Louis Limestone (Visean V3b) and range upward to the top of the Chester Series (Namurian A–E2). In England (Higgins & Varker 1982), *C. unicornis* is found in the Holkerian *Cavusgnathus* Zone, where it is equated with the V2b–V3a. The maximum age range of core 14 could be V2b–E2. However, core 12 (2231.4–2232 m) is dated as Visean V3a–V3c (see below) and this would most probably limit the age of core 14 to the interval Visean V2b–V3b (Fig. 3).

Core 15 (Fig. 4) contains elements of *Icriodus subterminus* and *Polygnathus xylus xylus*. These species, along with *Ozarkodina brevis* and *Ancyrodella* sp., are found in the lower part of the Gneudna Formation in outcrop (Seddon 1969; Nicoll unpublished AGSO collections). *P. xylus xylus* and *O. brevis* range in age from the *Polygnathus varcus* to Early *Palmatolepis hassi* Zone, and *I. subterminus* from the *Klapperina disparilis* Zone to the *Palmatolepis jamieae* Zone. *Ancyrodella* is confined to the Frasnian (Ziegler & Sandberg 1990). These species indicate an age range of the Gneudna Formation from the Late Givetian (*Klapperina disparilis* Zone to the Frasnian, at least as young as the *Palmatolepis hassi* Zone. The restriction of *P. xylus xylus* to only the lower half of the type section of the Gneudna Formation (Seddon 1969) indicates that the unit probably extends through much of the Frasnian. *I subterminus* and *P. xylus xylus* in core 15 indicate that this sample was probably from

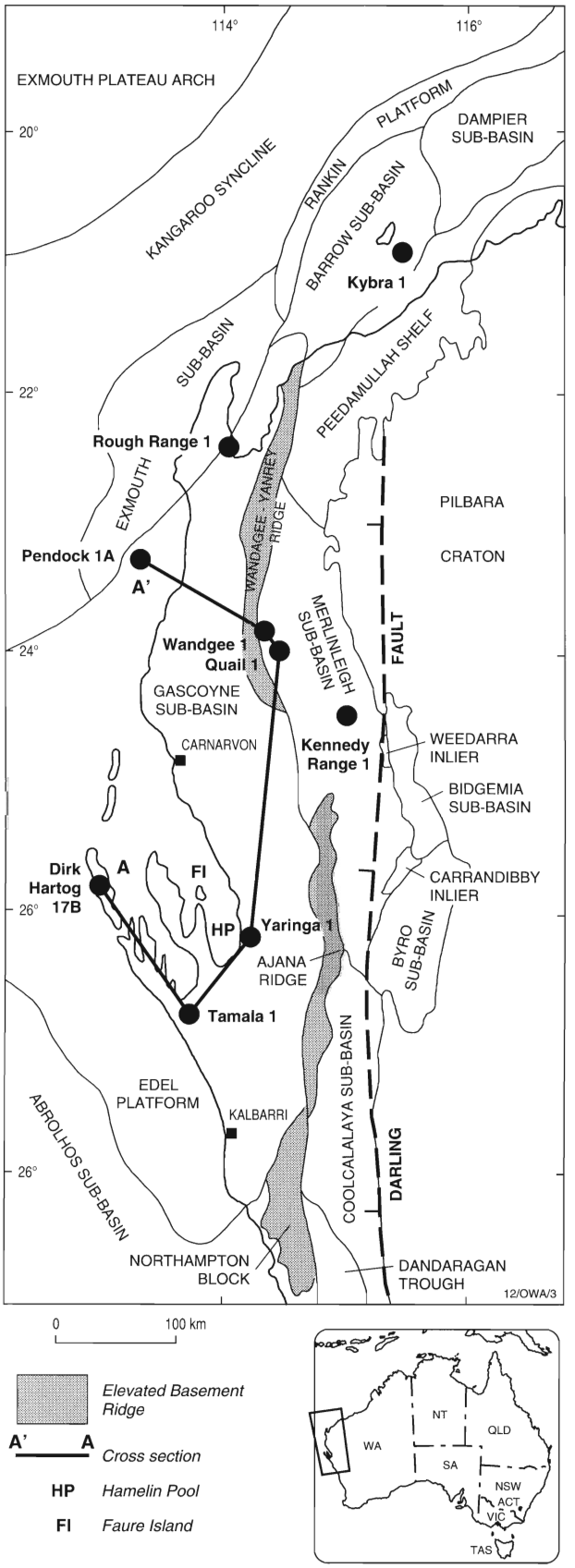

Figure 1. Locality map, showing the Carnarvon Basin and principal structural sub-divisions, position of wells referred to in text and the location of the Wandagee Province (after Hocking et al. 1987). The line of section of wells illustrated in Figure 6 is indicated.

the upper part of the lower half of the Gneudna Formation.

