1. INTRODUCTION[1]

Shipboard Scientific Party[2]

During Leg 133 of the Ocean Drilling Program, we drilled 16 sites (Sites 811 through 826) in the carbonate platforms and troughs of northeastern Australia (Fig. 1), breaking all records for meters drilled and core recovered. The object of this intense 62-day-long activity, which began in Guam and finished in Townsville, was a record of passive margin evolution. This record will define a landmark in our understanding of the evolution of such margins and, in particular, how the Great Barrier Reef has evolved and how it relates to its predecessor reefs on the Marion and Queensland plateaus. As is crucial, Leg 133 has shown that good science can and must be conducted safely in environmentally sensitive areas, as long as all precautions are taken and the science is worth the risks. Northeastern Australia is such an area, for the sediments that form its carbonate platforms contain an unparalleled record of vertical and horizontal tectonics, changes in sea level and paleoclimate, and paleoceanographic variations. This is because of the predominantly biologic, shallow-water origin of the platforms and the ability of the organisms to retain within their skeletons a record of the environment in which they lived. Such biologically built platforms are libraries of information regarding their own evolution.

Current knowledge of the evolution of carbonate platforms is based almost exclusively on studies in the Caribbean region, particularly the region of the Blake Plateau and Bahama Platform (Hollister, Ewing, et al., 1972; Schlager and Ginsburg, 1981; Austin, Schlager, et al., 1986; Eberli and Ginsburg, 1989). In addition, seismic studies of the eastern margin of the United States revealed Jurassic and Cretaceous carbonate platforms that extended from the latitude of New England to Florida (Sheridan et al., 1981; Jansa, 1981) and into the Gulf of Mexico (Kauffman, 1984). Studies of these carbonate platforms provided one model for the evolution of passive-margin platforms. The northeastern Australian margin provides a different perspective for the evolution of carbonate platforms–one that may be both more varied and, in some aspects, more complete (Davies et al., 1989). The region offshore of northeastern Australia is an extremely complex product of rifting, seafloor spreading, and margin accretion. Its geological development has juxtaposed rift sequences, thick fluviodeltaic accumulations, and coral reefs, making it of immense scientific interest. The Great Barrier Reef and the Queensland and Marion plateaus are large, shallow-water platforms that border deep rift basins. Their Cenozoic origin illustrates a 60-m.y. history of platform and basin development that includes initiation and demise, demonstrating clearly the facies diachroneity that results from the complex interdependence of the factors controlling the evolution of platforms and basins. These platforms and basins of northeastern Australia were the focus of Leg 133 of the Ocean Drilling Program. All participants of this program wish to thank the Australian Government and, particularly, the Great Barrier Reef Marine Park Authority for the opportunity to sample a unique World Heritage environment.

NORTHEASTERN AUSTRALIA–REGIONAL BACKGROUND

Onshore Geology

The coastal regions of Queensland are underlain by rocks of the Paleozoic Tasman Fold Belt, which extends from Tasmania in the south to Papua New Guinea in the north. The western border of the fold belt consists of Precambrian metamorphic rocks that, at least in the north, are separated from the Paleozoic sediments to the east by a major fault–the Palmerville Fault. Deep basinal sedimentation commenced in the Early Devonian in the Hodgkinson Basin and continued through to the Carboniferous, interrupted by a number of orogenies. Relative to the width of the New England and Lachlan fold belts to the south, an extensive area of the Tasman Fold Belt in northern Queensland appears to be absent. This, together with crustal refraction data, has led to the interpretation that the missing middle-upper Paleozoic rocks lie beneath the Queensland Plateau (Ewing et al., 1970). The Mesozoic–Holocene geological history of Queensland is one of terrestrial-to-marginal marine sedimentation in basins and troughs that border the Queensland coast. Principal among these are the Maryborough, Styx, Capricorn, Hillsborough, and Laura basins. A major hiatus is present in all onshore basins, separating Lower Cretaceous sediments from upper Tertiary–Holocene terrestrial deposits that infill depressions in the old land surface. The only known possible Upper Cretaceous(?) deposits are found in the offshore Capricorn Basin (Ericson, 1976). A thick section of nonmarine sediments was deposited during the early Tertiary in the Hillsborough Basin, and similar age sediments containing oil shales are found near Gladstone. In the Capricorn Basin, this sequence is unconformably overlain by upper Oligocene, marginal, marine quartzose sands, which in turn are overlain by a Miocene–Holocene, marine, calcareous shelf facies that includes coral reefs.

Offshore Physiography

The area of interest for Leg 133 (Fig. 1) was the southwestern part of the Coral Sea (Fig. 2); its main regional physiographic elements are the Great Barrier Reef and its adjacent slope, the Queensland and Marion plateaus, the Queensland and Townsville troughs, the Cato Trough, and the Capricorn Channel (Figs. 1 and 3).

The continental shelf is dominated by the Great Barrier Reef and reaches a maximum width of about 350 km in the southernmost part of the region at about 22°S. The shelf break occurs at 100 to 200 m. The slope of the Great Barrier Reef is steeply dipping and has canyons in the northern part of the area, particularly adjacent to the Ribbon Reefs; the slope decreases in the vicinity of Townsville Trough and becomes gentle adjacent to the Marion Plateau. The Queensland Pla-

[1] Davies, P. J., McKenzie, J. A., Palmer-Julson, A., et al., 1991. *Proc. ODP, Init. Repts.*, 133: College Station, TX (Ocean Drilling Program).
[2] Shipboard Scientific Party is as given in list of participants preceding the contents.

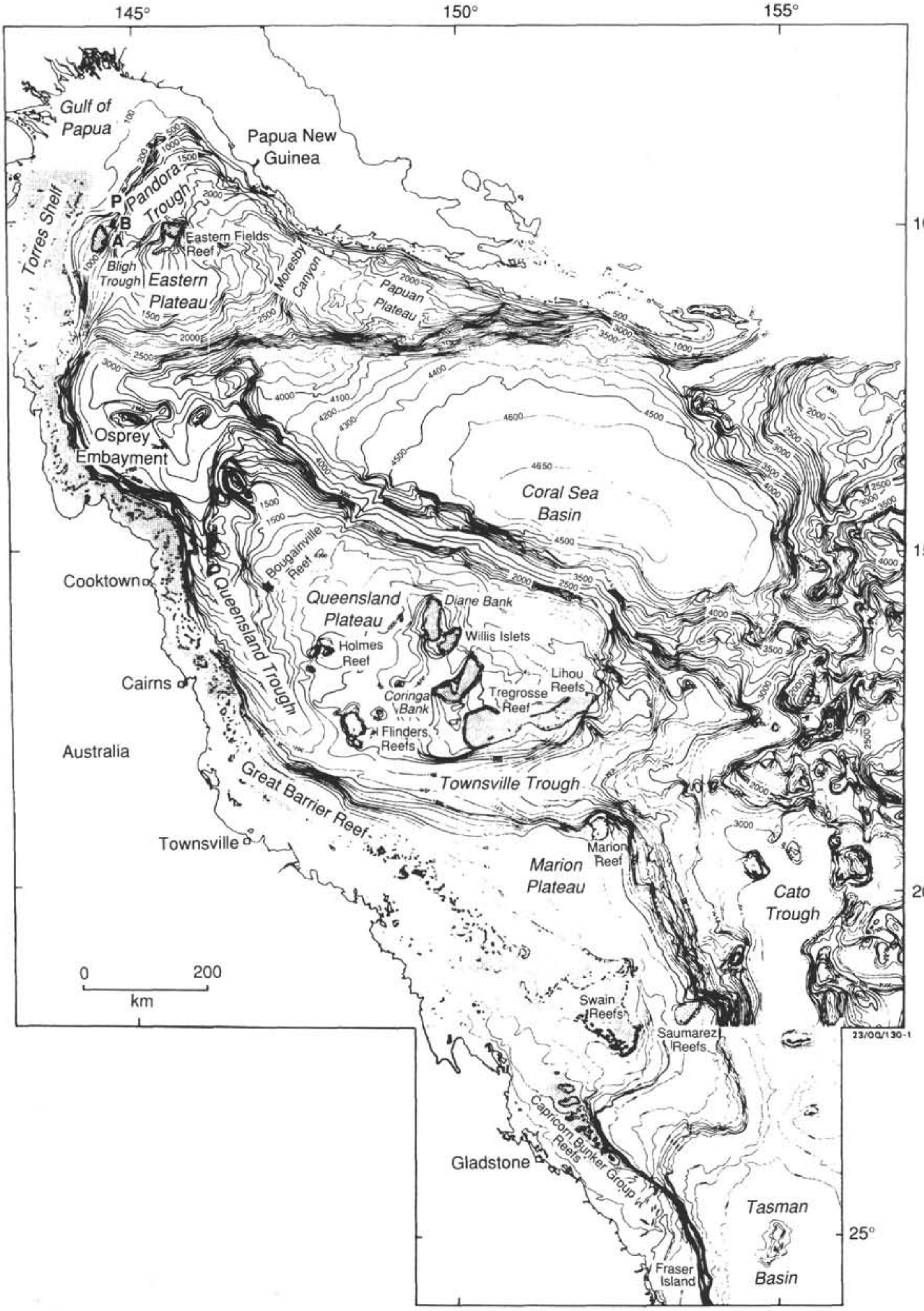


Figure 1. Locality map showing the principal bathymetric features of the northeastern Australia continental margin (modified after Taylor, 1977, and Marshall, 1977). Areas of modern reef growth are shaded; ABP = Ashmore-Boot-Porlock reef system. Bathymetry in meters.

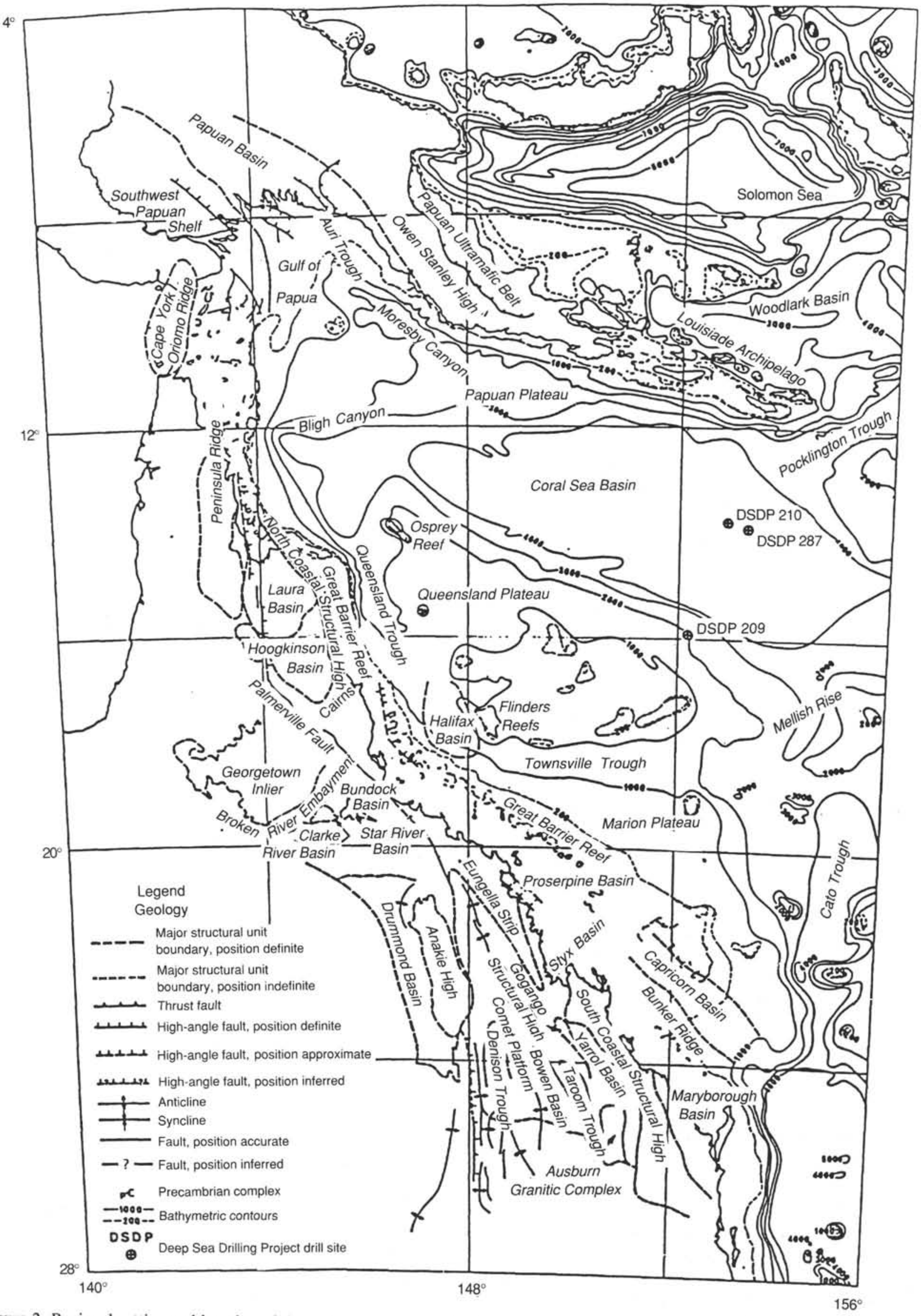


Figure 2. Regional setting and location of the main sedimentary basins offshore northeastern Australia. Bathymetry in meters.

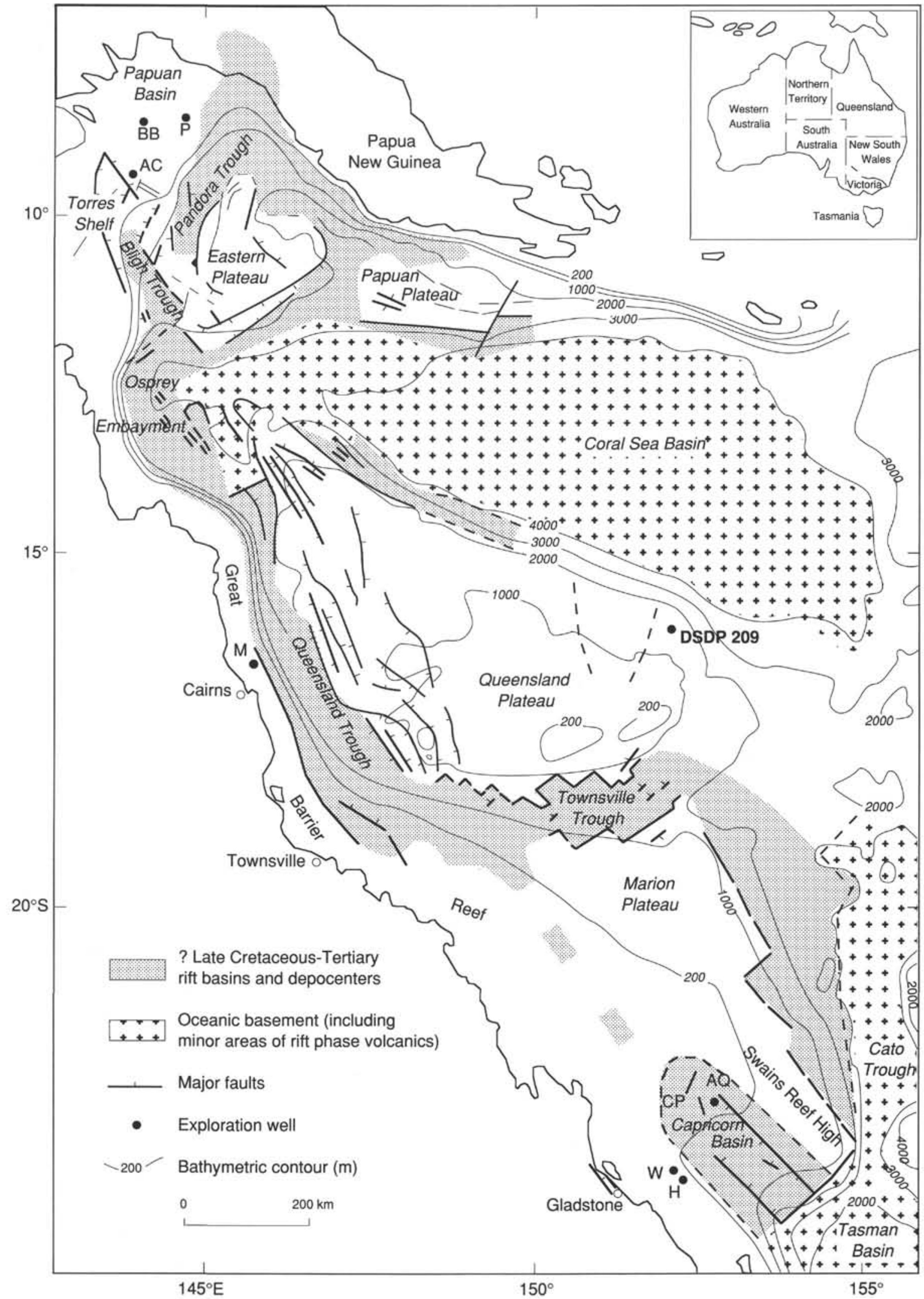


Figure 3. Map showing the major structural features of northeastern Australia (based on Davies et al., 1988). The location of exploration wells (BB = Borabi 1; P = Pasca A1 and C1; AC = Anchor Cay; M = Michaelmas Cay; AQ = Aquarius 1; CP = Capricorn 1A; W = Wreck Reef; H = Heron Island) and DSDP Site 209 also are shown.

teau is roughly triangular: while its western margin strikes north-northwest, its northeastern margin faces the Coral Sea Basin and strikes northwest, and its southern margin strikes east-west. Both its western and southern margins are bounded by linear troughs. Many valleys and canyons lead from the plateau surface into the bounding troughs and the Coral Sea Basin. The plateau surface lies at a medium depth of 1100 m and, away from reef areas, is generally smooth and flat. It exhibits a gentle northwest tilt, while its surface is most deeply submerged around Osprey Reef. Reefs currently occupy approximately 15% of the plateau surface. Fairbridge (1950) observed that these reefs had grown from as much as 1500 m below sea level, well beyond the normal ecological limit of reef growth, which led him to suggest that the plateau had subsided to its present depth from an initial elevation near sea level, while reef growth kept pace with subsidence. The Queensland Trough occupies the region between the continental shelf and the Queensland Plateau, between 14° and 17°S, adjacent to the Great Barrier Reef. Its western margin is much steeper than its eastern margin and has gradients of up to 1:3 (at 15°S). The trough has a smooth, flat floor that gently deepens to the north-northwest from about 1100 m at its junction with the Townsville Trough to about 3000 m at its junction with the Osprey Embayment, which lies between the Queensland and Eastern plateaus. The strike of the trough is that of the dominant structural grain of the Tasman Fold Belt in northern Queensland (Hill and Denmead, 1960). The Townsville Trough has no clear relation to any known structure onshore and is roughly perpendicular to the main Tasman Fold Belt trend. The trough has a symmetric, U-shaped profile that is maintained over most of its length. At its eastern end, at about 154°E, a bifurcation sends one branch south into the Cato Trough and the other winding sinuously north into the Coral Sea Basin. Mutter (1977) speculated that sediment derived from the Queensland Plateau or from mainland Queensland might have reached the adjacent deep ocean floor via the Townsville Trough.

