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Kenn Plateau off northeast Australia: a continental fragment in the southwest Pacific jigsaw

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The submarine Kenn Plateau, with an area of about 140 000 km^2, lies some 400 km east of central Queensland beyond the Marion Plateau. It is one of several thinned continental fragments east of Australia that were once part of Australia, and it originally fitted south of the Marion Plateau and as far south as Brisbane. It is cut into smaller blocks by east- and northeast-trending faults, with thinly sedimented basement highs separated by basins containing several kilometres of sediment. In the Cretaceous precursor of the Kenn Plateau, Late Triassic to Late Cretaceous basins probably rested unconformably on Palaeozoic to Triassic rocks of the New England Fold Belt. Rift volcanism was common on the northern plateau and was probably of Early Cretaceous age. Late Cretaceous extension and breakup were followed by Paleocene drifting, and the Kenn Plateau moved to the northeast, rotated 30° anticlockwise and left space that was filled by Tasman Basin oceanic basalts. During these events, siliciclastic sediments poured into the basins from the continental mainland and from locally eroding highs. After a regional Late Paleocene to Early Eocene unconformity, siliciclastic sedimentation resumed in proximal areas. In deep water, radiolarian chalks were widely deposited until biosiliceous sediment accumulation ended at the regional Late Eocene to Early Oligocene unconformity, and warming surface waters led to accumulation of pure biogenic carbonates. Calcarenite formed in shallow water on the margins of the subsiding plateau from the Middle Eocene onward. Some seismic profiles show Middle to Late Eocene compression related to New Caledonian obduction to the east. Hotspots formed parts of two volcanic chains on or near the plateau as it moved northward: Late Eocene and younger volcanics of the Tasmantid chain in the west, and Late Oligocene and younger volcanics of the Lord Howe chain in the east. As the volcanoes subsided, they were fringed by reefs, some of which have persisted until the present day. Other reefs have not kept up with subsidence, so guyots formed. The plateau has subsided 2000 m or more since breakup and is now subject solely to pelagic carbonate sedimentation.

KEY WORDS: Australia, hotspots, Kenn Plateau, pelagic carbonates, rift sediments, rift volcanics, submarine plateau.

INTRODUCTION

The region off northeastern Australia (north of 27°S) consists of very large bathymetric features (Figure 1) that lie in water depths of <1000 m to >3000 m (Kroenke *et al.* 1983). Off Queensland are the comparatively well-known Queensland Plateau, Townsville Trough and Marion Plateau. Further east are the Coral Sea Basin, Cato Basin, Cato Trough (the southernmost constriction of the Cato Basin) and northern Tasman Basin. Immediately east of these features, from north to south, are the Louisiade Plateau, Louisiade Trough, Mellish Rise, South Rennell Trough, Bampton Trough and Kenn Plateau, all of which trend northeast or contain northeast-trending structures, and the Middleton Basin and Lord Howe Rise, which trend north–south.

Geographically and structurally, we follow Exon *et al.* (2005b) in regarding the Kenn Plateau as being bounded by the Bampton Trough to the north, the Cato Basin and Cato Trough to the west, the Tasman Basin to the southwest, the Middleton Basin to the south, and the north–south ridge of Bellona Plateau to Capel Bank in the east (carbonate caps on volcanic edifices). This means that we include within the eastern Kenn Plateau that part of the Capel Basin (Stagg *et al.* 1999, 2002) that is west of the Bellona Plateau to Capel Bank ridge.

The aim of this paper is to describe the geology of the Kenn Plateau, and put it into its regional context to develop a geological history. Recently, it has been the subject of two geoscience surveys of RV *Southern Surveyor* (Exon *et al.* 2005a, b) and we draw heavily on these results here. Before these surveys, no rocks had

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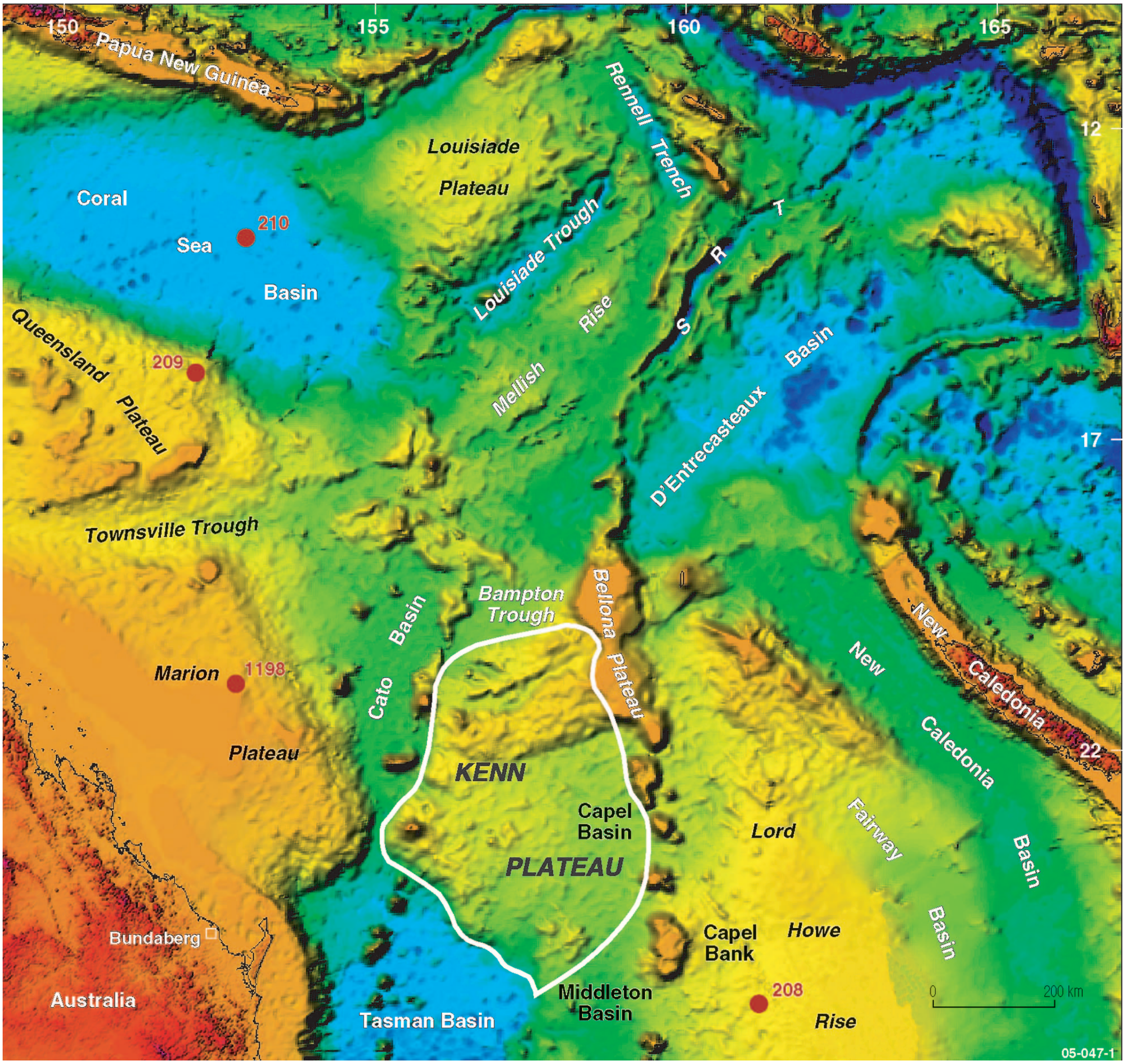


Figure 1 Location map showing Kenn Plateau in its regional context, between the Tasmantid (west) and Lord Howe (east) seamount chains. Four ocean drilling sites shown (DSDP & ODP) are referred to in the text. SRT, South Rennell Trough. Geographical names are in italics, and geological names in plain font. The image is hill-shaded, satellite-derived, predicted bathymetry, merged with GTOPO 30 elevation on land (Smith & Sandwell 1994, 1997). Orange tones show water shallower than 500 m, and blue tones show water deeper than 4000 m.

been recovered from the plateau, and although the geophysical evidence supported a continental origin, it was not unequivocal. The Kenn Plateau (named after Kenn Reef, which forms the plateau's northwest corner) is a large submerged crustal block off northeast Australia (Figure 1) which rifted from northeast Australia 63–52 million years ago (Gaina *et al.* 1998, 1999: note that our plate-tectonic reconstructions use the same set of rotations as Gaina *et al.* 1998). The plateau has an area of 140 000 km^2 and general water depths of 1500–3000 m. Its western part lies within Australian jurisdiction and its eastern part in French jurisdiction (Figure 2). The plateau contains presumed Cretaceous and younger rift basins, and lies in a critical position between seafloor-spreading terrains to the south, and ridge propagation and other terrains to the north.

The petrological and some micropalaeontological results summarised here are preliminary. The petrological interpretation is based solely on shipboard descriptions of hand specimens and slabbed rocks. Work on thin-sections of the igneous and sedimentary rocks, by Julie Brown (Australian National University) and Kinta Hoffmann (Geological Survey of Queensland), is under way. Preliminary results will be presented in the final cruise report (a Geoscience Australia Record) and full petrological results will be published in due course. Nannofossil studies of samples from the first survey have been completed (Howe 2004); those by Claire

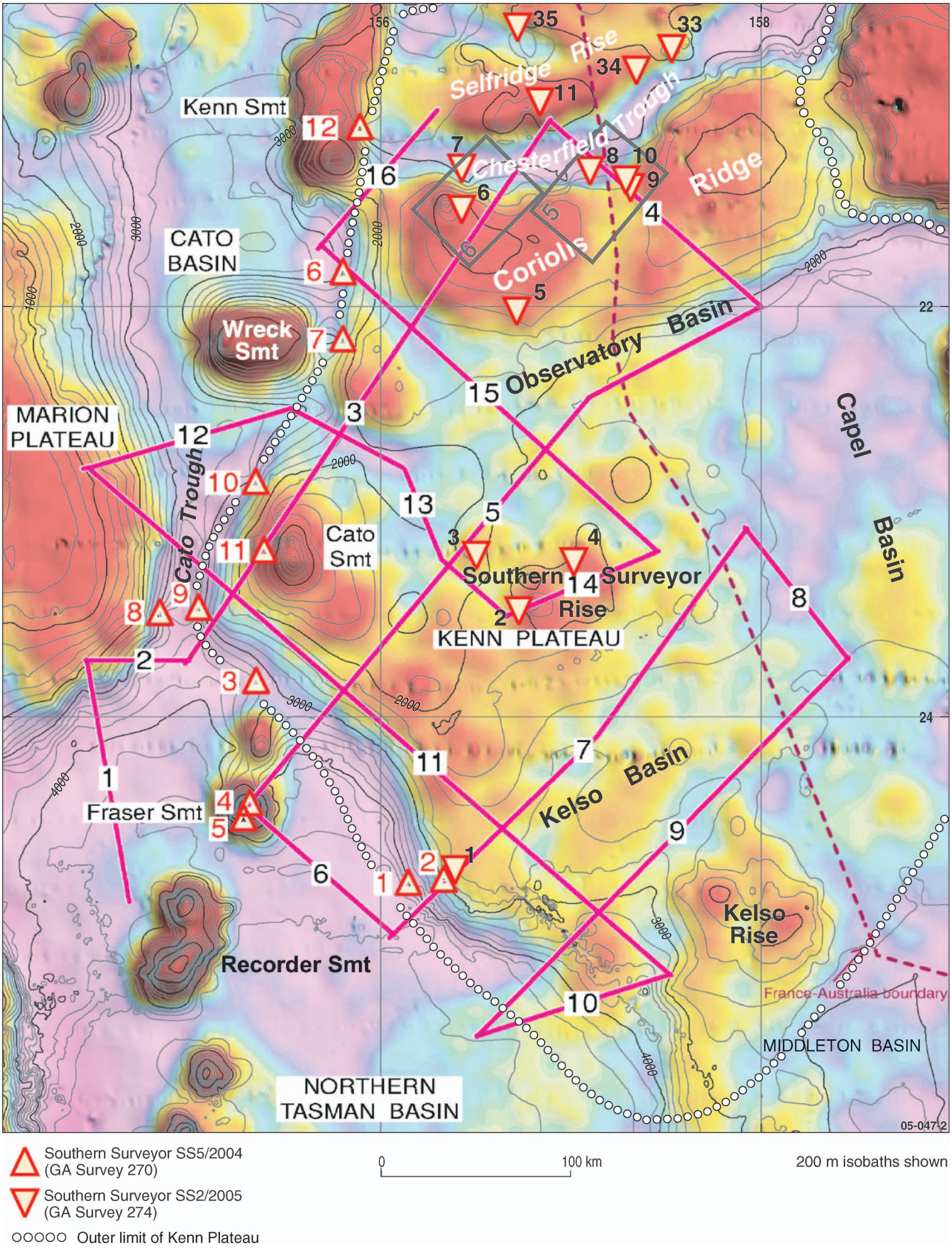


Figure 2 Map showing bathymetric contours in metres, free-air gravity anomaly in colour, structures, seismic profiles from *Southern Surveyor* Survey SS5/2004 (magenta lines with line numbers) and dredge stations from that survey and Survey SS2/2005 (triangles with dredge numbers). Boxes in the north, labelled 5 and 6, indicate the areas covered by Figures 5 and 6. The gravity image is based on satellite altimeter-derived gravity (Sandwell & Smith 1997), merged with shipboard data from Geoscience Australia's database: red, gravity high; mauve, gravity low.

Findlay (Geoscience Australia) for the second survey are also complete and will be presented in the final cruise report and elsewhere. Foraminiferal studies by Patrick Quilty (University of Tasmania) for the first survey are complete (Quilty 2004) and those for the second survey are well advanced and will be presented in the final cruise report and elsewhere.

GEOLOGICAL BACKGROUND

Kroenke *et al.* (1983) showed the Kenn Plateau as being separated from the Marion Plateau to the west by a north-trending depression, the Cato Trough, some 3000 m deep. Its southern end is a narrow, deep feature to which various authors have restricted the name Cato Trough. The restricted Cato Trough grades northward into a broader deeper bathymetric depression, a bathymetric feature that Exon *et al.* (2005b) named the Cato Basin. Thus, Kroenke *et al.*'s (1983) 'Cato Trough' is here split into two: the Cato Trough and Cato Basin.

