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STRUCTURAL AND STRATIGRAPHIC EVOLUTION OF THE TOWNSVILLE BASIN, TOWNSVILLE TROUGH, OFFSHORE NORTHEASTERN AUSTRALIA

by

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SUMMARY

The Townsville Basin (new name) is an extensional basin which underlies the Townsville Trough, an east-west trending bathymetric feature separating the Marion and Queensland Plateaus off northeastern Australia. The present study forms part of a wider study of the regional stratigraphic and structural framework of Australia's northeastern margin undertaken as part of AGSO's Continental Margin Program. It is the first integrated study of a regional seismic grid across the Townsville Basin, and details the results of the interpretation of 5667 km of AGSO and industry seismic reflection data across the area.

With the exception of several ODP holes which intersected Late Miocene to Recent sediments, there is no direct control on the stratigraphy of the Townsville Basin. The maximum sediment thickness in the basin reaches approximately 4.5 s TWT (≈ 6.5 km). The sedimentary fill can be subdivided into two main seismic megasequences, a synrift and a sag-phase megasequence. The synrift megasequence has a maximum thickness of up to 2 s TWT (≈ 2 km) and occurs in fault-controlled depocentres. The sag-phase megasequence occurs as drape fill and reaches a thickness of up to 2.6 s TWT (≈ 3.8 km). The two megasequences have been subdivided into regionally mappable sequences. An early synrift sequence can be distinguished in deeper half-graben. This is overlain by a regionally more extensive synrift sequence and a late-rift sequence. The early sag-phase sequences are thin or absent in the western Townsville Basin, but thicken into the central basin. The three overlying sequences consist of terrigenous and calcareous sediments of Neogene age, and are separated from the underlying section by a ?mid-Oligocene regional unconformity.

Depth to basement, total sediment thickness, synrift isopach and gravity data all indicate that the underlying rift-forming structures compartmentalise the basin into distinct sub-basins which are separated by major north-northwest to northwest-trending transverse structural zones. These transverse structures are associated with distinct changes in structural trends and are thought to represent major pre-existing crustal-scale terrane boundaries or shear zones. Overall, the structural style of the Townsville Basin is characterised by a half-graben morphology with occasional, apparently asymmetric graben structures. The half-graben are bounded by major rotational normal faults and are typically composed of a number of tilt blocks. The basin boundaries are defined by switches between steep normal faults and gently dipping hinges. An important feature of the Townsville Basin is the presence of northwest to north-northwest trending lineaments which generally offset half-graben bounding faults in a right-lateral sense along the basin margins. The rotational normal faults are compartmentalised by these lineaments which are interpreted as transfer fault zones or accommodation zones. Local thickening of late

rift sediments in the opposite direction to that of the early rift sediments probably reflects at least two significant extensional structuring events during basin formation. A younger wrenching event, which occurred during early sag-phase sedimentation, was followed by ?Late Miocene to Early Pliocene reactivation events.

The structural interpretation of the Townsville Basin confirms that it formed part of a complex rift system of probable Late Jurassic to Early Cretaceous age. This system formed through oblique extension which utilised pre-existing Palaeozoic structural trends. Comparison with interpreted structural trends of the adjacent Queensland Basin (Queensland Trough) supports the suggestion that formation of both basins was independent of the tectonism related to seafloor spreading in the Tasman and Coral Sea Basins.

INTRODUCTION

The Townsville Trough is an east-west trending bathymetric depression that separates the Marion and Queensland Plateaus off northeastern Australia (Fig. 1). It is located between 148°35'E and east of 153°E and ranges in width from 20 km in the west, to 120 km in the east. The term 'Townsville Trough' has been used to describe both the bathymetric feature and the structural feature which underlies it (e.g. Taylor & Falvey, 1977; Symonds et al., 1984; Symonds & Davies, 1988). The term Townsville Basin is used herein to describe the rift-related depocentre (Fig. 2), and the term Townsville Trough is retained for the bathymetric feature between the Marion and Queensland Plateaus. Similarly, the depocentre underlying the Queensland Trough (e.g. Falvey & Taylor, 1974; Symonds et al., 1984; Scott, 1993, 1994), is referred to as the Queensland Basin.

The present study forms part of a wider study of the regional stratigraphic and structural framework of Australia's northeastern continental margin, conducted as part of the Australian Geological Survey's (AGSO) Continental Margin Program. It is the first integrated study of a regional seismic grid across the Townsville Basin, and details the results of the interpretation of 5667 km of AGSO and industry seismic reflection data across the area.

Regional Setting

The main regional physiographic features of the northeastern Australian margin are illustrated in Figure 1. 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 continental slope along the eastern margin of the Great Barrier Reef is steep and incised by canyons in its northern part, but decreases in gradient in the vicinity of Townsville and becomes gentle adjacent to the Marion Plateau.

The Marion Plateau is the smallest of the marginal plateaus in the region and extends as a terrace beyond the continental shelf (Fig. 1). It deepens from about 200 to 300 m water depth near the Great Barrier Reef, to about 500 m in the

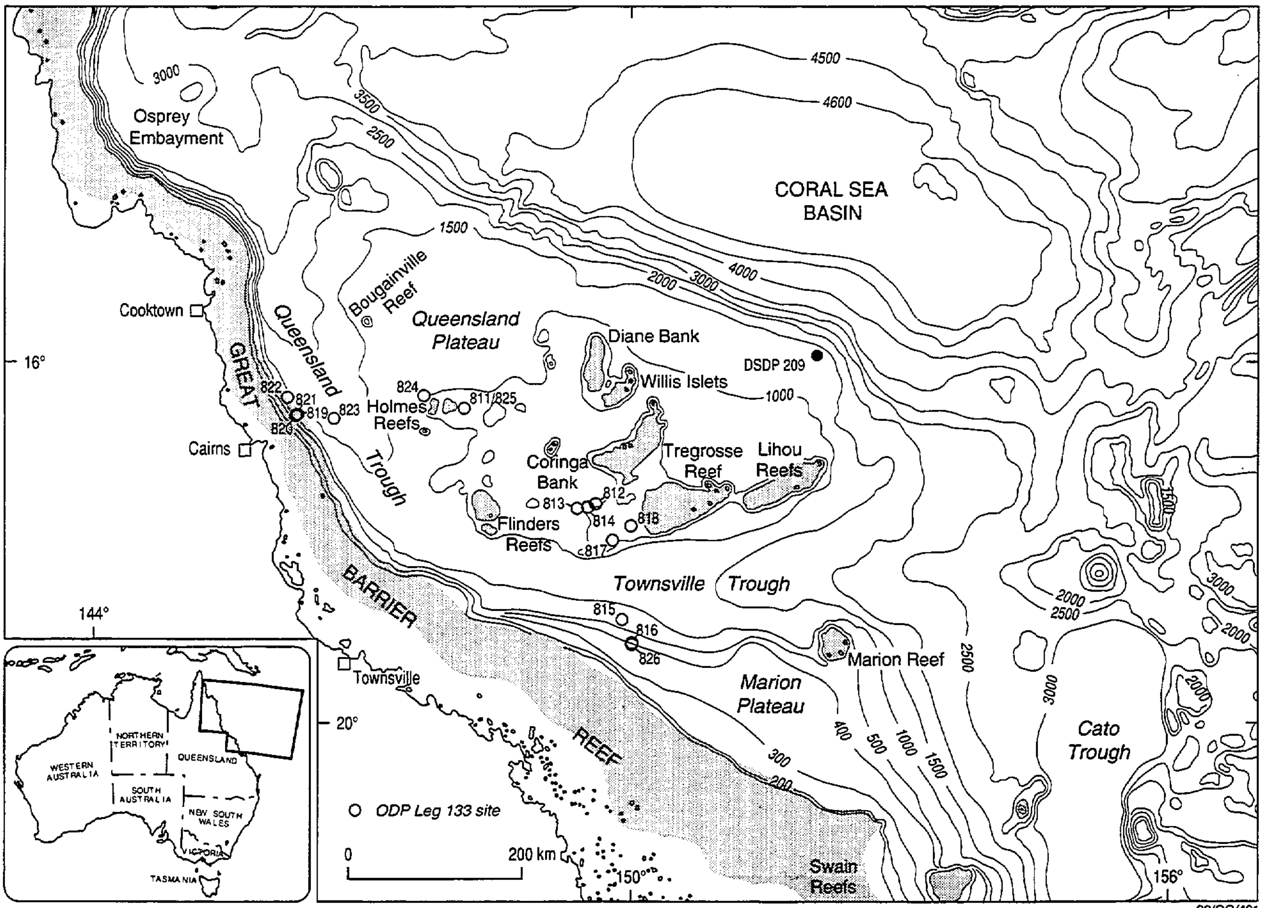

Figure 1: Location map showing the major physiographic features of the northeast Australian continental margin (after Taylor, 1977, and Davies et al., 1989). 811-826 refer to ODP Leg 133 drilling sites.

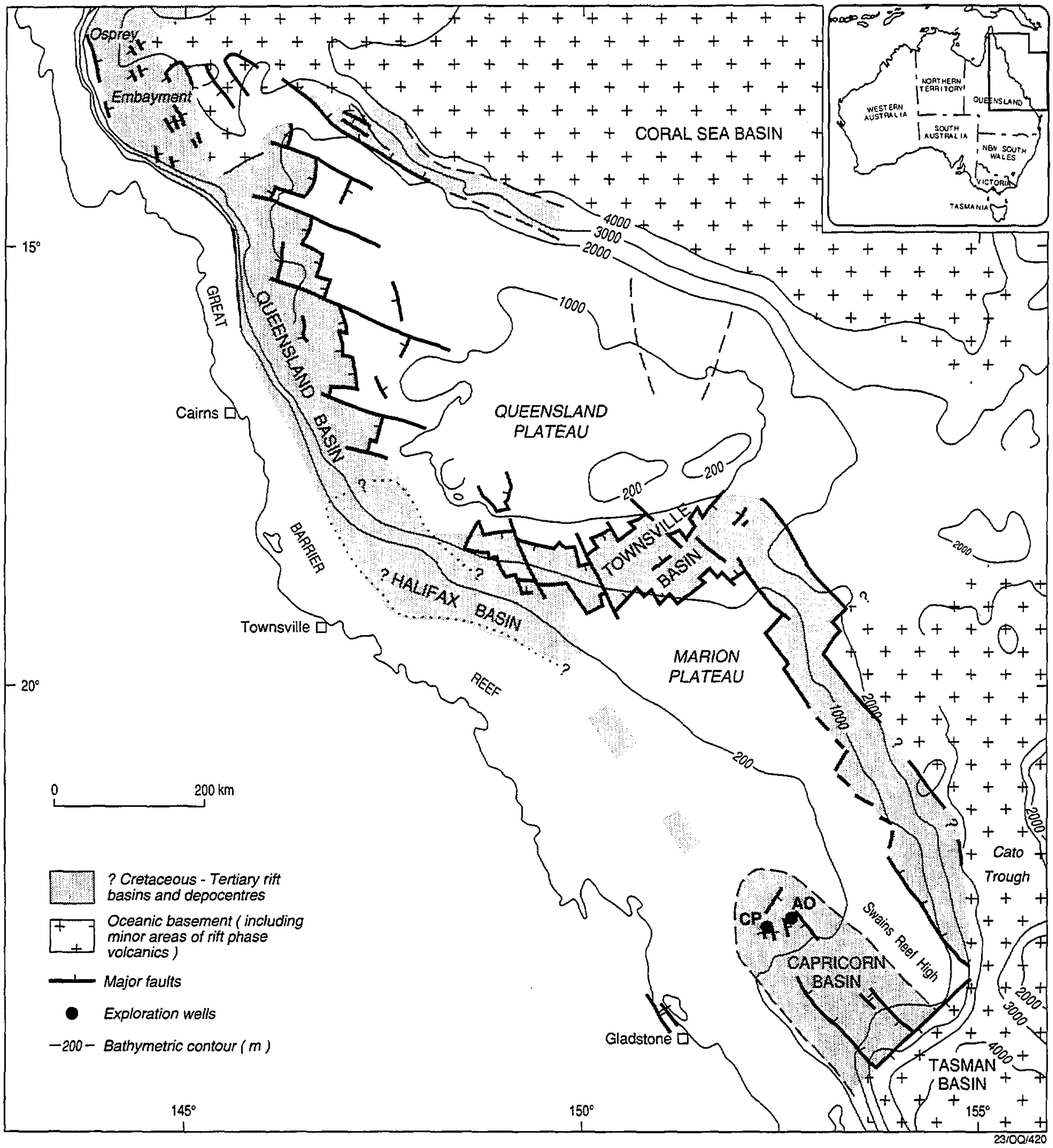

Figure 2: Map showing the major structural features of the northeastern Australian continental margin (modified from Davies et al., 1989); Queensland Basin trends are based on Scott (1994); CP = Capricorn 1A; AQ = Aquarius 1.

vicinity of Marion Reef at its northeastern corner. The north-northwest trending landward margin has a slope of moderate gradient, extending southwards to approximately 22°S. The Queensland Plateau is the largest marginal plateau of the Australian continental margin. The plateau is roughly triangular and lies at an average water depth of 1100 m. Extensive reef growth occurs on the plateau, particularly along its southern margin. Slopes are generally steep with extensive canyoning. Its western margin trends north-northwest, its northeastern margin facing the Coral Sea Basin trends northwest, and its southern margin trends east-west. The western and southern margins are both bounded by linear bathymetric lows, the Queensland and Townsville Troughs, respectively. Both the Queensland and Marion Plateaus are considered to be underlain by eroded basement platforms composed of Early Palaeozoic rocks of the Tasman Fold Belt, with north-northwest trending structural lineations (Taylor & Falvey, 1977; Mutter & Karner, 1980; Symonds et al., 1984).