The Marion Plateau lies directly east of the central Great Barrier Reef. It is bounded along its northern margin by the Townsville Trough and along its eastern margin by the Cato Trough (Figs. 1 and 3). The present plateau surface forms a deeper water extension of the Australian continental shelf, with water depths ranging from 100 m along the western border to 500 m along the eastern margin. At present, reef growth is restricted to Marion Reef on the northeastern corner and Saumarez Reef at the southeastern extremity of the plateau (Fig. 1). The plateau may be considered to extend south of Saumarez Reef and to include the Capricorn Channel area (Marshall, 1977). Its eastern margin has been formed by the slope leading down to the Cato Trough. This margin has a moderate grade and is cut by numerous canyons.

Previous Work—The Offshore Database

Previous work in the region has been largely geophysical, notably by GSI in the Queensland Trough, by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and the Bureau of Mineral Resources (BMR) across the Coral Sea Basin, and by BMR over the major platforms and rift basins throughout northeastern Australia (Chaproniere, 1984; Davies et al., 1987, 1989; Symonds et al., 1983). The 1985 and 1987 studies by BMR, together with the ODP site surveys (Feary et al., 1991) conducted by the same organization, represent the most modern and up-to-date data set in the region. Summaries of geophysical and geological data coverage over northeastern Australia are presented in Figures 4 through 7.

The most important sources of stratigraphic control in the region are the petroleum and scientific wells drilled at Anchor Cay (Oppel, 1969), Michaelmas Cay (Richards and Hill, 1942), Aquarius 1, Capricorn 1A, Wreck Island (Lloyd, 1973), Heron Island (Palmieri, 1971), and DSDP Sites 209, 210, and 287 (Burns, Andrews, et al., 1973).

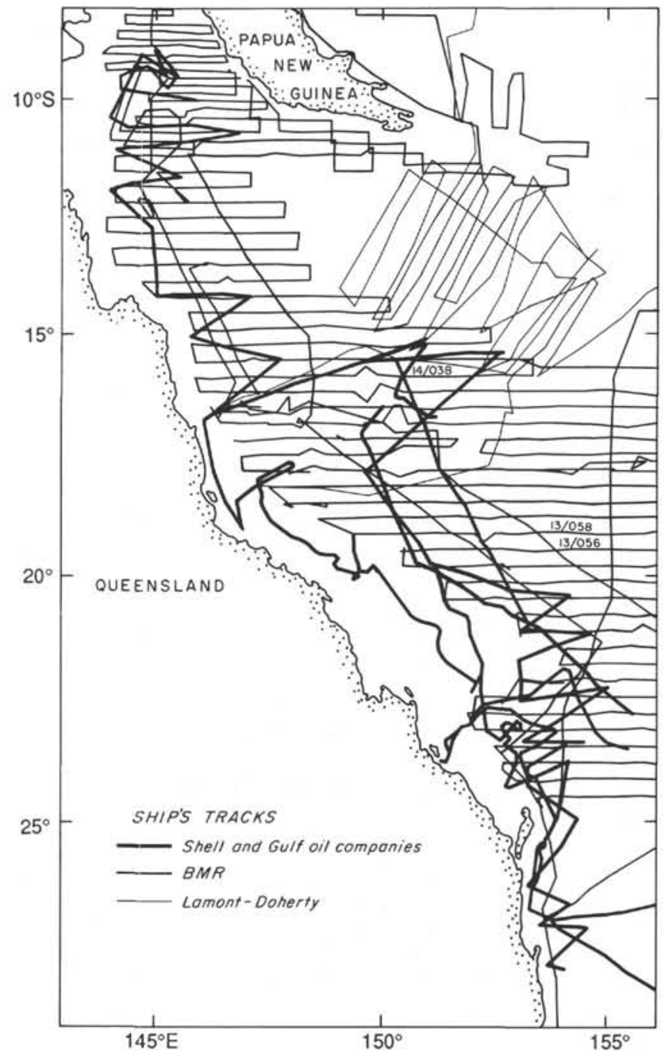


Figure 4. Distribution of 1970 to 1978 seismic data in northeastern Australia by BMR, Shell, Gulf, and Lamont-Doherty Geological Observatory.

Anchor Cay No. 1 was drilled to a depth of 3623.5 m (11,888 ft) by Tenneco-Signal in 1969 (Oppel, 1969) and is summarized in Figure 8. Two major unconformities representing the early Oligocene and the middle to late Miocene separate three carbonate sequences (i.e., temperate Eocene limestones, subtropical upper Oligocene to lower Miocene limestones, and tropical upper Miocene-Pliocene limestones). The Quaternary section is composed of mixed, prograding fluvioclastics and carbonates. Drilling at Wreck Island No. 1 in the Capricorn Basin reached a total depth of 579 m after penetrating 31 m of siliceous volcanic conglomerates (Fig. 8). The most significant result was the identification of Miocene carbonates and clastics, considered proof of a Tertiary marine basin in the area. Two petroleum exploration wells (Capricorn 1A and Aquarius 1) were drilled in the Capricorn Basin, adjacent to the southern Marion Plateau (Figs. 3 and 8). Basement consists of Cretaceous volcanics in Capricorn 1A (at 1710 m) and indurated (?)Paleozoic shale and siltstone in

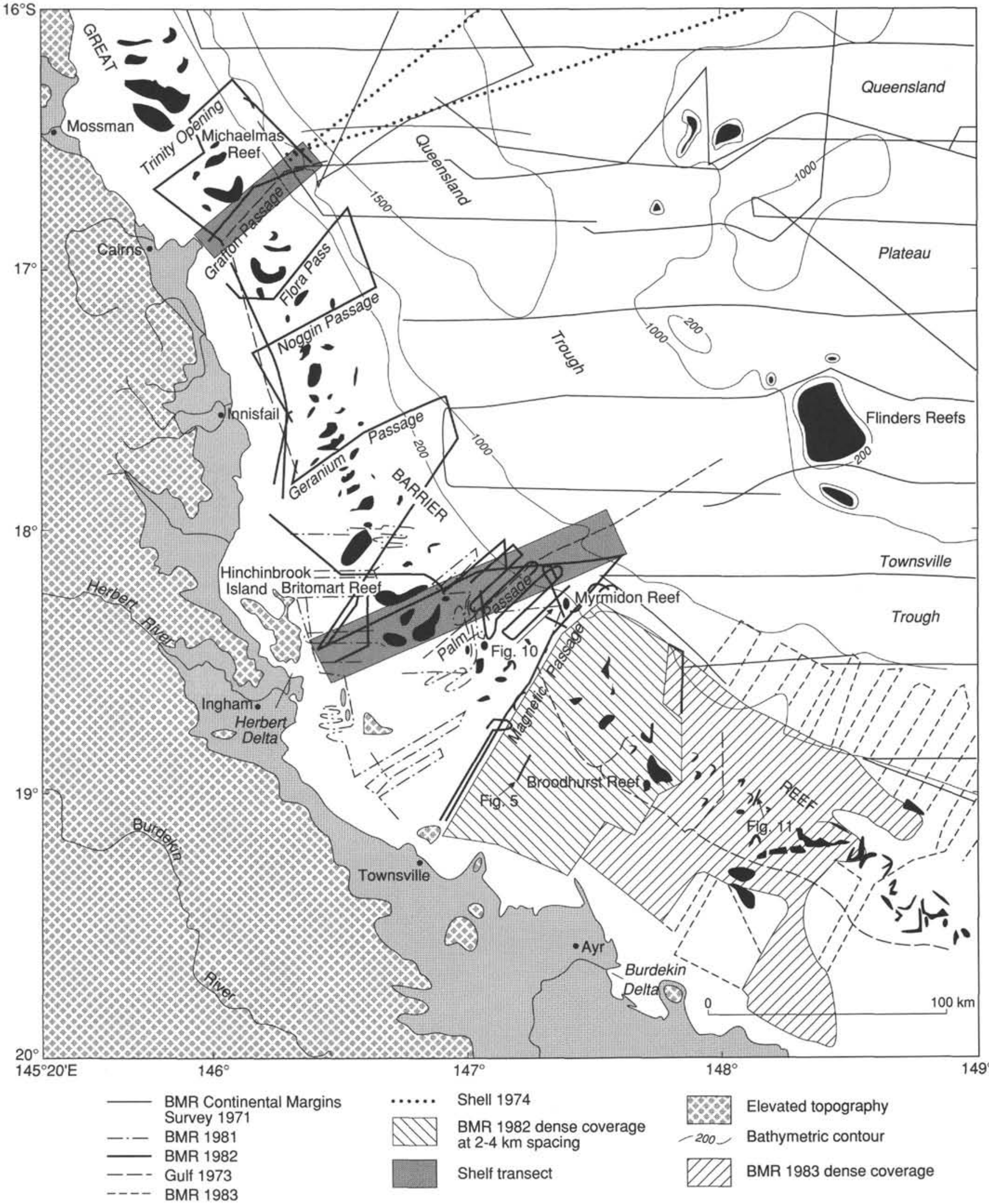


Figure 5. Distribution of BMR, Shell, and Gulf seismic data in the western area of Leg 133.

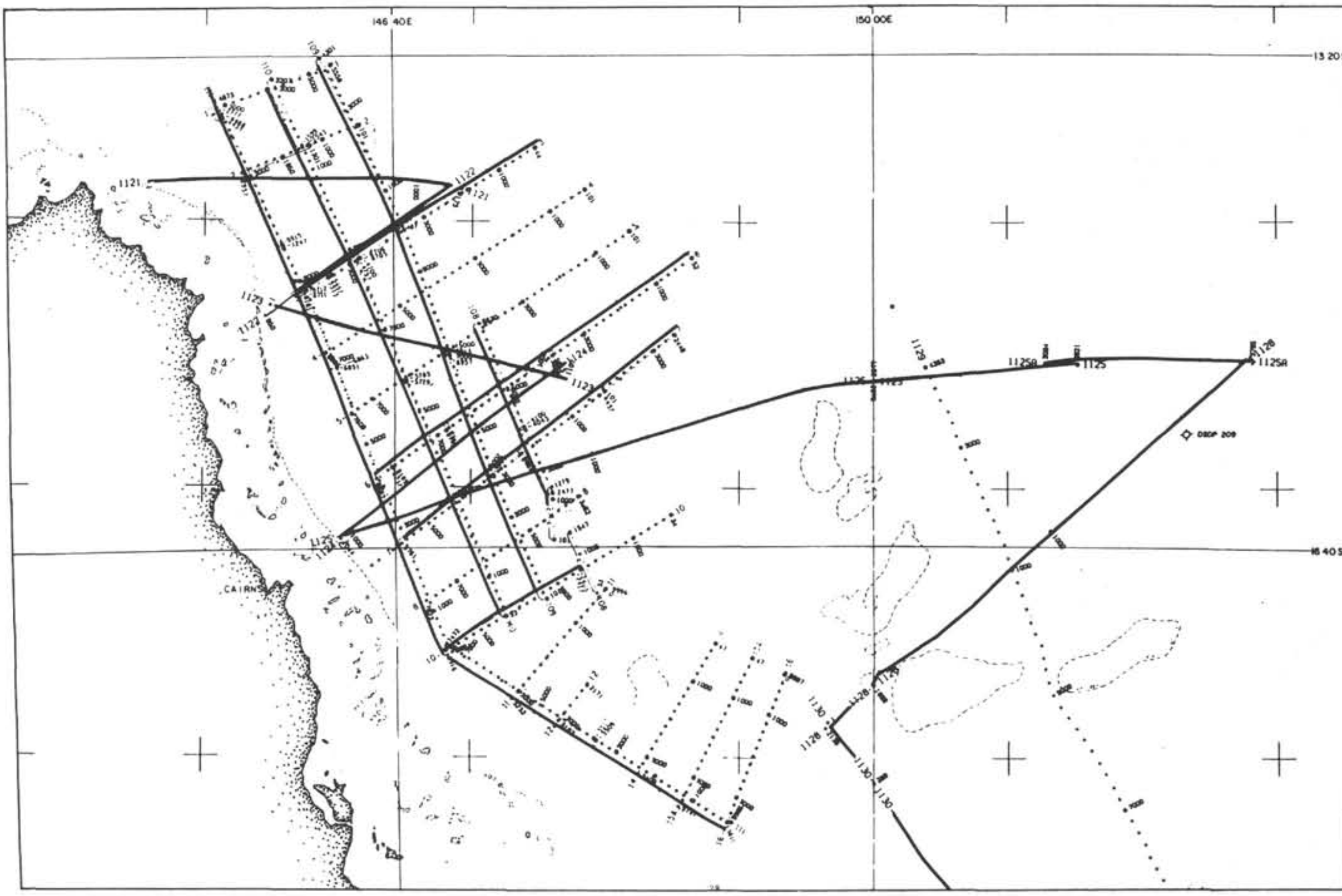


Figure 6. Location of the GSI group shot seismic lines over the Queensland Trough and Queensland Plateau.

Aquarius 1 (at 2658 m). In both wells, basement is overlain in turn by Paleocene to mid-Oligocene basal polymictic conglomerate and arkosic red beds, by shallow marine glauconitic and carbonaceous sandstones, and by Miocene to Holocene claystone and marl (Fig. 8; Ericson, 1976). The most important deep-sea geological data are from the three DSDP drill sites that were drilled during Legs 21 (Burns, Andrews, et al., 1973) and 30 (Andrews, Packham, et al., 1975). DSDP Site 209 was drilled on the eastern Queensland Plateau in 1428 m of water and penetrated three lithologic units (Fig. 8). The site bottomed in upper bathyal-to-neritic, upper middle Eocene, glauconite-bearing bioclastic and foraminifer-rich sediments. The overlying unit (uppermost middle Eocene to upper Eocene) is composed of terrigenous detritus and foraminiferal ooze, indicating subsidence of the margin. A major hiatus extends from the upper Eocene to upper Oligocene sequence that is probably the result of nondeposition and/or slight submarine erosion. This was followed by further subsidence to the present mid-bathyal depths and the deposition of almost pure foraminiferal and nannofossil ooze from the late Oligocene to the present, but with a period of nondeposition or erosion during the middle Miocene. The most important points to emerge from the data (Burns, Andrews, et al., 1973) are as follows:

1. The site records the history of subsidence of the Queensland Plateau from shallow water (neritic) in the late middle Eocene to its present depth at 1428 m (mid-bathyal).
2. The sediments are predominantly foraminiferal ooze throughout, with terrigenous content in the cores decreasing in the upper units, particularly from the middle to upper Eocene section.
3. A major period of nondeposition or submarine erosion spans most of the Oligocene sequence. After this hiatus, the sedimentary regime is almost purely pelagic carbonate ooze.
4. The effects of submarine current activity were recorded.

The Eocene–Oligocene hiatus has been attributed to submarine erosion caused by either a major change in circulation patterns following the final separation of Australia from Antarctica in the early Eocene (Kennett et al., 1972), or by the commencement of a significant equatorial circulation pattern (Taylor and Falvey, 1977). Winnowing is evident in the post-hiatus sediments, suggesting bottom-current activity. Depositional patterns (Mutter, 1977; Taylor and Falvey, 1977) also suggest the influence of currents on sedimentation.