The Kenn Plateau lies between the seamounts, guyots and reefs of two north–south hotspot chains: the Lord Howe chain to the east, and the Tasmantid chain to the west (Figure 1). Quilty (1993) described, dated (using foraminifers) and discussed the palaeoceanographic significance of the limestones capping several of the seamounts in both chains. The Lord Howe seamount chain extends northward about 1000 km from Lord Howe Island. Basalts from Lord Howe Island have been dated at 6.9–6.4 Ma by the K/Ar method (McDougall *et al.* 1981). The Chesterfield Group of guyots, forming the Bellona Plateau at the northern end of the Lord Howe chain, was interpreted as younger than Middle Eocene by Missegue and Collot (1987). However, if we apply a hotspot migration rate of about 70 km/million years (relative to the Australian Plate) and use the age of Lord Howe Island as a starting-point, the pedestal of the Chesterfield Group should have formed at about 25 Ma (latest Oligocene). Quilty (1993) determined foraminiferal ages from the limestone capping of several seamounts in the Lord Howe chain associated with the Kenn Plateau: from north to south Nova (latest Oligocene and earliest Miocene), Argo (Middle Miocene) and Gifford (Early Miocene). These limestone ages presumably are those of the hotspots or are younger, and fit with the ages of volcanism that were calculated for CPCEMR (1991): Chesterfield 25 Ma (Late Oligocene) to Gifford 15 Ma (Early Miocene).

The Tasmantid seamount chain (McDougall & Duncan 1988; Quilty 1993) extends about 1800 km in and north of the Tasman Basin, from Gascoyne Seamount in the south to Kenn Reef in the north. Kenn Reef (atop Kenn Seamount in Figure 2), Bird Island and Wreck Reef (atop Wreck Seamount) and Cato Island (atop Cato Seamount) are part of the Tasmantid seamount chain. The seamounts decrease in age southward. Queensland Seamount to the south (26.5°S) is the oldest seamount basalt yet dated (24 Ma: McDougall & Duncan 1988, using K/Ar and Ar/Ar techniques). The results of McDougall and Duncan (1988), in conjunction with broader plate-tectonic studies (CPCEMR 1991), indicate that the associated hotspot migrated southward (relatively) at about 70 km/million years and suggest that the pedestal of Kenn Reef should have formed at about 35 Ma (latest Eocene) and that of Cato Island at about 30 Ma (Early Oligocene).

The only previous study specifically of the Kenn Plateau was that of Walker (1992). A series of papers have dealt with the regional context of the plateau: marine seismic surveys (Mutter 1973; Symonds 1973); nearby plateaus (Symonds & Davies 1988); magnetic lineations in nearby oceanic basins (Hayes & Ringis 1973; Weissel & Hayes 1977; Shaw 1978; Weissel & Watts 1979; Mutter & Karner 1980); and plate-tectonic context (Gaina *et al.* 1998, 1999; Sdrolias *et al.* 2003).

Davies *et al.* (1989) and Feary *et al.* (1991) used a variety of geological information, including Australia's movement northward, to outline climatic evolution and its control on carbonate deposition off northeast Australia. They postulated that sea-surface temperatures in the Cenozoic were warm enough to support reef growth before 45 Ma and after 25 Ma. Later studies have generally corroborated their views.

Table 1 lists the basinal features around the Kenn Plateau (for locations, see Figure 1), with their ages estimated by selected workers. Ages in the northern Tasman Basin, the Coral Sea Basin and the South Rennell Trough come largely from magnetic anomalies, whereas those in other depressions come from less-direct seismic interpretation and plate-tectonic reconstructions. The table suggests that the Townsville Trough first formed in the Early Cretaceous, followed by the Middleton, Fairway, northern Tasman

Table 1 Postulated age of formation of basins near the Kenn Plateau.

Feature	Age of formation	References
Townsville Trough	Early Cretaceous	Struckmeyer and Symonds (1997)
Middleton Basin	Late Cretaceous: 95–74 Ma	Gaina *et al.* (1998)
Fairway Basin	Late Cretaceous: 95–74 Ma	Lafoy *et al.* (2005)
Northern Tasman Basin	Late Cretaceous–Early Eocene: 74–52 Ma	Hayes and Ringis (1973) Gaina *et al.* (1998)
D'Entrecasteaux Basin	Late Campanian: 76–73 Ma	CPCEMR (1991)
Coral Sea Basin	Paleocene–Early Eocene: 62–52 Ma	Weissel and Watts (1979), 62–56 Ma; Gaina *et al.* (1998), 62–52 Ma
Louisiade Trough	Paleocene–Early Eocene: 62–52 Ma	Kroenke (1984), 53–44 Ma; Gaina *et al.* (1998, 1999), 62–52 Ma
South Rennell Trough	Early Oligocene: 30 Ma	Larue *et al.* (1977)

and D'Entrecasteaux Basins in the Late Cretaceous, but the evidence for the age of the Middleton, Fairway and D'Entrecasteaux Basins is tenuous. Gaina *et al.* (1999) argued, on plate-tectonic grounds, that the northern Tasman Basin, the Coral Sea Basin and the Louisiade Trough formed a triple junction in the Paleocene. The South Rennell Trough appears to be an Early Oligocene spreading centre that propagated southwest with time (Larue *et al.* 1977). It is not recognisable south of where the Late Oligocene Bellona Plateau of the Lord Howe volcanic chain is present, but we suggest that the hotspot chain may be on a line of weakness related to the earlier spreading centre.

Nearby basins

A detailed study of the offshore Maryborough and Capricorn Basins (locations in Figure 3) was carried out by Hill (1992, 1994) following a multichannel reflection seismic survey (AGSO Survey 91). The Maryborough Basin developed in the latest Triassic to mid-Jurassic, probably as a foreland depression, and Neocomian volcanism and rifting led to a second phase of deposition. Total sediment thickness may be as much as 8–9 km. The Capricorn Basin, beneath the physiographic Capricorn Channel, is a northwest-trending failed rift, related to that in the Tasman Sea, which formed in the Late Cretaceous to Paleocene. It contains as much as 6 km of sediment.

Two commercial wells were drilled in the Capricorn Basin (Ericson 1976) in 1967 and 1968: Capricorn 1A (Carlsen & Wilson 1968a) and Aquarius 1 (Carlsen & Wilson 1968b). Capricorn 1A reached a total depth of 1710 m, and Aquarius 1 of 2650 m. The stratigraphy is summarised in Figure 4. From Capricorn 1A, Carlsen and Wilson (1968a) published a Santonian K/Ar age of 86 Ma from the basal doleritic volcanics or sills at ~1660 m, but suggested that the age was a minimum, because these rocks are weathered. As no other Late Cretaceous igneous ages have yet been recorded in northeast Australia, these rocks are most probably at least as old as the youngest rocks (*ca* 95 Ma) in the widespread Early Cretaceous igneous province of northeast Australia (Ewart *et al.* 1992; Bryan *et al.* 1997). A Neocomian K/Ar age of 129 Ma, from a pebble in a much shallower, polymictic boulder conglomerate at ~1245 m, suggests that the pebble is reworked. In Aquarius 1, the conglomerate overlying basal metasediments has not been dated, but Hekel (1972) showed that the overlying redbeds contain palynomorphs (*Myrtaceidites*, *Cupanieidites*, *Nothofagites*) lying in the Paleocene to mid-Oligocene time range. A latest Maastrichtian K/Ar age of 67 Ma in glauconite in quartz sandstone from the overlying lower marine section in Aquarius 1, at 1654 m (Carlsen & Wilson 1968b), apparently represents reworking. Hekel (1972) identified the palynomorphs of the lignite-bearing section in both wells as Late Oligocene. Palmieri (1971) studied foraminifers in the carbonate sequence in the two wells, and planktonic foraminifers dated that sequence as Late Oligocene and younger. Hekel (1973) studied the calcareous nanofossils in the same carbonate sequence and refined the dating. He showed that proportions of discoasters, coccoliths and *Micrascidites* (ascidian spicules) varied considerably in the carbonates, because of environmental changes. Chaproniere *et al.* (1990) partly reinterpreted the wells in terms of age and palaeo-water depths (Figure 4). In summary, the wells indicate that the basin contains: (i) Miocene and younger open-marine marl and some limestone; (ii) Upper Oligocene marine sequence of limestone, bentonitic claystone and (in Aquarius 1) claystone with glauconite; (iii) Eocene–Oligocene quartz sandstone with lignite and anhydrite (anhydrite present only in Aquarius 1), overlying either shallow-marine quartz sandstone with bentonitic claystone or shelly limestone; (iv) a probably Paleocene (but possibly younger) redbed section about 600 m thick in Aquarius 1 consisting of red-brown claystone with lesser interbedded conglomerate and sandstone; (v) Upper Cretaceous to Paleocene continental conglomerate and arkosic sandstone in both wells; and (vi) basement of Cretaceous doleritic volcanics or sills in Capricorn 1A, and black siliceous slates (metasediments) of presumed Palaeozoic age in Aquarius 1.

Volcanism

There are two major periods of Jurassic and younger volcanism in the region:

(1) The latest Jurassic and Early Cretaceous (largely Neocomian) explosive rift-related volcanism of the Grahams Creek Formation in the Maryborough Basin: tuffs, agglomerates and volcanic breccias, overlain by trachyte and rhyolite flows, overlain by basaltic andesite and dacite (Ewart *et al.* 1992; Cranfield 1993; Sutherland 1995; Bryan *et al.* 1997). There was also Early Cretaceous (mostly 120–105 Ma) volcanism in the Whitsunday and Cumberland Islands (Whitsunday Volcanic Province) much further north: dacite, rhyolite and andesitic ignimbrite (Sutherland 1995; Bryan *et al.* 1997). The youngest dated volcanic rock in the Whitsunday Islands is 98 Ma, and the youngest granite in the Cumberland Islands is 95 Ma (Ewart *et al.* 1992; Bryan *et al.* 1997).

(2) The Late Eocene to Early Miocene hotspot volcanism of the Tasmantid and Lord Howe chains: basalts and hyaloclastites (McDougall & Duncan 1988). The western part of the region was affected by the Tasmantid seamount trail, which trends north–south, continuing the trail of seamounts in the northern Tasman Sea. CPCEMR (1991) predicted an age of 38 Ma for a seamount southeast of Mellish Reef, near the northern (oldest) part of the seamount chain, based on a hotspot track model for the Tasmantid seamounts. The Lord Howe seamount trail, further east, parallels the Tasmantid trail (Figure 1), and CPCEMR (1991) predicted an age of 25 Ma for the northern end of Bellona Plateau, the most northerly and oldest part of that chain. Bentonitic claystone from the northern Kenn Plateau, dated by nannofossils as Late Eocene to Early Oligocene (Claire Findlay pers. comm. 2005), and bentonitic claystone of similar age from the Capricorn Basin (Figure 4), are presumably related to this phase of volcanism.

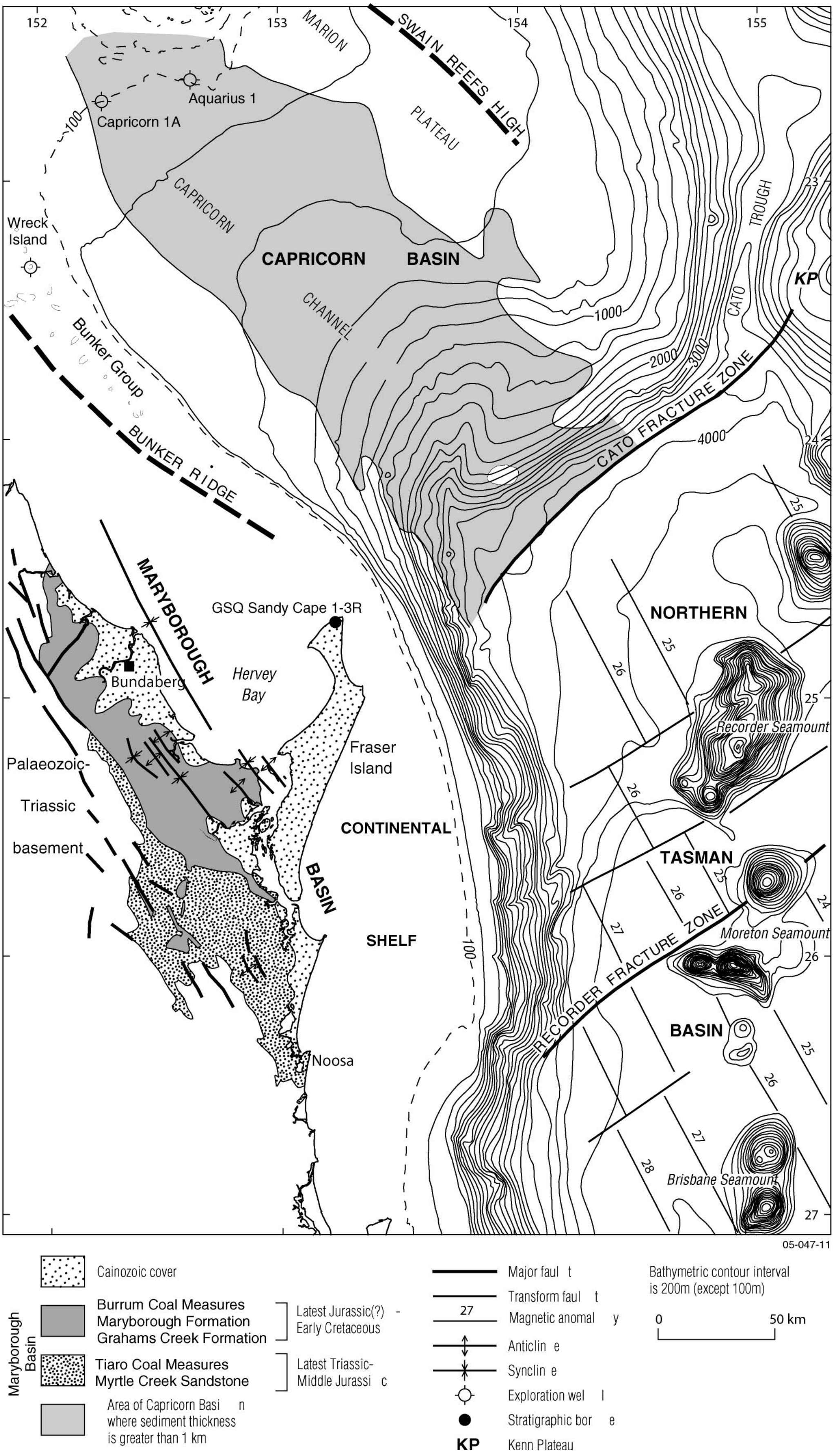


Figure 3 Main structural elements of the Maryborough and Capricorn Basins area (after Hill 1994).