Palynological examination of cores 11 to 16 by Powis (1985) resulted in dateable material from only cores 12, 15 and 16. The sample from core 12 (2231.4–2232.0 m) had a low-yield microflora containing *Grandispora maculosa*, which dates it as belonging to the *G. maculosa* Assemblage and indicates an age range of Visean V3b–V3c (P.J. Jones, AGSO, personal communication, 1994). Cores 15 and 16 yielded acritarchs of Devonian or probable Devonian age (Powis 1985), supporting the age indicated by the conodonts in core 15.

Stratigraphic revision and correlation

Analysis of the conodonts (cores 14 and 15) and microflora (core 12) allows a reinterpretation of the regional stratigraphy of the interval 2100–3121 m in Quail 1 (Fig. 2). The type section of the Quail Formation (2100–2453 m) is here equated with the Harris Sandstone (see following discussion), a unit defined in outcrop (Condon 1967) 50 km east of Quail 1. In the well, this unit is dated by Powis (1985) and Helby (personal communication in Roberts 1985) as belonging to the *Grandispora maculosa* Assemblage.

The carbonate interval 2453–2710 m, previously identified as Moogooree Limestone (Hocking et al. 1987; Bentley 1988), is now recognised as Yindagindy Formation. The conodont fauna of the outcropping Yindagindy Formation (unpublished AGSO data) contains a limited fauna of *Clydagnathus cavusformis*, *Hindeodus cristulus* and *Patrognathus* sp. Based principally on the range of *H. cristulus*, the age of this fauna is from the early Visean (V1a or V1b) to Late Namurian (E2). *Cavusgnathus unicornis* and *H. cristulus* in core 14 somewhat restrict the age range, but confirm the correlation of the outcrop and subsurface sections. In the Carnarvon Basin, *H. cristulus* is confined to the Yindagindy Formation and does not occur in the underlying Moogooree Limestone. The *G. maculosa* flora in the overlying Quail Sandstone constrains the age of the Yindagindy Formation to Visean V2b–V3a.

The thin sandstone at 2710–2741 m has not been dated and could be assigned to any of a number of Devonian or Carboniferous units. It most probably represents the Munabia Sandstone, which overlies the Gneudna Formation. It could also belong to the Williambury Formation, which underlies the Yindagindy Formation, but Hocking et al. (1987) interpreted this unit as an alluvial fan and it probably has only limited areal distribution.

The interval 2741–3082 m is occupied by the Gneudna Formation, and can be correlated to the outcrop by the conodonts recovered from core 15. These place core 15 in the upper-middle part of the Gneudna Formation (Fig. 4). The Nannyarra Sandstone is probably restricted to 3082–3121 m. The stratigraphy of the interval 3121 to 3580 m (T.D.) is discussed by Gorter et al. (1994).

In Kybra 1 well, the interval 2146.5–2170 m, identified as the Quail Formation (Bentley 1988), is correlated with the Harris Sandstone. Purcell & Ingram (1988) found no miospores from this interval, but recovered miospores of the *Grandispora maculosa* Assemblage from a sample at 2170 m and miospores of the *Anapiculatisporites largus* Assemblage from 2192–2562 m. These assemblages indicate that the interval 2170–2562 m. is Visean in age