Drilling at DSDP Sites 210 and 287 in the central southeastern Coral Sea Basin penetrated lithologic sequences of essentially the same age (Andrews, Packham, et al., 1975). The more complete section was intersected at Site 210. The bottom part of the section is composed of lower to upper Eocene detrital clays and biogenic pelagic sediment, which accumulated above the foraminifer solution depth. These clays are thought to have been derived from high-grade metamorphic and volcanic rocks to the west (Burns, Andrews, et al., 1973). Deposition was interrupted in the late Eocene to early Oligocene by an erosional/nondepositional hiatus, which is of regional extent and was caused by a marine bottom-water current (Kennett, 1977; Edwards, 1975). Mid-Oligocene nannofossil oozes, deposited near the carbonate

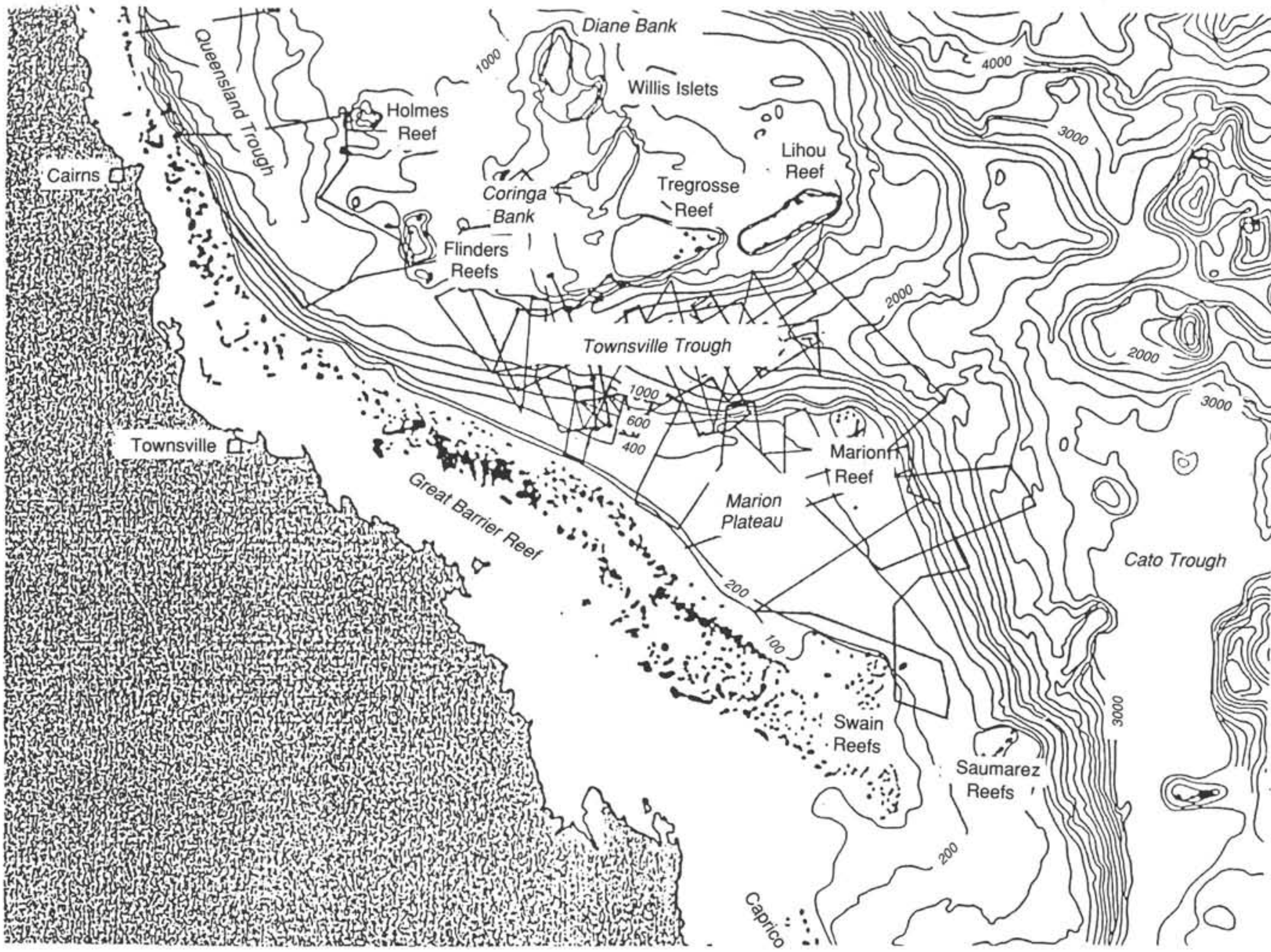


Figure 7. Location of the 1985 and 1987 BMR seismic grid in the Townsville Trough.

compensation depth (CCD), overlie the unconformity and are followed by a late Oligocene to early Miocene period of nondeposition and/or erosion. Overlying this unconformity is a lower-middle Miocene abyssal clay, indicating deepening of the seafloor to below the CCD. The clays are thought to have been derived from the Papuan area to the northwest (Burns, Andrew, et al., 1973). During the late Miocene to late Pleistocene, turbidity currents deposited graded cycles of silt and clays, with the sediment again being derived from sources in Papua New Guinea. Nearly 700 core and dredge stations have been occupied over the northeastern Australian margin by BMR, BGR, and U.S. research institutes. These show that the deep-water parts of the margin currently are receiving pelagic sedimentation. Some areas near the Great Barrier Reef and near large reefs on the Queensland Plateau currently receive reef-derived debris. At present, the Coral Sea receives terrigenous sediment largely deposited as turbidites.

Tectonic Setting

The passive continental margin off northeastern Australia extends over a distance of about 2000 km between Fraser Island in the south and the Gulf of Papua in the north and covers an area of some 930,000 km^2 (Figs. 1 and 3). The margin comprises the Eastern, Queensland, and Marion plateaus; the Pandora and Bligh troughs; the Osprey Embayment; and the Queensland and Townsville troughs. In addition, a zone of narrow rift basins, which extend southeast from the Queensland Trough toward the Capricorn Basin, separates the Marion Plateau from the continental shelf. The entire margin generally is considered to be underlain by modified continental crust that formed as a result of fragmentation of a northeastern extension of the Tasman Fold Belt (Gardner, 1970; Ewing et al., 1970; Falvey, 1972; Falvey and Taylor, 1974; Taylor, 1975; Mutter, 1977; Taylor and Falvey, 1977; Mutter and Karner, 1980; Symonds, 1983; Symonds et al., 1984). The rift phase of margin development, which may have commenced in the Early Cretaceous but was certainly in progress by the Late Cretaceous, preceded continental breakup and the formation of small ocean basins to the east and south (the Coral Sea Basin, Cato Trough, and Tasman Basin). Tasman Basin seafloor spreading commenced in the Late Cretaceous (Hayes and Ringis, 1973; Weissel and Hayes, 1977; Shaw, 1978) and then extended northward to form the Cato Trough and Coral Sea Basin by the Paleocene (65 Ma; Weissel and Watts, 1979). Seafloor spreading had ceased along the length of this system by the earliest Eocene (56 Ma). Although the exact structural style and development history of the rift system of the northeastern Australia region is not completely understood, there is little doubt that it has controlled the gross architecture of the margin and the form of the

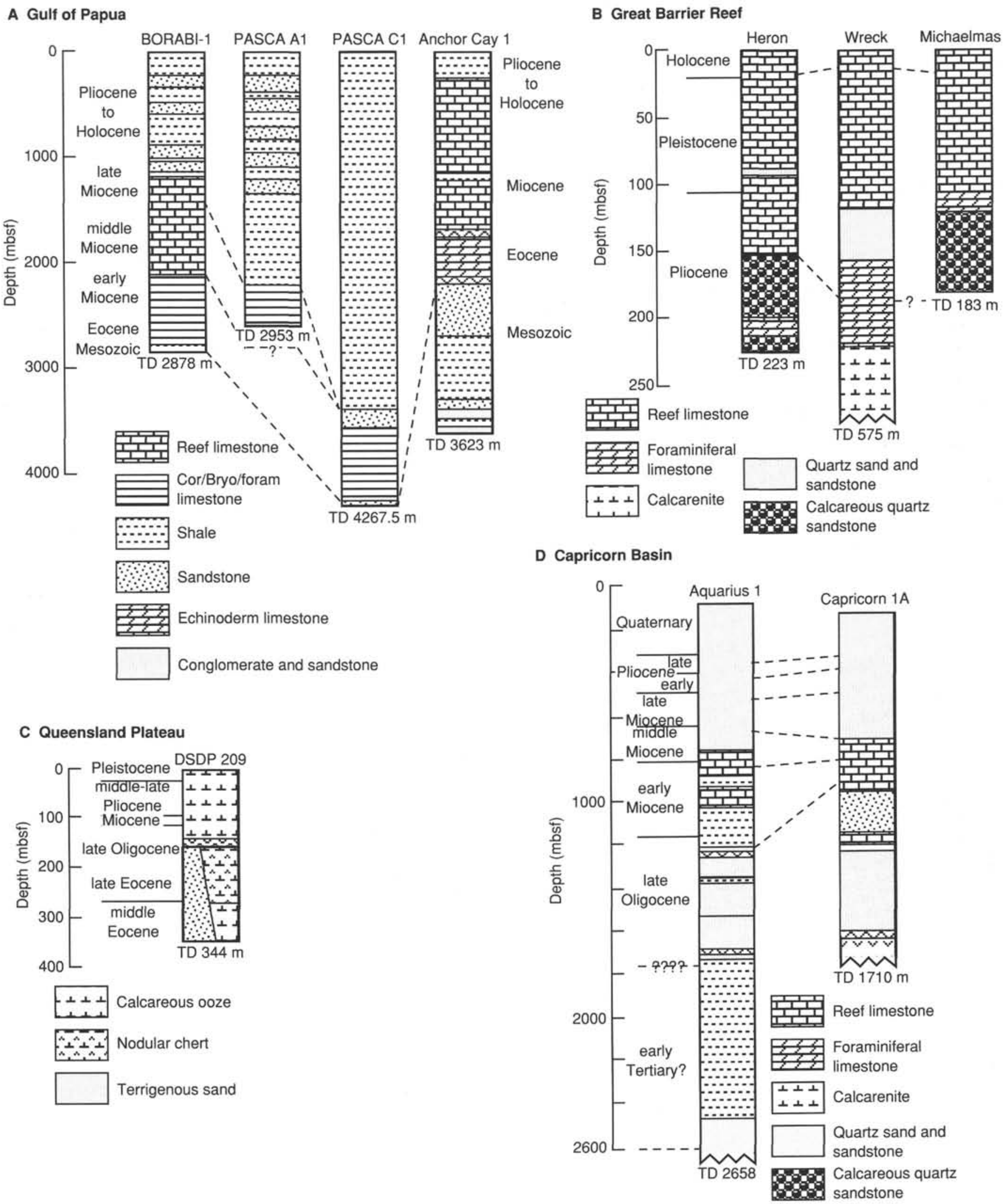


Figure 8. Summary lithostratigraphic logs from drill holes. **A.** Gulf of Papua. **B.** Great Barrier Reef. **C.** Queensland Plateau. **D.** Capricorn Basin.

high-standing structural elements on which the carbonate platforms have evolved (i.e., the origins of the troughs and platforms are closely related).

Queensland and Townsville Troughs

A section across the Queensland Trough illustrating its general structural style and that of its margins is shown in Figure 9. Shallow (1.7 s two-way traveltime, or TWT) planated basement tilt blocks occur beneath the western Queensland Plateau (common depth points, or CDPs, = 200–1100) and are bounded by relatively steep, westerly-dipping, rotational normal faults. Half-grabens formed by these blocks contain an easterly-dipping (?)Upper Cretaceous syn-rift section that is up to about 800 m thick. The tilt blocks were eroded during the formation of the Paleocene "breakup" unconformity that corresponds to the beginning of seafloor spreading in the Coral Sea Basin to the northeast. Beneath the eastern flank of the Queensland Trough (CDP = 1400–1700), the dip of the faults bounding the tilt blocks switches to the east and the corresponding syn- and pre-rift sections dip to the west. Complex faulting beneath the eastern part of the trough (CDP = 1700–2000) may be related to wrenching, which indicates that strike-slip movement probably played an important part in the development of the trough. A large planated basement block in the center of the trough (CDP = 2000–2300) may be bounded by a major near-vertical fault on its eastern flank and a series of smaller high-angle normal faults on its western flank that progressively downstep basement to the west. This high can be identified in seismic data along the strike of the trough both north and south. West of this high, sediment thickness may be as much as 3000 m. In the center of the trough (CDP = 2600–2900), another major half-graben containing (?)Cretaceous pre- and syn-rift sections occurs at a depth of 3.1 s TWT. Both these sections and the underlying basement tilt block are planated by the Paleocene "breakup" unconformity. The western flank of the high is formed by a complex vertical fault system. Another planated basement high occurs beneath the western flank of the trough (CDP = 3600–3800) at a depth of 2.9 s TWT; this is bounded by high-angle faults. A broad anticline, formed by flexural and compaction drape over this block, extends to high levels within the section. The thickest sedimentary section in the trough occurs beneath its western flank, where it may be more than 4000 m thick.

A major lower-middle Miocene carbonate buildup occurs on top of the large basement high in the center of the trough (CDP = 2000–2300) and is associated with a substantial debris apron that extends westward into the deeper part of the trough. A marked change in depositional style occurs across the upper middle Miocene(?) unconformity from essentially conformable sequences to onlapping basin-fill sequences. On the western flank of the trough, the Pliocene–Pleistocene section displays strong downlapping character. The thickest part of this section occurs in the prograding wedge beneath the slope of the Great Barrier Reef. The relatively thin Miocene and younger section covering the western Queensland Plateau (Site 811) thins dramatically westward. The complexity of the sequence stratigraphy in the vicinity of Site 824 is a result of the interaction between trough and plateau depositional processes.

A composite section across the Townsville Trough from the Queensland to the Marion plateaus is shown in Figure 10. Most of this schematic section is based on two tied seismic profiles that extend across the Townsville Trough from the Queensland Plateau in the north to the Marion Plateau in the south. The northernmost part of the section, in the vicinity of

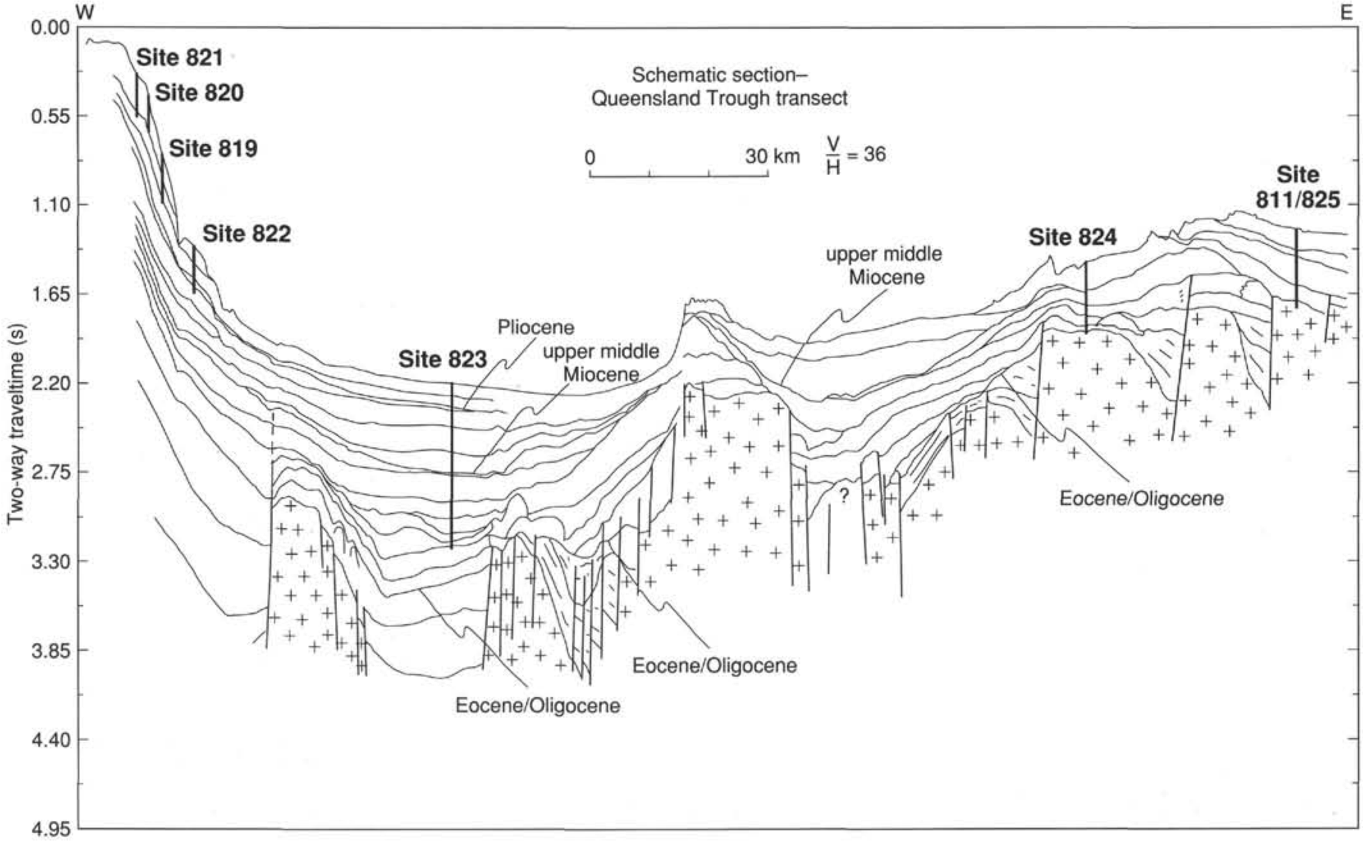


Figure 9. Schematic transect across the Queensland Trough.