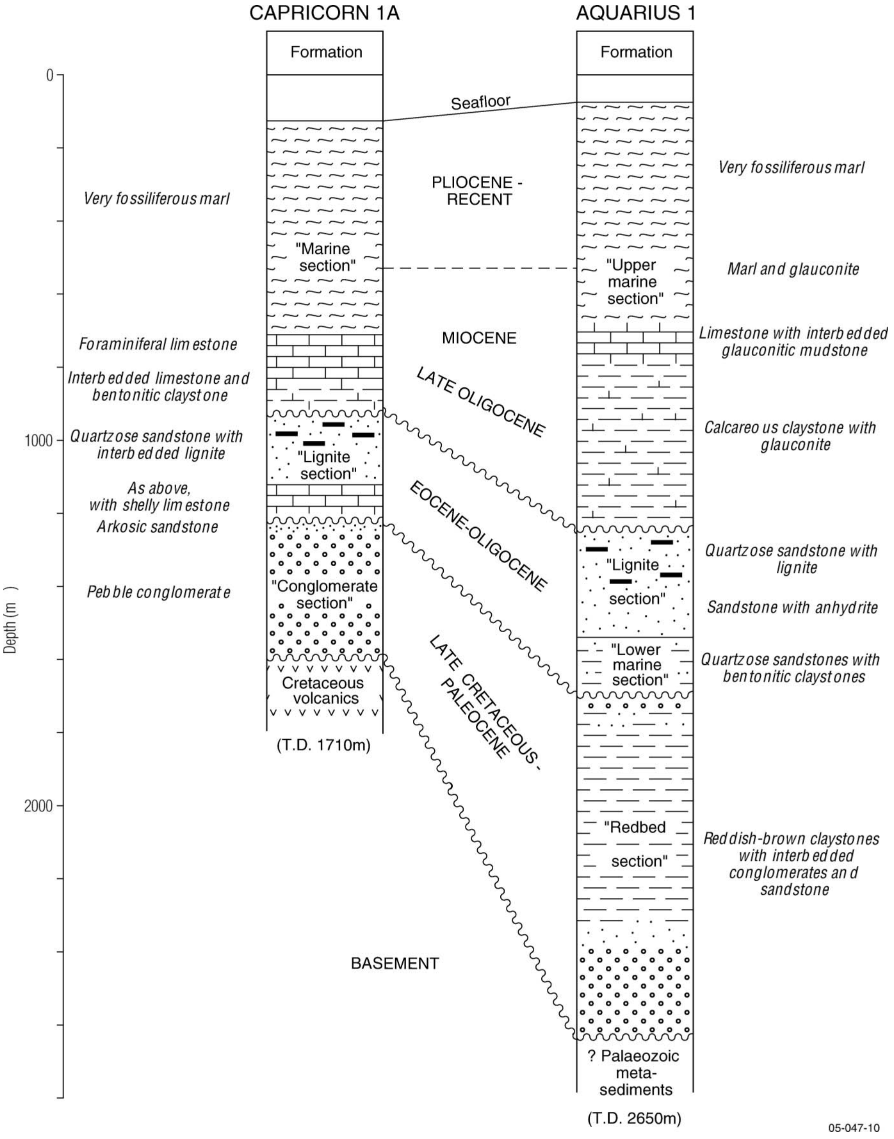


Figure 4 Capricorn 1A and Aquarius 1 geological well logs and cross-section (after Chaproniere *et al.* 1990), modified to allow lignites of Late Oligocene age (Hekel 1972). Well locations are shown in Figure 3.

The Santonian (86 Ma) age for the doleritic volcanics or sills in Capricorn 1A well (Carlsen & Wilson 1968a) is probably too young, and caused by alteration of the rock. However, it is possible that it is correct, in which case it would fit with the assumed Late Cretaceous to Paleocene age (Isern, Anselmetti, Blum *et al.* 2002) of the rift-related volcanics 200 km to the northwest on the Marion Plateau (altered basalt flows and volcaniclastic breccia and conglomerate drilled in ODP Leg 194). Alternatively, the Marion Plateau volcanics are Early Cretaceous, like all other dated volcanics in the region.

Ocean drilling

Deep Sea Drilling Project (DSDP) Leg 21 drilled stratigraphic sequences in areas near the Kenn Plateau (Burns, Andrews *et al.* 1973). Table 2 summarises representative sites from the abyssal Coral Sea Basin (Site 210), Queensland Plateau (Site 209) and northern Lord Howe Rise (Site 208). The locations of the representative sites are shown in Figure 1. Basement was not reached in any of them. At Site 210, the lowermost 190 m consists of Eocene and Oligocene pelagic nannofossil chalk, which gives way to Miocene and younger muddy graded beds, which represent turbidite sedimentation. Sites 209 and 208 were drilled in bathyal depths, and the Eocene and younger sequences were similar in both. The Oligocene and younger sequences are calcareous ooze, and the Eocene sequences are chalk grading to radiolarite (with some chert). At Site 208, the Eocene is underlain by Paleocene radiolarian nannofossil chalk, and variably cherty Maastrichtian nannofossil chalk. Thus, in these pelagic sites, deposition of radiolarians and other biosiliceous organisms is concentrated in the Paleocene and Eocene.

DSDP drilling proved that there are two very widespread regional unconformities in the region (Edwards 1973). The younger is the regional Eocene–Oligocene unconformity, which spans at least the late Late Eocene and the early Early Oligocene (present in all sites).

Table 2 DSDP and ODP drillsites in the region around Kenn Plateau.

	Site 210 Coral Sea Basin	Site 209 Queensland Plateau	Site 1198 Marion Plateau	Site 208 North Lord Howe Rise
Location	13°45.99′S 152°53.78′E	15°56.19′S 152°11.27′E	20°57.93′S 152°44.00′E	26°06.61′S 161°13.27′E
Water depth	4643 m	1428 m	319.4 m	1545 m
Pleistocene	120 m graded silt–clay turbidites with nannofossil ooze	20 m calcareous ooze	110 m outer neritic limestone with clay	40 m calcareous ooze
Pliocene	240 m graded silt–clay turbidites with nannofossil ooze	20 m Middle to Upper Pliocene calcareous ooze	90 m outer neritic limestone with clay	60 m calcareous ooze
Miocene	165 m total: 110 m Upper Miocene graded silt–clay turbidites with nannofossil ooze; 55 m Lower and Middle Miocene silty clay.	65 m foraminiferal ooze	315 m total proximal slope limestone: 200 m Middle and Upper Miocene; 108 m Lower and Middle Miocene; over basalt	330 m calcareous ooze: 130 m Upper Miocene; 85 m Middle Miocene; 115 m Lower Miocene
Oligocene	20 m Lower to Middle Oligocene clayey nannofossil chalk	40 m Upper Oligocene foraminiferal ooze		50 m Upper Oligocene calcareous ooze
Eocene	>170 m nannofossil chalk to nannofossil clay: 15 m Upper Eocene; 130 m Middle Eocene; >25 m Lower Eocene	>200 m calcareous ooze with terrigenous detritus: 135 m Upper Eocene sandy foraminiferal ooze and chert; >60 m Middle Eocene outer neritic sandy foraminiferal limestone with glauconite		50 m Middle Eocene foraminiferal radiolarian nannofossil chalk to nannofossil-bearing radiolarite
Paleocene				35 m Lower to Middle Paleocene radiolarian nannofossil chalk
Latest Maastrichtian				>20 m foraminiferal nannofossil chalk, variably cherty, with rare radiolarians
Total thickness	711 m	344 m	522.6 m	594 m

The older is the Paleocene–Eocene unconformity, which spans at least all of the Late Paleocene and the early Early Eocene (present in DSDP Sites 206, 207 and 208). This is the best dating of the regional unconformities represented in our seismic profiles.

DSDP Leg 21 also drilled a rhyolite in Site 207 on the southern Lord Howe Rise, which was K/Ar dated as 94 Ma (McDougall & van der Lingen 1974). This is a comparable age to that of the youngest Cretaceous volcanics in the Whitsunday Islands, and the youngest Cretaceous granite in the Cumberland Islands, both on the central Queensland coast (Ewart *et al.* 1992; Bryan *et al.* 1997).

Important comparative sedimentological information for the Neogene comes from the Ocean Drilling Program (ODP). ODP Leg 133 cored the Queensland and Marion Plateaus, and in the Great Barrier Reef (McKenzie, Davies, Palmer-Julson *et al.* 1993). ODP Leg 194 on the Marion Plateau (Isern, Anselmetti, Blum *et al.* 2002) tested the amplitude of the major Middle Miocene sea-level fall (Pigram *et al.* 1992) and studied many other aspects of carbonate and siliciclastic sedimentation on drowned reefs, reef slopes and in the basin. Marion Plateau Site 1198 is summarised in Table 2. Carbonate platforms first formed in the Early Miocene on the Marion Plateau (25–18 Ma) from cool subtropical calcareous faunas, and there was extensive reef growth by the Middle Miocene. Acoustic basement was cored on the Marion Plateau during ODP Leg 194 at five sites, and altered lava flows and volcaniclastics were recovered. They have not been dated but are immediately overlain by Lower Miocene carbonates. Isern, Anselmetti, Blum *et al.* (2002) suggested that the lack of deformation of the volcanics indicates that they may have been emplaced after the main orogenic phases, i.e. during the Late Cretaceous to Paleocene rifting in the region.

RESULTS OF TWO RECENT SURVEYS

In 2004, RV *Southern Surveyor* carried out a geoscientific study of the Kenn Plateau known both as *Southern Surveyor* Survey SS5/2004 and as Geoscience Australia Survey 270. The survey was designed to test whether there were any fundamental differences in basement geology and margin development across the plateau, related to proximity to the seafloor-spreading terrains in the south or the ridge propagation terrains in the north, and to address other fundamental questions about its nature and tectonic evolution.

The survey acquired 3090 km of 24-channel reflection seismic profiles, about 25 000 km^2 of multibeam sonar mapping data using a Kongsberg-Simrad EM300 mid-range system, and 12 dredge hauls of rocks. Exon *et al.* (2005b) reported the results in detail and integrated them with DSDP and other relevant results in adjacent areas. In 2005, another 15 dredge hauls were made on the Kenn Plateau during *Southern Surveyor* Survey SS2/2005 (Geoscience Australia Survey 274), and preliminary results were reported by Exon *et al.* (2005a).

Geophysical results

The gravity anomaly as determined from satellite altimeter data (Sandwell & Smith 1997) and the satellite-predicted bathymetric data (Smith & Sandwell 1994; Smith & Sandwell 1997), in conjunction with various bathymetric datasets, allowed the compilation of a map showing the broad structural features of Kenn Plateau (Figure 2). Using this map, the program of reflection seismic profiling was designed to cut the broad features in suitable directions, and to image the basement and the overlying sedimentary sequences in representative settings. The seismic profiling substantiated the broad structures revealed by satellite gravity mapping.

Following Exon *et al.* (2005b), the plateau can be subdivided into a northern, generally shallower part, and a southern, generally deeper part (Figure 2). The plateau has marked east–west trends in the northwest and northeast trends elsewhere. The northern part includes the Selfridge Rise (this name replaces the name Chesterfield Rise used by Exon *et al.* 2005b, because of potential confusion with the nearby, unrelated Chesterfield Bank), Chesterfield Trough and Coriolis Ridge. The southern part is differentiated in the west into the Observatory Basin, Southern Surveyor Rise, Kelso Basin and Kelso Rise. In the east is the north–south-trending Capel Basin, which is terminated northward by the Coriolis Ridge. Complicating the western margin of the plateau are the volcanic edifices of Kenn, Wreck and Cato Seamounts, surmounted respectively by Kenn, Wreck and Cato Reefs.

SWATH-MAPPING

Swath-mapping by *Southern Surveyor* has detailed the morphology of key parts of the plateau (Exon *et al.* 2005a, b). The western and southwest margins are slopes that are steep in part but are largely blanketed by Neogene and Quaternary chalk and ooze. The western slope is cut by shallow canyons that must have originated when the plateau was near sea level in the Palaeogene, and the steeper and more rugged lower slope averages 5–10°. This slope was affected by the slumping of carbonates, neotectonic faulting and possibly erosion by bottom currents. The continental slope of the southwest margin lacks canyons and is generally smoother than that of the western margin.

The northern rifted margin (Figures 2, 5, 6), including Coriolis Ridge and Selfridge Rise, is much more varied morphotectonically than the western and southern margins. In the east, the northern margin of Coriolis Ridge (location in Figure 2) is an irregular, and in places terraced, escarpment about 500 m high. Its morphology suggests structural control by northeast-, east-northeast- and west-northwest-trending faults. The steep slopes are marked by numerous slump scars, some 1–2 km wide. In the middle (left part of Figure 5), the slope is gentle (2°), smooth, sedimented and mostly gently undulating, with minor relief due to sediment drifts and shallow channels, plus small fault scarps (<50 m high). Further west (right part of Figure 5), there is a scarp up to 700 m high, containing two slump scars that are each about 2 km wide. The height and steepness of the scarp diminishes westward, and the scarp eventually becomes <200 m high (left part of Figure 6). In the west, the slope is not very steep, but it is rugged (right part of Figure 6) because of numerous downslope canyons and gullies 50–200 m deep. Here, the slope lies below a steep-sided volcanic topographic high located just to the south (‘Seamount’ on the far right of Figure 6). The presence of bottom currents is indicated by low-amplitude northwest-trending sand waves (assumed to be in foraminiferal sand) on the crest of Coriolis Ridge.

Selfridge Rise lies north of Coriolis Ridge and is separated from it by the Chesterfield Trough (Figure 2). North of Selfridge Rise is the Bampton Trough (Figure 1), which separates Kenn Plateau from Mellish Rise. The southern slope of Selfridge Rise is steep, whereas its northern slope is more gradual. A series of highs occurs along the southern margin of Selfridge Rise, which geophysical data suggest are part of a volcanic ridge.

SEISMIC PROFILES AND INTERPRETATION

Sixteen regional seismic profiles (located in Figure 2) were recorded from *Southern Surveyor* and described by Exon *et al.* (2005b), and three of these profiles are illustrated here (Figures 7–10). Only limited stratigraphic information is available to control the seismic stratigraphy on Kenn Plateau. The nearest apposite deep-sea drillsite is DSDP Site 208 (Burns *et al.* 1973) located on the northern Lord Howe Rise to the southeast (Table 2), where drilling finished in Maastrichtian chalk. As noted earlier, regional Eocene–Oligocene and Paleocene–Eocene unconformities were documented in DSDP Leg 21 (Edwards 1973).