The Townsville Trough has a symmetric U-shaped profile which is maintained over most of its length. Water depths along the central axis vary from 1100 to 2000 m, deepening to the east where the Townsville Trough merges to the southeast into the Cato Trough (Enclosure 1). To the east-northeast it branches into a complex north-trending trough system which eventually feeds into the southeastern Coral Sea Basin. The Queensland Trough trends north-northwest and has a relatively smooth, flat floor which deepens in a stepwise fashion northwards from about 1100 m at its junction with the Townsville Trough to about 2800 m at its junction with the Osprey Embayment. Both the Townsville and Queensland Troughs are underlain by rift basins here referred to as the Townsville and Queensland Basins, respectively.

Two styles of basin development can be identified along the central part of the northeast Australian margin. The first style consists of structurally controlled, intracratonic downwarps containing mainly clastic terrestrial to paralic sediments, including Middle Jurassic to Early Cretaceous coal measures (the Laura, Styx and Maryborough Basins), that straddle the coast. The second style consists of a series of rift basins, which lie beneath the Queensland and Townsville Troughs, the western Queensland Plateau and the slope adjacent to the eastern Marion Plateau. They are thought to be related to continental margin development, and to contain Cretaceous and Tertiary sediments. The Townsville Basin is generally considered to belong to this style, but could be underpinned by pre-rift section related to the earlier, intracratonic phase.

The Townsville Basin has been recognised as part of a complex structural association of rift troughs and marginal plateaus extending along Australia's northeastern margin (Fig. 2). Mutter (1975,1977) and Mutter & Karner (1978) argued that there was little evidence for the pre-breakup, rift-valley, or taphrogenic phase of development normally associated with continental rifting, beneath the continental margin around the Coral Sea Basin. Falvey & Taylor (1974), Taylor (1977) and Taylor & Falvey (1977), however, suggested that continental fragmentation in the region closely followed the usual sequence of events for the development of 'Atlantic-type' margins, and they inferred the presence of 'rift-valley' sequences beneath the Queensland and Townsville Troughs. Mutter & Karner (1980) concluded that the distribution of the marginal plateaus and troughs, and the geometry of the continent-ocean boundaries in the area, may have resulted from the development of a series of interconnected, three-branch rift systems, as described by Burke & Dewey (1973). Symonds et al. (1984) suggested that, in general, the development of the northeast Australian continental margin followed the typical sequence of passive continental margin evolution from uplift, through rifting accompanied by volcanism, to seafloor spreading in one of the arms of a complex rift basin system encompassing the Queensland Plateau.

These models all suggest that the formation of the Townsville and Queensland Basins was related to extensional phases in the Early to Late Cretaceous, which led ultimately to seafloor spreading in the Cato Trough to the southeast, and later to spreading in the Coral Sea to the north. However, more recently, Symonds & Davies (1988), Symonds et al. (1987, 1988) and Falvey et al. (1990) argued that the northwest-southeast, slightly oblique extension, which apparently initiated the Townsville and Queensland Basins, was independent from the northeast—southwest and east-northeast—west-southwest directed extensional events that led to seafloor spreading in the adjacent ocean basins. They suggested that deformation associated with these latter events may have reactivated and overprinted the older structures. Similarly, in a more detailed study of the

Queensland Basin, Scott (1993) also concluded that the basin formed as a result of oblique extension which predated and was kinematically independent from tectonism in adjacent spreading centres.

Data

Figure 3 and Enclosure 2 show the location of the 5667 km multichannel seismic grid interpreted for this study. Survey 50 was acquired by AGSO (formerly the Bureau of Mineral Resources - BMR) in 1985 as 11 lines which form a zigzag pattern across the Townsville Trough, connected by one tie line through the centre of the trough. Survey 76 (47 lines) was shot by AGSO (BMR) in 1987 in a more or less rectangular grid of north-northwest - south-southeast and east-northeast - west-southwest lines with a grid spacing of less than 10 km to more than 60 km. The survey also includes three southwest - northeast lines across the eastern margin of the Marion Plateau into the Cato Trough. In addition, two long northwest-southeast lines, acquired for Shell in 1973-1974 (Survey 73), cross the central Townsville Trough, and three northeast-southwest lines and one northwest-southeast line, shot by GSI in 1979 (Survey 79), are located at the junction of the Townsville and Queensland Troughs as part of a group shoot over the Queensland Trough. The resulting grid spacing for the survey area is thus highly variable (Fig. 3, Enclosure 2). The largely unprocessed sparker data from the original Continental Margin Survey conducted by BMR in 1971 and the high resolution Survey 75 were not interpreted in detail but were used to resolve specific problems in areas with sparse data. Acquisition details and line kilometres interpreted for each survey are given in Table 1.

Magnetic and gravity data were collected on all AGSO/BMR surveys. A two-ship refraction survey was run cooperatively by the Lamont-Doherty Geological Observatory and the University of New South Wales in 1967. Analyses of the refraction data were published by J. Ewing et al. (1970) and M. Ewing et al. (1970) and have subsequently been used by Gardner (1970), Falvey (1972), and Taylor and Falvey (1977). Three lines from this refraction survey tie into the seismic grid interpreted for this study (Fig. 3).

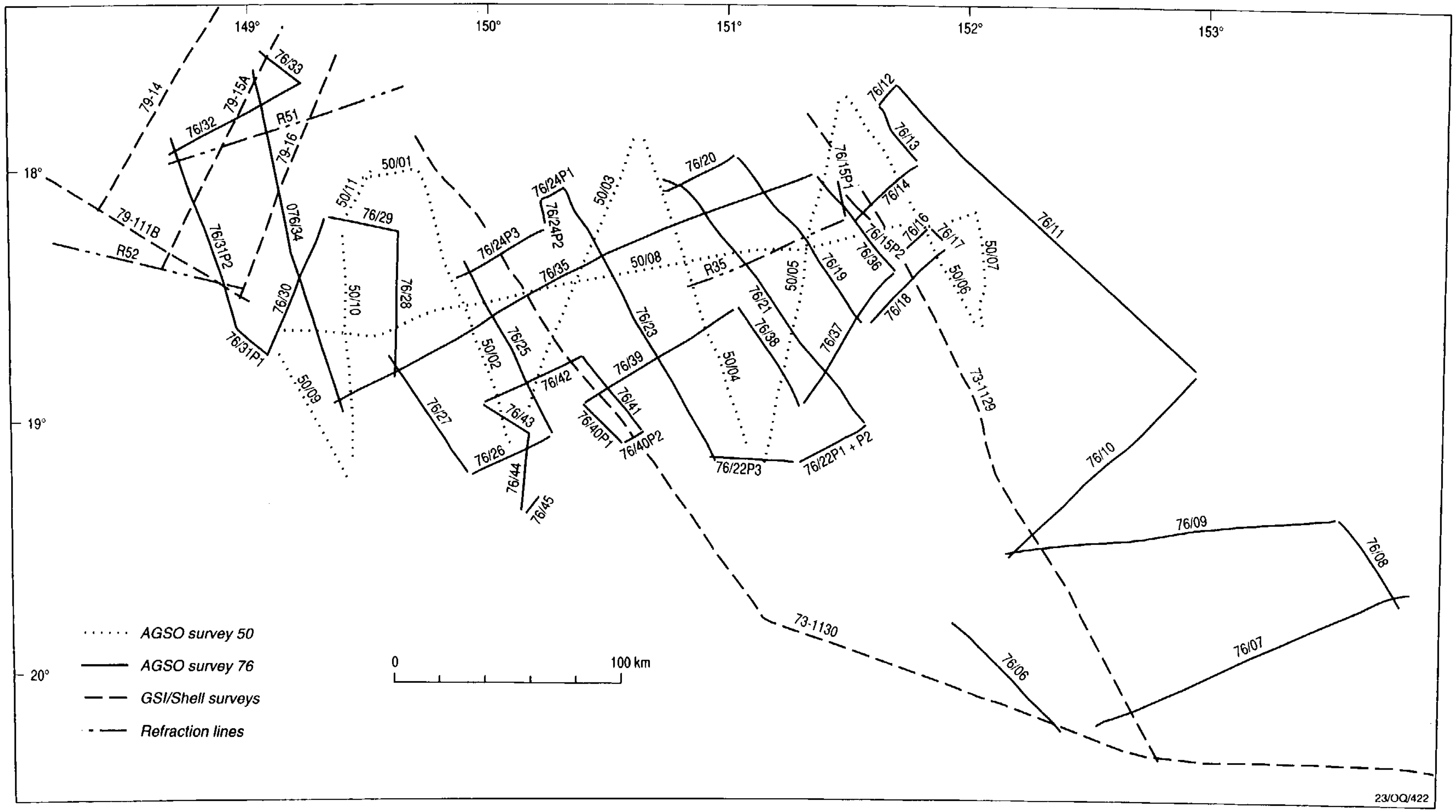

Figure 3: Location map showing seismic grid interpreted for this study.

Table 1: Seismic reflection surveys across the Townsville Basin area since 1970.

Survey No.	Year	Company	Vessel	Streamer Channels	Group Length	Source	CDP Fold	Total Line Length Interpreted (km)	Record Length (s TWT)
13/14	1971	BMR	MV Hamme	6	50m	4 x 30 KJ Sparker	6	*	not processed
(73)	1973-1974	Shell	MV Eugene McDermott	48	50m	1200 cu-inch airguns	24	957	6-7
(79)	1979	GSI	MV Eugene McDermott	48	66m	27.76 / airguns	24	482	6-7
50	1985	BMR	RV Rig Seismic	48	50m	2 x 500 cu-inch airguns	24	1323	7
75	1987	BMR	RV Rig Seismic	24	12.5/25m	1.31 / watergun	24	*	4
76	1987	BMR	RV Rig Seismic	48	50m	20 x 2.62 / airguns	24	2905	10

* Not interpreted as part of present study

Method

Detailed interpretations of seismic profiles were digitised (Enclosures 15-18) using the Petroseis mapping software. Nine major horizons (Table 3) were mapped and a series of time structure and time thickness maps showing posted values were produced using the Petroseis database (Enclosures 3-13). The data were machine-contoured and only very minor manual editing was carried out. Fault maps produced for major horizons were digitised and, where applicable, were utilised during contouring; only major normal faults were utilised for structure and time thickness contouring. Time thickness maps were generated for major sequences, using zero sedimentation edges as contouring boundaries where applicable. The water bottom reflector (WB) interpreted for Surveys 50 and 76 was also contoured and is displayed in Enclosure 1. Gravity and magnetic data recorded during these surveys are displayed as profiles along track in Enclosures 28 and 29.