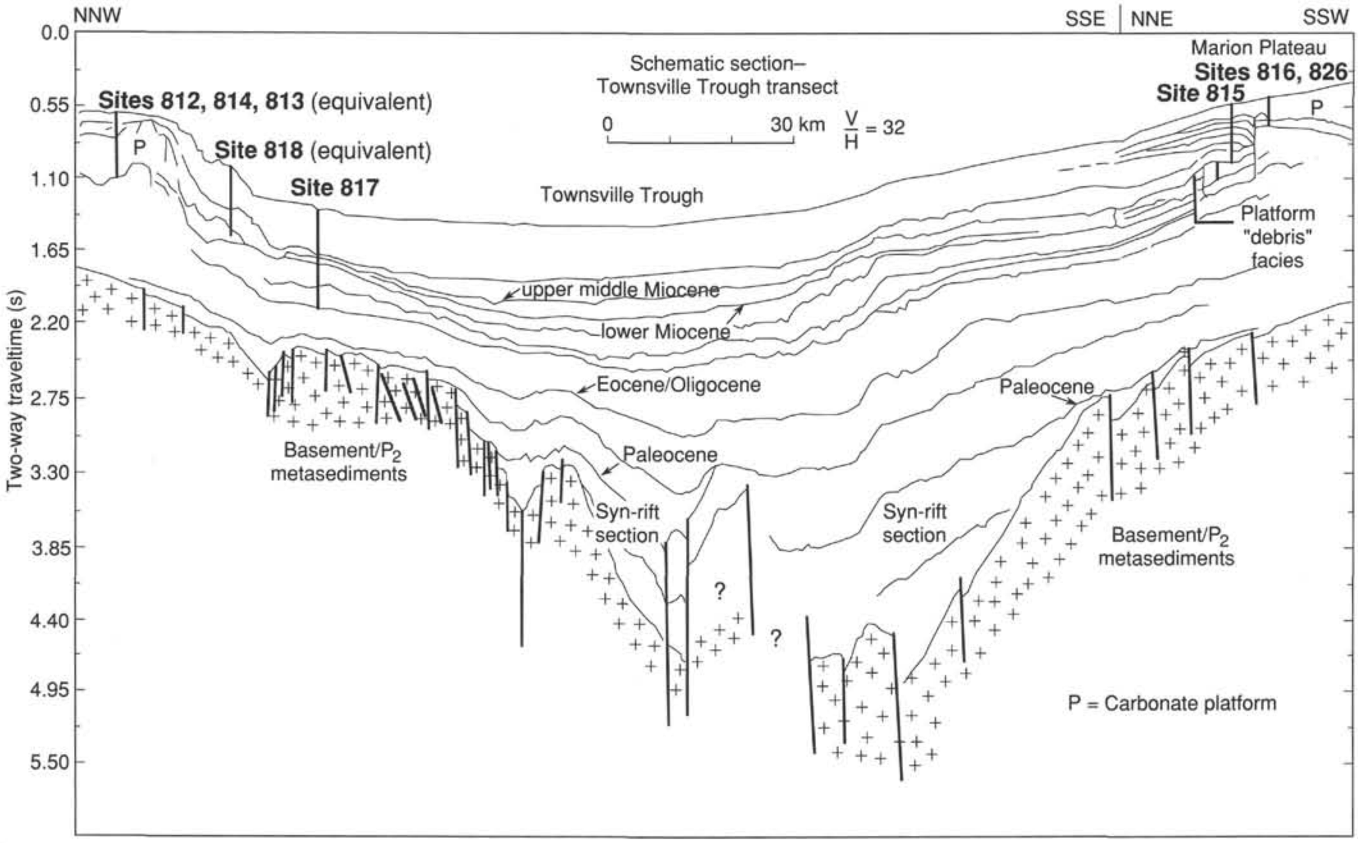


Figure 10. Schematic transect across the Townsville Trough.

Sites 812 to 815, is entirely schematic and is based on a combination of seismic profiles. This section illustrates the general structural style of the Townsville Trough and places Sites 812 to 816 within a regional structural and stratigraphic framework.

The northern margin of the Townsville Trough is underlain by a relatively flat "basement" platform, which exhibits small-throw, down-to-the-north normal faults beneath the southern Queensland Plateau. In places, southward-dipping reflectors occur within the "basement" platform and may represent Paleozoic metasediments or a pre-rift Mesozoic section. On this section, the southern edge of the platform forms a hinged margin that dips into the Townsville Trough and is associated with only minor down-to-basin faulting (time 269.2100–2200). Large tilt blocks, some having eroded and planated corners, occur beneath the main depocenter of the trough, which is about 70 km wide. Beneath the northern part of the trough, a large tilt block up to 12 km wide (time 269.2150–2330) is bounded by several relatively steep, northward-dipping, rotational normal faults. The half-graben to the south of this block contains a southward-dipping (?)Upper Cretaceous syn-rift section that is up to about 1500 m thick. A switch in the direction of faulting occurs about a complex fault zone (transfer fault/accommodation zone) beneath the center of the trough (time 269.2330–2340). Fault blocks south of this zone are bounded by southward-dipping normal faults, and this style extends beneath the northern flank of the Marion Plateau. Thus, for this schematic section, the southern margin of the Townsville Trough is also a hinged or dip-slope margin that formed by northward-tilted "basement" blocks bounded by southward-dipping rotational normal faults. The (?)Upper Cretaceous synrift section is considerably thicker beneath the southern part of the trough—up to 3000 m (1.6 s TWT) thick. Broad anticlines related to flexural and compaction drape over tilt blocks and the edges of the bounding "basement" platforms, particularly on the Queensland Plateau side, in places can extend to high levels (lower [?]Miocene) within the section (e.g., time 269.2 150–2230).

The sedimentary fill within the Townsville Trough can be broadly divided into three main units: (1) an (?)Upper Cretaceous synrift section, which is restricted to the half-grabens (as described above); (2) a Paleocene–Eocene post-breakup section, which generally onlaps the syn-rift section and the flanks of the bounding "basement" platforms; and (3) an upper Oligocene to Holocene section, which covers both the trough and the adjacent platforms. The Paleocene–Eocene section is basically a basin-fill unit that has a relatively uniform, conformable reflection character throughout the trough. This section can be as much as 2000 m thick beneath the center of the trough. The overlying (?)upper Oligocene to Holocene unit is much more variable in reflection character, both across the trough and up through the section. In the center of the trough, where the unit can be as much as 2000 m thick, it commonly contains chaotic, mounded, and channelled facies, particularly toward its base, suggesting that along-trough depositional processes have been important during post-late Oligocene time. A possible lower Miocene shelf edge occurs beneath the southern part of the Townsville Trough (day 270 194.26), and the top of the main shelf edge sequence may correspond to the base of the debris facies in front of the carbonate platform at Site 815 (i.e., the carbonate platform beneath the northern Marion Plateau, CDP = 24 on the section), which appears to have built up on the inner edge of a lower Miocene shelf. The post-platform facies in this area have a prominent downlapping character and may correspond to a late Miocene–Pliocene period of current-controlled contourite deposition. An apparently older phase (late Oligocene–early Miocene) of carbonate platform development is indicated beneath the southern slope of the Queensland Plateau on the northern flank of the Townsville Trough (time 269.1740–1840), and Site 817 should intersect the distal facies shed into the trough in front of this platform. Shown in the schematic section is the southern edge of the oldest part of the carbonate platform that forms the base of the modern Tregrosse reefal platform. The "back-platform" facies east of the western edge of a younger portion of this platform was drilled at Sites 812, 813, and 814. This is illustrated conceptually at the northern end of the schematic profile. The structural style and seismic sequence geometries defined in Figures 9 and 10 are consistent with the following three-phase simplified tectonic history:

1. *Pre-Breakup Development—Jurassic to Late Cretaceous*. During the Jurassic to Early Cretaceous, the northeastern Australian continental margin, incorporating the present marginal plateaus and parts of Papua New Guinea, lay adjacent to the Pacific Plate. Continental-to-marginal marine sediments of this age were deposited throughout the region in intracratonic downwarps (e.g., the Laura Basin and the older part of the Papuan Basin). These sediments also may have extended beneath parts of the Queensland and Townsville troughs and the northeastern Queensland Plateau. During the Cretaceous, probably mainly the Late Cretaceous, rifting occurred throughout the region. Northwest-southeast extension resulted in the low-angle normal faulting and block rotation that initiated the Townsville Trough, whereas wrenching and possible transtensional, pulling-apart development of the basin produced the Queensland Trough. Tectonism was probably accompanied by uplift in adjacent regions. During this episode of Cretaceous extension/rifting, continental, marginal marine, and perhaps restricted shallow-marine sediments were deposited in developing half-grabens/grabens of the Queensland and Townsville troughs. During the Late Cretaceous, prior to the Paleocene–Eocene opening of the Coral Sea Basin, a final and perhaps separate pulse of rifting may have occurred throughout the region, resulting in reactivation and overprinting of the older basin-forming structures. This phase of northeast-southwest extension focussed on the locus of future Coral Sea breakup and produced significant faulting along the northern margin of the Queensland Plateau.

2. *Continental Breakup—Late Cretaceous to Paleocene*. From the Late Cretaceous to early Paleocene (late rift phase), movement on the normal faults continued, but at a greatly reduced level. Some of these tilt blocks were capped and buried by late rift-phase sedimentation, which exhibits flexural drape and thinning over the block corners. Increased marine influence in the troughs, particularly the Townsville Trough, probably followed Campanian breakup and seafloor spreading in the Tasman Basin and Cato Trough. Restricted shallow-marine sediments may have been deposited in parts of the Queensland and Townsville troughs, particularly to the north and east of their junction, and graded-to-marginal marine and continental sedimentation on the flanks of the troughs, on the adjacent emergent Queensland and Marion plateaus, and on the Queensland shelf.

3. *Post-Breakup Subsidence—Paleocene to Oligocene*. During the Paleocene to Eocene episode of seafloor spreading in the Coral Sea Basin to the north, only minor reactivation and structuring occurred in the Queensland and Townsville troughs, enhancing flexural and compaction drape in the early post-breakup sediments. At this time, partially restricted shallow-marine conditions probably existed in the trough, with paralic-to-shallow shelf environments on the trough margins. In post-middle Eocene time, slow regional subsidence during the post-breakup sag phase of the development of the continental margin resulted in the establishment of shallow-marine conditions on the Queensland and Marion plateaus, although parts of both these features probably were still emergent until at least the end of the Eocene. During the middle to late Eocene, the Queensland and Townsville troughs received neritic-to-bathyal high- and low-energy deposits that consisted mainly of terrigenous and calcareous turbidites. During the early Oligocene, a widespread unconformity resulted from the initiation of a significant equatorial circulation pattern over the subsiding margin and basins that is reflected by a widespread unconformity (Taylor and Falvey, 1977). In post-early Oligocene time, as a consequence of subsidence, pelagic ooze, turbidites, and slump deposits became the major components of trough sedimentation.

Carbonate Platforms

The Great Barrier Reef

The Great Barrier Reef is approximately 2000 km long and is made up of approximately 2500 reefs. The shelf occupied by these reefs is generally narrowest in the north (the minimum width of 23 km occurs at 14°S) and widens to the south, to a maximum width of 290 km at 21°S. Reefs occupy the whole shelf in the northern region, but only the middle to outer shelf in the central and southern parts. The Great Barrier Reef is a diverse physiographic province (Maxwell, 1968; Hopley, 1982) and may be divided into five distinct areas using the terminology most commonly applied to carbonate platforms (Ginsburg and James, 1974; Wilson, 1975). The northernmost area (9°–16°S) is a narrow, rimmed, high-energy platform (Fig. 11A), characterized by a shallow, narrow shelf (generally 50–75 km wide) and steep continental slope (10°–60°). Reefs have grown across the full width of the shelf and occur as large mid-shelf platform reefs (Figs. 12A and 12B), and as an almost continuous line of ribbon reefs that form the outer barrier (Figs. 12A through 12C). Between 16° and 18°S, the shelf is a narrow, partially rimmed, high-energy platform (Fig. 11B), 50 to 75 km wide, with a steep continental slope. Reefs generally occur on the middle to outer shelf and are separated from the coast by a channel or inner lagoon approximately 35 m deep. The outer-shelf ribbon reefs are less continuous to the south and have been replaced by a line of shoals on the shelf edge. The central Great Barrier Reef (18°–20°S) is a wide, unrimmed, high-energy platform (Fig. 11C), 90 to 125 km wide, with a gentle continental slope (<2°). Reefs are sparse and have been largely restricted to the outer shelf. A drowned barrier reef complex occurs on a 75-m terrace at the shelf break and extends for about 200 km (Davies and Montaggioni, 1985). Between 20° and 22°S, the shelf is an extremely wide, rimmed, high-energy platform (Fig. 11D) that ranges in width from 125 km in the northwest to 290 km in the southeast. The gentle, narrow continental slope passes northeastward into the Marion Plateau. Reefs are confined to the outer one-third of the shelf (Fig. 12D), but are separated from the shelf edge by several kilometers of relatively deep shoals. In the south (23°–24°S), the shelf is a narrow, unrimmed, high-energy platform (Fig. 11E), up to 100 km wide, with reefs occupying a narrow zone on the mid-shelf. The shelf edge occurs about 12 to 20 km east of the reefs, in about 70 m of water. No drowned barrier reefs have been found along the shelf edge, although reef carbonates have been reported from the slope in 175 m of water (Veeh and Veevers, 1970).

The physiographic variation throughout the modern Great Barrier Reef includes many features that some authors have placed within an evolutionary sequence (e.g., Read, 1985).