The closest relevant petroleum exploration wells are Capricorn 1A and Aquarius 1 (Figure 4) in the northern Capricorn Basin (Ericson 1976; Hill 1994). One of the important outcomes of the 2004 *Southern Surveyor* dredging program was the recovery of early Middle Eocene shallow-marine chalk from the Cato Basin

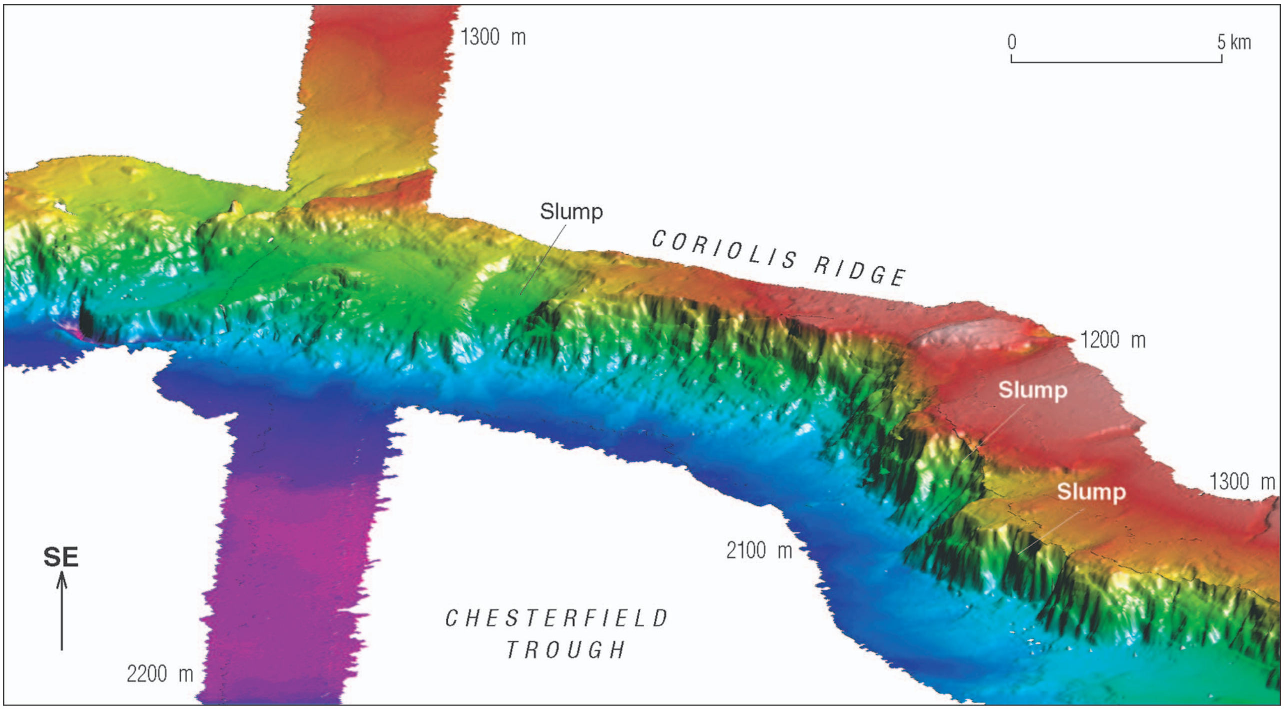


Figure 5 View to the southeast of the central north margin of Coriolis Ridge based on multibeam sonar data from *Southern Surveyor*. The location is shown by the box in Figure 2.

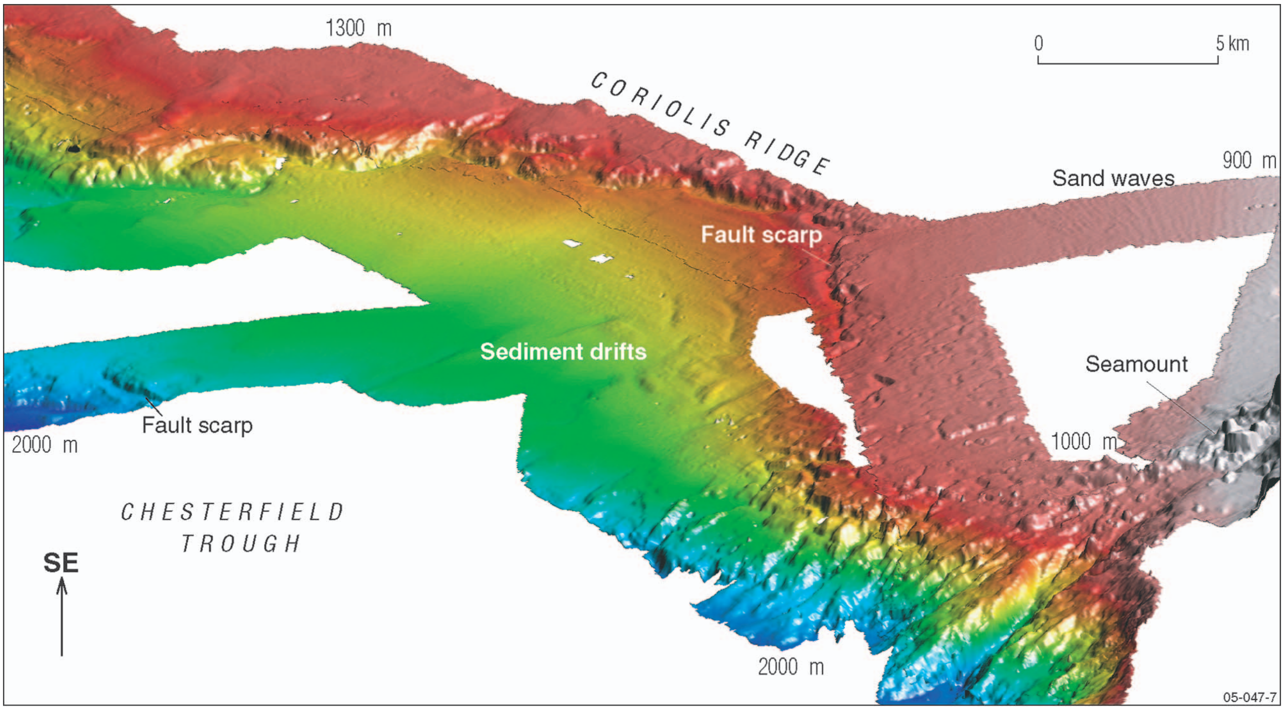


Figure 6 View to the southeast of the northwest margin of Coriolis Ridge based on multibeam sonar data from *Southern Surveyor*. The location is shown by the box in Figure 2.

margin of the Kenn Plateau (270/DR6), providing some stratigraphic control.

Two prominent regional unconformities are recognised in seismic profiles crossing Kenn Plateau. These are interpreted as a Late Eocene to Early Oligocene unconformity and a mid-Eocene unconformity, the latter probably superimposed on the regional Late Paleocene to Early Eocene unconformity. The Eocene–Oligocene unconformity is attributable (in part at least) to changes in global ocean circulation and

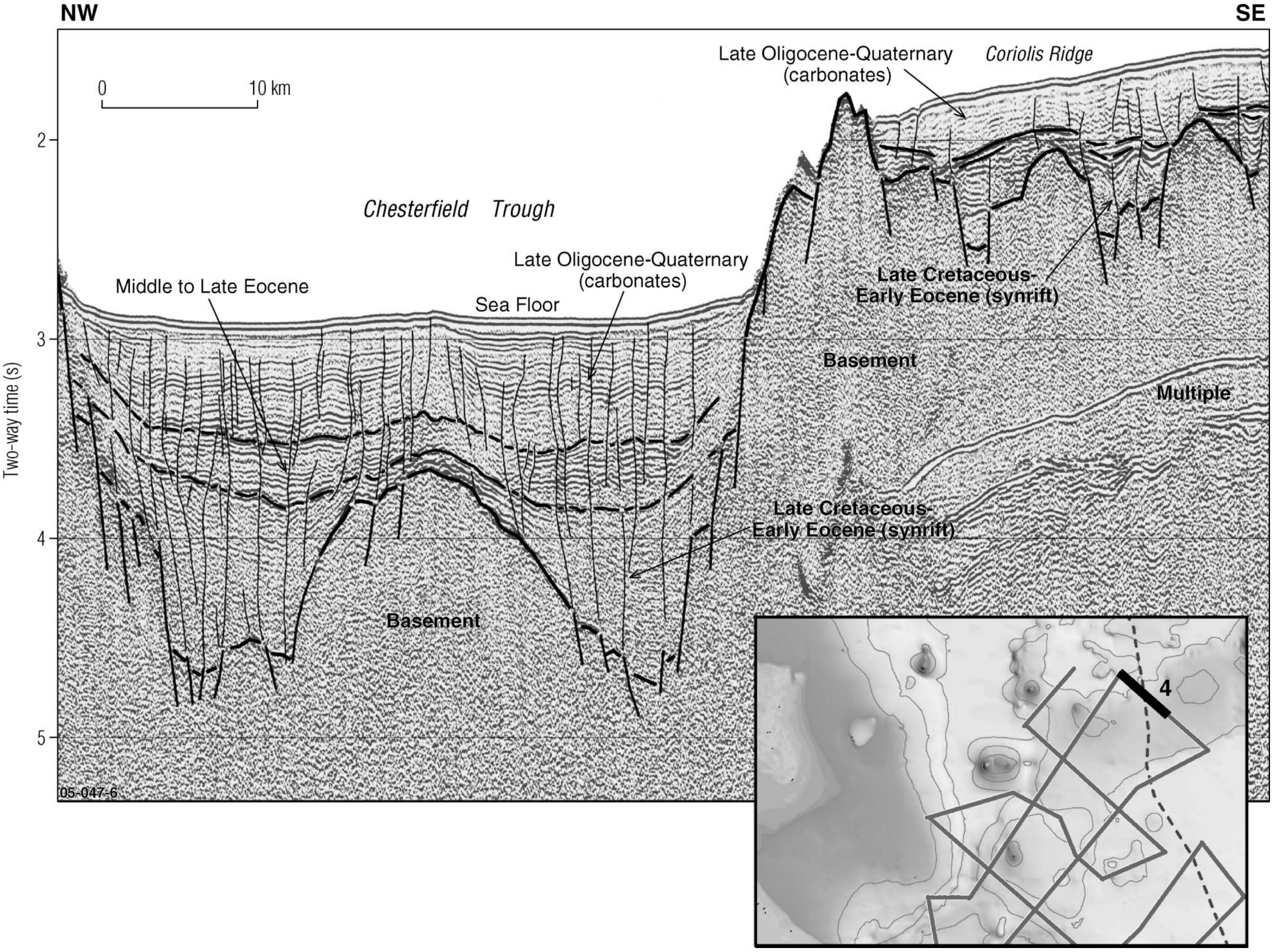


Figure 7 Sequences apparent on part of migrated seismic profile 270/4 (location in Figure 2) across the Chesterfield Trough and Coriolis Ridge on the northern Kenn Plateau. The trough contains up to 2 s twt of sediment, consisting of deformed synrift and early sag phase deposits, Late Eocene fill, and a thick sequence of Oligocene and younger pelagic carbonates. Small-scale faulting extends upward into the latest Neogene sequences and in places into the Quaternary.

climate associated with development of the Antarctic Circumpolar Current (Kennett 1977; Kennett & Exon 2004), namely development of erosive bottom currents and/or erosion associated with sea-level fall caused by the growth of glaciers on Antarctica. The mid-Eocene unconformity is attributed to compressional tectonics associated with collision of the Loyalty Arc with New Caledonia and the resultant obduction of ophiolites over New Caledonia. This collision occurred in the interval 45–38 Ma (Sdrolias *et al.* 2003; Crawford *et al.* 2003 proposed *ca* 40–38 Ma) and was possibly triggered by increased convergence of the Australian and Pacific Plates at about this time. The upper two megasequences correspond to Sequences A and B of Hill (1994) in the Capricorn Basin. Deeper seismic horizons are present in the Kenn Plateau succession (Figures 7, 8), but mid-Eocene deformation and widespread diapirism make mapping them widely difficult. Three major sequences are identified in our seismic data:

(1) An upper, Upper Oligocene to Quaternary megasequence (Figures 7, 8), which is of consistent seismic character over Kenn Plateau, and characterised by low amplitude and low continuity reflectors. It can be directly correlated with DSDP Site 208 where it postdates the Late Eocene to Early Oligocene regional unconformity. It is present throughout the whole study area as a post-tectonic sequence. Its thickness averages 0.6 s (twt) and it is commonly 300–700 m thick. Our dredging results (Table 3) and extrapolation from drilling and coring elsewhere in the region (Table 2; Figure 4) indicate that it consists of pelagic chalk and calcareous ooze.

(2) An underlying megasequence is characterised by generally higher amplitude and higher continuity reflectors (Figures 7, 8). It is indirectly correlated with DSDP Site 208 and is assumed to post-date the Late Paleocene to Early Eocene unconformity and hence to be of Middle to Late Eocene age. It is generally much thinner than the overlying megasequence but varies in thickness, probably due to the uplift and erosion of the summits of highstanding features as a result of Middle to Late Eocene compressive events in New Caledonia (Avias 1967; Paris 1981). In the basins, it is relatively