BASIN GEOMETRY

The Townsville Basin extends from about 148°35'E to about 152°30'E, and broadens from less than 20 km in the west to more than 120 km in the east. To the north and south, the basin is flanked by the basement platforms underlying the Queensland and Marion Plateaus. The platform surfaces dip towards the basin, and range in depth from less than 1.0 s TWT to 3.5 s TWT (≈ 0.4-3.8 km). The boundaries of the Townsville Basin with the flanking platforms are extremely variable, ranging from steep normal faults to gently dipping hinges. The eastern boundary of the Townsville Basin, where it joins with the Cato Trough, cannot be resolved by available data, but a fault-bounded sedimentary basin which is present along the eastern slope of the Marion Plateau may have a connection to the Townsville Basin.

The geometry of the linkage between the Townsville and Queensland Basins remains unresolved as no modern seismic data are available for much of the area which is shown as the 'Halifax Basin' in Figure 2. The term 'Halifax Basin' was used by Allen & Hogetoorn (1970), Swarbrick (1976) and Rasidi & Smart (1979) for the sedimentary basin underlying the southern Queensland Trough. Since then the name 'Halifax Basin' has not been widely used in the literature; however, the area of convergence between the Queensland and Townsville Basins may well be defined by a separate basin, possibly extending to the southwest beneath the Great Barrier Reef. The area is marked by structural complexity in available data.

Each of the maps in Plates 1 to 4 and Enclosures 4 and 9 indicate a major transverse NW-trending structure at approximately 150°30'E (herein named the Tregrosse Fault Zone; Fig. 4). This feature marks a switch in the axial trend of the rift zone from east-southeast in the west, to northeast in the east. As depicted in the maps, the basin width, average intra-rift depth to basement and synrift-fill thickness all change dramatically across the Tregrosse Fault Zone. Such changes along rift zones are not uncommon; for example, the Rukwa lineament which obliquely crosses the Tanganyika rift zone of East Africa as a horst, marks

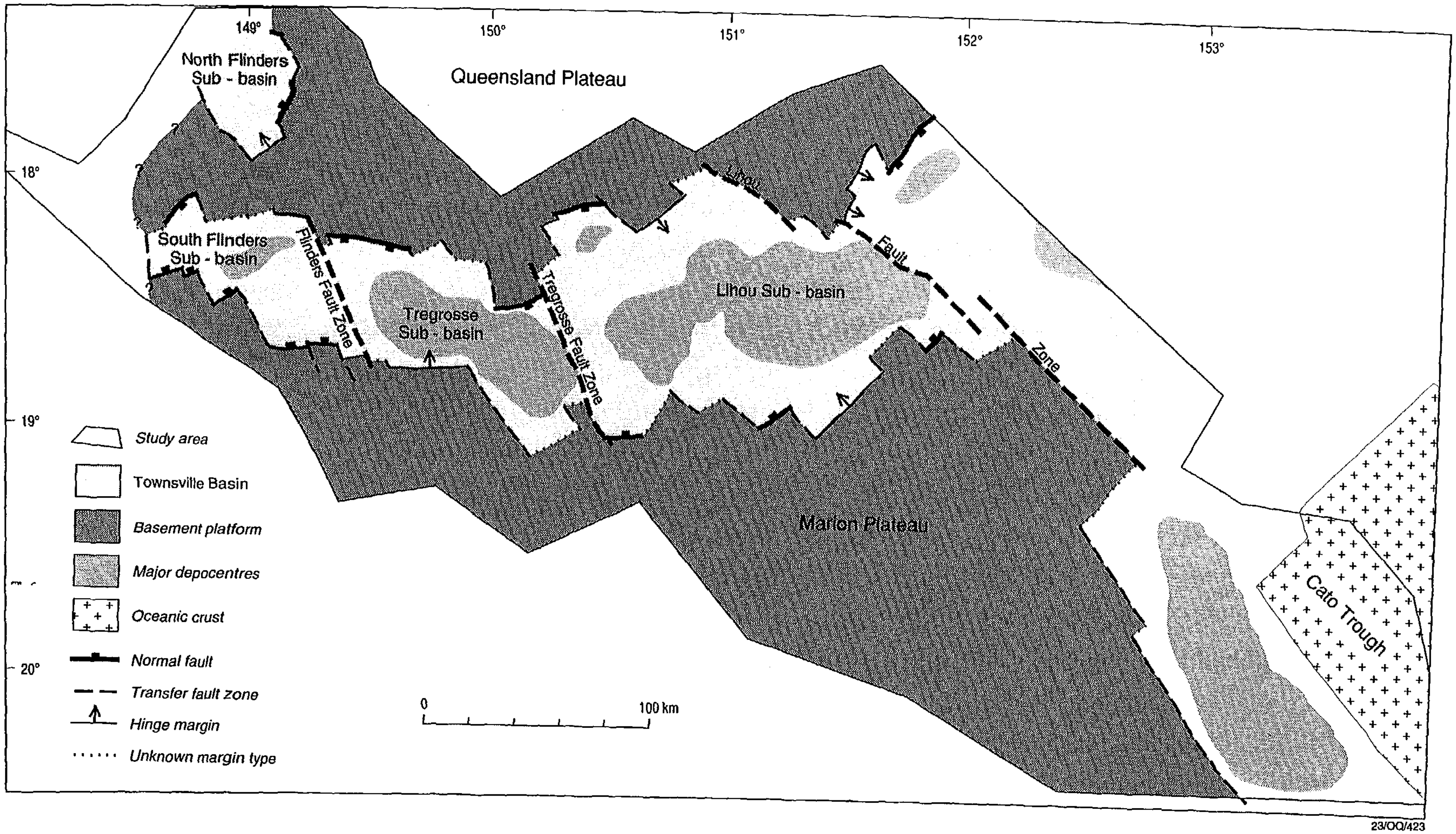

Figure 4: Major structural elements of the Townsville Basin.

a change in rift axis orientation and influences the geometry of adjacent half-graben (Scott et al., 1992; Scott, 1994).

Although the Townsville Trough bathymetric feature trends nearly east-west, gravity, depth to basement, total sediment thickness and synrift isopach maps (Plates 1-4, Enclosures 4 & 9) all clearly indicate that the underlying rift-forming structures divide the rift zone into distinct sub-basin compartments which are separated by major north-northwest to northwest-trending transverse structures. From west to east, these individual depocentres are herein referred to as the Flinders, Tregrosse and Lihou Sub-basins (Fig. 4). A fourth, unnamed element is present in the easternmost part of the mapped area but, with the exception of its western boundary, the Lihou Fault Zone (new name), it is poorly defined owing to the lack of data coverage to the east. The sub-basins themselves are composed of a series of discrete half-graben which vary in width and polarity. The major rift zone transverse boundaries (the Flinders, Tregrosse and Lihou Fault Zones), which delineate the sub-basin boundaries are associated with changes in the trend of rift transverse structures (Table 2). The sub-basin boundaries are thought to reflect reactivated, pre-existing crustal-scale terrane boundaries or shear zones. Although the structural elements map presented in Figure 4 can only be considered schematic because of the regional nature of the seismic grid, it does provide a means of understanding the linkages between structural elements within the Townsville Basin, and between the basin and adjacent tectonic elements.

Table 2: Observed trends of major rift-zone structures in the Townsville Basin.

Structural Feature	Flinders Sub-basin North	Flinders Sub-basin South	Tregrosse Sub-basin	Lihou Sub-basin	Eastern Townsville B.
Basin Margin	NE - ?NNE	ENE - EW	West: ESE East: ENE-EW	North: ENE - NE South: NE	NNE
Rift Axis	?	ESE	ESE	ENE	?
Transverse Structures	? NNW	NNW	West: NNW East: NW	NW	?

The Flinders Sub-basin in the west is the most sparsely covered by the available seismic data. Structural complexity is expected to be high in this area of convergence of the Townsville and Queensland Basins. The sub-basin is divided into a northern and southern part by a southeast trending basement high (Plates 1 & 4), which approximately parallels the western rift axis. The Flinders Sub-basin is probably best considered as two separate sub-basins, the North and South Flinders Sub-basins. The North Flinders Sub-basin is approximately 40 km wide and may be an element of linkage between the Townsville and Queensland Basins. Depth to basement in the deepest part of this sub-basin is close to 4.0 s TWT (≈ 6 km). The width of compartments within the South Flinders Sub-basin ranges from 20 km in the eastern compartment to 60 km in the western compartment. Basement depths reach 4.0 s TWT (≈ 6 km) in isolated half-graben.

The South Flinders and Tregrosse Sub-basins are separated by a zone of high basement flanked by north-northwest trending lineaments (Plate 1), which is confirmed by a similarly trending free-air anomaly (Plate 2). A major fault zone on the eastern edge of the basement high, the Flinders Fault Zone, constitutes the boundary between the two sub-basins (Fig. 4). This fault zones is associated with a change in the trend of transverse structures from north-northwest in the South Flinders Sub-basin to more northwest in the Tregrosse Sub-basin (see also Enclosure 14), and in the trend of basin margin structures from east-northeast and east-west in the South Flinders Sub-basin, to east-southeast in the western Tregrosse Sub-basin.

The Tregrosse Sub-basin is divided into three compartments by northwest trending transverse structures (Enclosure 14). It reaches a width of about 60 km in the western compartment, broadens along a transverse structure to about 100 km in the central compartment, and narrows to about 50 km in the eastern compartment (Fig. 4). Basement depths reach over 5.0 s TWT (≈ 7 km) in the deeper parts of the western and central compartments (Plate 1, Enclosures 3 & 4).

The Tregrosse and Lihou Sub-basins are separated by the Tregrosse Fault Zone (Fig. 4), a northwest-trending lineament which corresponds to a zone of relatively high basement (Plate 1) and a northwest-aligned free-air anomaly (Plate 2). As detailed above, the fault zone delineates a change in trend of the rift axis, transverse structures and basin boundaries (Table 2).

The Lihou Sub-basin is 70 to 120 km wide and is the deepest depositional compartment of the Townsville Basin. Basement depths in the central Lihou Sub-basin are considerably deeper than in the Flinders and Tregrosse Sub-basins, reaching in excess of 6.0 s TWT (≈ 8.5 km). The sub-basin itself is further compartmentalised by northwest-trending transverse structures; two main compartments are delineated by two distinct depocentres (Plates 1 & 3; Enclosures 4, 8 & 9). The western compartment is up to 40 km in width, but the eastern compartment is more than 60 km in width. A change in basin margin trends from east-northeast and northeast in the Lihou Sub-basin, to north-northeast in the easternmost Townsville Basin occurs in the vicinity of the Lihou Fault Zone, a complex zone of northwest-trending, linked transverse structures which form the eastern boundary of the Lihou Sub-basin.