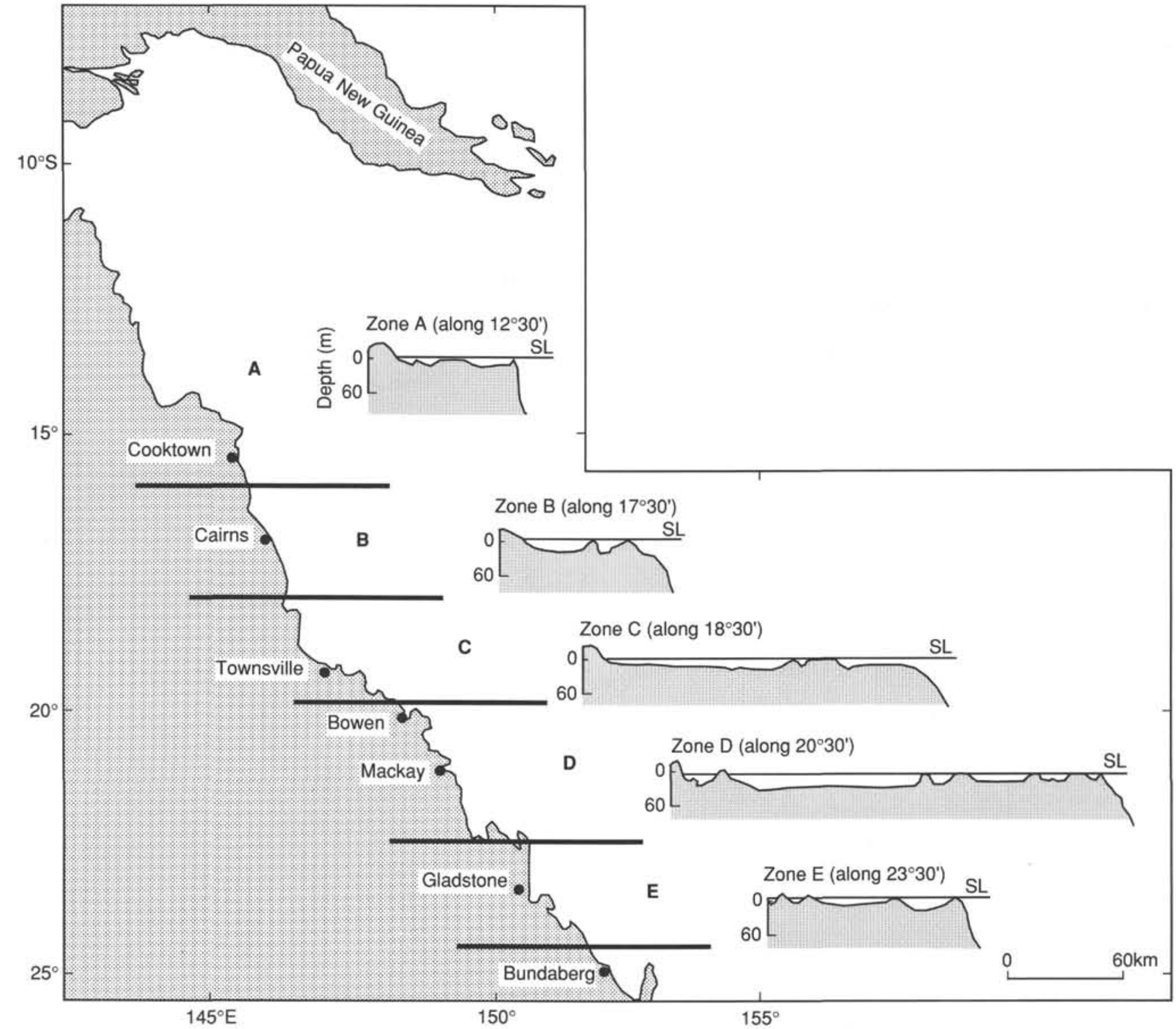


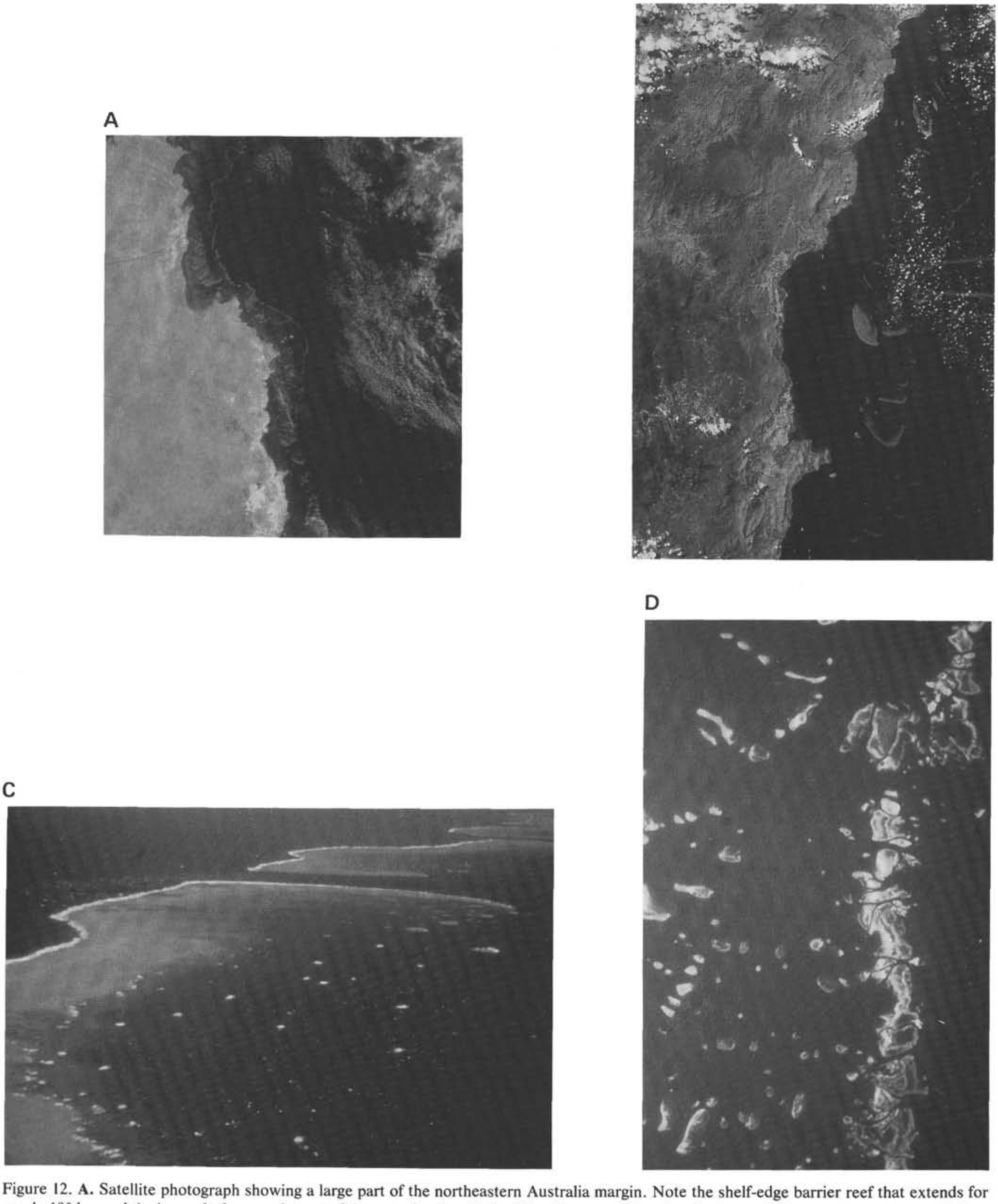
Figure 11. Physiographic variations throughout the Great Barrier Reef province. **A.** Narrow, rimmed platform (nomenclature after Ginsburg and James, 1974; Wilson, 1975). **B.** Narrow, partially rimmed platform. **C.** Wide, unrimmed platform. **D.** Extremely wide, rimmed platform. **E.** Narrow, unrimmed platform.

that process diachroneity is a fundamental factor in platform evolution. The major subsurface characteristics of the Great Barrier Reef carbonate platform have been deduced from extensive geological (e.g., Davies, 1977; Davies, 1983; Davies and Marshall, 1985) and geophysical (summarized in Symonds et al., 1983; Davies, Symonds, et al., 1988) investigations and are summarized in schematic sections shown as Figure 13. In the northern Great Barrier Reef and Gulf of Papua, the occurrence of subsurface reefs is well documented by seismic data and drill holes (Tanner, 1969; Tallis, 1975; Fig. 14). Miocene reefs occur in the subsurface of the Gulf of Papua (Figs. 14A through 14C), and Pliocene reefs and Miocene limestones containing algal rhodoliths occur at the northern end of the Great Barrier Reef (Marshall, 1983) in Anchor Cay 1 (Fig. 8A). Seismic data (Davies, Symonds, et al., 1988) from the northern area confirm both the presence of buried reefs and the existence of a thick reef section (Figs. 14D through 14F). The data also show that modern reefs have been constructed on a more extensive Miocene and Pliocene reef complex up to 1.5 km thick, whereas on the adjacent shelf, (?)Miocene–Pliocene buried reefs may be precursors of the modern shelf-edge ribbon reefs. A seismic profile across one of these features (Fig. 14E) shows episodic reef growth throughout a 1500-m section. A prominent fore-reef slope having shallow-dipping beds appears to have built up concurrently with the reef complex and has been overlain by a thick Pliocene(?) and younger fluviodeltaic sequence. In contrast, buried and partially buried relict Quaternary(?) shelf-edge reefs, up to 100 m thick, occur along the easterly-trending section of the outer Papuan shelf (Fig. 14F). Therefore, in the northern Great Barrier Reef and Gulf of Papua, seismic and drill-hole data indicate that a reef sequence of varying thickness and age began to develop during the Miocene.

On the outer continental shelf of the central Great Barrier Reef region, the 250- to 300-m-thick reef complex (Fig. 15) comprises a series of reef slices separated by low sea-level-generated unconformities (Davies, 1983; Symonds et al., 1983). The reef complex forms only the uppermost part of a

B

A



C

D

Figure 12. **A.** Satellite photograph showing a large part of the northeastern Australia margin. Note the shelf-edge barrier reef that extends for nearly 100 km and the huge platform reefs west of the outer barrier. **B.** Satellite photograph showing the large platform reefs northeast of Cairns in the northern Great Barrier Reef. **C.** Oblique air photo showing shelf-edge barrier on ribbon reefs in the northern Great Barrier Reef. From left to right, note surf marking the windward margin, the reef flat, sand sheets, and abundant patch reefs in the back-reef area. **D.** Satellite photograph showing extremely large and complex shelf-edge reefs in the Pompey complex of south-central Great Barrier Reef.

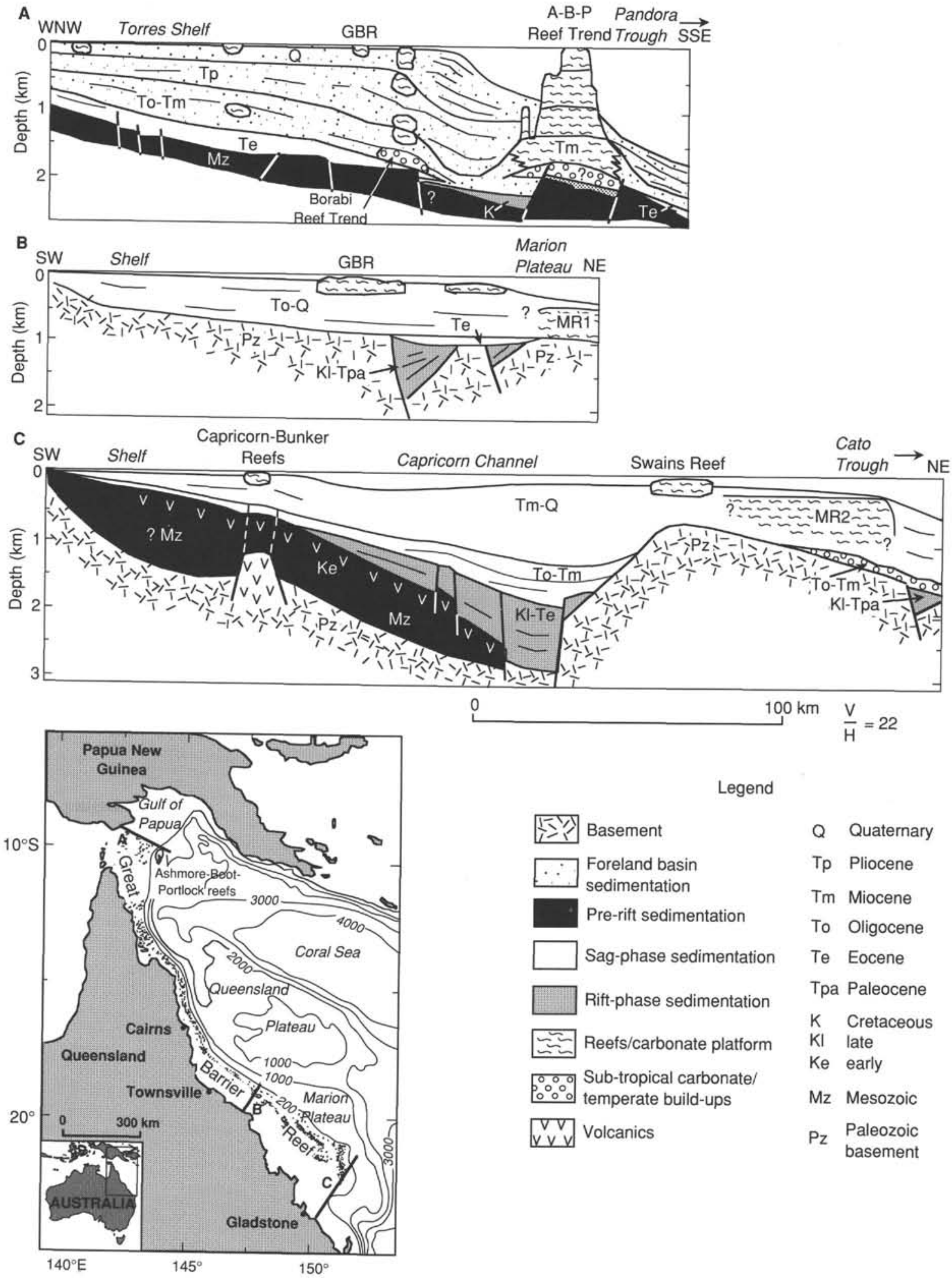


Figure 13. Schematic sections showing generalized structural and sedimentary geometry in the Great Barrier Reef Province. **A.** Northern. **B.** Central. **C.** Southern. MR1 and MR2 = different phases of development of carbonate platforms on the Marion Plateau. Section locations are shown in the inset.

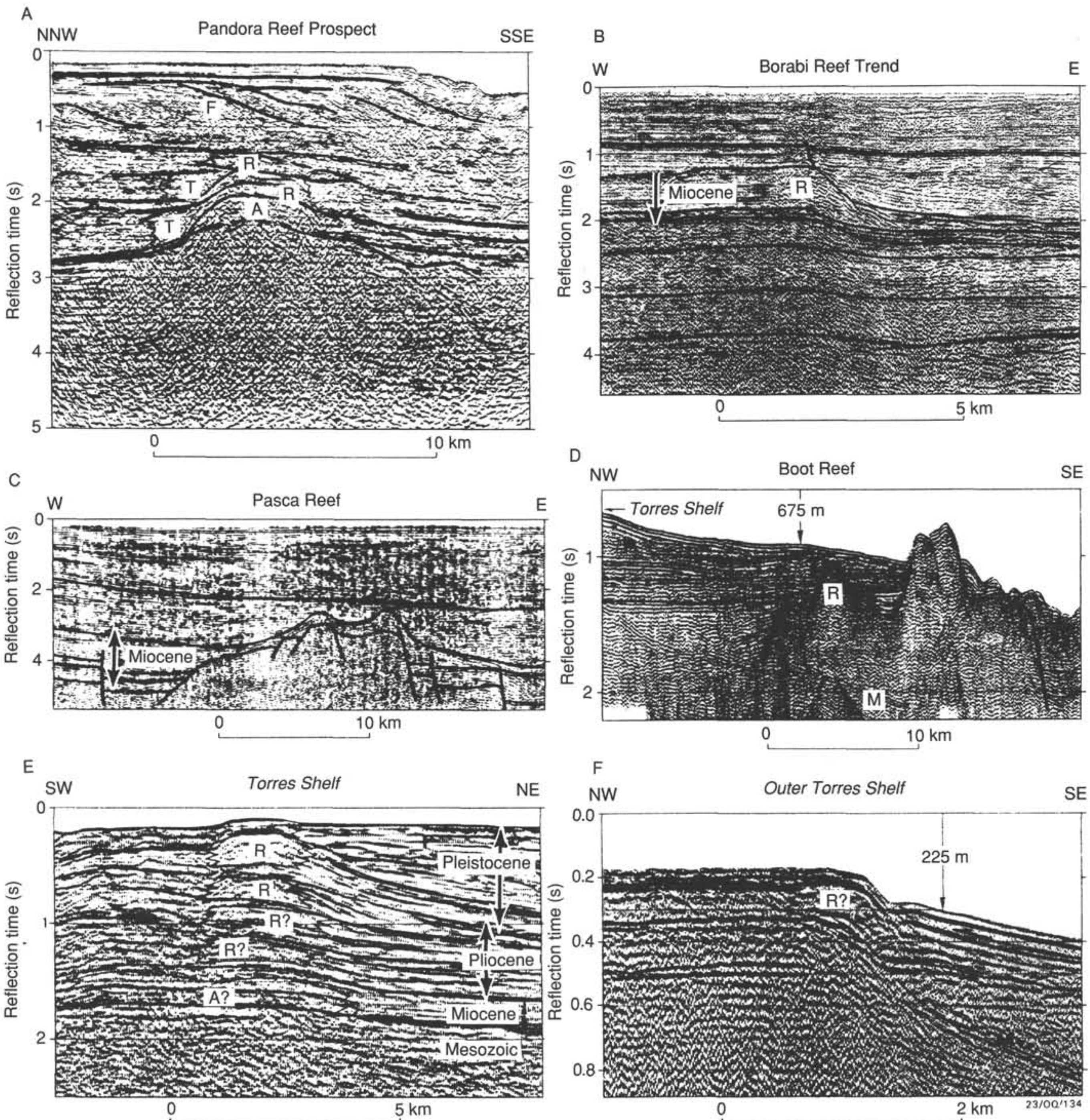


Figure 14. Seismic sections showing buried or partially buried reef complexes in the Gulf of Papua and northern Great Barrier Reef. M = first water-bottom multiple. **A.** Air-gun seismic section over a buried Miocene reef at the northern end of the Ashmore-Boot-Porlock reef complex. The early stage of carbonate buildup (A = perhaps a subtropical algal mound) that developed on the corner of a fault block is overlain by more areally restricted reef facies (R). A leeside talus facies (T) may also be present. The entire complex is buried by fluvioclastic sediments (F) derived from the west. **B.** Seismic section showing the Miocene Borabi Reef trend in the Gulf of Papua. **C.** Seismic section showing the Miocene Pasca Reef Complex sitting on a structural high in the Gulf of Papua. **D.** Sparker seismic section across the saddle between Boot and Porlock reefs showing buried and submerged parts of reef (R) and a possible leeside talus facies (T). The reef complex has been partially buried by fluvioclastic sediments (F) derived from the west. **E.** Air-gun seismic section across the edge of the Torres Shelf, showing the buried northern extension of the modern shelf-edge ribbon reefs. Pliocene-Pleistocene reefs (R) overlie a broader Miocene buildup, which may consist in part of a subtropical algal mound (A). **F.** Sparker seismic profile across the outer Torres Shelf, showing a 100-m-thick (?)Pleistocene reef (R) that has been partially buried by terrigenous sediment.

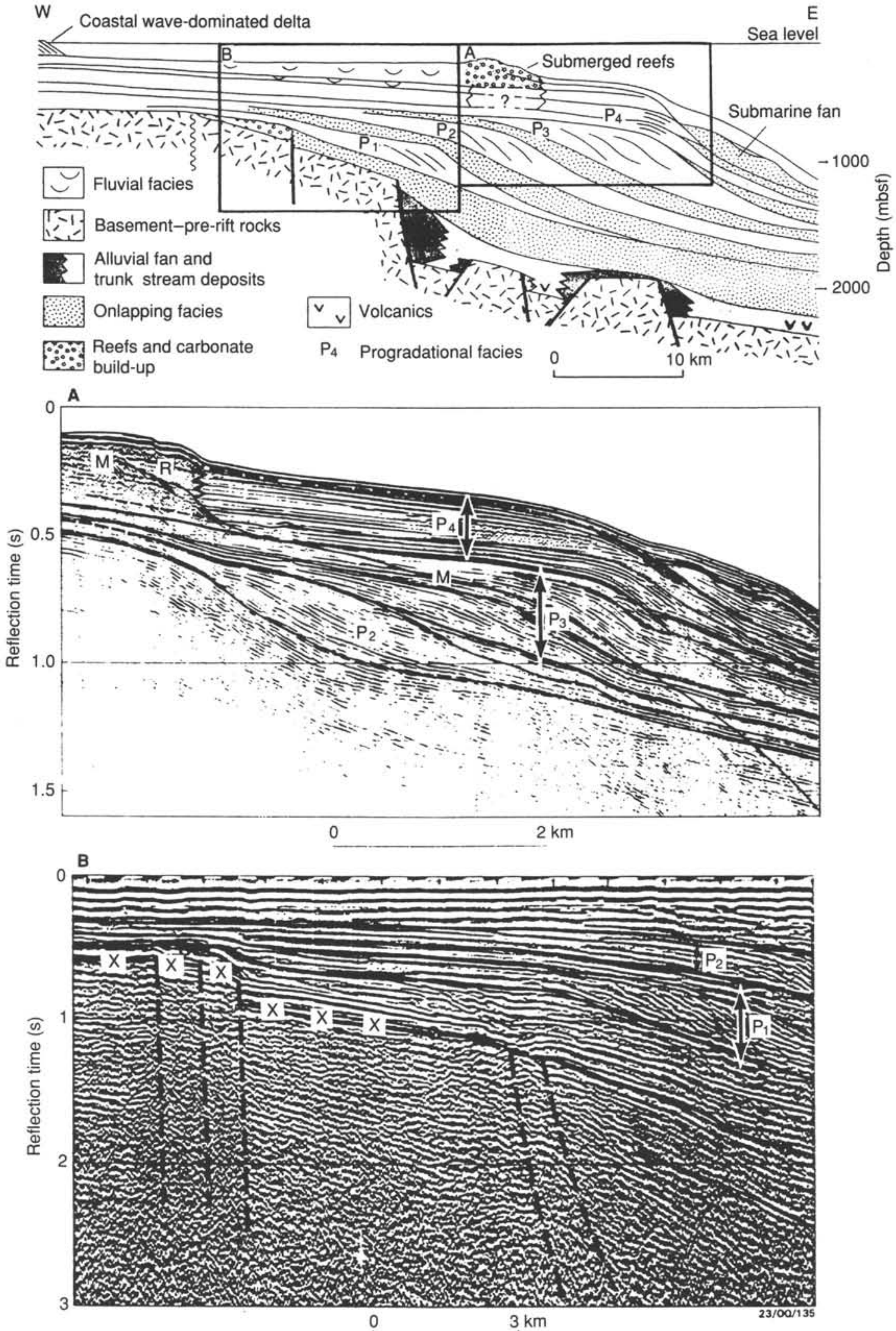


Figure 15. Carbonate-terrigenous facies geometry on the upper slope and outer shelf of the central Great Barrier Reef (modified after Symonds et al., 1983). **A.** A sparker seismic section off Cairns, showing a submerged reef (R) and siliciclastic prograding units (P_2–P_4). M = the first water-bottom multiple. **B.** An Aquapulse seismic section, showing the position of outer-shelf sequences, particularly the two lower prograding Units P_1 and P_2, with respect to underlying basement (X) structure.