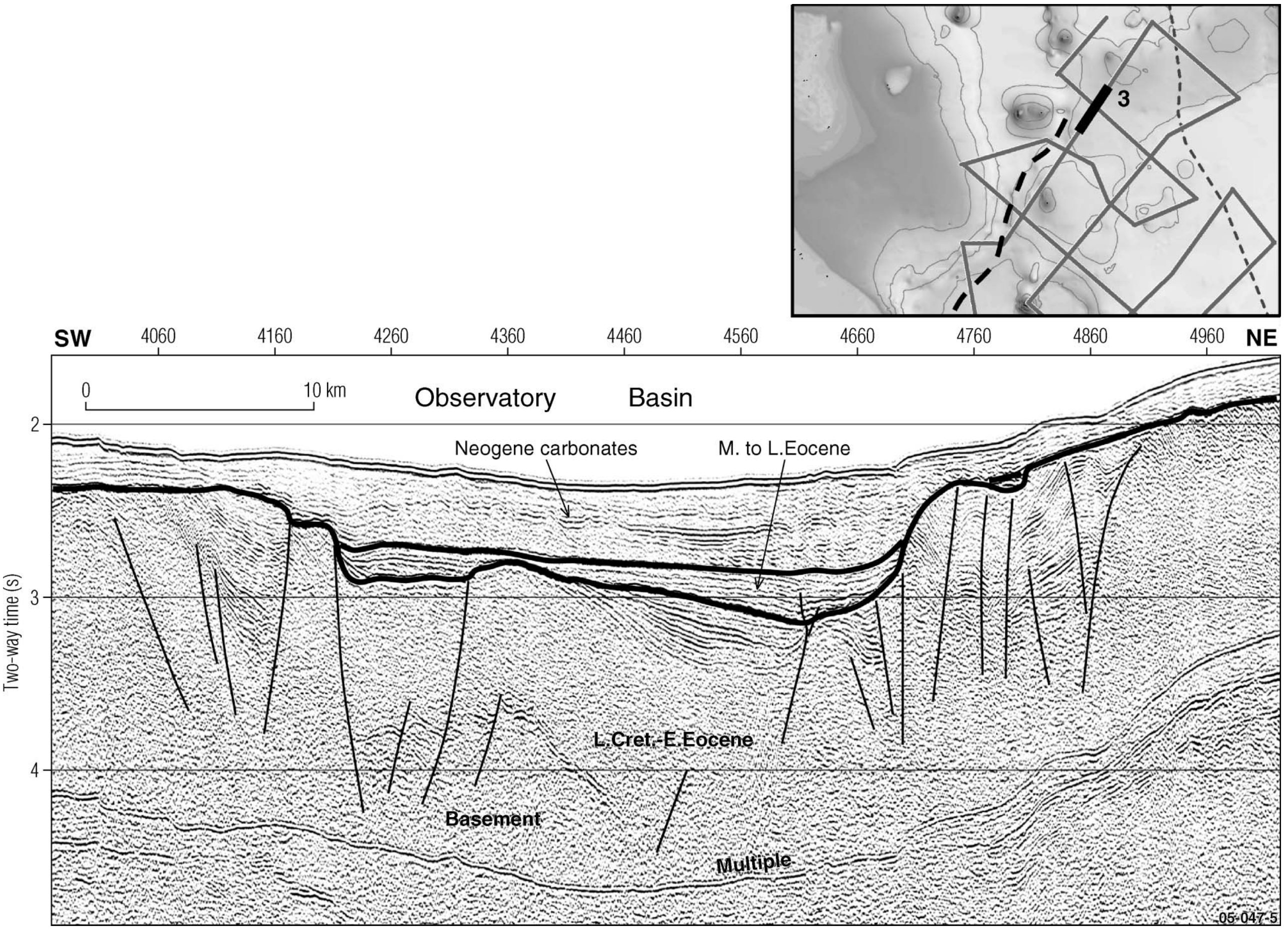


Figure 8 Part of migrated seismic profile 270/3 (location in Figure 2) showing complex structuring in thick pre-Middle Eocene sedimentary sequences south of the western Coriolis Ridge near the Cato Fracture Zone (location in Figure 11). The section has undergone folding, faulting, uplift and erosion caused by a combination of rifting, possible Paleocene strike-slip movement of the fracture zone, and especially Middle Eocene inversion. Post-tectonic infill in the Late Eocene and Oligocene was followed by Neogene draping of pelagic carbonates.

consistent in thickness, averaging 0.3 s (twt), and generally 100–300 m thick. On Kenn Plateau, this sequence is interpreted as being deposited during the Eocene uplift of ridges off eastern Australia, such as the Dampier Ridge. It probably consists mainly of shallow-marine chalk and limestone, but locally it is likely to include siliciclastic sediments eroded from uplifted blocks following mid-Eocene inversion.

(3) The lowest megasequence is of variable seismic character (Figure 8). It overlies acoustic basement and is bounded at its top by a strong reflector, commonly an erosional unconformity. This unconformity is highly angular in places, particularly on uplifted blocks. This syn-rift and early sag megasequence is extensively deformed by folding, faulting or tilting (Figure 8), and is presumably of Late Cretaceous to Early Eocene age. Its visible thickness is commonly 1–2 km, but limited seismic penetration and masking by high-level volcanics (sills and lava flows can be identified within it) could mean that it is actually much thicker in places. It thickens toward the west-southwest-trending Observatory Basin in the central Kenn Plateau, where it can reach a maximum thickness of 1.2 s (twt), about 1500 m. The lower part of this succession probably consists largely of siliciclastic deposits (like the Aquarius 1 sequence shown in Figure 4), but the upper part may contain shallow-marine carbonates.

Profile 3 (Figure 9) extends northeast from the Cato Trough to the southern edge of Selfridge Rise (Figure 2). It shows a few hundred metres of Cenozoic pelagic carbonate cover over acoustic basement (probably Lower Oligocene volcanics) on the western slope of the plateau; the Oligocene volcanic edifice of Cato Seamount; pelagic carbonate cover over basement northeast of Cato Seamount; the graben of the Observatory Basin containing >2000 m of presumed Cretaceous and Cenozoic sediments; the broad planated basement rise of Coriolis Ridge, with small Cretaceous–Palaeogene half-grabens overlain by a veneer of Cenozoic pelagic carbonate; the graben of the Chesterfield Trough, apparently containing >2000 m of presumed Cretaceous and Cenozoic sequences; and the basement slope of the Selfridge Rise.

Profile 15 (Figure 10) extends northwest from the Capel Basin to the Cato Basin (Figure 2). The Cenozoic

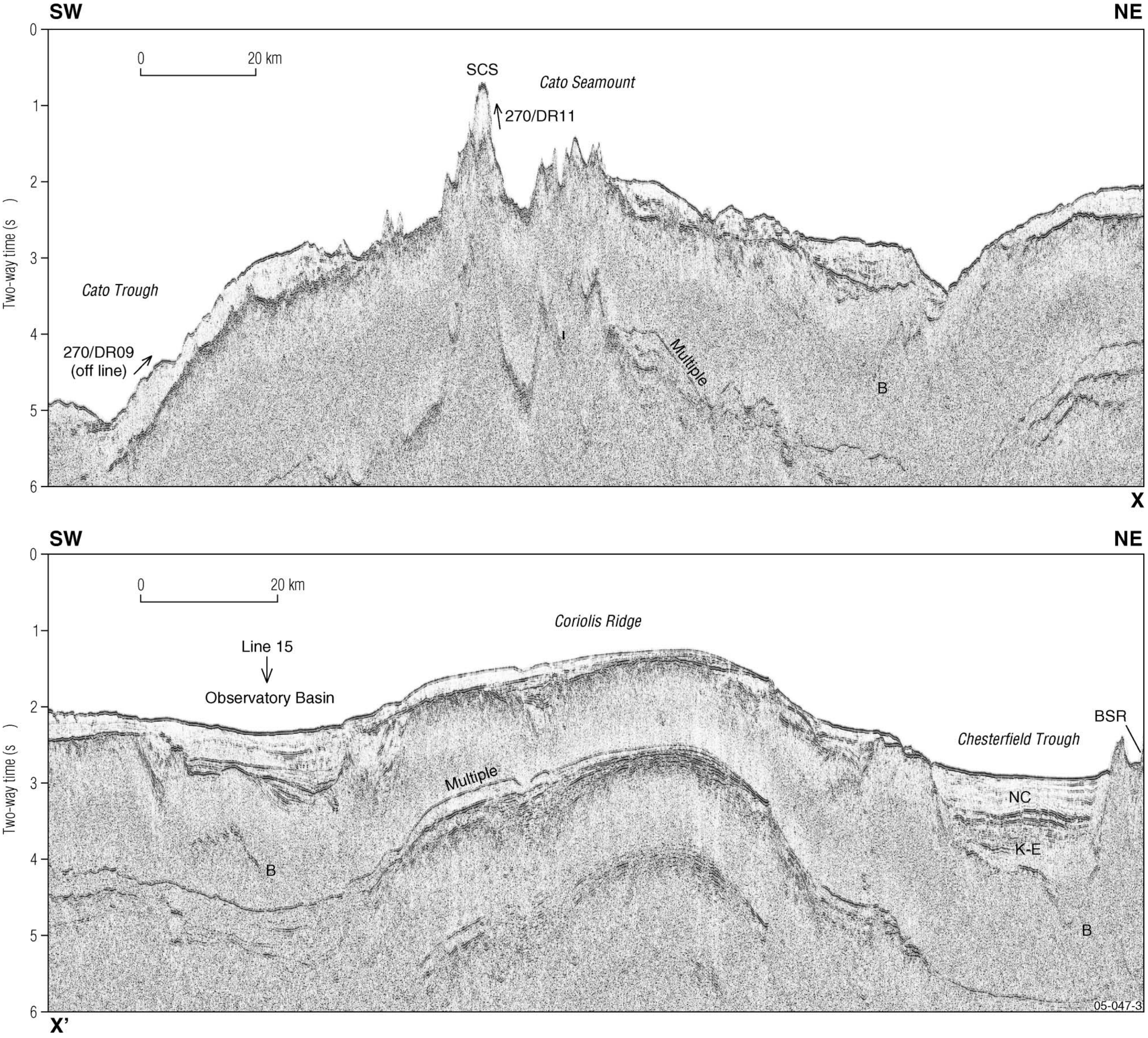


Figure 9 Migrated seismic profile 270/3 extending 351 km northeast from the Cato Trough to the Chesterfield Trough (location in Figure 2). X on the top panel coincides with X′ on the lower panel. B, acoustic basement; SCS, satellite of Cato Seamount; BSR, base of Selfridge Rise; NC, Neogene carbonates; K-E, Cretaceous to Early Eocene syn-rift sequence.

pelagic carbonate is generally thicker than on Profile 3, with the Neogene seismically transparent sequence 300 – 400 m thick. The profile shows 2500 m of Cretaceous and Cenozoic sequences in the Capel Basin; the older sequences pinching out against the Southern Surveyor Rise; a number of half-grabens containing as much as 3000 m of Cretaceous and Cenozoic sequences in the Observatory Basin; a relatively thin slumped Cenozoic pelagic carbonate sequence over basement on the slope above the Cato Basin; and 1500 – 2000 m of Cretaceous and Cenozoic sequences onlapping basement in the Cato Basin.

Geological results

The geological sampling of older (pre-Quaternary) rocks by dredging from *Southern Surveyor* in 2004 and 2005 was planned using seismic profiles and swath-mapping. Dredge locations are shown on Figure 2, and dredge results are summarised in Table 3. Dredging on the shallower and steeper margins of the northern Kenn Plateau was much more successful than dredging on the western and southern margins, or on the low rises of the central plateau. In part, this may be because resistant rift volcanics are widespread in the north and rare elsewhere. Perhaps more volcanism was related to the separation of Selfridge Rise and Coriolis Ridge than occurred during rifting elsewhere. A contributing factor may be that the shallower northern margin is more current swept (sand waves in Figure 6) and hence has less Cenozoic carbonate blanketing the older rocks (Figure 9). But the main reason for the older rocks being more accessible to sampling here is that Selfridge Rise and Coriolis Ridge were uplifted

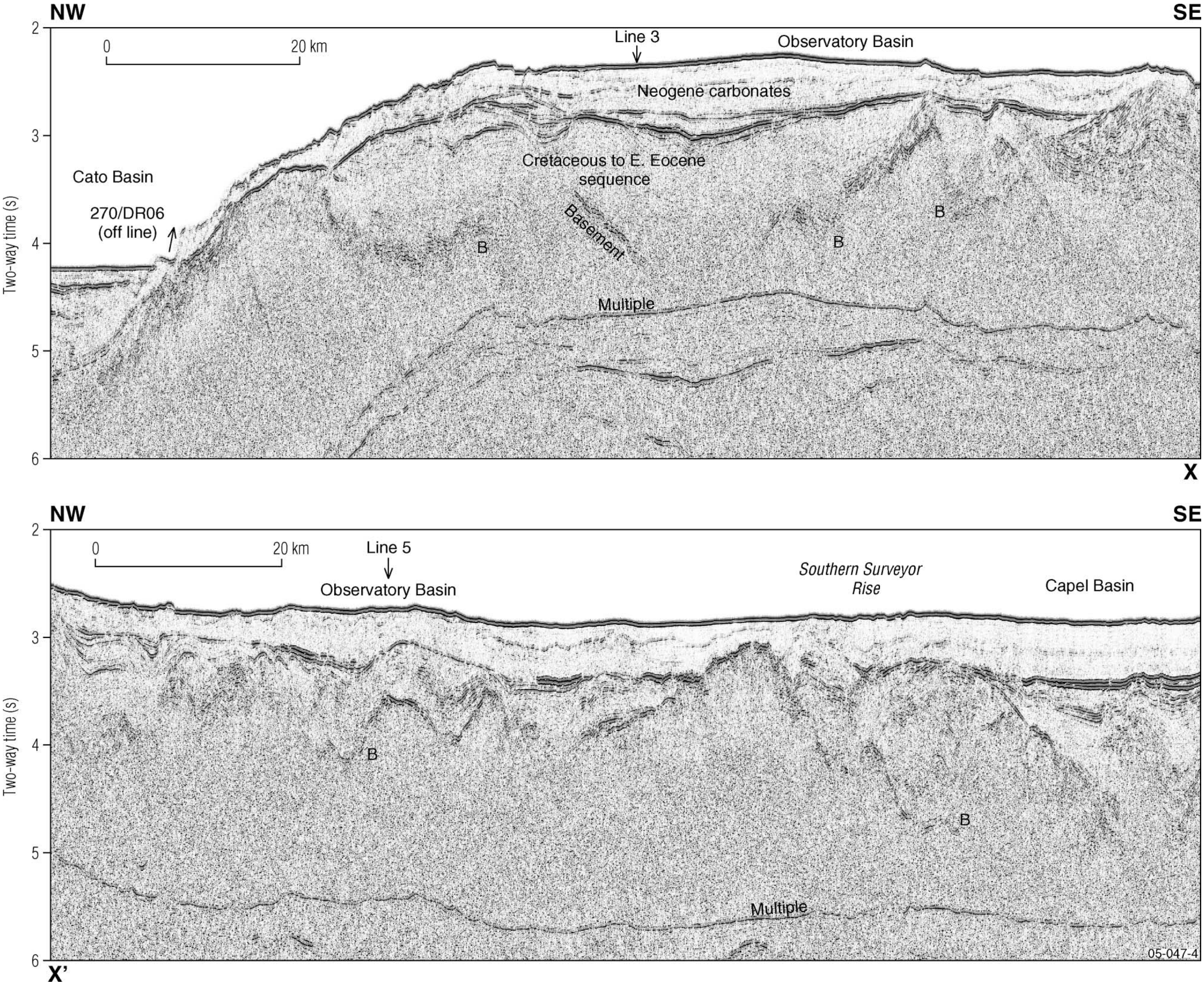


Figure 10 Migrated seismic profile 270/15 extending 244 km northwest from the Capel Basin to the Cato Basin (location in Figure 2). See Figure 9 for abbreviations.

during Eocene compression, with basement and rift-related rocks exposed in fault scarps and on elevated blocks, where wave-base/subaerial erosion removed overburden.