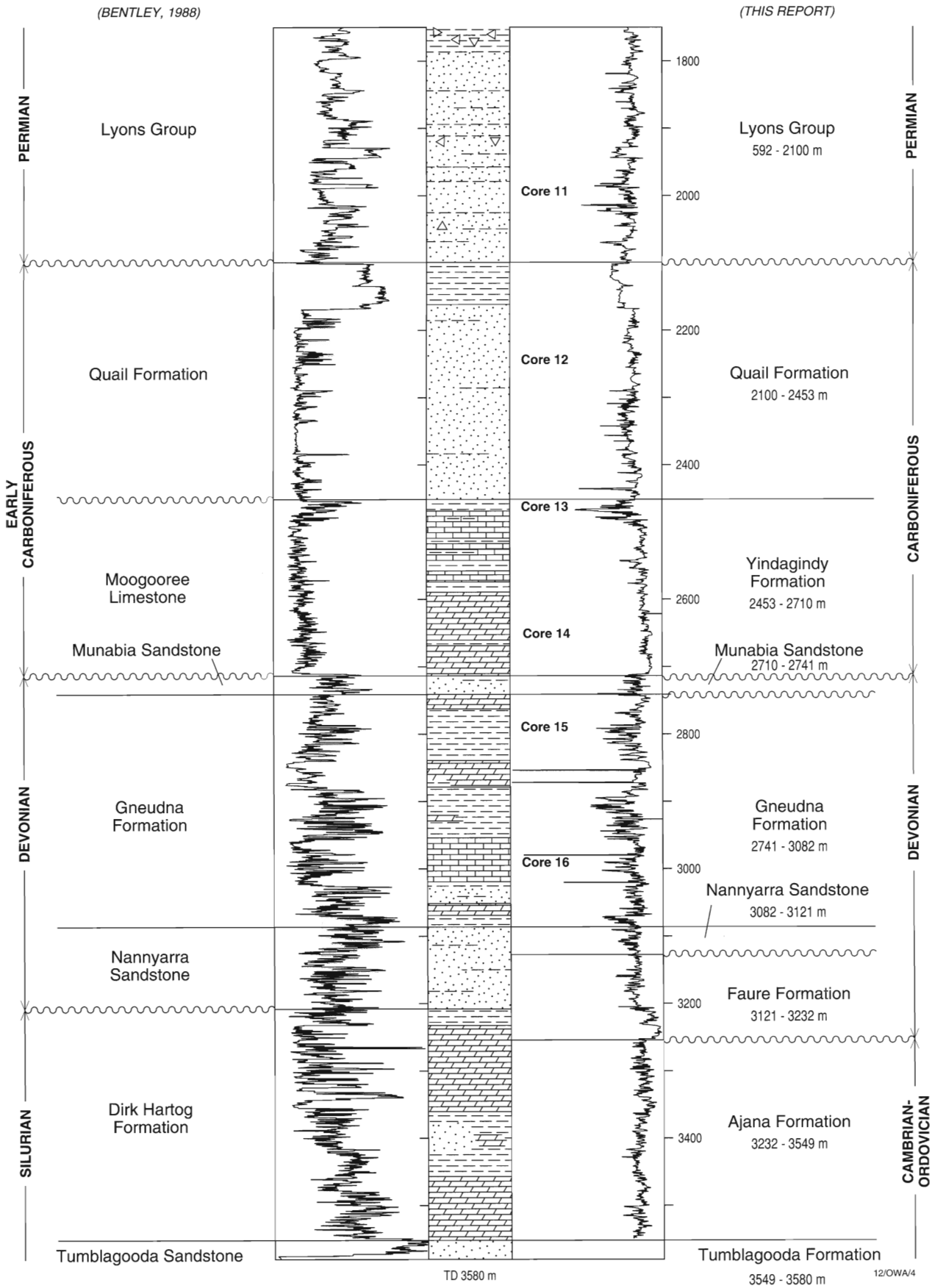

Figure 2. Part of the Quail 1 well log, showing the interpretation of Bentley (1988) and modifications suggested in this report. Lower part of the interpretation based on Gorter et al. (1994).

and thus represents the Yindagindy Formation rather than the Moogooree Formation, which is Tournasian. This well, therefore, indicates that the top of the Yindagindy Formation (2170 m) is as young as the *G. maculosa* Assemblage, an age also reported by Powis (1985) in Quail 1, core 12 (2231.4–2232.0 m), from the Quail Formation.

Table 1. Palaeontological determinations for samples from Quail 1, Kybra 1 and Wandagee (WAPET) corehole 1. Palynological determinations from Quail 1 after Powis (1985). Miospore determinations from Kybra 1 after Purcell & Ingram (1988).

Quail 1

Core 12: 7319–7321 ft (2231–2232 m)

Conodont sample: not sampled.