However, at the same time, their existence currently suggests thick, outer-shelf sequence that is dominated by prograding fluviodeltaic and onlapping slope sediments overlying a rifted basement (Symonds et al., 1983). The reef thickness and a tie to DSDP Site 209 in the Coral Sea indicate a probable late Pliocene to Pleistocene age or younger for initiation of reef growth in this region. Drilling was intended to test this hypothesis. A borehole at Michaelmas Cay (Fig. 1) shows 100 m of (?)Pliocene–Pleistocene reef facies overlying siliciclastic sediments (Fig. 8). The boreholes on Heron Island and Wreck Reef (Fig. 8), at the southern end of the Great Barrier Reef, show that less than 150 m of reef overlies quartz sand and that reef growth began in the Pliocene–Pleistocene (Lloyd, 1973; Palmieri, 1971, 1974). Thus, principal conclusions derived from studies of the Great Barrier Reef carbonate platform are (1) that the reef sequence thins dramatically and (2) that the age of initial reef growth becomes younger to the south. The Great Barrier Reef thus is a mixed carbonate/siliciclastic province having reefs that form a discontinuous wedge largely enclosed within terrigenous fluviodeltaic deposits. However, in some areas the underlying sequence has been dominated by nonreefal carbonate facies.

The Queensland Plateau

The Queensland Plateau, with an area of approximately 160,000 km^2, is the largest marginal plateau of the Australian continental margin and is one of the largest features of its type in the world (Fig. 1). Approximately the same size as the Bahama Platform, this plateau is bounded on the northeast by the Coral Sea Basin, on the west by the Queensland Trough, and on the south by the Townsville Trough. Approximately one-half of the plateau surface lies above the 1000-m isobath, and living reef systems at or near the present-day sea level make up 10% to 15% of the surface. The largest modern reef complexes are Tregrosse and Lihou reefs, which lie along the southern margin of the plateau (Fig. 1). Both these complexes are nearly 100 km long and 50 and 25 km wide, respectively. The other major areas of modern reef growth are the Coringa, Willis, and Diana complexes, which are aligned north to south in the center of this plateau, and the large isolated pinnacles of Flinders, Holmes, Bougainville, and Osprey reefs, which lie along the western margin of the plateau (Fig. 1). Drowned reefs have been reported from at least 25 different locations (Taylor, 1977; Mutter, 1977; Davies, Symonds, et al., 1988). Away from reef areas, the plateau surface is generally smooth and slopes northward. A distinct terrace at a depth of approximately 450 to 500 m connects both the Willis and Diana reef complexes and the Tregrosse-Lihou-Coringa reef complexes. The major characteristics of the Queensland Plateau carbonate platform, as deduced from analysis of extensive seismic and sampling data, are summarized in schematic sections shown in Figures 16B and 16C.

Basement on the Queensland Plateau is composed of probable Paleozoic(?) rocks that form a basement surface dipping generally northeast toward the Coral Sea Basin (Mutter, 1977; Taylor, 1977). Beneath the western one-third of the plateau, basement is progressively downfaulted toward the Queensland Trough (Fig. 17A). South of Tregrosse and Lihou reefs, the basement surface slopes gently south toward the northern boundary fault of the Townsville Trough (Fig. 16B). Large parts of the basement surface were exposed and planated during the Cretaceous-Oligocene. Scientists think that during the Eocene this surface was progressively submerged and overlain, first by shallow-marine siliciclastic sediments and then by deeper-water pelagic sediments (Burns, Andrews, et al., 1973). A period of nondeposition or submarine erosion occurred from the late Eocene until the late Oligocene. The sedimentary sequence reflects constant gradual subsidence until the late Miocene, followed by increased subsidence to the present day.

Although carbonate deposition may have begun earlier, the Queensland Plateau has been a carbonate-dominated province at least since the earliest Miocene. Along the western margin of the Queensland Plateau, steep-sided pinnacle reefs 1 to 2 km wide rise from depths of 1200 m to within 10 m of sea level (e.g., Fig. 17C). Dredged samples indicate that the flanks of these features comprise a reef framework that contains larger foraminifers of Miocene-Pliocene age (Davies, Symonds, et al., 1988). Seismic data indicate that at least some of these pinnacles developed on the raised corners of fault blocks. In addition to the buildup of carbonate on the plateau margins noted above, seismic data show that a thick, carbonate platform sequence was deposited on the central part of the plateau (Fig. 17D). At least two phases of separate but superimposed reef and periplatform facies (QR1 and QR2; Figs. 16B, 16C, and 17D) form the core of these carbonate platforms. Dredge samples from this complex on the southern slope of the Queensland Plateau, in depths of between 1000 and 1300 m, consist of middle Miocene to Pliocene reefal material (Davies, Symonds, et al., 1988). The presence of shallow-water sediments at these depths confirms that unusually rapid subsidence of the plateau has existed since the middle Miocene. The deeper water areas between reef complexes are the sites of hemipelagic sedimentation. A terrace that occurs at a depth of 450 to 500 m represents the end of QR2 reef growth (Figs. 16B, 16C, and 17D). A third, more restricted phase of reef growth (QR3) was developed on this surface, with associated periplatform sedimentation in front of the reef (Fig. 17D). This reefal platform grew to sea level, and as a result of an increase in relative sea level, it now forms another terrace at a depth of approximately 50 m. The most recent reef complexes (QR4) developed on the 50-m terrace (Figs. 16B and 16C) and are even more restricted than previous phases. Descriptions of the modern coral faunas (Orme, 1977; Done, 1982) suggest that these modern reefs are oceanic equivalents of high-energy reefs present in the Great Barrier Reef. Thus, it is likely that throughout their evolution, all the different phases of Queensland Plateau reef development have been products of high-energy environments.

The Marion Plateau

The 77,000-km^2 area of the Marion Plateau lies directly east of the central Great Barrier Reef and is bounded along its northern margin by the Townsville Trough and along its eastern margin by the Cato Trough (Fig. 1). The present plateau surface forms a deeper-water extension of the Australian continental shelf and has water depths ranging from 100 m along the western border to 500 m along the eastern margin. At present, reef growth is restricted to Marion Reef, on the northeastern corner, and Saumarez Reef, at the southeastern extremity of the plateau (Fig. 1). Little detailed information exists about the distribution of structure and facies for the Marion Plateau (Mutter and Karner, 1980). The results of a study in progress, which is based on extensive air- and water-gun and sparker seismic data, combined with sampling data, are summarized in schematic sections across the plateau (Figs. 16B, 16D, and 16E). The plateau is bounded on three sides by rifts: the Cato Trough to the east; the Townsville Trough to the north; and a series of north-south, oriented, narrow, discontinuous half-grabens separating the plateau from the continent to the west (Fig. 3). During the Tertiary, siliciclastic shelf sediments prograded eastward across these half-grabens and onto the western Marion Plateau. The most northern of these half-grabens appears to join the confluence

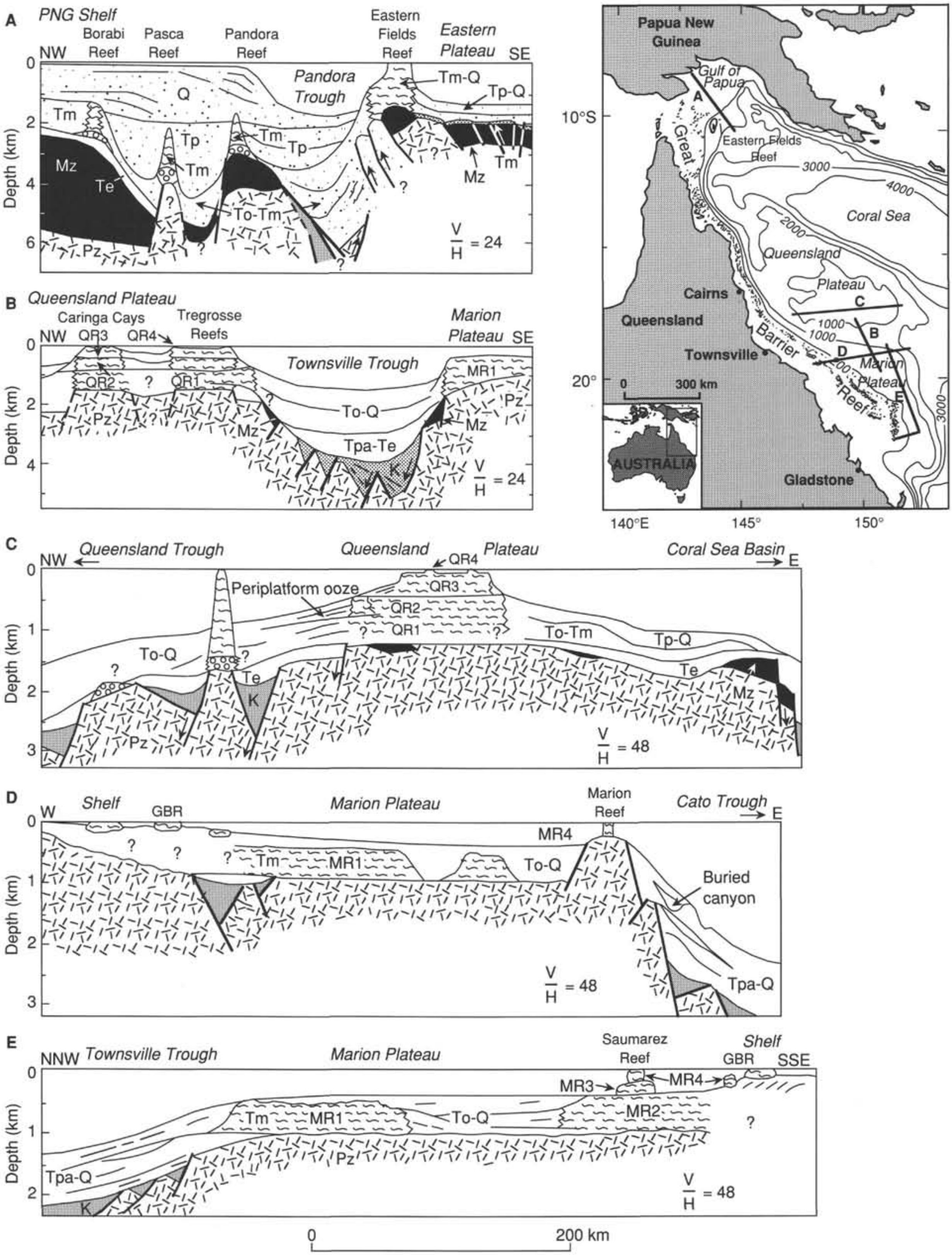


Figure 16. Schematic cross sections showing the generalized structure and sedimentary sequences on the Eastern (**A**) and Queensland (**B** and **C**) and Marion (**B**, **D**, and **E**) plateaus. QR1 to QR4 and MR1 to MR4 denote phases of carbonate-platform growth on the Queensland and Marion plateaus.

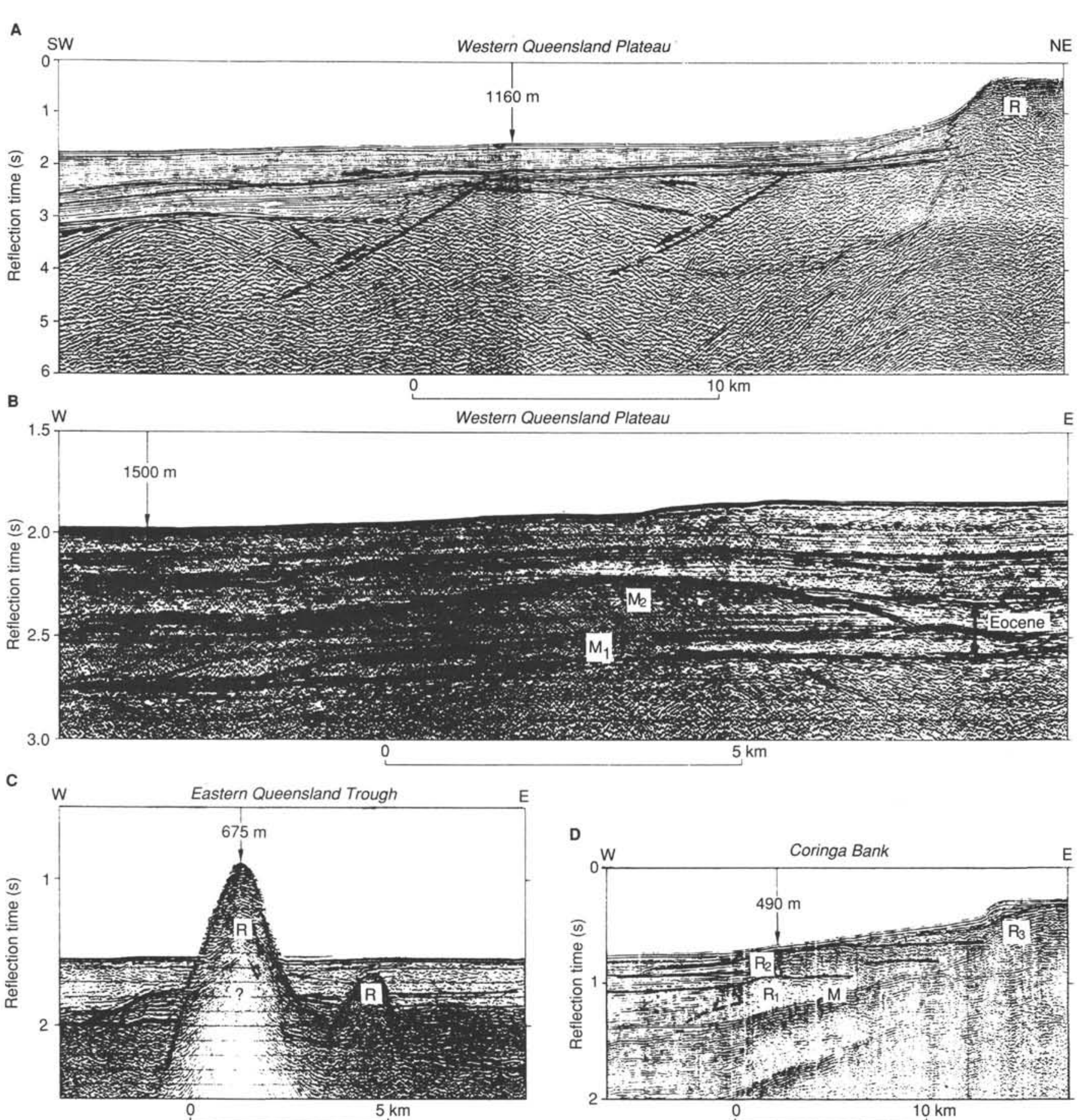


Figure 17. Seismic sections across the Queensland Plateau carbonate platforms. **A.** Air-gun section across the western Queensland Plateau, showing fault-bounded tilt blocks and half-graben and an overlying carbonate bank (R). **B.** Sparker section showing mounded features (M1 and M2), possibly Eocene carbonate buildups, overlying basement on the western flank of the Queensland Plateau. Recent work indicates that this structure is probably circular and accordingly is not a barrier reef, as suggested by previous studies. **C.** Sparker section over a steep-sided pinnacle (R) that rises from a water depth of 1200 m on the eastern side of the Queensland Trough. Miocene and Pliocene reef framework samples were dredged from the lower slopes of this pinnacle. **D.** Sparker section showing three major phases of platform reef growth (QR1 to QR3) at Coringa Bank.

of the Townsville and Queensland troughs. Thus, the Marion Plateau may have formed a separate marginal plateau during the early Tertiary. To the south, the Marion Plateau is separated from the Capricorn Basin by a northwest-trending basement ridge. Basement beneath the Marion Plateau is a planated surface that dips gently toward the northeast. The only disruption to this surface occurs in the northeastern corner of the plateau, where a basement high forms the pedestal on which Marion Reef developed. Basement beneath the plateau margins steeply downfaults into the troughs to the north and east. The slope sequences on both the northern and eastern margins of the plateau onlap and are progradational. Small reef complexes overlie some of these progradational sequences along the northern margin (Fig. 18A). The basement surface was completely transgressed during the (?)early Miocene, resulting in development of an extensive carbonate platform (MR1; see Fig. 16). The top of this platform currently lies at a depth of 450 to 500 m. Shelf-edge barrier reefs (Fig. 11B) and platform reefs separated by lagoons and inter-reef areas (Fig. 18C) can be identified over the northwestern two-thirds of the platform. Barrier reefs formed a distinct rimmed margin only along the northern edge of the plateau. The second phase of platform development (MR2) was more restricted and was confined to the southern one-third of the plateau. This phase was initiated at a level considerably below the top of the earlier phase (Fig. 16E). The top of the MR2 platform currently lies at 350 to 400 m below sea level. The third phase of reef growth on the Marion Plateau (MR3) is represented by small platform areas that have grown on the 350- to 400-m surface. Toward the southern Marion Plateau, part of the Great Barrier Reef overlies this third phase of carbonate-platform growth. The final, restricted phase of growth on the Marion Plateau (MR4) is represented by Marion and Saumarez reefs. Thus, the successive phases of carbonate-platform growth became progressively more restricted in area (Figs. 16D and 16E). At the present time, the top of the Marion Plateau is swept by moderately strong currents, with the result that away from the areas of modern reef growth, only thin hemipelagic sediments are accumulating in restricted areas.