A single cobble of metamorphic quartzite (Dredge 274/DR11) and some very hard quartz-rich sandstone (274/DR35), both collected from the Selfridge Rise, are the only unequivocally continental basement rocks dredged in the region. Rift volcanics and high-level intrusions are the most abundant hard rocks recovered by dredging (274/DR7, DR8, DR11). Quartz-rich meta-dolerite (274/DR34), basaltic agglomerate, and silicic volcanics (lithic tuffs, agglomerate and felsic volcanics: 274/DR7, DR8, DR11) were recovered from the Coriolis Ridge and the Selfridge Rise. They are all associated with steep slopes, escarpments and terraces. Agglomerate, tuff and related greywacke contain numerous lithic fragments including basalt and shale, in a matrix that is commonly very fine-grained to aphanitic. Welded textures occur as banding and stretching of clasts, and they define layering.

Various siliciclastic sedimentary rocks were collected (Dredges 274/DR8, DR11, 270/DR2). Greywacke from Selfridge Rise (274/DR11) contains clasts, including basalt and shale, that are very similar to the clasts in the pyroclastic volcanics, and there appears to be a gradation between proximal tuffs and more distal greywackes. Labile volcaniclastic sandstone came from the Coriolis Ridge (274/DR8). Pisolitic quartzo-feldspathic sandstone from the Coriolis Ridge (274/DR8) shows graded bedding and load casts. The pisolites are non-calcareous. Ferruginised quartz-bearing sandstone came from the Selfridge Rise (274/DR33). A breccia of quartz-rich sandstone fragments in ironstone came from the southern margin of the plateau (270/DR2). Bentonitic claystone, dated by nannofossils as Late Eocene to Early Oligocene, occurs on the Selfridge Rise (274/DR35), and such claystone is common on the Mellish Rise further north (Exon *et al.* 2005a). Aquarius 1 in the Capricorn Basin contains Eocene bentonitic claystone associated with quartzose sandstone (Figure 4).

Table 3 Relevant dredges (south to north).

Dredge	Lat (S) Long (E)	Depth (m) weight	Rock description and age[a]
270/DR01	24°47.8′ 156°08.6′	4000 10 kg	Calcareous claystone. Early Oligocene nannofossils. Early Miocene foraminifers.
270/DR02	24°46.8′ 156°19.8′	2800 10 kg	Breccia of sandstone in ironstone, with thick manganese crust.
270/DR05	24°29.1′ 155°16.6′	1600 5 kg	Basaltic hyaloclastite breccia.
270/DR04	24°24.8′ 155°18.5′	450 4 kg	Reefal biostromal limestone. Middle Pliocene nannofossils.
270/DR03	23°49.4′ 155°20.5′	3280 30 kg	Chalk. Middle and Late Miocene nannofossils.
270/DR08	23°29.6′ 154°50.1′	3050 80 kg	Foram nannofossil chalk, foraminiferal–nannofossil claystone. Early and Middle Eocene nannofossils.
270/DR09	23°28.0′ 155°02.5′	3300–3100 100 kg	Highly and weakly lithified foraminiferal–nannofossil chalk, yellow claystone. Middle Miocene nannofossils.
274/DR02	23°27.7′ 156°46.8′	1700 15 kg	Early Oligocene and late Middle Miocene fine-grained limestone with bivalves; fine grained ?metasediment
270/DR11	23°11.35′ 155°23.0′	1000–800 10 kg	Reefal framework limestone. Early and Middle Miocene, plus Late Pliocene foraminifers.
270/DR10	22°51.3′ 155°20.4′	3100 5 kg	Highly and weakly lithified foraminiferal–nannofossil chalk. Middle Miocene nannofossils.
270/DR07	22°09.5′ 155°47.9′	2700 50 kg	Pelagic foraminiferal chalk, semi-lithified chalk. Middle Miocene nannofossils.
274/DR05	22°08.0′ 156°44.6′	1600 30 kg	Chalk. Late Miocene to Early Pliocene nannofossils.
270/DR06	21°49.6′ 155°48.0′	2800 20 kg	Pelagic foraminiferal limestone, chalk. Middle Eocene, Early Oligocene, Early Miocene nannofossils.
274/DR06	21°30.85′ 156°24.65′	700–400 10 kg	Micritic limestone, calcarenite. Middle Miocene foraminifers in calcarenite.
274/DR08	21°25.85′ 157°06.8′	1500–1400 200 kg	Volcanic agglomerate with calcareous matrix, welded agglomerate, fine felsic volcanics, volcaniclastic sandstone, pisolitic sandstone.
274/DR07	21°25.5′ 156°24.45′	1600–1500 60 kg	Silicic tuff, calcarenite. Late Middle Eocene foraminifers.
274/DR10	21°21.9′ 157°14.8′	1600 100 g	Calcarenite
274/DR09	21°21.5′ 157°14.6′	1800 300 kg	Friable calcarenite–calcirudite (Oligocene–Miocene boundary foraminifers), water-worn volcanic pebbles. Reworked Miocene nannofossils.
274/DR11	21°04.5′ 156°52.6′	1800–1700 50 kg	Metamorphic quartzite, volcanogenic graywacke, welded tuff.
274/DR34	20°50.6′S 157°22.2′E	1700 4 kg	Quartz-rich metadolerite
274/DR33	20°45.7′S 157°32.1′E	1800–1700 0.5 kg	Ferruginised quartz-bearing sandstone. Chalk with Early to Middle Miocene nannofossils.
274/DR35	20°36.7′S 156°43.5′E	2200–1950 150 kg	Hard quartz-rich sandstone, bentonitic claystone, pebbly micritic mudstone, concretionary micritic mudstone, micritic calcarenite. Late Eocene to Early Oligocene nannofossils in bentonitic claystone.

[a] Survey 270 ages after foraminiferal studies by Quilty (2004) and calcareous nannofossil studies by Howe (2004). Survey 274 nannofossil and foraminiferal ages after Claire Findlay and Patrick Quilty (pers. comms 2005).

Shallow-marine limestones, mostly calcarenites, are present in dredges from the northern margin of the Coriolis Ridge: 274/DR7 from a steep slope, and 274/DR9 and DR10 from a terraced region further east. Present water depths are 1600–1800 m, indicating comparable subsidence since sediment deposition, from the Middle Eocene (DR7) to the Late Oligocene (DR9). The calcarenites are variably cemented, and often poorly consolidated. They consist of variable proportions of bryozoans, bivalves and echinoid spines, with lesser serpulid worm tubes, solitary corals and larger benthic foraminifers. Upper Eocene to Lower Oligocene micritic calcarenite occurs on the Selfridge Rise (274/DR35).

Cenozoic reefal limestones were dredged (270/DR4, DR11, DR12, 274/DR6) from four volcanic seamounts of inferred Late Eocene to Early Oligocene age in the Tasmantid (western) chain (CPCEMR 1991). Foraminiferal ages from low in the limestone edifices varied from Early Oligocene to Early Miocene (Quilty 2004; P. G. Quilty pers. comm. 2005). Some reefs had kept up with subsidence, and others had not, the latter forming guyots.

Eocene and younger chalk and related deepwater limestone, dated using foraminifers by Quilty (2004) and using calcareous nannofossils by Howe (2004) and Claire Findlay (pers. comm. 2005), were dredged at a number of locations. The examined foraminifers all lived in the tropical realm.

KENN PLATEAU STRATIGRAPHY

We have pieced together a generalised stratigraphy of the Kenn Plateau from the available rather fragmentary evidence (Table 4). It has been built up by using the results from nearby wells, the dredge and core samples, and the reflection seismic information. Because what became the northern plateau was adjacent to the southern Marion Plateau (Capricorn Basin and Swain Reefs High) well into the Paleocene, the Late Cretaceous and Palaeogene sequences from the Capricorn Basin exploration wells are particularly relevant. In general terms, the reliability of Table 4 improves as the rocks get younger.

MAIN STRUCTURAL FEATURES

Kenn Plateau is an extended and thinned continental block bounded on its southwestern side by a continent–ocean boundary (COB) that roughly coincides with the foot of slope in the adjacent northern Tasman Basin (Figures 2, 11). To the northwest, the nature of basement in the Cato Basin can only be inferred from indirect evidence, including gravity data and plate reconstructions. Existing seismic profiles shot with low-powered sources do not image Cato Basin basement well. Basement may be highly extended continental crust and/or incipient oceanic crust. We interpret the limit of Kenn Plateau continental crust to lie west of Cato Seamount (supporting Cato Island), unlike Gaina *et al.* (1999), who showed a COB located to the east of this feature with the western tip of Kenn Plateau underlain by oceanic crust.

The passive southwest margin of Kenn Plateau was formerly conjugate to southeast Queensland, while the northwest margin between Coriolis Ridge and Cato Seamount is a transform margin, formerly conjugate to the southern Marion Plateau. Transform movement took place along the Cato Fracture Zone to form the southern margin of Marion Plateau and the western margin of Kenn Plateau (Figure 11). The bend in the middle of this structure, at the Cato Trough (southwest of Cato Island), suggests that separation of Kenn Plateau from Australia (*ca* 63–52 Ma) was initially in a northeast direction and finished in a north-northeast direction.

The only unequivocally continental basement rocks recovered from Kenn Plateau are from Selfridge Rise (Figure 2). In addition, an undated quartz-rich ironstone from the southwest margin of Kenn Plateau was almost certainly deposited in a continental setting before breakup. The conjugate southeast Queensland margin is underlain by Palaeozoic–Triassic basement of the New England Fold Belt. Several stacked and contiguous basins, which range in age from Late Triassic to mid-Cretaceous and include the Ipswich, Nambour and Maryborough Basins (Stephenson & Burch 2004), overlie the basement rocks. Equivalent basement and Mesozoic sedimentary bedrock could be expected beneath the Kenn Plateau. Structural trends on the adjacent Australian continent (southeast Queensland, Capricorn Basin and Marion Plateau) are predominantly northwest to north-northwest, probably reflecting the underlying structural fabric of the New England Fold Belt. When the plateau is reconstructed against the Australian continent, faults along the southwest margin of Kenn Plateau and in the western Observatory Basin would parallel this trend.

Table 4 Kenn Plateau stratigraphy.

Age	Igneous rocks	Sedimentary strata
Late Oligocene to Quaternary	Lord Howe seamount chain: basalt and hyaloclastites. In this region, the ages are 25 Ma to 15 Ma.	Pelagic chalk and calcareous ooze, above major unconformity: 300–700 m thick. Calcarenite in shallow water. Reefal framework limestone on seamounts. Upper Oligocene proximal siliciclastics probably present.
Late Early to Late Eocene	Tasmantid seamount chain: basalt and hyaloclastites. In this region, the ages are 35 to 30 Ma.	Pelagic radiolarian chalk and limestone above major unconformity: 100–300 m thick. Calcarenite in shallow water. Reefal framework limestone on seamounts. Proximal non-marine to shallow marine sandstone, siltstone, lignite and bentonitic claystone.
Late Cretaceous to early Early Eocene	–	Proximal syn-rift and early sag phase non-marine polymictic conglomerate, arkosic sandstone, siltstone and mudstone above basement unconformity, overlain by redbed mudstone: 1–2 km thick. Pelagic radiolarian chalk and radiolarite in distal areas.
Early Cretaceous	Rift-related volcanics and intrusives (like Grahams Creek Volcanics) form ‘basement’ in parts of Kenn Plateau. Tuffs and agglomerates, silicic flows, basalts and dolerite were dredged in north.	Non-marine, deltaic and shallow-marine early rift siliciclastic sequences. Probably similar to the Aptian shallow-marine sandstone and carbonaceous beds of the Maryborough Formation, and the Albian deltaic Burrum Coal Measures.
Older rocks	Palaeozoic to Triassic basement	Late Triassic to Late Jurassic stacked non-marine sedimentary basins

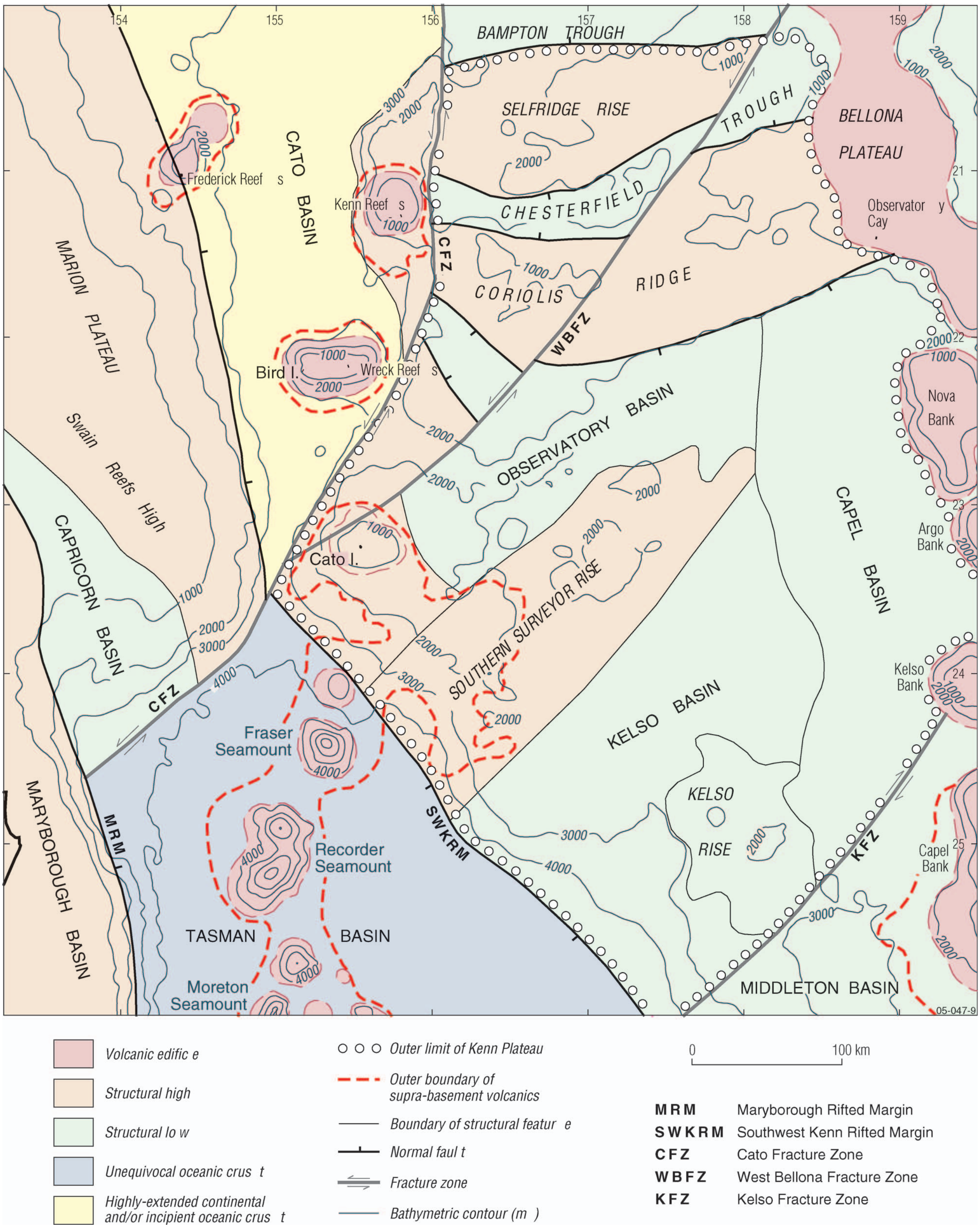


Figure 11 Tectonic sketch map of Kenn Plateau area, showing structural features. From 63 to 52 Ma, the basic structural framework of the area developed as Kenn Plateau moved northeastward. The SWKRM and the MRM separated by seafloor spreading, with the Tasman Basin filling with oceanic basalt. The motion was taken up along the CFZ, between Marion and Kenn Plateaus, and also along the WBFZ and the KFZ. The Cato Basin is floored with highly extended continental crust and/or incipient oceanic crust. The highs and lows on Kenn Plateau were in part pre-existing, but were heavily modified during spreading. The western volcanic edifices are part of the Tasmantid hotspot chain and vary in age from about 35 Ma in the north (Kenn) to 30 Ma in the south (Cato). The eastern volcanic edifices are part of the Lord Howe hotspot chain and vary in age from about 25 Ma in the north (Bellona) to about 19 Ma in the south (Kelso).