STRATIGRAPHY

With the exception of several Ocean Drilling Program (ODP) holes drilled in the study area during ODP Leg 133 (Davies et al., 1991; Mckenzie et al., 1993), there is no direct control on the stratigraphy of the Townsville Basin. Up to 700 m of section was drilled at the ODP sites (Sites 812-817, 826; Figure 1), which typically bottomed in Middle Miocene reefal and reef-derived deposits (Davies et al., 1991; Betzler & Chaproniere, 1993; Chaproniere & Betzler, 1993). The Late Miocene section is either absent or thin and consists of pelagic to periplatform deposits. These are overlain by up to 400 m of Pliocene to Pleistocene, mostly pelagic sediments. Pigram (1993) carried out a detailed seismic stratigraphic study of the ?Late Oligocene to Recent carbonate platform of the Marion Plateau and interpreted four seismic megasequences which correspond to major sealevel-controlled depositional cycles on the plateau. Within the context of a

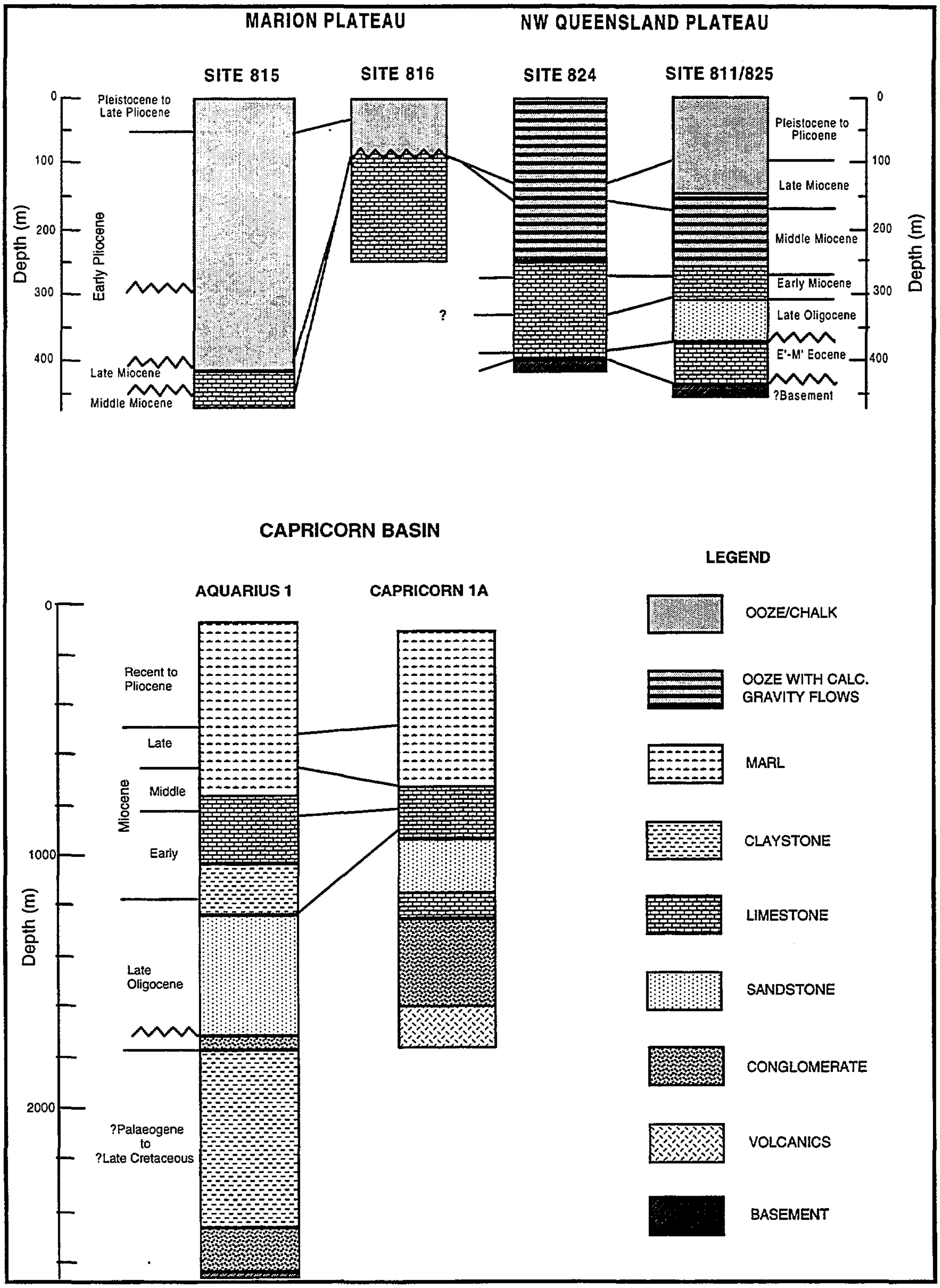

Figure 5: Correlation of drillholes in the wider study area (modified after Davies et al., 1989, and Chaproniere & Betzler, 1993).

regional study such as this, not all of these sequences are mappable. However, two of Pigram's sequence boundaries can be tied to the regional grid via Sites 815 and 816 (Fig. 5); a Middle Miocene, top carbonate platform reflector (Horizon M) and a Pliocene downlap surface (Horizon O) are prominent unconformities which can be mapped across the Townsville Basin (Fig. 6).

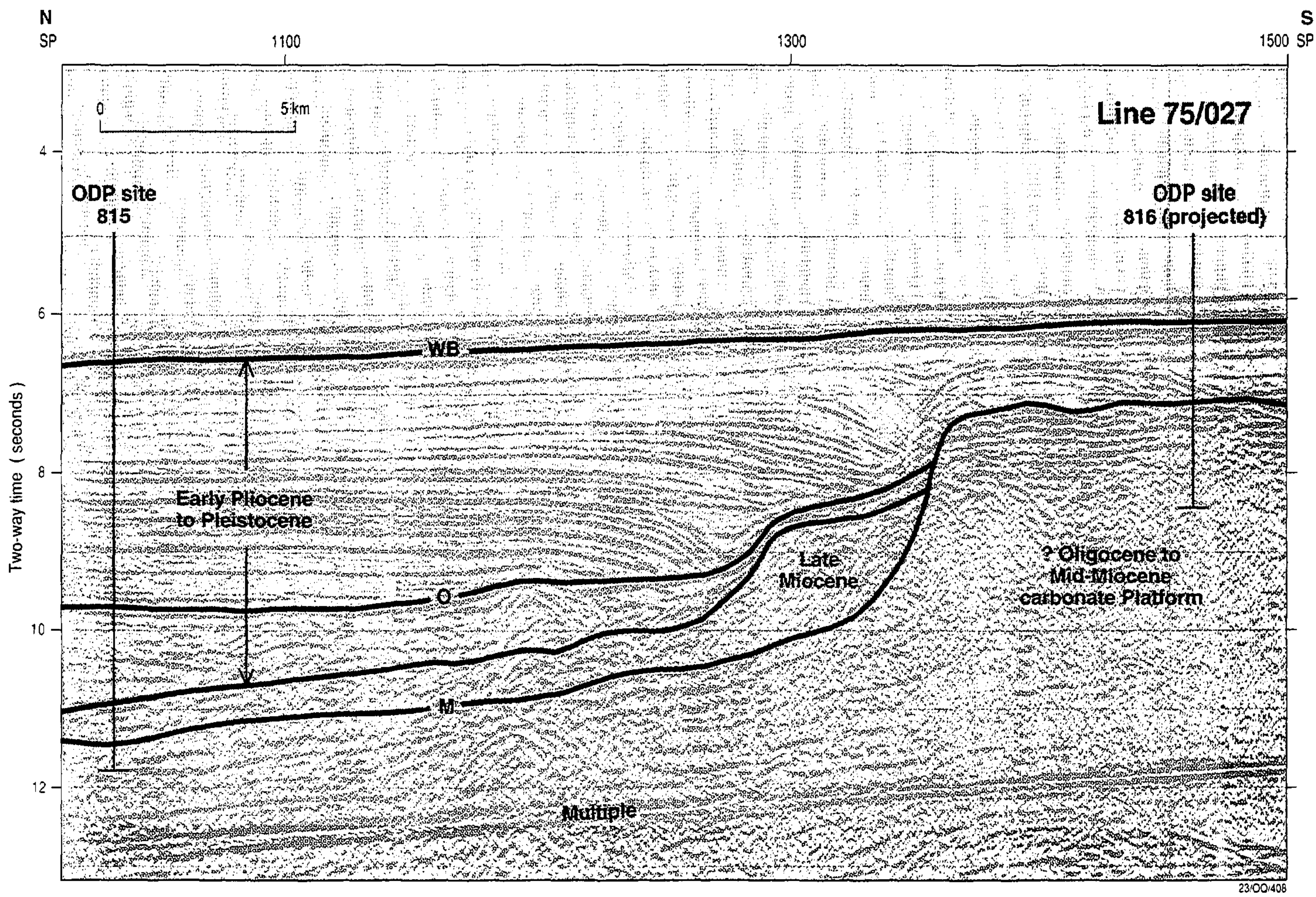

Figure 6: Portion of AGSO seismic line 075/27 from the northern Marion Plateau through ODP Leg 133 Sites 815 and 816 showing Neogene horizons tied to the regional survey (for legend refer to Table 3).

Older sediments and underlying basement were intersected at ODP Sites 811/825 and 824 on the western Queensland Plateau (Fig. 5). At these sites, less than 10-75 m of Early to Middle Eocene shallow water carbonates are overlain by hemipelagic upper Oligocene fine-grained packstones and latest Oligocene to

Early Miocene reefal and reef-derived carbonates (Betzler & Chaproniere, 1993). Basement intersected at both these sites consists of deformed metasediments. In addition, granodioritic and tonalitic intrusives are intercalated with the metasediments at Site 824. Feary et al. (1993) correlated these basement rocks with those of the Devonian Hodgkinson Formation of northern Queensland. The presence of these rocks on the Queensland Plateau confirms that rocks of the Tasman Fold Belt are likely to underlie both the Queensland and Marion Plateaus.

The nearest oil exploration wells (Capricorn 1A, Aquarius 1) are located in the central Capricorn Basin, approximately 500 km southwest of the Townsville Basin on the southern margin of the Marion Plateau (Fig. 2). The deeper of these wells, Aquarius 1, intersected 2600 m of Late Mesozoic to Cainozoic sediments overlying Palaeozoic basement (Fig. 5). Late Cretaceous (?) to Palaeogene coarse- to fine-grained non-marine rocks are overlain by up to 500 m of Eocene to Oligocene terrestrial to shallow-marine quartzose sands. The overlying Miocene to Recent section contains marine calcareous and siliceous rocks and reaches a thickness of about 1100 m at Aquarius 1 (Ericson, 1976).

Based on the information from the Capricorn Basin and velocity data from refraction surveys across the Queensland Plateau (M. Ewing et al., 1970), Rasidi and Smart (1979) interpreted a Late Cretaceous to Recent sedimentary sequence of up to 3000 m overlying Palaeozoic metasediments for the 'Halifax Basin' (Allen and Hogetoorn, 1970). However, distinction of basin-fill age by velocity alone is inconclusive and rift-fill may be much older locally. Given the sparsity of direct well control in the study area, the age and nature of the sedimentary fill which underlies the Miocene carbonates and thus the age of initiation of the Townsville Basin, can only be interpreted within a regional tectonostratigraphic context.

According to Weissel & Hayes (1977), Weissel et al. (1977) and Veevers & Li (1991), seafloor spreading in the Tasman Sea Basin occurred between 80 and 55.5 Ma (magnetic anomalies 33-24). In the Coral Sea Basin, seafloor spreading is thought to have taken place between 63.5 and 55.5 Ma (magnetic anomalies 27-24) (Weissel & Watts, 1979; Veevers & Li, 1991). Shaw (1978, 1979) concluded that spreading in the northernmost Tasman Sea Basin did not occur until 63.5 Ma (magnetic anomaly 27), and that the Cato Trough and Coral Sea Basin opened at approximately the same time. However, no clear magnetic anomalies have been identified for the Cato Trough; it is also possible that it formed part of an early spreading system (80 to 70 Ma; anomaly 33 to 31) postulated by Shaw (1979) for the Middleton and Lord Howe Basins east of the Dampier Ridge in the Tasman Sea. Mutter & Karner (1980) suggested that the Cato Trough is at least as old as the northern Tasman Sea Basin. Thus, the pattern of seafloor spreading suggests that regional extension and related sedimentation has a minimum Late Cretaceous age. A better age constraint for rift onset in the Townsville Basin is given by the age of rift-related volcanics in the region. Ewart et al. (1990, 1992) interpreted a zone of Early Cretaceous volcanics (Whitsunday and Proserpine Volcanics) along the central Queensland coast, inboard of the Great Barrier Reef, as rift-related pyroclastics, lavas and dykes which were extruded during an extensional phase along Australia's northeastern margin. The age of these volcanics ranges from 95 to 132 million years.

SEISMIC SEQUENCES

Basement

The nature of basement varies beneath the Townsville Basin, ranging from steeply dipping, high amplitude reflectors, to an incoherent to near transparent seismic character. The contact between synrift sediments and basement is generally characterised by loss of seismic character rather than a sharp boundary. In places, complexly structured reflectors can be observed within basement indicating that it is probably composed of a variety of Palaeozoic metasediments and igneous rocks of the Tasman Fold Belt. On the Queensland and Marion Plateaus, basement typically lies at depths of less than 1.0 to 3.5 s TWT (≈ 0.4-3.8 km), whereas in the central Townsville Basin depths range from 3.0 to greater than 6.0 s TWT (≈ 3.0-8.5 km).