Principal Factors Affecting the Evolution of Northeastern Australia

The five factors considered to be most important during development of the platforms and basins of northeastern Australia are summarized as follows:

1. *Rifting*. Late Cretaceous extension formed the Queensland-Townsville-Cato Trough rift basin system, with another apparently less-developed system extending southeast from the Queensland Trough to the Capricorn Basin. This rift system separated the continental shelf from the Queensland and Marion plateaus (Figs. 1 and 3). Continental breakup and seafloor spreading began in the Latest Cretaceous-Paleocene and ceased in the early Eocene. The main physical elements of the northeastern Australian margin thus may have existed since the early Tertiary. The rifting process has influenced how carbonate platforms developed off northeastern Australia both in a general way, by providing large shallow-water areas suitable for platform growth, and in a specific way, in the case of reefs that have grown on the corners of fault blocks or along major rift boundary faults.

2. *Subsidence*. Quantitative subsidence data have been derived from geohistory analysis of Anchor Cay 1, DSDP Site 209, Capricorn 1A, and Aquarius 1 (summarized in Davies et al., 1989; Fig. 19). Subsidence data from these wells indicate that northeastern Australia did not subside completely as a result of uniform post-rift thermal cooling, but that subsidence pulses occurred at different times.

The Anchor Cay 1 well at the northern end of the Great Barrier Reef indicates an accelerated subsidence rate of 50 m/m.y. that affected this region during the Miocene (25–5 Ma), increasing to 140 m/m.y. during the Pliocene (Fig. 19A).

DSDP Site 209, drilled in 1428 m of water on the northeastern margin of the Queensland Plateau, provides the only source of quantitative subsidence data for the plateau. The subsidence history of the plateau at this site was characterized by progressively increased rates of subsidence (Fig. 19B). An initial slow rate (20 m/m.y.) was succeeded by a markedly increased rate (40 m/m.y.) after the middle Miocene (11 Ma).

Two petroleum exploration wells (Capricorn 1A and Aquarius 1) were drilled in the Capricorn Basin, adjacent to the southern Marion Plateau. The geohistory curves for Aquarius 1 (Fig. 19C) and Capricorn 1A exhibit similar subsidence patterns: a Cretaceous to mid-Oligocene (88–30 Ma) slow subsidence phase (20 m/m.y.) was succeeded by increased subsidence (75 m/m.y.) until the middle Miocene (11 Ma). Decreased subsidence, followed by uplift during the late Miocene and early Pliocene, was succeeded by a final increased subsidence pulse (75 m/m.y.) from the mid-Pliocene. This analysis shows that the northeastern Australian carbonate platforms have developed within a variety of subsidence regimes. In addition, shallow-water reef limestones of Pliocene(?) age within the basins at depths of 1200 m indicate a substantial pulse that affected parts of the Queensland Plateau during the Pliocene.

3. *The Effects of Plate Motion on Paleoclimate*. Hot-spot and magnetostratigraphic studies (summarized in Davies et al., 1989) provide a reconstruction of Indian-Australian Plate movement throughout the Cenozoic. These studies indicate that since the end of the Eocene, when northeastern Australia was located between 29° and 44°S, the region moved almost directly north to its present-day location at between 9° and 24°S. On this basis, the Cenozoic paleolatitudes for the northeastern Australia region may be determined (Fig. 20A). This latitudinal motion should have resulted in profound climatic changes along the eastern Australian shelf, particularly because plate movement was essentially normal to developing climatic zones. Analysis of this latitudinal motion and all available paleoclimatic and paleoceanographic data (Feary et al., 1991) have allowed us to define the approximate sea-surface water temperatures for northeastern Australia throughout the Cenozoic (Fig. 20B). If correct, the following conclusions may be drawn from this curve: (1) temperatures in the earliest middle Eocene were briefly warm enough for coral reef growth; corroboration is provided by the identification of early middle Eocene larger foraminifers from the northwestern margin of the Queensland Plateau (Chaproniere, 1984) that indicate sea-surface temperatures of 18°–27°C; (2) temperatures from the late middle Eocene to the middle early Miocene were not conducive for the development of tropical carbonate platforms; (3) a tropical climate developed progressively over northeastern Australia from the early middle Miocene to the present day.

The consequences of these conclusions appear to be borne out by both the thinning of the Great Barrier Reef from north to south and the replication of the modern climate-controlled sediment facies of the eastern Australian margin in drill holes through the northern part of the Great Barrier Reef (Davies et al., 1989). However, drilling during Leg 133 indicates that the picture is more complicated and that the initiation and demise of platforms is related to both autocyclic as well as allocyclic causes.

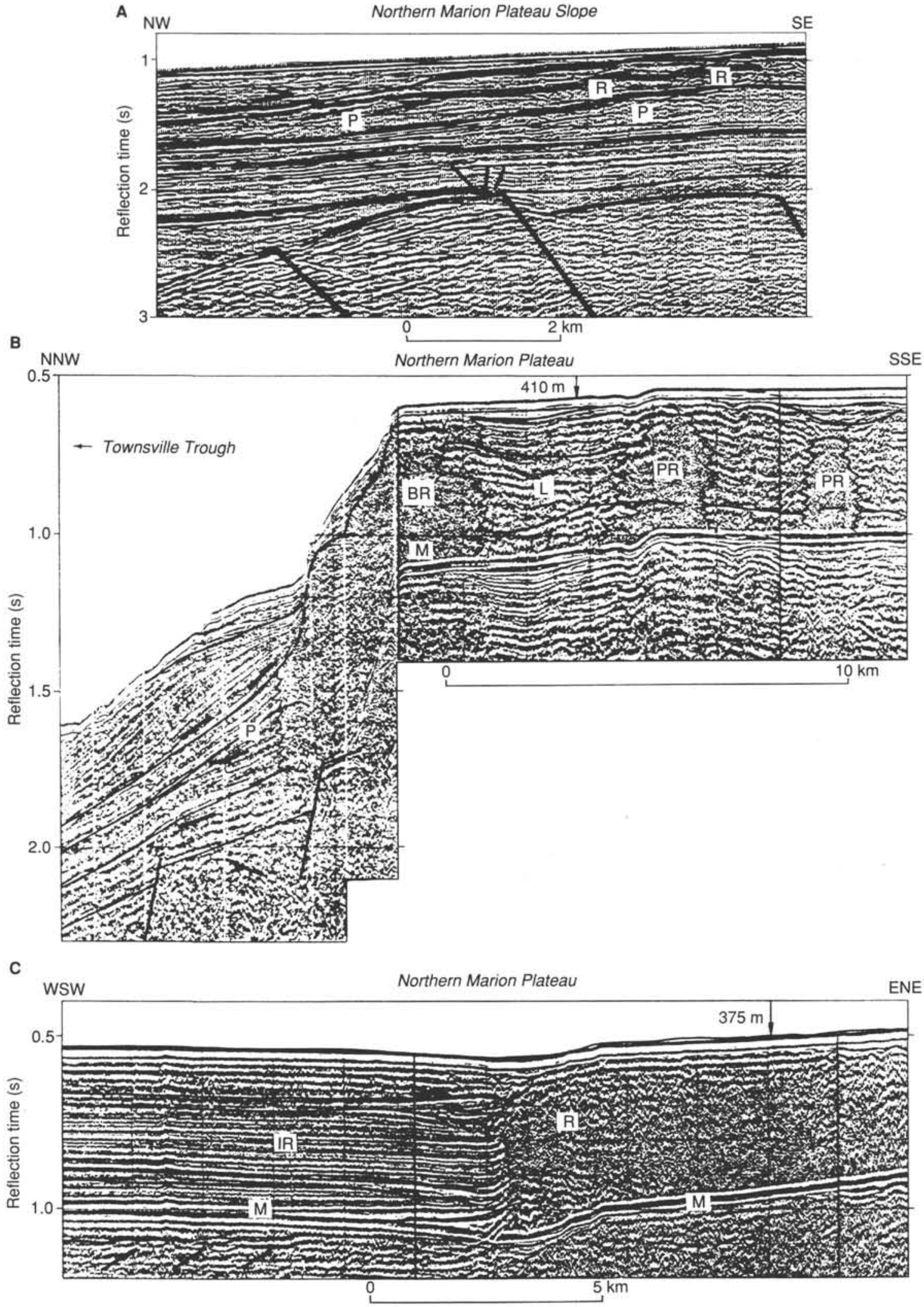


Figure 18. Seismic sections across the Marion Plateau carbonate platforms. **A.** Air-gun section across the northern margin of the Marion Plateau, showing buried reefs (R) overlying a prograding sequence (P). **B.** Water-gun section showing the MR1 platform margin adjacent to the Townsville Trough. Note the reflection-free, thick, barrier-reef (BR) and patch reef (PR) facies; fore-reef periplatform facies (P); and back-barrier, bedded, lagoonal facies (L). Note that some reflectors pass into and through the reef facies and may represent low sea-level erosional surfaces. **C.** Water-gun section across the northeastern Marion Plateau, showing development of platform.

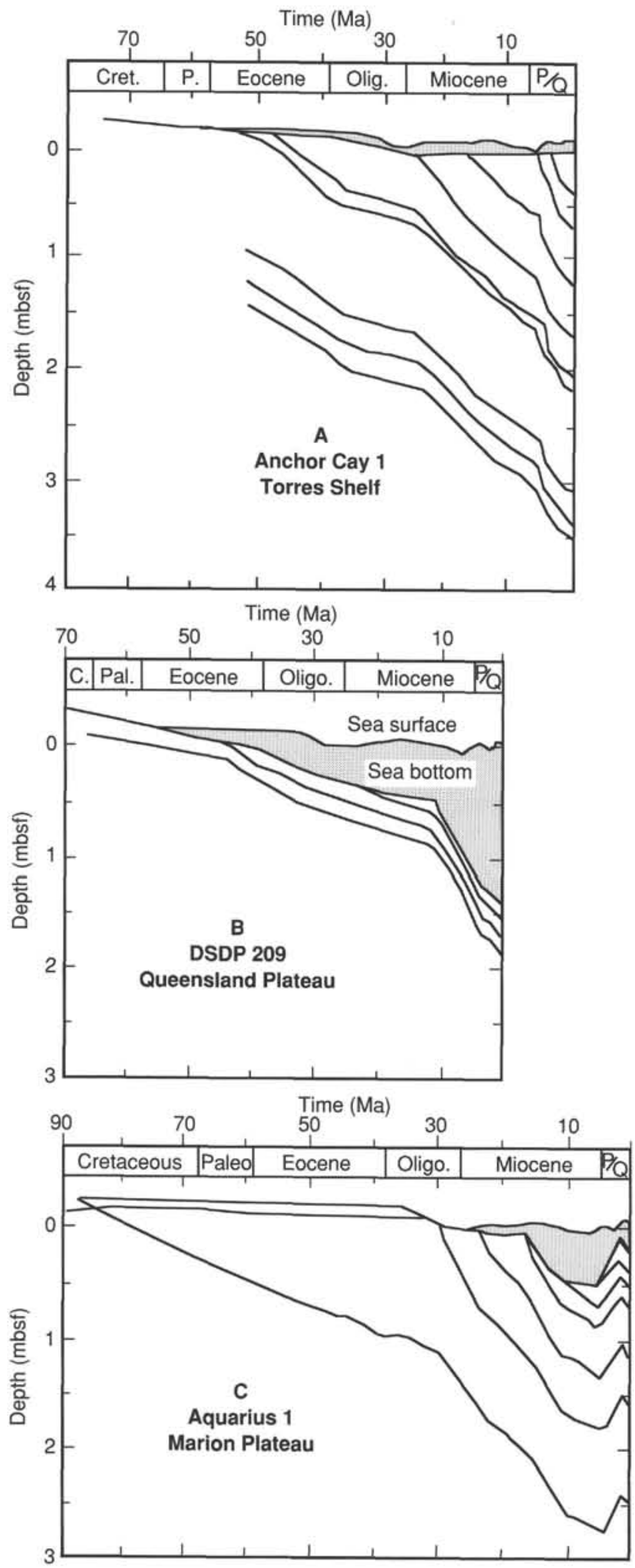


Figure 19. Geohistory plots. **A.** Anchor Cay 1. **B.** DSDP Site 209. **C.** Aquarius 1 (note that the plot for Capricorn 1A is not presented because it is essentially identical to that of Aquarius 1).

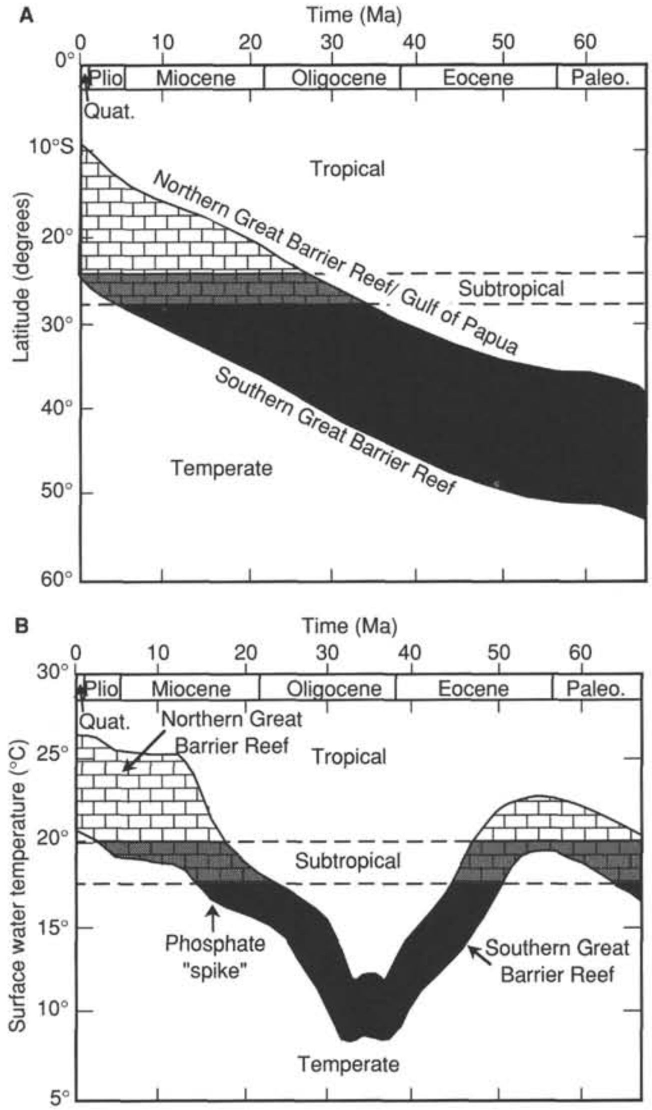


Figure 20. **A.** Projected latitudinal movement of the northeastern Australia region throughout the Cenozoic (modified after Davies et al., 1987). The northern boundary corresponds to Anchor Cay 1 (presently at 9°30′S) and the southern boundary to Heron Island (presently at 24°S). **B.** Surface-water temperature envelope for the northeastern Australian region throughout the Cenozoic, showing periods when temperatures were suitable for reef growth. The Miocene "phosphate spike," which inhibited reef growth, is also shown (Riggs, 1984).

4. *Variations in Sea Level*. The effects of variations in sea level on the development of carbonate platforms have been established for the Great Barrier Reef and for offshore marginal plateaus through seismic and sedimentologic studies. In the central Great Barrier Reef, high sea-level deposition currently is occurring either (1) as progradation of prodeltaic sediments on the inner shelf, or (2) as aggradation of the middle to outer shelf because of reef growth and inter-reef sedimentation. High sea-level reef sedimentation occurs in restricted areas and reflects both the high physical energy of the system and the transgressive/stillstand history of the Quaternary increases in sea level (Marshall and Davies, 1982, 1984; Davies, 1983; Davies and Hopley, 1983; Davies et al., 1985). The reefs are composite features composed of stacked reef facies that grew as a consequence of successive high

sea-level growth phases and separated by unconformities representing low sea-level erosion. The high physical energy of the environment restricted expansion to the leeward or backreef direction. In the inter-reef areas on the middle to outer shelf, high sea-level platform aggradation is represented by bioherms, biostromes, and a sediment blanket of varying thickness (<1–10 m) deposited on the previously exposed shelf surface (Davies and Marshall, 1985). This sediment blanket is composed of a lower, terrigenous (mud- and quartz-rich; carbonate-poor), transgressive facies, and an upper, carbonate-rich (less mud; little quartz), stillstand facies. At the present time, after 10,000 yr of transgression and stillstand, little high sea-level progradation of coastal terrigenous facies has occurred on the inner shelf. It seems likely that the terrigenous/carbonate facies couplet that occurs over wide areas of the middle to outer shelf probably is representative of high sea-level sedimentation on the Great Barrier Reef platform throughout most of the Pliocene–Pleistocene. Therefore, this couplet should have provided a source of carbonate sediments as detrital components for the slope during periods of lower sea level, during which sedimentation occurred both as aggradation of fluvial and siliciclastic/carbonate mixtures on the middle to outer shelf and as progradational shelf-edge deltas composed of terrigenous/carbonate sand and sandy mud on the upper slope. In summary, rising and high sea-level periods in the central Great Barrier Reef were characterized by both reefal and inter-reef carbonate deposition, with siliciclastic deposition restricted largely to the inner shelf. In contrast, falling and low sea-level periods were characterized by fluvial or shallow-marine, mixed, siliciclastic/carbonate aggradation on the outer shelf and progradation on the upper slope.