Palynology sample: 7319–7321 ft; *G. maculosa*

Core 13: 8098–8104 ft (2468.90–2470.73 m)

Conodont sample: 8098–8104 ft; 0 elements

Other fauna: ? phosphatic shell fragments

Palynology sample: 8102–8104 ft; essentially barren

Core 14: 8650–8654 ft (2637.20–2638.41 m)

Conodont sample: 8650–8654 ft; 5 elements; **CAI 4**

Cavusgnathus unicornis (1)

Hindeodus cristulus (2)

S element fragments (2)

Other fauna: pyritised scolecodonts

Palynology sample: 8652–8654; essentially barren

Core 15: 9163–9172 ft (2793.60–2796.34 m)

Conodont sample: 9163–9172 ft; 27 elements; **CAI 4**

Icriodus subterminus (4)

Polygnathus xylus xylus (11)

Other fauna: pyritised bivalves and ostracods, fish scales

Palynology sample: 9169–9172 ft; acritarchs (Devonian)

Core 16: 9741–9751 ft

Conodont sample: not sampled

Palynology sample: acritarchs (?Devonian)

Kybra 1 (from Purcell & Ingram, 1988; based on cuttings samples)

2170 m

Palynology: *Grandispora maculosa* Assemblage

2192–2542 m

Palynology: *Anapiculatisporites largus* Assemblage

WAPET Wandagee core hole

1600–1615 ft (182.9–187.5 m)

Other fauna: ostracods, bivalves & brachiopods, fish

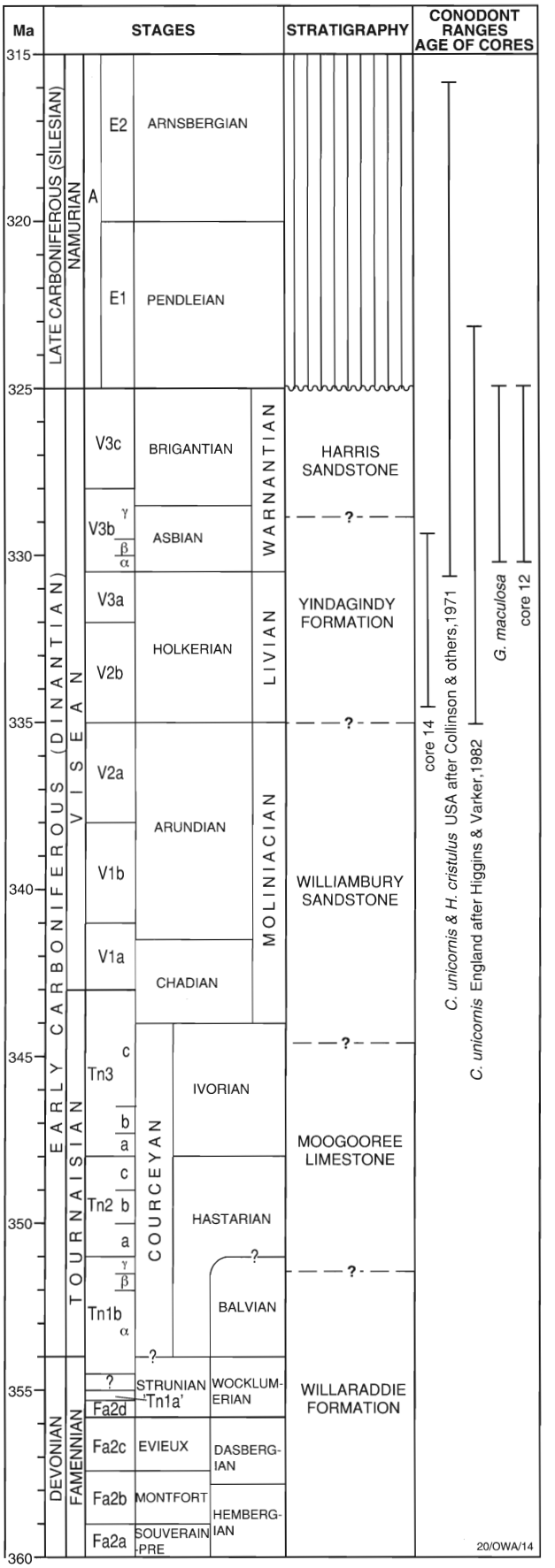

Figure 3. Comparative age ranges of conodonts from core 14 of Quail 1, outcrop sections, North America (after Collinson et al. 1971) and England (after Higgins & Varker 1982). The estimated age ranges of Carboniferous stratigraphic units in the Carnarvon Basin are also shown.