Northern Kenn Plateau consists largely of the fault-bounded basement highs of Coriolis Ridge and Selfridge Rise, divided by the 20–40 km-wide Chesterfield Trough (Figures 2, 11) which broadly trends east-northeast, but is controlled by northwest-trending faults at its western end and northeast-trending faults at its eastern end. The shallow basement block that forms the core of Coriolis Ridge contains a number of small grabens. Its upper surface is 1100–1500 m deep, has been planated by erosion, and dips gently to the south and southeast (away from the Chesterfield Trough). The upper levels of the ridge consist of rift volcanics of assumed Early Cretaceous age and Palaeogene calcarenites. Northeast-striking faults separating the two main blocks of Coriolis Ridge may be transform or transfer faults associated with extension in this direction during the Late Cretaceous to Palaeogene.

Apart from margin-parallel normal faults along the southwest margin of Kenn Plateau, southern Kenn Plateau exhibits no strong structural fabric, although the Observatory Basin and Southern Surveyor Rise trend northeast overall. The plateau's western corner is dominated by a widespread Early Oligocene hotspot volcanic terrain (now mostly covered by Neogene carbonates), including Cato Seamount, numerous surrounding cones, and extensive lava fields. The central and southern parts of southern Kenn Plateau are characterised by numerous diapiric structures and folding in the sedimentary section and a seismic basement that appears to be largely volcanic.

When Kenn Plateau is reconstructed against southeast Queensland, the western Observatory Basin links with the Capricorn Basin. The combination of the Capricorn and Observatory Basins would have formed a basin similar in shape and orientation to the northwest-trending Queensland Trough, but of somewhat smaller scale. In such a reconstruction, the western end of Coriolis Ridge abuts the Swain Reefs High on southeast Marion Plateau, and the western end of Chesterfield Trough is roughly aligned with the early rift on the eastern margin of Marion Plateau, joining at a local complex graben. However, the nature of the small crustal block on which Kenn Seamount is constructed, and which extends just north of the seamount, is poorly known. Much of it is hidden by overlying Upper Eocene hotspot volcanics and it may be allochthonous, with its eastern boundary a possible transform fault. Its northeast-trending northern margin may be a fracture zone. Future discoveries of the nature of the Cato Basin—whether it is extended continental or incipient oceanic crust, or indeed partly oceanic crust—will clearly affect details of any reconstruction.

Edifices of the north–south-oriented Tasmantid and Lord Howe hotspot seamount chains are major morphological features on and adjacent to Kenn Plateau. These chains are progressively younger to the south, with the larger seamounts typically spaced 70–80 km apart and up to 4 km high. Most of the larger seamounts are capped by carbonate platforms that grew upwards as their volcanic pedestals subsided. The inferred age progression in the Tasmantid chain adjacent to Kenn Plateau is roughly: Kenn Seamount 34 Ma, Cato Seamount 30 Ma and Fraser Seamount 28 Ma (CPCEMR 1991). Similarly, for the Lord Howe chain, the inferred age progression of nearby seamounts/banks is: northern Bellona Plateau 25 Ma, Argo Bank 20 Ma and Capel Bank 17 Ma. Aprons of volcaniclastic sediments and flows, now buried by post-eruption deposits, commonly extend 15 km or more from the bases of the hotspot volcanoes. Our swath-mapping, seismic and sampling results suggest that the carbonate platforms are commonly 500 m or more thick.

Basin development

The distribution of basins and depocentres in the region is indicated in Figure 11 (see Exon *et al.* 2005b figure 50 for details). The mapped sediment thickness largely represents Late Cretaceous and younger deposits. The thicker depocentres contain >3 s twt (~ 4 km) of sedimentary section. These include: (i) a north-trending graben in the southern, deep-water Capricorn Basin that represents a failed rift arm at the northern end of the Tasman rift system; (ii) post-breakup deposits on oceanic crust of the northern Tasman Basin adjacent to the Cato Fracture Zone south of the Marion Plateau; and (iii) a broad depocentre in the northern Capel Basin just south of the eastern Coriolis Ridge. Depocentres with at least 2 s twt (~ 2.5 km) of section include: (i) post-breakup deposits at the foot of the continental slope along the entire southeast Queensland and southern Marion Plateau margins; (ii) post-breakup deposits beneath the abyssal plain (on oceanic crust) off the southwest Kenn Plateau margin; (iii) most of the Capel Basin, west of the Lord Howe seamount chain; (iv) the Observatory Basin; (v) Cato Basin, south and north of Wreck Seamount; (vi) a north-northwest-trending graben on the Marion Plateau margin west of Frederick Seamount; (vii) eastern Chesterfield Trough; and (viii) a small marginal basin at the far northeast corner of Kenn Plateau. Areas with <200 m of sedimentary section visible in seismic profiles include: (i) the elevated parts of Selfridge Rise and Coriolis Ridge on northern Kenn Plateau; (ii) volcanic terrain at the western end of southern Kenn Plateau, around Cato Seamount and to the southeast; and (iii) presumed volcanic massifs on the Southern Surveyor Rise and Kelso Rise. The flanks of the hotspot seamounts appear to have little sediment cover.

GEOLOGICAL HISTORY

In the Mesozoic, the future Kenn Plateau region was an integral part of eastern Australia, south of the present Marion Plateau and north of the present Brisbane. It was presumably underlain by Palaeozoic to Triassic basement of the New England Fold Belt. Probably, overlying basement were stacked Late Triassic to Late Cretaceous basins, corresponding to the Ipswich, Nambour, Maryborough and Capricorn Basins. The structural grain was predominantly north-northwest. The hard siliceous sandstone (metamorphic quartzite) and the quartz metadolerite dredged from northern Kenn Plateau were probably part of these older sequences.

In the Maryborough Basin, older sequences were overlain by the largely Neocomian explosive rift-related volcanics of the Lower Cretaceous Grahams Creek Formation (and there was similar volcanism in the Whitsunday Volcanic Province in the Neocomian to Albian), the Aptian shallow-marine siliciclastic Maryborough Formation, and the deltaic Albian Burrum Coal Measures (Hill 1994). Doleritic sills and volcanics (dated as 86 Ma, Santonian, although weathering has given a minimum age) in the Capricorn Basin, and similar rocks further northwest on the Marion Plateau (ODP Leg 194), and the silicic explosive volcanics, dolerite and basalt dredged from northern Kenn Plateau are all probably of similar Early Cretaceous age. In the Late Cretaceous, the transpressional Winton Movement (85–80 Ma: Lipski 2001) caused widespread uplift, folding and erosion. Several kilometres of Maryborough Basin sediments were removed by erosion (Hill 1994), and some of the detritus would have finished up in depocentres on what is now Kenn Plateau.

The tectonic development of Kenn Plateau can be reconstructed with the aid of a map of the main tectonic elements of the region (Figure 11). Rifting started south of this region at *ca* 95 Ma and slowly propagated northward, forming the Middleton Basin and the Capel Basin of today's eastern Kenn Plateau (Gaina *et al.* 1998). It is likely that there was a western basin system (Middleton/Capel Basin) and an eastern basin system (Fairway Basin), separated by the proto-Lord Howe platform. Those two systems converged north of the Lord Howe platform into the present-day Capel Basin between the Bellona Plateau/Fairway Ridge and Kenn Plateau, and were terminated by a strike-slip fault south of the Coriolis Ridge/Bellona Plateau.

We postulate that, in the Late Cretaceous, the basement high of the southwestern margin of today's Kenn Plateau was conjugate to the present-day Maryborough Basin on the Australian margin, and that both the Coriolis Ridge and the basement of the future Bellona Plateau were located southeast of the Marion Plateau (Figure 12, 83.0 Ma). The western part of Coriolis Ridge, still today oriented northwest, was a southern continuation of the Swain Reefs High on the outer Marion Plateau (Figure 11). Sediment was being shed into the lows from the uplifted and eroding Maryborough Basin. The eastern parts of some of these features (and the Chesterfield Trough, Selfridge Rise and Bampton Trough further north) are now offset and oriented northeast, suggesting that younger northeast strike-slip faults rotated them counter-clockwise (Figure 11).

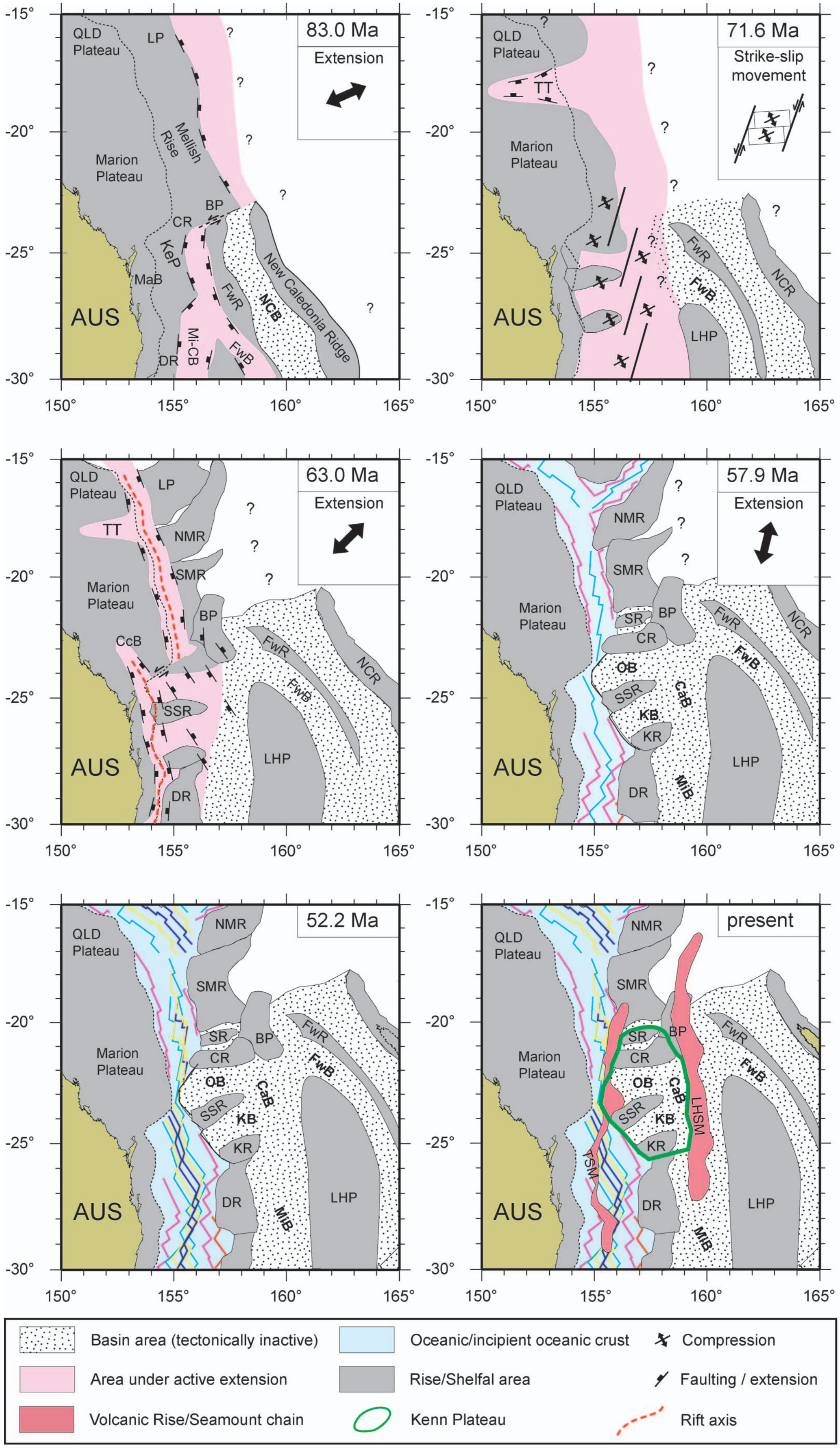
From 83 Ma onwards, the locus of extension migrated further west, probably triggered by the northward-propagating spreading ridge in the southern and central Tasman Sea (Gaina *et al.* 1998). Extension had probably ceased in the easternmost basins of the region (Fairway and New Caledonia Basins), whereas the western Middleton/Capel Basin system took up most of the stretching (Figure 12, 71.6 Ma). This could probably explain the great sediment thickness observed in the northern Capel Basin and eastern Observatory Basin. General motion of the greater Lord Howe Rise block, comprising the Fairway Ridge and Basin, and the Lord Howe platform, was towards the east-northeast.

A change in plate motion of the greater Lord Howe Rise block towards the north-northeast resulted in strike-slip motion in the Kenn Plateau part of the margin, possibly causing the formation of the anticlines and compressional structures which are visible on the seismic lines (Figures 7, 8). Related wrench faults in the already stretched crust of the northern Lord Howe Rise/Kenn Plateau area probably triggered the disintegration of that area into smaller blocks (Figure 12, 71.6 Ma), giving rise to the observed present-day basin and ridge structure (e.g. Coriolis Ridge, Observatory Basin, Southern Surveyor Rise: cf. Figures 9 and 10). The Townsville Trough might have been affected by the change in extension direction and might have undergone further subsidence during this period.