Ties between the interpreted seismic reflection data and the refraction survey of M. Ewing et al. (1967) indicate an interval velocity of 6.3 km/s for probable Early Palaeozoic/ Precambrian basement of the Tasman Geosyncline. In places, this is overlain by a layer of about 5.7 km/s interval velocity which Rasidi & Smart (1979) interpreted as lithified marine sediments of Middle Palaeozoic age in their study of the Halifax Basin. On lines in the northwestern Townsville Basin, near the junction with the Queensland Basin (Enclosures 15 & 24-25; Figure 7b), the boundary between the two velocity layers corresponds to a detachment surface, which may well coincide with the boundary between metasediments and crystalline basement. The 5.7 km/s velocity layer was not interpreted in the eastern Townsville Basin (Refraction line R35, Figure 3). The absence of this layer may be explained by removal of the metasediments by extension or by a change in basement type in the eastern Townsville Basin. The latter explanation is supported by a distinct change in the seismic character of basement across the Tregrosse Fault Zone, from high amplitude reflections to nearly transparent, and an accompanying change in structural trends. In the western Lihou Sub-basin, basement is obscured by volcanics and lava flows of the early sag-phase sequence, suggesting that basaltic volcanism may have occurred in the deepest, more highly extended part of the Townsville Basin.

Sedimentary Fill

The maximum sedimentary fill in the Townsville Basin is approximately 4.5 s TWT (≈ 6.5 km) and occurs in the Lihou Sub-basin (Plate 3, Enclosure 8). The sedimentary section can be divided into two main seismic megasequences — a synrift (R) and a sag-phase (S) megasequence (Fig. 7). The synrift megasequence reaches a thickness of up to 2.0 s TWT (≈ 4 km) and occurs in fault-controlled depocentres; the sag-phase megasequence occurs as drape fill and reaches a thickness of up to 2.6 s TWT (≈ 3.8 km), mainly associated with the Tregrosse and Lihou Sub-basins. The two major megasequences were subdivided into further, regionally mappable sequences — rift sequences R1, R2, R3, and sag sequences S1, S2, S3, S4, and S5 (Figures 8 and 9). In places, a sequence of sometimes transparent, sub-parallel to disrupted reflectors occurs between basement and the synrift section (Fig. 9) and is interpreted as a pre-rift a)

b)

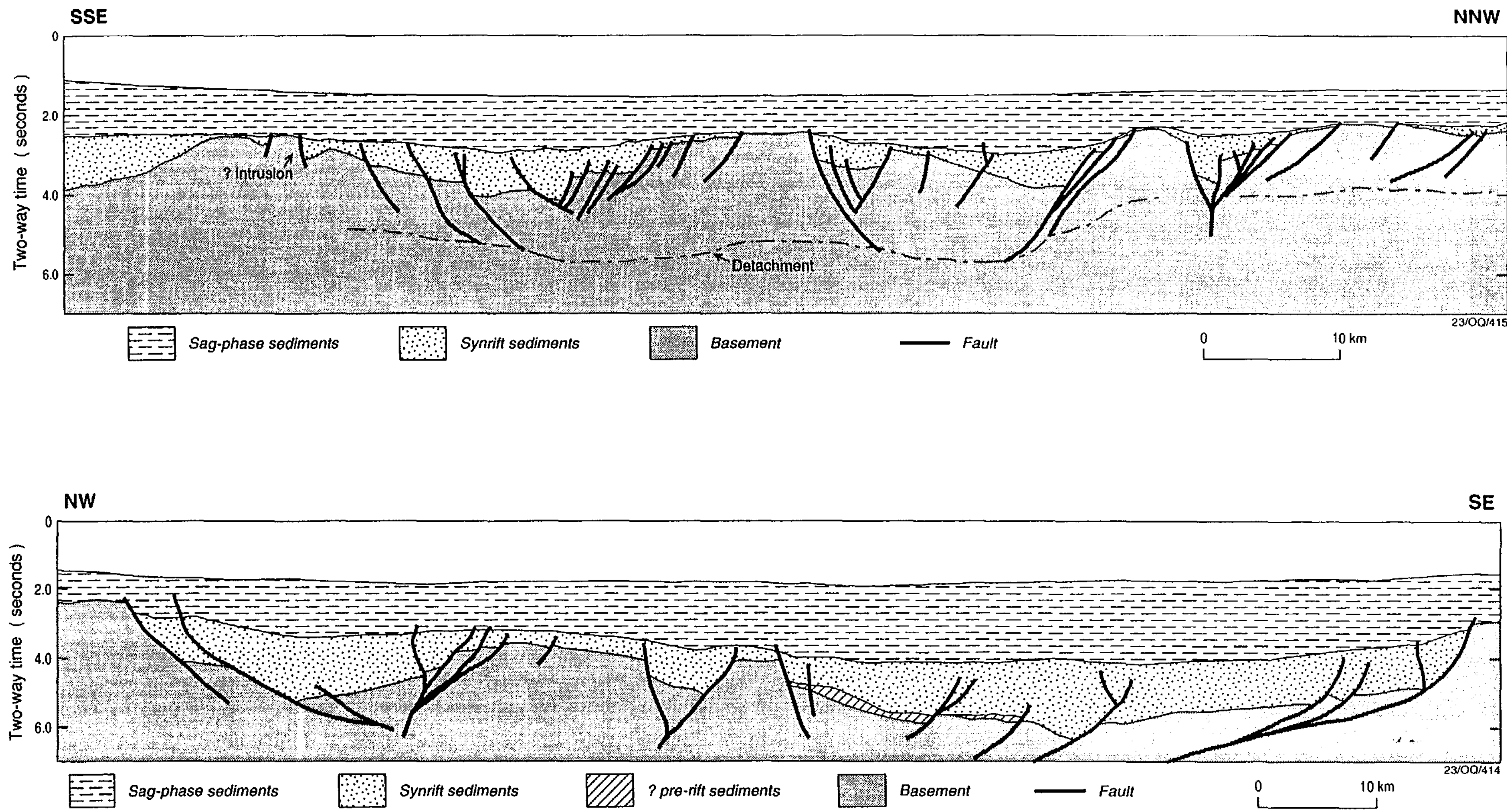

Figure 7: Line drawings of seismic profiles across the Townsville Basin showing the distribution of the synrift and sag-phase megasequences; a) line 76/31P2, South Flinders Sub-basin; b) line 76/23, western Lihou Sub-basin.

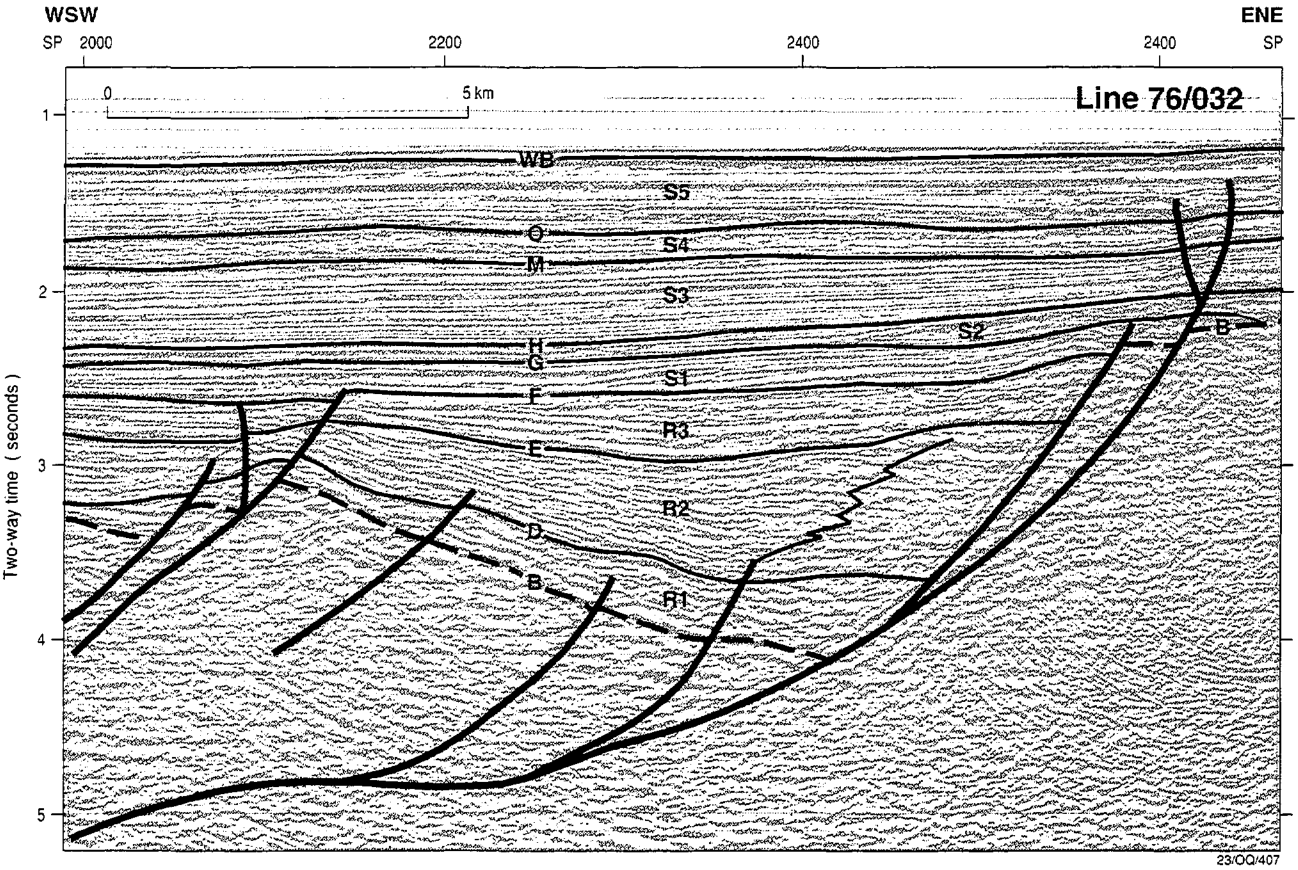

Figure 8: Portion of seismic line 76/32 in the northern Flinders Sub-basin illustrating the character of mapped seismic sequences and a typical low-angle basin-bounding fault (for legend refer to Table 3; for location refer to Enclosure 2).