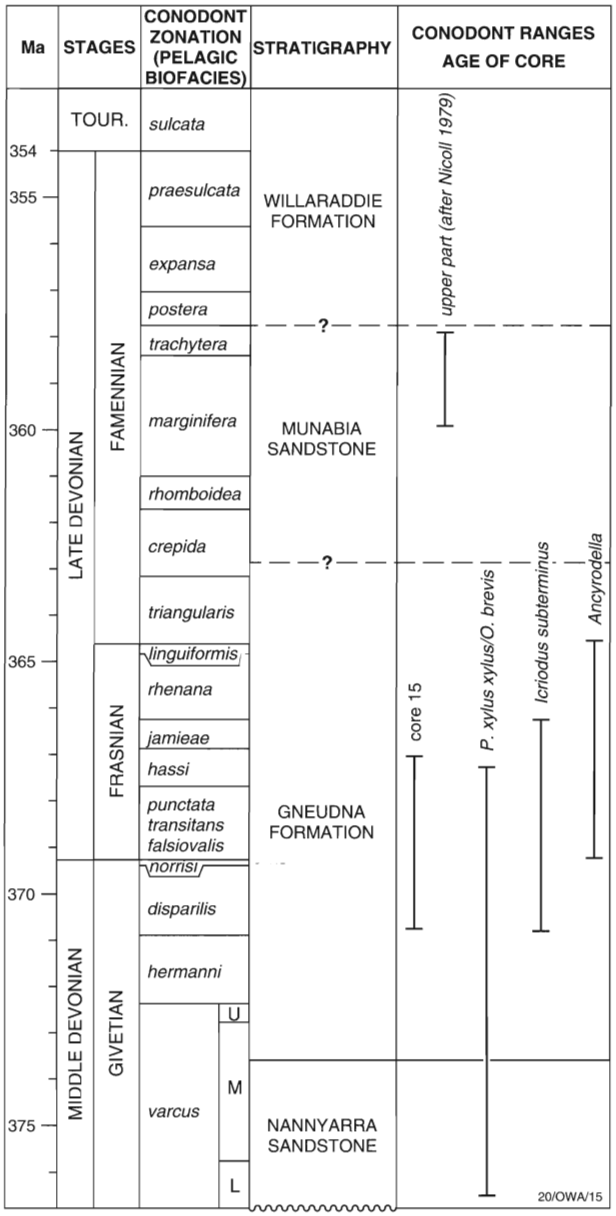

Figure 4. Comparative ranges of conodonts from core 15 of Quail 1 and outcrop sections, and the age of the Gneudna Formation and Munabia Sandstone (after Nicoll 1979). The estimated age ranges of Devonian units in the Carnarvon Basin are also shown.

Structural history

This revised stratigraphy of Quail 1 and Kybra 1 wells has regional structural and geohistory implications (Fig. 5). In Quail 1, the apparent absence of the Moogooree Limestone and the Willaraddie and Williambury Formations, along with the greater part of the Munabia Sandstone, indicates an extended period of uplift and erosion in the Late Devonian and Early Carboniferous in an area corresponding with the Wandagee–Yanrey Ridge. Condon (1968) indicated that the Wandagee–Yanrey Ridge was a positive feature as early as the Devonian, but Hocking et al. (1987) have suggested that it did not start forming until the Triassic, when it developed in association with structuring that was part of the breakup margin rift tectonics. The new age control in Quail 1 well, conodont thermal maturation data (see below), and previous data interpreted along the ridge by Hocking et al. (1987) now suggest that the ridge was a positive feature throughout the Middle to Late Palaeozoic and that it was only occasionally covered by moderately deep sea water.

Harris Sandstone–Quail Formation relationship

Correlation of the subsurface Quail Formation with outcrop of the Harris Sandstone relies on demonstrating lateral continuity or age equivalence of the units. The age of the Harris Sandstone is critical to the correlation, because the existing seismic sections do not allow definitive tracing of the Quail Formation to the outcrop. Unfortunately, the only fossils reported from the Harris Sandstone (*sensu* Condon 1967) are plants. White (1957,