The marginal plateaus essentially were isolated from terrigenous influx, and accordingly, their facies response to variations in sea level must have been different. Although high sea-level periods in these areas also are marked by carbonate aggradation, low sea-level periods are characterized by unconformities representing exposure of the previous reef surfaces. This response to variations in sea level can be used to interpret the evolutionary history of the Cenozoic sequences on the marginal plateaus by attributing unconformities within the carbonate platforms to low episodes and by attributing reef sequences to periods of high sea level. In the absence of a specific Cenozoic sea-level curve for northeastern Australia, the global sea-level curve proposed by Haq et al. (1987) can be used. On this basis, episodes of reef growth during the early middle Miocene (QR1, MR1—see Fig. 16), the middle to late Miocene (QR2, MR2), the Pliocene-Pleistocene (QR3, MR3), and the Quaternary (QR4, MR4) are separated by unconformities representing erosion during the late middle Miocene (1–2), late late Miocene (2–3), and the Quaternary (3–4).

5. *Collision*. If a passive margin moves into a compressional tectonic regime as a result of plate motion, carbonate platforms developing on that margin will be profoundly affected. The northern and northeastern Australian margin has undergone just such a collision since the late Oligocene. The effects of collision were defined by Pigram et al. (1989) and need not be reiterated here. However, these effects are manifest in the Leg 133 study area, probably as subsidence and drowning of the platforms.

Drilling Objectives of Leg 133—Northeastern Australia

Drilling on the northeastern Australian margin has defined sea level, paleoclimate, and paleoceanographic signatures in upper Paleogene, Neogene, and Pliocene-Pleistocene sediments on a passive margin dominated by both mixed siliciclastic/carbonate and pure carbonate sediments. In addition, Leg 133 results have added substantially to our understanding of the evolution of carbonate platforms at different stages of development. When generating new data and ideas about sea level, paleoclimate, oceanography, and platform evolution, our objectives were as follows:

1. To define the sedimentary response to global changes in sea level in the late Cenozoic and Quaternary. Two approaches were applied during our study of shelf-margin coastal onlap sequences and marginal plateau reef stratigraphy. Along the margins of the Great Barrier Reef, seismic data suggest that low sea-level, shelf-edge siliciclastic, prograding, and middle and toe-of-slope fans alternate with high sea-level onlapping sequences and are overlain by high and low sea-level aggradational couplets that correlate with periods of reef growth. Our drilling of such sequences provided the ground truth essential for testing the major tenets of the hypothesis for global sea level. Sites on the upper slope near the shelf hinge defined a shallow-water sea-level signal, whereas those on the lower slope and in the Queensland Trough defined the related shelf-to-basin stratigraphy and deep-water signal. Sites on the Queensland and Marion plateaus (Fig. 1) revealed Miocene and Pliocene reefs growing in oceanic situations.
2. To define the influence of paleochemistry, paleoclimate, and paleoceanography on the initiation, growth, and demise of carbonate platforms and the effect of shifting from temperate to tropical latitudes (or vice versa) as a result of plate motion on the biological and lithological facies types in an environment analogous to the Jurassic eastern margin of the United States.

These objectives are best achieved in pure carbonates where climatic and oceanographic signatures have been preserved. Sites drilled on the Queensland and Marion plateaus (Fig. 1) were aimed at study of the Neogene and Pliocene-Pleistocene reefal and periplatform sequences. Sites in adjacent troughs were to define relationships among facies, climate, and oceanography throughout the late Paleogene and Neogene.

In addition to our two primary objectives, the drill sites also were chosen (1) to define the slope-to-basin variations on both sides of a rift basin for evaluating facies and stratigraphic models of passive margin evolution and (2) to define the diagenetic history of contrasting mixed carbonate/siliciclastic and pure carbonate margins in an environment considered to be undersaturated with respect to aragonite and high-magnesium calcite at relatively shallow-water depths. The 16 sites drilled were located along the two transects shown in Figures 9 and 10: Sites 811 through 818 cross the Townsville Trough along the north-to-south transect from the Queensland Plateau to the Marion Plateau, and Sites 819 through 824 cross the Queensland Trough on the east-to-west transect from the Great Barrier Reef slope to the Queensland Plateau. All sites were located with multichannel seismic data acquired and processed by the Australian Bureau of Mineral Resources, Geology and Geophysics.

REFERENCES

Andrews, J. E., Packham, G., et al., 1975. *Init. Repts. DSDP,* 30: Washington (U.S. Govt. Printing Office).

Austin, J. A., Jr., Schlager, W., et al., 1986. *Proc. ODP, Init. Repts.,* 101: College Station, TX (Ocean Drilling Program).

Burns, R. E., Andrews, J. E., et al., 1973. *Init. Repts. DSDP,* 21: Washington (U.S. Govt. Printing Office).

Chaproniere, G.C.H., 1984. Oligocene and Miocene larger Foraminiferida from Australia and New Zealand. *BMR Australia Bull.,* 188:1–98.

Davies, P. J., 1977. Modern reef growth—Great Barrier Reef. *Proc. 3rd Int. Coral Reef Symp., Miami,* 2:325–330.

_______, 1983. Reef growth. In Barnes, D. J. (Ed.), *Perspectives on Coral Reefs: Australian Institute of Marine Science*: Canberra (Brian Clouston), 69–106.

Davies, P. J., and Hopley, D., 1983. Growth fabrics and growth rates of Holocene reefs in the Great Barrier Reef. *BMR J. Austral. Geol. Geophys.,* 8:237–251.

Davies, P. J., and Marshall, J. F., 1985. *Halimeda* bioherms—low energy reefs, northern Great Barrier Reef. *Proc. 5th Int. Coral Reef Symp., Tahiti,* 5:1–7.

Davies, P. J., Marshall, J. F., and Hopley, D., 1985. Relationships between reef growth and sea level rise in the Great Barrier Reef. *Proc. 5th Int. Coral Reef Symp., Tahiti,* 3:95–103.

Davies, P. J., and Montaggioni, L., 1985. Reef growth and sea-level change: the environmental signature. *Proc. 5th Int. Coral Reef Symp., Tahiti,* 3:477–515.

Davies, P. J., Symonds, P. A., et al., 1988. *Rig Seismic* Research Cruises 4 and 5: northeast Australia post-cruise report. *BMR Australia Rept.,* 281.

Davies, P. J., Symonds, P. A., Feary, D. A., and Pigram, C. J., 1987. Horizontal plate motion: a key allocyclic factor in the evolution of the Great Barrier Reef. *Science,* 238:1697–1700.

_______, 1988. Facies models in exploration—the carbonate platforms of northeast Australia. *APEA J.,* 28.

_______, 1989. The evolution of the carbonate platforms of northeast Australia. *Soc. Econ. Paleontol. Mineral., Spec. Publ.,* 44:233–258.

Done, T. J., 1982. Patterns in the distributions of coral communities across the central Great Barrier Reef. *Coral Reefs,* 1:95–108.

Eberli, G. P., and Ginsburg, R. N., 1989. Cenozoic progradation of the north western Great Bahamas Bank. *Soc. Econ. Paleontol. Mineral., Spec. Publ.,* 44:339–351.

Edwards, A. R., 1975. Southwest Pacific Cainozoic paleogeography and an integrated Neogene palecirculation model. *In* Andrews, J. E., Packham, G., et al., *Init. Repts. DSDP,* 30: Washington (U.S. Govt. Printing Office), 667–684.

Ericson, E. K., 1976. The Capricorn Basin. *In* Leslie, R. B., Evans, H. J., and Knight, C. L. (Eds.), *Economic Geology of Australia and Papua New Guinea,* Vol. 3, Petroleum: Canberra (Australasian Inst. of Mining and Metallurgy), Monogr., 7:464–473.

Ewing, W., Hawkins, L. V., and Ludwig, W. J., 1970. Crustal structure of the Coral Sea. *J. Geophys. Res.,* 75:1953–1962.

Fairbridge, R. W., 1950. Recent and Pleistocene coral reefs of Australia. *J. Geol.,* 58:330–401.

Falvey, D. A., and Taylor, L.W.H., 1974. Queensland Plateau and Coral Sea Basin: structural and time-stratigraphic patterns. *Bull. Australian Soc. Explor. Geophys.,* 5:123–126.

Falvey, D. A., 1972. The natural and origin of marglnal plateaus and adjacent ocean basins off northern Australia [Ph.D. thesis]. Univ. of New South Wales, Australia.

Feary, D. A., Davies, P. J., Pigram, C. J., and Symonds, P. A., 1991. Climatic evolution and control on carbonate deposition in northeast Australia. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 89:341–361.

Gardner, J. F., 1970. Submarine geology of the western Coral Sea. *Geol. Soc. Am. Bull.,* 81:2599–2614.

Ginsburg, R. N., and James, N. P., 1974. Holocene carbonate sediments of continental shelves. *In* Burk, C. A., and Drake, C. L. (Eds.), *Continental Margins:* Berlin (Springer-Verlag), 137–154.

Haq, B. U., Hardenbol, J., and Vail, P. R., 1987. Chronology of fluctuating sea levels since the Triassic: *Science,* 235:1156–1166.

Hayes, D. E., and Ringis, J., 1973. Seafloor spreading in the Tasman Sea: *Nature,* 243:454–458.

Hill, D., and Denmead, A. K. (Eds.), 1960. *Geology of Queensland.* J. Geol. Soc. Australia, 7:1–474.

Hollister, C. D., Ewing, J. I., et al., 1972. *Init. Repts. DSDP,* 11: Washington (U.S. Govt. Printing Office).

Hopley, D., 1982. *The Geomorphology of the Great Barrier Reef: Quaternary Development of Coral Reefs:* New York (Wiley).

Jansa, L. F., 1981. Mesozoic carbonate platforms and banks of the eastern North American margin. *Mar. Geol.,* 44:97–117.

Kauffman, E. G., 1984. Paleobiogeography and evolutionary response dynamic in the Cretaceous Western Interior Seaway of North America. *In* Westermann, G.E.G. (Ed.), *Jurassic-Cretaceous Biochronology and Paleogeography of North America.* Geol. Assoc. Can. Spec. Pap., 27:273–306.

Kennett, J. P., 1977. Cenozoic evolution of Antarctic glaciation, the circum-Antarctic Ocean, and their impact on global paleoceanography. *J. Geophys. Res.,* 82:3843–3860.

Kennett, J. P., Burns, R. E., Andrews, J. E., Churkin, M., Jr., Davies, T. A., Dumitrica, P., Edwards, A. R., Galehouse, J. S., Packham, G. H., van der Lingen, G. J., 1972. Australian-Antarctic continental drift and paleocirculation changes and Oligocene deep-sea erosion. *Nature, Phys. Sci.,* 239:51–55.

Lloyd, A. R., 1973. Foraminifera of the Great Barrier Reef bores. *In* Jones, 0. A., and Endean R. (Eds.), *Biology and Geology of Coral Reefs* (Vol. 1): New York (Academic Press), 347–366.

Marshall, J. F., 1977. Marine geology of the Capricorn Channel area. *BMR Australia Bull.,* 163.

_______, 1983. The Pleistocene foundations of the Great Barrier Reef. *In* Baker, J. T., Carter, R. M., Sammarco, P. W., and Stark, K. P. (Eds.), *Proc. Inaugural Great Barrier Reef Conf.*: Townsville (James Cook Univ. Press), 123–128.

Marshall, J. F., and Davies, P. J., 1978. Skeletal carbonate variation on the continental shelf of eastern Australia. *BMR J. Australian Geol. Geophys.,* 3:85–92.

_______, 1982. Internal structure and Holocene evolution of One Tree Reef, southern Great Barrier Reef. *Coral Reefs,* 1:21–28.

_______, 1984. Last interglacial reef growth beneath modern reefs in the southern Great Barrier Reef: *Nature,* 307:44–46.

Maxwell, W.G.H., 1968. *Atlas of the Great Barrier Reef:* Amsterdam (Elsevier).

Mutter, J. C., 1977. The Queensland Plateau. *BMR Geol. Geophys. Bull.,* 179.

Mutter, J. C., and Karner, G. D., 1980. The continental margin off northeast Australia. *In* Henderson, R. A., and Stephenson, P. J. (Eds.), *The Geology and Geophysics of Northeast Australia:* Brisbane (Geol. Soc. of Australia, Queensland Div.), 47–69.

Oppel, T. W., 1969. *Tenneco-Signal Anchor Cay No. 1 Offshore Queensland, Well Completion Report*: Houston (Tenneco Oil Co.) (in-house publ.).

Orme, G. R., 1977. The Coral Sea Plateau—a major reef province. *In Jones, O. A., and Endean, R. (Eds.), Biology and Geology of Coral Reefs (Vol. 4): New York (Academic Press), 267–306.*

Palmieri, V., 1971. Tertiary subsurface biostratigraphy of the Capricorn Basin. Geol. Surv. Queensland Rept., 52.

_______, 1974. Correlation and environmental trends of the subsurface Tertiary Capricorn Basin. *Geol. Surv. Queensland Rept.,* 86.

Pigram, P. J., Davies, P. J., Feary, D. A., and Symonds, P. A., 1989. Tectonic controls on carbonate platform evolution in southern Papua New Guinea: Passive margin to Foreland Basin. *Geology,* 17:199–202.

Read, J. F., 1985. Carbonate platform facies models. *AAPG Bull.,* 69:1–21.

Riggs, S. R., 1984. Paleoceanographic model of Neogene phosphorite deposition, U.S. Atlantic continental margin. *Science,* 223:123–131.

Richards, H. S., and Hill, D., 1942. Great Barrier Reef bores, 1926 and 1937. Descriptions, analyses and interpretations. *Repts. Great Barrier Reef Committee,* 5:1–122.

Schlager, W., and Ginsburg, R. N., 1981. Bahama carbonate platforms - the deep and the past. *In* Cita, M. B., and Ryan, W.B.F. (Eds.), *Carbonate Platforms of the Passive-Type Continental Margins, Present and Past.* Mar. Geol., 44:1–24.

Shaw, R. D., 1978. Seafloor spreading in the Tasman Sea: a Lord Howe Rise-eastern Australian reconstruction. *Australian Soc. Explor. Geophys. Bull.,* 9:75–81.

Sheridan, R. E., Crosby, J. T., Bryan, G. M., and Stoffa, P. L., 1981. Stratigraphy and structure of southern Blake Plateau, northern Florida Straits, and northern Bahama Platform from multichannel seismic reflection data. *AAPG Bull.,* 65:2571–2593.

Symonds, P. A., 1983. Relation between continental shelf and margin development—central and northern Great Barrier Reef. *In* Baker, J. T., Carter, R. M., Sammarco, P. W., and Stark, K. P. (Eds.), *Proc. Inaugural Great Barrier Reef Conf.:* Townsville (James Cook Univ. Press), 151–157.

Symonds, P. A., Davies, P. J., and Parisi, A., 1983. Structure and stratigraphy of the central Great Barrier Reef. *BMR J. Australian Geol. Geophys.,* 8:277–291.

Symonds, P. A., Fritsch, J., and Schluter, H. U., 1984. Continental margin around the western Coral Sea Basin: structural elements, seismic sequences and petroleum geological aspects. *In* Watson, S. T. (Ed.), *Trans. 3rd Circum-Pacific Energy and Mineral Resources Conf., Hawaii:* Tulsa (Am. Assoc. Pet. Geol.), 243–252.

Tallis, N. C., 1975. Development of the Tertiary offshore Papuan Basin. *APEA J.*, 15:55–60.

Tanner, J. J., 1969. The ancestral Great Barrier Reef in the Gulf of Papua. *U.N. Economic Commission for Asia and the Far East, Mineral Resour. Develop. Ser.*, 41:283.

Taylor, L.W.H., 1975. Depositional and tectonic patterns in the western Coral Sea. *Bull. Australian Soc. Explor. Geophys.*, 6:33–35.

———, 1977. The western Coral Sea: sedimentation and tectonics [Ph.D. thesis]. Univ. of Sydney, Australia.

Taylor, L.W.H., and Falvey, D. A., 1977. Queensland Plateau and Coral Sea Basin: stratigraphy, structure and tectonics. *APEA J.*, 17:13–29.

Veeh, H. H., and Veevers, J. J., 1970. Sea level at -175 m off the Great Barrier Reef 13,600 to 17,000 years ago. *Nature*, 226:536–537.

Weissel, J. K., and Hayes, D. E., 1977. Evolution of the Tasman Sea reappraised. *Earth Planet. Sci. Lett.*, 36:77–84.

Weissel, J. K., and Watts, A. B. 1979. Tectonic evolution of the Coral Sea Basin. *J. Geophys. Res.*, 84:4572–4582.

Wilson, J. L., 1975. *Carbonate Facies in Geologic History:* Berlin (Springer-Verlag).

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