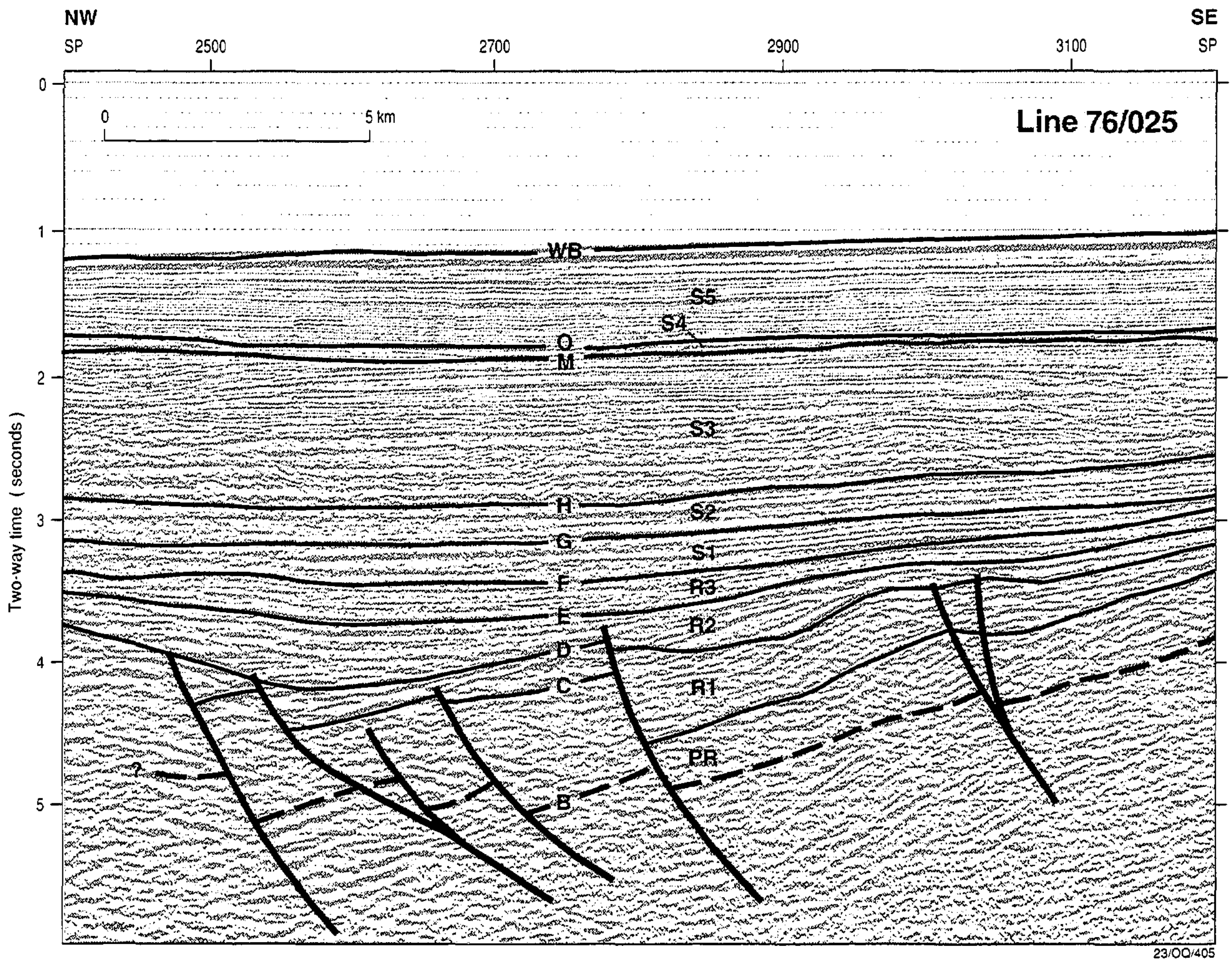

Figure 9: Portion of seismic line 76/25 in the eastern Tregrosse Sub-basin illustrating the character of mapped seismic sequences (for legend refer to Table 3; for location refer to Enclosure 2).

sedimentary sequence (PR). These nine sequences were mapped throughout the Townsville Basin, although continuity of the synrift reflectors across basement highs is rare and interpretation of specific sequences is frequently based on seismic character alone. Other more or less prominent reflectors can be identified in places, but they do not appear to be of regional extent. The unconformities separating the sequences have been assigned ages (Table 3) based on the regional tectono-stratigraphic context and ties to the ODP sites. The major seismic characteristics of each sequence, and interval velocities estimated from refraction survey tie points with surveys 50 and 76 and from seismic stacking velocities, are summarised for each sequence in Table 4.

Synrift Megasequence

Distribution and thickness of the synrift megasequence is shown in Enclosure 9 and on Plate 4. This megasequence was deposited during the active extensional phase of basin development, which appears to have occurred in several distinct pulses in some depocentres. The megasequence occurs in fault-controlled depocentres and reaches a thickness of more than 2 s TWT (≈ 4 km) in the Lihou and Tregrosse Sub-basins. In the North and South Flinders Sub-basins, it decreases in thickness to a maximum of 1.5 s TWT (≈ 3 km) and the depocentres are small and isolated compared to the Tregrosse and Lihou Sub-basins. The upper boundary of the synrift section is typically a strong erosional unconformity (Horizon F, Figure 10) along faulted basin margins and basement highs, but becomes conformable with sag-phase characteristics in the deeper parts of the basin. Generally, sediments of the synrift section terminate against the tops of fault blocks as a diverging wedge of reflectors and thicken towards fault scarps. The major depocentres of the synrift section are illustrated in Plate 4. They are separated by basement highs, some of which remained high and formed a source of sediment throughout megasequence deposition. Major structural boundaries between the sub-basins are characterised by thin synrift deposition. Throughout most of the Townsville Basin, the synrift megasequence can be subdivided into three distinct sequences separated by erosional unconformities; these are an early synrift sequence (R1), a main synrift sequence (R2), and a late synrift sequence (R3). However, in areas of generally thin synrift deposition in the western Townsville Basin, sequences R1 and R2 cannot always be distinguished. In some areas of the Lihou Sub-basin, where the synrift megasequence is thickest, sequences R1 and R2 loose their distinctive characteristics and can only be mapped as one sequence. A thick synrift section is interpreted to occur in a deep graben along the eastern margin of the Marion Plateau adjacent to the Cato Trough in the southeastern part of the study area (Enclosures 5, 9 & 19). It is not possible to resolve whether these sediments are of the same age as the synrift sequence of the Townsville Basin, because there is no direct tie to line 76/11 in the eastern Townsville Basin. In the absence of this information, the sequences mapped for the Cato Trough and the Townsville Basin are correlated in the synrift sediment contour maps (Enclosures 5 & 9; Plate 4), mainly because of seismic character similarities between the sections.

The early synrift sequence (R1) represents the earliest extension-related deposits in the Townsville Basin and shows considerable variation in spatial distribution and thickness. Overall, sequence R1 is characterised by divergent reflectors of low continuity. Occasional high amplitude events within the sequence are interpreted to represent volcanic flows, dykes or sills. The sequence is of possible Early Cretaceous age and, apart from the igneous rocks, is likely to consist of coarse terrigenous deposits derived from the Queensland and Marion Plateaus and other, intra-basinal basement highs.

As with sequence R1, R2 is also of highly variable thickness, but overall it is more widely distributed. It onlaps sequence R1 and represents the main phase of rift sedimentation in the Townsville Basin. It either onlaps basement blocks or, in the deeper parts of the basin, occasionally covers eroded edges of basement blocks. Faulting continued during deposition of R2 with block rotation observable along major faults (Fig. 8). Like sequence R1, sequence R2 displays a disrupted, divergent, variable amplitude character; however, the frequency content is higher than in R1. Diffuse seismic facies typically occur along some fault scarps; they are likely to represent alluvial fans (Fig. 8). The sequence probably consists of terrigenous and volcanic sediments deposited in a variety of environments, ranging from alluvial fans to fluvial and fluvio-lacustrine environments. It is proposed that sequence R2 is of a minimum mid- to Late Cretaceous age.

Table 3: Interpreted tectonostratigraphic summary for the Townsville Basin.

SEQUENCE	HORIZON Top	HORIZON Base	INFERRED AGE Top	INFERRED AGE Base	TECTONO-STRATIGRAPHIC UNIT	SPECULATIVE LITHOLOGY/FACIES
S 5	WB	O	Recent	Early Pliocene	Post-breakup sag phase	pelagic oozes, terrigenous and calcareous turbidites and slump deposits;
S 4	O	M	Early Pliocene	Late Miocene	Post-breakup sag phase	bathyal to neritic; oozes and slump deposits; minor reef growth;
S 3	M	H	?Middle Miocene	Oligocene	Post-breakup sag phase	bathyal to neritic low and high energy deposits; period of reef growth; terrigenous and calcareous turbidites;
S 2	H	G	?Oligocene	Eocene	Post-breakup sag phase	paralic to open marine; shelf clastics, oozes, submarine fans;
S 1	G	F	Eocene	?Paleocene	Early post-breakup sag phase	terrestrial to marginal marine in central basin; minor lava flows and volcaniclastics; open marine in Cato Trough;
a*	GB	GA				
b*	GA	BB				
R 3	F	E	?Paleocene	?Late Cretaceous	Late rift phase	fluvio-lacustrine to marginal marine coarse- to fine-grained clastics;
R 2	E	D	?mid/Late Cretaceous	Early Cretaceous	Synrift phase	alluvial, fluvial and fluvio-lacustrine; volcaniclastics and coarse clastics;
R 1	D	C (B)	Early Cretaceous	?Late Jurassic	Early synrift phase	alluvial, fluvial; volcanics, volcaniclastics;
PR	C	B	?Mesozoic to	?Palaeozoic	?Pre-rift phase	continental - ?marginal marine sediments and metasediments

*Cato Trough only

Table 4: Major seismic sequences mapped for the Townsville Basin.

Sequence		Boundary		External Form	Reflection				Thickness	Interval Velocity
		lower	upper		configuration	continuity	amplitude	frequency	(ms TWT)	(km/s)#
Sag Phase	S5	downlap/onlap to concordant	seafloor	sheet drape	subparallel to parallel, minor channeling, hummocky and mounded	moderate	variable	low to moderate	200-700	1.9
	S4	onlap/downlap	erosional	sheet drape, minor slope front fill	sub-parallel, divergent, hummocky, mounded features and channel fills; onlap to divergent fill;	low to moderate	moderate	moderate to high	0-500	2
	S3	concordant, some onlap	concordant to erosional	sheet drape, slope front fill	hummocky to sub-parallel, some mounded features and channel fills;	variable	moderate to high	variable	300-1100	2.9
	S2	mostly concordant downlap in places	concordant to erosional	sheet drape	sub-parallel to divergent, occasional progradation	moderate to high	variable	low	0-500	3.2
	S1	onlap to concordant, downlap in places	concordant, partly erosional, minor toplap	sheet drape	sub-parallel to divergent; occasional volcanic mounds and progradation	moderate	variable	low	0-900	3.4
Synrift	R3	downlap/onlap to concordant	concordant to erosional, minor toplap	wedge to sheet drape	mostly sub-parallel, divergent and onlap fill	low to moderate	low to moderate	low	0-500	3.6
	R2	downlap/onlap to concordant	erosional to concordant	wedge	divergent to sub-parallel, disrupted complex fill, partly reflection-free	low	variable	low	0 - 800	4
	R1	basement	erosional	wedge	divergent to sub-parallel, disrupted complex fill, partly reflection-free adjacent to basement highs	low to moderate	variable	low to moderate	0 - 1100	4.5
	PR	basement	erosional	?wedge	sub-parallel to disrupted, partly reflection-free	low	variable	low	0 - 1000	> 4.5

#estimated from refraction and stacking velocities

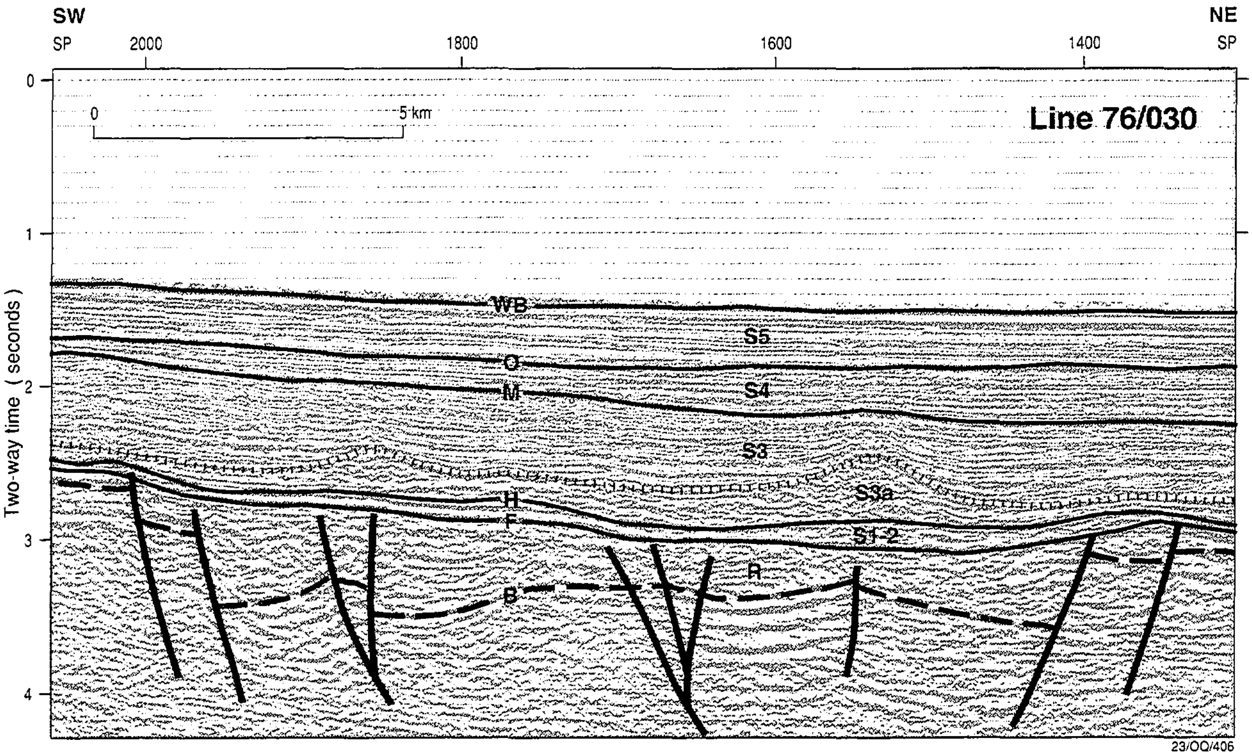

Figure 10: Portion of seismic line 76/30 in the southern Flinders Sub-basin. The top of the synrift sequence is characterised by a marked erosional unconformity (Horizon F). Very thin early sag-phase sequences S1 and S2 are overlain by ?volcanic mounds within the lower part of sequence S3 [S3a] (for legend refer to Table 3; for location refer to Enclosure 2).