Later in the Cretaceous and through the Paleocene, the northward propagation of the Tasman Sea spreading ridge, and a further change in extension direction back to a northeasterly direction, triggered the formation of a major rift system extending northward into the Capricorn Basin, up the eastern margin of the Marion Plateau, and into the Townsville and Queensland Troughs (Struckmeyer & Symonds 1997). Block faulting in the Kenn Plateau area, partly reactivating older trends and structures, probably formed the observed present-day basement structures (Figure 12, 63.0 Ma). In the Late Cretaceous, the relevant structural features from west to east (after Hill 1994 and Stephenson & Burch 2004) were the Late Triassic to Early Cretaceous Maryborough Basin, the Bunker Ridge, the Cretaceous Capricorn Basin, and the Swain Reefs High (Figure 3), and their eastern and southern extensions that are now beneath Kenn Plateau.

The Observatory Basin and its eastern counterpart, the Capel Basin (including that part now east of the younger Lord Howe seamount chain) probably formed during the first extension interval (83–71.6 Ma) and the following transtensional movements (71.6–63 Ma).

The Kenn Plateau region started to separate from Queensland at *ca* 63 Ma (Cretaceous–Cenozoic boundary), and moved northeast, later north-northeast, and eventually almost north, along the concave-west Cato Fracture Zone (CFZ in Figure 11; Figure 12, 63.0 to 52.2 Ma), a strike-slip zone that terminates the Capricorn Basin southward, and now forms the southeast margin of Marion Plateau and the northwest margin of Kenn Plateau. This motion continued until *ca* 52 Ma and amounts to more than 200 km of translation at the western end of the southwest Kenn Plateau margin, and 400 km at the eastern end, indicating an overall anticlockwise rotation of 30°. During this period of motion, Kenn Plateau was cut by a strike-slip fault, the West Bellona Fracture Zone (WBFZ in Figure 11), splaying off the Cato Fracture Zone, which was named by Exon *et al.* (2005b) but identified earlier by various authors and illustrated by CPCEMR (1991). The West Bellona Fracture Zone extends northeastward to form the northwest margin of Bellona Plateau, and modified the Cretaceous structures in the Palaeogene. The West Bellona Fracture Zone separates structures to the west, now trending northwest or west, from structures to the east, now trending northeast. The northeast trend (Figure 11) corresponds to that of the oceanic fracture zones in the


83.0 Ma
Extension
71.6 Ma
Strike-slip movement
63.0 Ma
Extension
57.9 Ma
Extension
52.2 Ma
present
QLD Plateau
Marion Plateau
AUS
LP
Mellish Rise
BP
CR
KeP
MaB
DR
Mi-CB
FwR
FwB
NCB
New Caledonia Ridge
TT
NCR
LHP
NMR
SMR
CcB
SSR
SR
OB
CaB
KB
KR
MiB
LHSM
TSM
?
-15°
-20°
-25°
-30°
150°
155°
160°
165°
Basin area (tectonically inactive)
Area under active extension
Volcanic Rise/Seamount chain
Oceanic/incipient oceanic crust
Rise/Shelfal area
Kenn Plateau
Compression
Faulting / extension
Rift axis

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northern Tasman Basin (see Figure 3), so the margins of the Southern Surveyor Rise and the Kelso Fracture Zone (KFZ in Figure 11) are presumably related to the oceanic fractures. We take the Kelso Fracture Zone as marking the southeast margin of Kenn Plateau, and the boundary between the Capel and Middleton Basins.

During the rifting and drifting phase in the Late Cretaceous to Early Paleocene, although continental stretching and thinning were taking place, and the region was subsiding, much of Kenn Plateau was still above sea-level and being eroded. Up to 2500 m of non-marine and shallow-marine siliciclastic sediments, derived largely from the Maryborough Basin in the Cretaceous and local subaerial ridges of the Kenn Plateau in the Palaeogene, were deposited in the various troughs and basins. The Capricorn Basin (Figure 4) filled with conglomerate, sandstone and redbed mudstone (Ericson 1976; Chaproniere *et al.* 1990). Such sediments are probably present at depth in Kenn Plateau, and redbed mudstone is very common to the north on Mellish Rise (Exon *et al.* 2005a). By the latest Cretaceous and through into the Paleocene, radiolarian chalks were being deposited in deep-water areas in the region (Tables 2, 4). On Kenn Plateau, siliciclastic deposition was probably slowing before the regional Late Paleocene to Early Eocene unconformity. This unconformity coincided with the end of drifting at *ca* 52 Ma and was probably caused by the establishment of strong bottom currents as much of the area deepened, most of the ridges became submarine, and the region became susceptible to regional current patterns. These currents could have caused both physical erosion and dissolution of carbonate.

By the time drifting ceased in the Early Eocene, Kenn Plateau and its surroundings had taken up a modern tectonic configuration, with oceanic crust to the south in the Tasman Basin, and possibly to the west in the Cato Basin. Most of the thinned continental crust had subsided below sea-level. Gaina *et al.* (1999) regarded the crust underlying the Cato Basin as oceanic, where late north–south-oriented transtensional movements resulted in the overlapping isochrons shown in our model (Figure 12, 52.2 Ma and present). As the nature of basement in the southern Cato Basin (oceanic or highly extended and sheared continental crust) is not yet properly resolved, our isochrons are not necessarily seafloor-spreading anomalies but may be simple lines of equal age illustrating the block motions between Australia and the Lord Howe Rise blocks.

In the Eocene and Oligocene, siliciclastic sediments, peat, shelly limestone and bentonitic claystone were laid down in the Capricorn Basin (Figure 4). Calcarenites were deposited on the subsiding flanks of high blocks on the northern Kenn Plateau and are particularly widespread on the Coriolis Ridge (Table 3). The bentonitic claystone dredged on northern Kenn Plateau is dated as Late Eocene to Early Oligocene by nannofossils, and the abundant bentonitic claystone on Mellish Rise (Exon *et al.* 2005a) may well be of this age. The source of the bentonite was probably the hotspot volcanism of the Tasmantid seamount chain, which would have been modified by its passage through thinned continental crust in the Kenn Plateau region. Late in the Early Eocene, pelagic sedimentation returned to the basinal areas, and a few hundred metres of uppermost Lower to Upper Eocene, radiolarian-bearing and sometimes cherty chalk was laid down (Table 2). This was a period of compression in the New Caledonian and Fairway Ridge areas to the east, and there is evidence of its effects in the Kenn Plateau region in the seismic profiles. There may have been associated uplift, as suggested by Middle Eocene upper bathyal limestone dredged on the western margin of Kenn Plateau, more than 1500 m lower than the crest of Coriolis Ridge, which was presumably above sea-level. Anticlines formed in the Observatory Basin and other basinal parts of Kenn Plateau at that time. Mid-Eocene uplift and erosion, reactivation of basement structures and minor folding is recorded in the nearby Capricorn Basin (Hill 1992, 1994).

The regional Late Eocene to Early Oligocene unconformity was caused largely by the onset of the circum-polar current system at 33 Ma, and the associated cooling of Antarctica and strengthening of thermohaline circulation provided cold, strong, acid bottom currents from the Antarctic margin that dissolved pelagic carbonates (Kennett 1977). Locally, there were tectonic complications. The unconformity is fully developed at nearby DSDP sites. However, in our deep-water samples, the Middle and Upper Eocene are missing, although Lower Oligocene chalks are present.

In the latest Eocene and Early Oligocene, as the Australian Plate moved northward at ~70 km/million years, the Tasmantid hotspot was crossed by the western margin of Kenn Plateau. The hotspot formed the volcanic edifices of Kenn, Wreck, Cato and Fraser Seamounts, in that order. The seamounts were initially subaerial volcanoes, but erosion and subsidence turned them into flat-topped guyots later in the Oligocene, and

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Figure 12 Plate-tectonic reconstructions of the Kenn Plateau area from 83.0 Ma to present for key times, with Australia held fixed in present-day coordinates: 83.0 Ma, extension; 71.6 Ma, strike-slip movement; 63.0 Ma, extension; 57.9 Ma, extension; 52.2 Ma, quiescence; present-day configuration. Rotation poles are based on Gaina *et al.* (1998), but we have modified some of the structural elements. Isochrons are based on Gaina *et al.* (1999): red, C28 (62.5 Ma); magenta, C27 (61.2 Ma); aqua, C26 (57.9 Ma); yellow, C25 (55.8 Ma); blue, C24 (53.3 Ma). The Cato Basin is assumed to be oceanic in this diagram but may not be. BP, Bellona Plateau; CaB, Capel Basin; CcB, Capricorn Basin; CR, Coriolis Ridge; DR, Dampier Ridge; FwB, Fairway Basin; FwR, Fairway Ridge; KB, Kelso Basin; KeP, Kenn Plateau; KR, Kelso Rise; LHP, Lord Howe platform; LHSM, Lord Howe seamount chain; LP, Louisiade Plateau; MaB, Maryborough Basin; MiB, Middleton Basin; MiCB, Middleton/Capel Basin area; NCB, New Caledonia Basin; NCR, New Caledonia Ridge; NMR, northern Mellish Rise; OB, Observatory Basin; SMR, southern Mellish Rise; SR, Selfridge Rise; SSR, Southern Surveyor Rise; TT, Townsville Trough; TSM, Tasmantid seamount chain.

long-lived limestone reefs formed on their summits. Volcanic sills and dykes, presumably of this age, are visible in the seismic profiles.

Some reefs have not kept up with subsidence, and guyot tops are now hundreds of metres deep. As much of the region subsided below sea-level, shallow-marine calcarenite and related carbonates were laid down, at least on northern Kenn Plateau.

From the Late Oligocene onwards, pelagic carbonates, generally lacking radiolarians, were deposited slowly in deep water. Calcareous tests appear to have been swept from the shallow areas into the troughs, so that the thickness of the pelagic carbonates is ~200 m on Coriolis Ridge, but up to 700 m in the troughs. From the latest Oligocene, another hotspot formed the Lord Howe chain and associated sills and dykes in the east, perhaps along the basin axis formed by earlier extension between the Lord Howe Rise and the Kenn Plateau/Dampier Ridge. This axis was probably reactivated by the Early Oligocene spreading centre that formed the South Rennell Trough, which joined the axis from the north. The Lord Howe chain also subsided to allow carbonate banks to form.

CONCLUSIONS

Two recent research cruises of RV *Southern Surveyor* and the related scientific studies have elucidated much of the geological framework of this previously very poorly known submarine plateau off northeast Australia. The expeditions have provided real geological information to help constrain tectonic models of this complex part of the southwest Pacific. New data include 3090 km of reflection seismic data, the detailed bathymetry of the seabed from multibeam-sonar swathes along the ship's tracks, 22 successful dredge hauls and several sediment cores. Kenn Plateau is bounded by the northern Tasman Basin to the south, the Cato Basin to the west, Bampton Trough to the north, seamounts and related carbonate banks of the Lord Howe seamount chain to the east, and Middleton Basin to the southeast. Kenn Plateau has an area of 140 000 km^2 and largely lies in water depths of 1500–3000 m. Most of it is within Australia's marine jurisdiction, but the eastern part is in French jurisdiction. Satellite gravity data, plus our newly acquired seismic reflection profiles, indicate that the plateau consists of a number of blocks (Figure 2).

Geophysical evidence from the recent research cruises and other sources strongly suggests that Kenn Plateau is continental. Such evidence includes the continental conjugate margin to the west, high-standing blocks suggesting thinned continental crust, and seismic profiles showing rift structures that could well be continental. For the northern plateau, we can now add the direct geological evidence of dredged continental rocks, such as metamorphic quartzite, quartz-rich sandstone and silicic volcanics. A varied volcanic sequence of tuff, agglomerate, basalt and more acidic flows, and dolerite is present on the northern plateau. This volcanic sequence is considered to be equivalent to the Grahams Creek Volcanics of the Maryborough Basin to the west, and hence of Early Cretaceous age. For the southern plateau, the direct geological evidence of a continental origin is not as strong, but an ironstone breccia containing fragments of quartz-rich sandstone was certainly derived from a continental terrain.

Kenn Plateau consists essentially of a series of northeast-trending highs and lows. Seismic profiles indicate that the highs consist of shallow basement, and our sampling suggests that the basement consists of continental rocks. The basement highs correspond to bathymetric highs, with crestal water depths usually between 1000 and 2000 m. The intervening lows are sediment-filled grabens containing >2500 m of shallow-dipping section in places. Seismic profiles indicate that there are three megasequences. Correlations with exploration wells in the Capricorn Basin to the west, and to DSDP and ODP sites in the general region, plus our dredging on the Kenn Plateau margins, help date the megasequences and provide lithological information. The oldest megasequence overlies basement, is >2000 m thick in places, and has the appearance of syn-rift deposits. Various lines of evidence suggest that it is probably of Late Cretaceous to Early Eocene age, and mostly non-marine siliciclastic rocks, perhaps grading upward into shallow-marine carbonates. The unconformably overlying megasequence is generally 100–300 m thick. It is considered to be of Middle to Late Eocene age, and DSDP cores and our dredge hauls indicate that it consists of shallow-marine limestone and radiolarian chalk, with some chert, and siliciclastic sediments derived from basement highs. The youngest megasequence unconformably overlies the middle megasequence and is commonly 300–700 m thick. It is of Late Oligocene to Quaternary age, and DSDP cores and our dredge hauls and cores show that it consists largely of pelagic chalk and calcareous ooze, with some shallow-marine limestone on highs.

By combining our sampling and seismic data with information from exploration wells and ocean-drilling sites, we have built up a stratigraphic column for Kenn Plateau (Table 4) where none existed before. Although this column is based on limited, patchy and sometimes circumstantial information, we consider that it reasonably represents the major depositional events on the plateau. Clearly, there are major variations in tectonic setting across this large and complex plateau, which will be reflected in the nature and thickness of the various sequences present.

What is now Kenn Plateau was originally part of the Maryborough and Capricorn Basins, with rifting and extension starting early in the Late Cretaceous (*ca* 83 Ma). The plateau started to separate from Queensland near the Cretaceous–Cenozoic boundary (*ca* 63 Ma), and seafloor-spreading and strike-slip motion moved it several hundred kilometres away to the northeast until the Early Eocene (*ca* 52 Ma), rotating it 30° anticlockwise. Thereafter, the plateau was essentially passive, with its various highs and lows sinking 2000 m or more and accumulating shallow-water and pelagic carbonates. As the plateau moved northward on the Australian Plate, two hotspot plumes formed volcanic chains along its western and eastern margins. The western hotspot formed the Tasmantid chain commencing in the latest Eocene, and the eastern hotspot formed the Lord Howe chain commencing in the latest Oligocene. These chains have subsided and now consist of guyots and limestone banks.

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