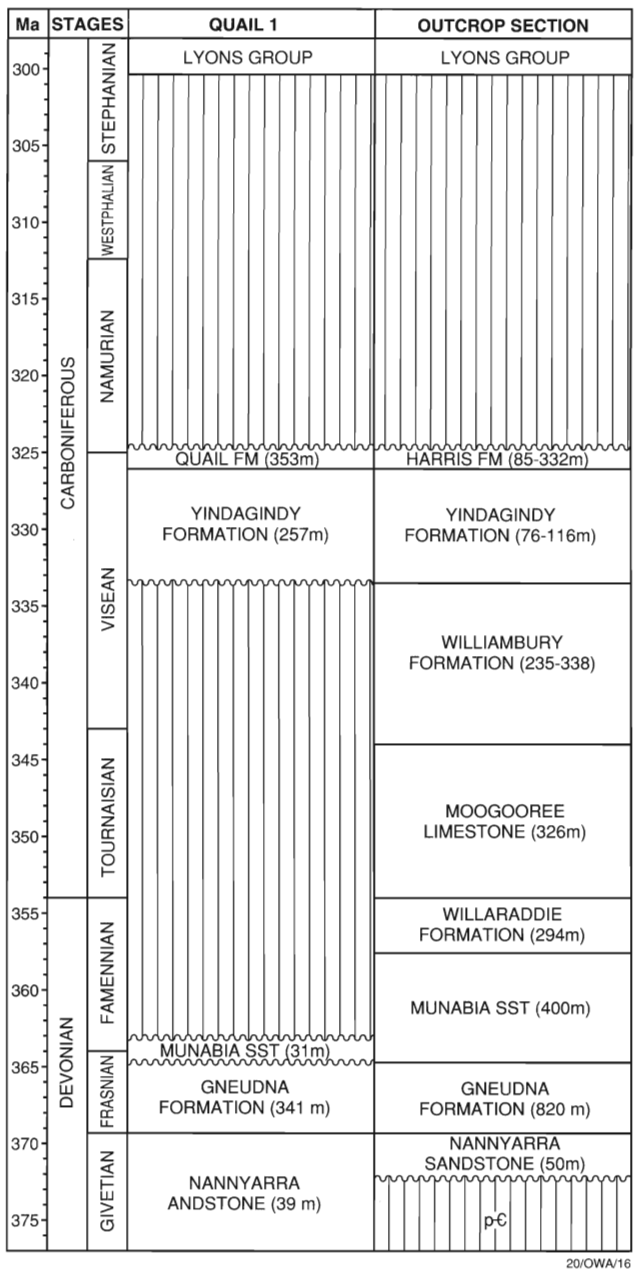

Figure 5. Age relationships of Devonian and Carboniferous stratigraphic units in the outcrop on the eastern margin of the Carnarvon Basin and from Quail 1. Modified from Hocking et al. (1987) and Bentley (1988).

1959) identified specimens from near the base of the Harris Sandstone as *Lycopodiopsis pedroanus* and ascribed them a Lower Permian age. White & Condon (1959) applied the name *Lepidodendron* to other specimens from additional localities and regarded their age as Devonian–Permian. Condon (1967), emphasising the Permian age determinations by White (1957, 1959), associated the Harris Sandstone with the Lyons Group. However, John Rigby (Queensland University of Technology, personal communication, 1994) has indicated that the genus *Lepidodendron* has not been confirmed from the southern hemisphere and that none of the fossils from the Harris Sandstone are well enough preserved to be identified to generic level. He further noted that lepidodendroid plants are thought to be confined to subtropical or tropical environments and are unlikely to have been able to have grown in the proximity of glacial climatic conditions. If correct, this environmental control indicates it is unlikely the Harris Sandstone is associated with glacial conditions of the Late Carboniferous or Early Permian. No definitive age can be assigned to the Harris Sandstone, except that it is younger than the Visean Yindagindy Formation and older than the Austin Formation of the Lyons Group, which is of Asselian to Sakmarian age (Dickins & Thomas 1959; Archbold 1993).

Stratigraphic and lithological relationships tend to indicate correlation of the Quail Formation and the Harris Sandstone, and in a detailed study of the Yindagindy Formation–Harris Sandstone relationship, Read et al. (1973) concluded the two units were disconformable, but the discordance between the two amounted to only a few of metres. In contrast, the relationship of the Austin Formation, the basal unit of the Lyons Group (Condon, 1967), was described as an angular unconformity (Read et al., 1973). Condon (1965) made similar observations on the Yindagindy–Harris relationship, but later placed the major regional unconformity between the Yindagindy Formation and the Harris Sandstone (Condon, 1967).

Condon (1967) and Read et al. (1973) differentiated the Harris Sandstone from the overlying Austin Formation lithologically, but Condon (1967) suggested that the Harris Sandstone was laterally gradational with the Austin Formation. However, exposures of these units are poor and contacts difficult to interpret. Hocking et al. (1987) did observe striated surfaces and cobbles or boulders that may be of glacial origin in the lower part of the Harris Sandstone (*sensu* Condon, 1967) and, on the basis of this, included the Austin Formation within the broader concept of the Harris Sandstone (Hocking 1985; Hocking et al. 1987).