Sequence R3 represents late rift-fill sedimentation. It onlaps sequence R2 and is of probable Late Cretaceous to ?Paleocene age. It is ponded in the depressions between tilt blocks but also occasionally covers the eroded corners of the blocks. Some faulting continued during deposition of R3 particularly at major basin-bounding structures. The sequence is absent over the platforms flanking the basin and is very thin to occasionally absent in the Flinders Sub-basin, but thickens eastward to a maximum of about 0.5 s TWT (≈ 1 km). Generally, the sequence has a more continuous character with less variable amplitudes, indicating probable deposition in a lower energy, fluvial to possibly marginally marine or coastal environment. The unconformity at the top of R3 can be tentatively correlated with reflectors interpreted as oceanic crust in the Cato Trough. It is therefore likely that R3 was deposited just before or during initial breakup in the Cato Trough during the latest Cretaceous to Paleocene. This would have resulted in greater marine influence within the Townsville Basin rift system, particularly to the east. Sequence R3 reflects this increasing influence.

Sag-phase Megasequence

The sag-phase megasequence was probably deposited during lithospheric cooling following continental breakup and the commencement of seafloor spreading in adjacent ocean basins. It reaches a maximum thickness of 2.6 s TWT (≈ 3.8 km) in the central Townsville Basin but thins westwards and onto the adjoining platforms to less than 1.0 s TWT (≈ 1.5 km) (Plate 5; Enclosure 10). A very thick sag-phase sequence, up to 2.0 s TWT (≈ 3 km) thick, is also present on the eastern margin of the Marion Plateau where it slopes towards the Cato Trough. The sag-phase megasequence can be sub-divided into five sequences, with sequences S1 and S2 representing initial drape before establishment of carbonate platform environments on the adjacent platforms in the ?Late Oligocene. Sequence S3 comprises ?Late Oligocene to mid-Miocene carbonate platform and derived sediments; sequence S4 is a Late Miocene to Early Pliocene marine clastic and calcareous depositional phase, and sequence S5 represents Early Pliocene to Recent marine deposits.

The two pre-carbonate platform sequences, S1 and S2, can be identified in most parts of the Townsville Basin with major depocentres in the Lihou Sub-basin (Plate 6) and in the Cato Trough (Enclosure 11). They thin rapidly towards the west, where a distinction between S1 and S2 is not always possible, and onto the platforms. Both sequences exhibit some flexural and compaction drape over the edges of buried fault blocks. They typically show sub-parallel reflection configurations, with moderate continuity and low frequencies indicating more stable depositional environments. In the southern Lihou Sub-basin, sequence S1 includes a mounded section of high amplitude events which is likely to represent volcanics and lava flows; these are onlapped by sequence S2 (Fig. 11). Deposition of the early sag phase sequences was controlled by thermal subsidence with the locus of deposition in the area of greatest deep thinning/extension, the Lihou Sub-basin, while deposition in the Tregrosse Sub-basin and, particularly in the Flinders Sub-basin, was minimal. The erosional nature of the sequence boundary between the synrift and sag phase megasequences indicates that uplift at the end of the synrift phase may have been more pronounced in the western Townsville Basin. Alternatively, the sequence boundary could be the result of a major fall in sealevel, the effects of which could have been more pronounced in the western part of the basin. Apart from some sediment derived from the adjacent basement platforms in the north and south, the western area is likely to have provided a major source for the thick early sag phase sediments in the Lihou Sub-basin. This suggests that deposition in the Townsville Basin during this time was predominantly axial.

Major fault reactivation, mainly on basin margin faults, occurred towards the end of sequence S1 deposition. In the Cato Trough, the top of S1 can be correlated with an horizon (GB) disrupted by intensive reactivation faulting (Fig. 12). In this area, sequence S1 is very thick (about 1.5 s TWT) and is subdivided into two sub-sequences S1a and S1b which can be mapped on all lines in the Cato Trough. Rapid landward thinning of S1a and S1b and thickening of S2 is observed at the interpreted continent/ocean boundary on line 76/07 (Fig. 12; Enclosure 19). Clear onlap and fill relationships occur between sequences S1 and S2. The top of sequence S2 probably represents the regional Late Eocene to Early Oligocene hiatus which has been related to a major eustatic sealevel fall

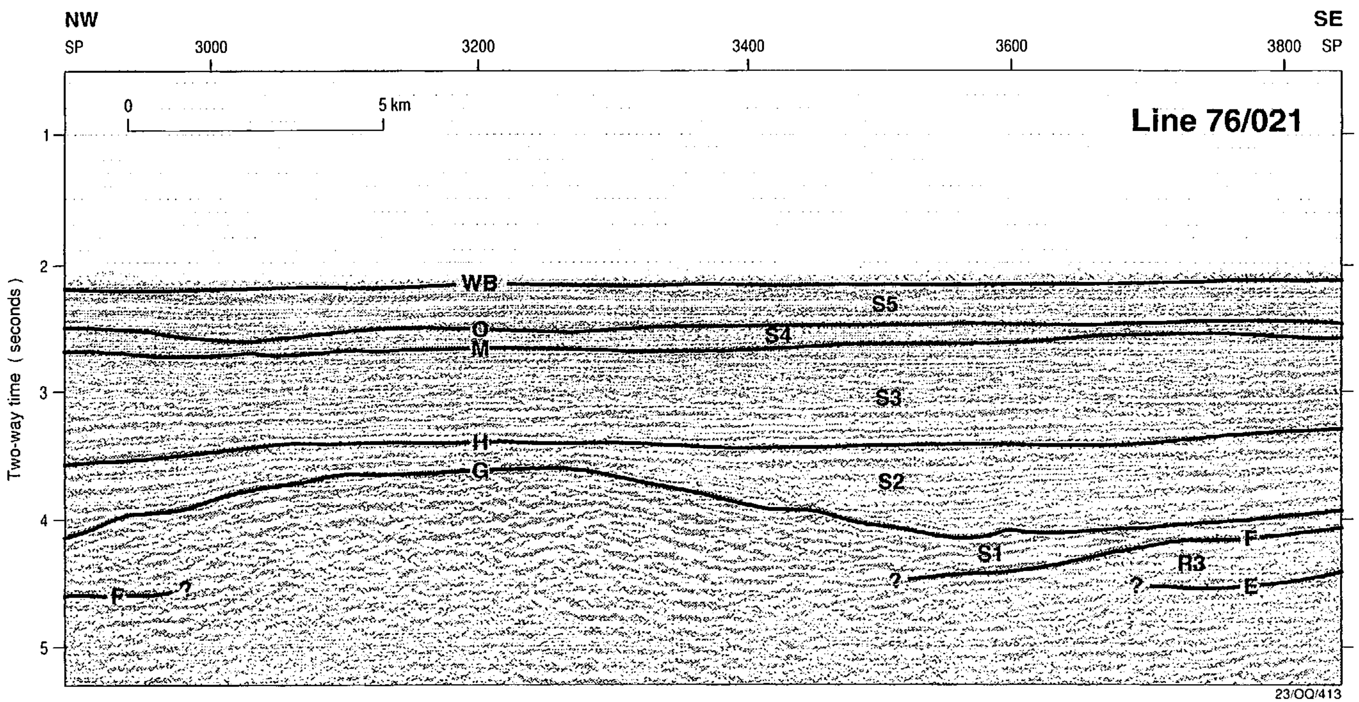

Figure 11: Portion of seismic line 76/21 in the Lihou Sub-basin. The section shows a mounded volcanic feature within sequence S1, which is onlapped by horizons of sequence S2 (for legend refer to Table 3; for location refer to Enclosure 2).

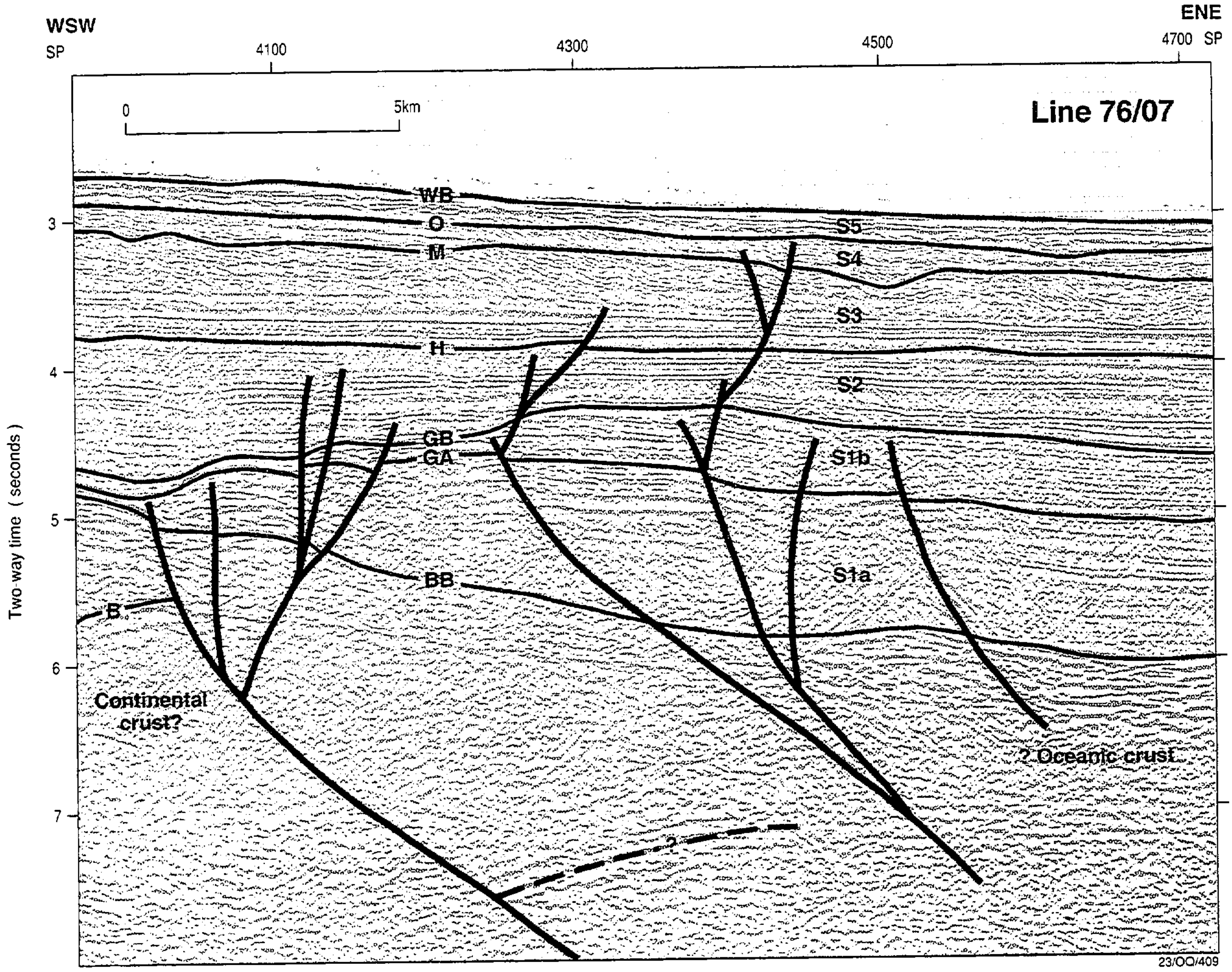

Figure 12: Portion of seismic line 76/07 in the Cato Trough, imaging a complex reactivation structure at the continent-ocean-boundary (for legend refer to Table 3; for location refer to Enclosure 2).