We conclude that the Asselian–Sakmarian Austin Formation, as defined by Condon (1967), and not the Harris Sandstone, is the lowest unit of the Lyons Group and represents the onset of extensive marine glacial sedimentation in the Carnarvon Basin. This means that the Harris Sandstone, as originally defined by Condon (1965, 1967) and interpreted by Read et al. (1973), is probably no younger than Visean or Namurian, and that the ages of the Harris Sandstone and Quail Formation, of the subsurface, probably overlap. For this reason we have equated the units, but cannot recommend abandoning the term Quail Formation until physical continuity or age equivalence is conclusively documented.

The depositional break between a Late Visean Harris Sandstone/Quail Formation and the Sakmarian Austin Formation indicates a time gap of approximately 25 million years (Peter J. Jones, AGSO, personal communication, 1994). The relationship is substantiated by the pronounced unconformity between the Lyons Group and a wide suite of older units.

Thermal maturation

Conodont faunas from Quail 1, cores 14 and 15 (Table 1), have a colour alteration index (CAI) of 4, which indicates exposure to a temperature of 190–300°C (Epstein et al. 1977), well into the overmature hydrocarbon zone. This contrasts with CAI values of 1 from all outcrop samples of the Gneudna Formation, Moogooree Limestone and Yindagindy Formation (unpublished AGSO data). However, it is on the same gradient (Fig. 6) as wells like Dirk Hartog 17B, Tamala 1, and Wandagee 1 (Gorter et al. 1994). Only the CAI 2 value at 2190 m in Pendock 1A suggests a more moderate thermal gradient.

The comparatively high CAI value of 4 obtained at 2600–2800 m in Quail 1 can be explained in two ways: either the regional thermal gradient in the central and southern part of the Carnarvon Basin was significantly higher than that of the northwestern part of the basin, or a considerable thickness of Permian or Mesozoic sediments has been stripped from this area. Nicoll & Foster (1994, fig. 6) summarised the range of conodont CAI ranges from the northwestern Australian margin, showing that a CAI value of 4 at a depth of 3000 m could be produced with the same geothermal gradient as recorded in the Broome Arch area of the Canning Basin. However, the same CAI value could also be the product of a much lower thermal gradient and burial to a depth of 5000 m, which is the composite thickness suggested by Hocking et al. (1987) for the Permian rocks in the vicinity of Kennedy Range 1. The evidence suggests there is no significantly thicker Permian section in the immediate vicinity of Quail 1 or over the nearby Wandagee–Yanrey Ridge. However, the Permian section is at least 1500 m thicker in the vicinity of Wandagee Hill, some 13 km NNW of Quail 1 (Hocking et al. 1987).

Alternatively, an elevated thermal gradient could be related to the Late Jurassic alkali-picrite intrusives of the Wandagee Province (Jaques et al. 1986) in the vicinity of Quail 1. Data from the Canning Basin (Nicoll 1981) indicate that individual small intrusives had a negligible thermal impact, except very close to them. However, Nicoll & Gorter (1984b) have associated a hot thermal trend on the Lennard Shelf close to the Miocene lamproites of the West Kimberley Province (Jaques et al. 1986). Thus, with depth, a measurable regional thermal imprint appears to be associated with such volcanic fields. The intrusive complex would thus have produced a limited area of high thermal impact centred on the zone of surface extrusion.

The conodonts and other phosphatic fossils recovered from Wandagee 1 (Gorter et al. 1994) and WAPET Wandagee No. 1 have CAI values (or equivalents; see Table 1) at gradient with the conodont elements in cores 14 and 15 in Quail 1. They indicate burial of the Devonian rocks on the Wandagee–Yanrey Ridge by no more than 1000 m of additional, post-Carboniferous, sediment. This substantiates the concept of the Wandagee–Yanrey Ridge as a positive structure before the initiation of Permian sedimentation in the basin. Had there been 2500 m of Permian overlying the Wandagee–Yanrey Ridge, the ex-

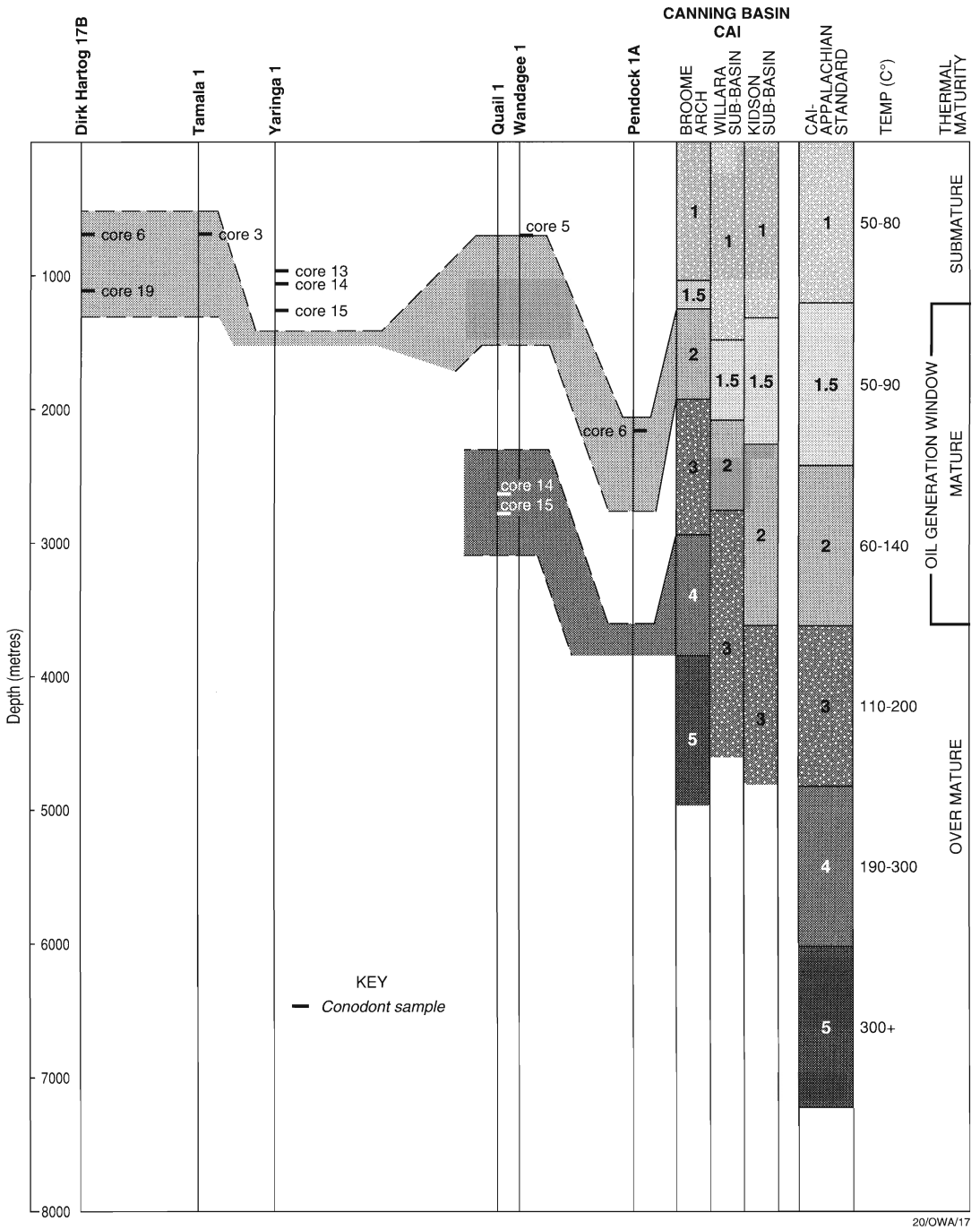

Figure 6. Comparison of CAI values in Dirk Hartog 17B, Tamala 1, Yaringa 1, Quail 1, Wandagee 1 and Pendock 1A compared with wells in the Canning and Bonaparte Basins. Modified from Nicoll & Gorter (1984a, 1984b) and Nicoll & Foster (1994). Line of section located on Figure 1.

pected conodont CAI values in the Wandagee wells would have been similar to the CAI 4 recorded in Quail 1.

While conodont colour alteration (CAI) and miospore thermal alteration (TAI) data (Powis 1985) indicate that both Early and Middle Palaeozoic rocks in the southern and central parts of the onshore Carnarvon Basin have been heated to a level where the Early Palaeozoic sediments are within the oil-generation window or are gas prone, away from the direct influence of Jurassic volcanism, the Devonian (Gneudna Formation) and Carboniferous sedimentary rocks (Moogooree Limestone and Yindagindy Formation) have source potential. This applies especially to units of marine black shales of Middle to Late Devonian age.

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