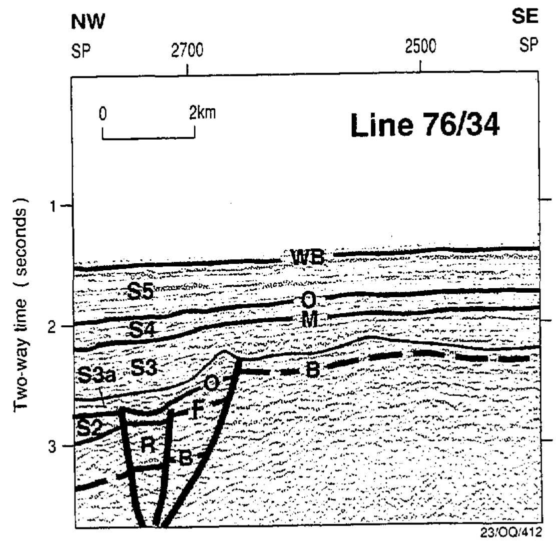

Figure 13: Portion of seismic line 76/34 in the northwestern Townsville Basin illustrating ?reefal mounds within sequence S3 (3a), associated with basin-bounding fault (for legend refer to Table 3; for location refer to Enclosure 2).

(e.g. Haq et al., 1988; Davies et al, 1989) in conjunction with the collision of the Pacific and Australian Plates during this time (Davies et al., 1989; Struckmeyer et al., 1993).

The distribution and thickness of sequence S3 is shown in Plate 7 and in Enclosures 7 and 12. It is evident that maximum deposition occurred within the western part of the central basin as a main northwest-southeast trending depocentre in the Tregrosse Sub-basin, where the sequence reaches a thickness of 1.3 s TWT (≈ 1.9 km). In contrast to sequences S1 and S2, which onlap the Queensland and Marion Plateaus, sequence S3 was deposited across the study area although it thins onto the plateaus. It is characterised by a hummocky to sub-parallel reflection configuration with mounds and channelling evident on many lines. The mounded features occur predominantly on the basin margins, where they are likely to represent reefal build-ups or carbonate platforms as shown in Figure 13. However, occasional high-relief mounds also occur in the lower part of the sequence in basinal areas where they typically sit above faults (Fig. 10). These features are thought more likely to be of volcanic origin.

Within the central Townsville Basin, sequence S3 probably consists of oozes, calcareous turbidites, and slump deposits which accumulated during a period of carbonate platform growth on the adjacent platforms (Davies et al., 1989; Pigram, 1993). The variable reflection character is probably an expression of the complex depositional system resulting from this environment. The sequence contains several strongly reflecting horizons but these cannot be mapped regionally. The top of sequence S3 is an erosional unconformity throughout the shallower parts of the basin and along the basin margins, but becomes conformable in the deeper basin. This unconformity probably correlates with a mid-Miocene to early Late Miocene hiatus described for the area by Chaproniere & Pigram (1993).

Sequence S4 is of Late Miocene to Early Pliocene age and is of less regional extent than sequence S3 (Plate 8). It reaches a maximum thickness of 0.5 s TWT (≈ 0.5 km) in depocentres of the South Flinders Sub-basin, the northern Tregrosse Sub-basin and the Lihou Sub-basin. S4 onlaps sequence S3 and is likely to have been deposited after a Middle to Late Miocene erosional episode during a period of slowly rising sealevel (Pigram, 1993). Large areas of the adjacent plateaus were exposed during this time and previous depositional centres experienced only minor sedimentation or sediment bypass. Some channelling and reefal build-ups are present in the upper part of the sequence. The sequence is likely to consist mainly of interbedded reefs, gravity flows and oozes, and minor terrigenous material. The top of sequence S4 is defined by a prominent downlap surface which is mappable throughout the survey area (Fig. 6).

Plate 9 shows that during deposition of sequence S5 depocentres shifted westward. The sequence is characterised by parallel to sub-parallel reflection configurations with rare hummocky or mounded features, and cut and fill structures on the northwestern margin of the Marion Plateau (Fig. 6). The sequence ranges in thickness between 0.2 and 0.7 s TWT (≈ 0.2-0.6 km). ODP drill sites indicate that, on the adjacent plateaus, most of this sequence consists of oozes and gravity flows. The Great Barrier Reef was probably a contributing source of sediments in the central Townsville Basin, and terrigenous material sourced from mainland Australia probably by-passed the reefs and reached the basin through channels.

Plates 7-9 show a distinct change in depocentre distribution within the sag-phase megasequence (note that colours are not consistent between plates). However, the plates clearly reflect the gradual drowning of the Marion and Queensland Plateaus during the Neogene and an overall westward shift in the locus of deposition. The most striking depocentre shift occurs between sequences S3 and S4. Sequence S3 has a much wider distribution than sequence S4 with the main S3 depocentre in the southern Tregrosse Sub-basin and the main S4 depocentre in the northern Tregrosse and Lihou Sub-basins, i.e. in areas where S3 is comparatively thin. The stratal patterns in the main S3 depocentre display basal onlap fill which grades into divergent to mounded onlap fill. The major sediment sources for this depocentre were likely to be contemporaneous reefal structures on the northwestern Marion Plateau.

Sequence S4 onlaps sequence S3 (e.g. Fig. 6) and has an overall onlapping fill character. It was, at least partially, sourced by S3 as indicated by the presence of an erosional unconformity between the two sequences. The distribution pattern of sequences S3 to S5 suggests that deposition during the Miocene was predominantly lateral, whereas Pliocene to Recent sediments were deposited as axial fill. The distribution and variation in the location of depocentres within the sag-phase megasequence is likely to be the result of a complex interaction between eustatic sealevel changes, the direction of sediment transport, the distribution of local sag centres, and subtle inversion. Sequence S3 was deposited during a period of sealevel rise in the Late Oligocene to Early Miocene (Haq et al., 1988). Pigram (1993) concluded that the distinct unconformity between sequences S3 and S4 is a result of a second order fall in sealevel which led to the demise of the Oligocene to Early Miocene carbonate platforms, and that sequence S4 was deposited during a period of slowly rising sealevels in the Late Miocene to Early Pliocene.

STRUCTURE

Integrated interpretation of the regional seismic grid across the Townsville Basin has improved our understanding of the structural style of this rift zone. However, the complexity of the bounding and intra-basin faults, and regional data coverage, make interpretation of the exact geometries of the various sub-basins difficult. Thus, by necessity, interpretation of structures in the Townsville Basin (Fig. 14) was to some extent model-driven, utilising the very simple concept of orthogonal extension (e.g. Gibbs, 1984; Etheridge et al., 1984; Lister et al., 1986). Application of such a model is problematic in basins with multiple deformation phases, and the effects of inversion, reactivation faulting and lateral motion along rift transverse faults need to be carefully considered. The structure map of the Townsville Basin (Fig. 14) is a representation of mapped interpreted structures which are very likely the result of at least three structural events. In the following sections we firstly describe the observed structural style in the Townsville Basin and then discuss how the observed features relate to structural models and the implications for the timing of structural events.

Structural Style

At the profile interpretation level, the Townsville Basin has the typical structural style of an extensional basin (e.g. De Charpal et al., 1978; Le Pichon & Sibuet, 1981; Bally, 1984; Gibbs, 1984, 1987; Etheridge et al., 1985; Rosendahl, 1987; Etheridge et al., 1989); it is characterised by a half-graben morphology with occasional, apparently asymmetric graben structures. The half-graben are bounded by major rotational normal faults and are typically composed of a number of tilt blocks. Fault displacements on major basin-forming faults range from less than 1.0 s to 2.0 s TWT. The structural style of the Townsville Basin is summarised in Enclosures 15-18.

An important feature of the Townsville Basin is the presence of northwest to north-northwest trending lineaments which generally offset half-graben bounding faults in a right-lateral sense along the basin margins (Fig. 14; Enclosure 14). The rotational normal faults are compartmentalised by these lineaments which are

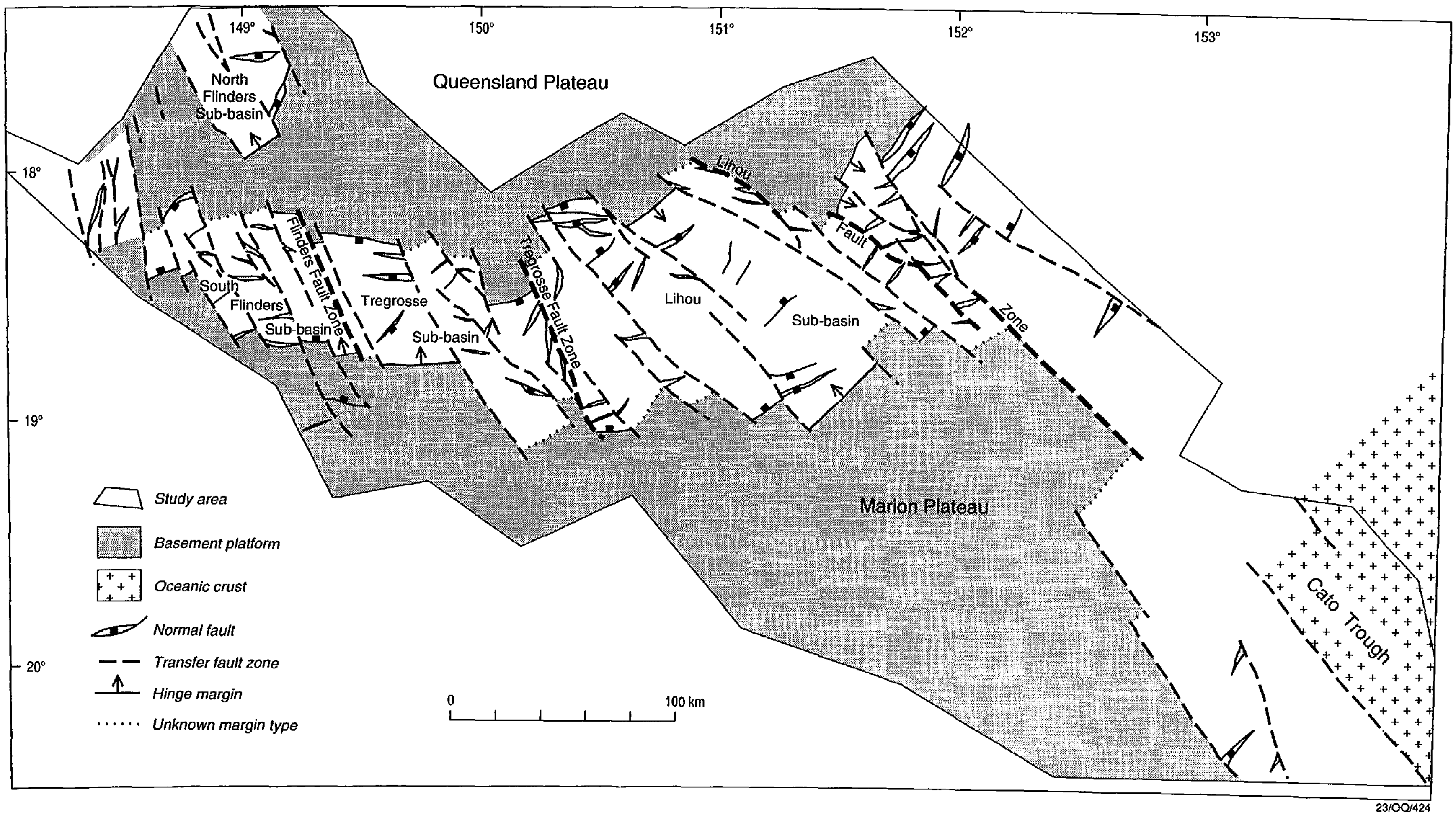

Figure 14: Major structural trends interpreted for the Townsville Basin.

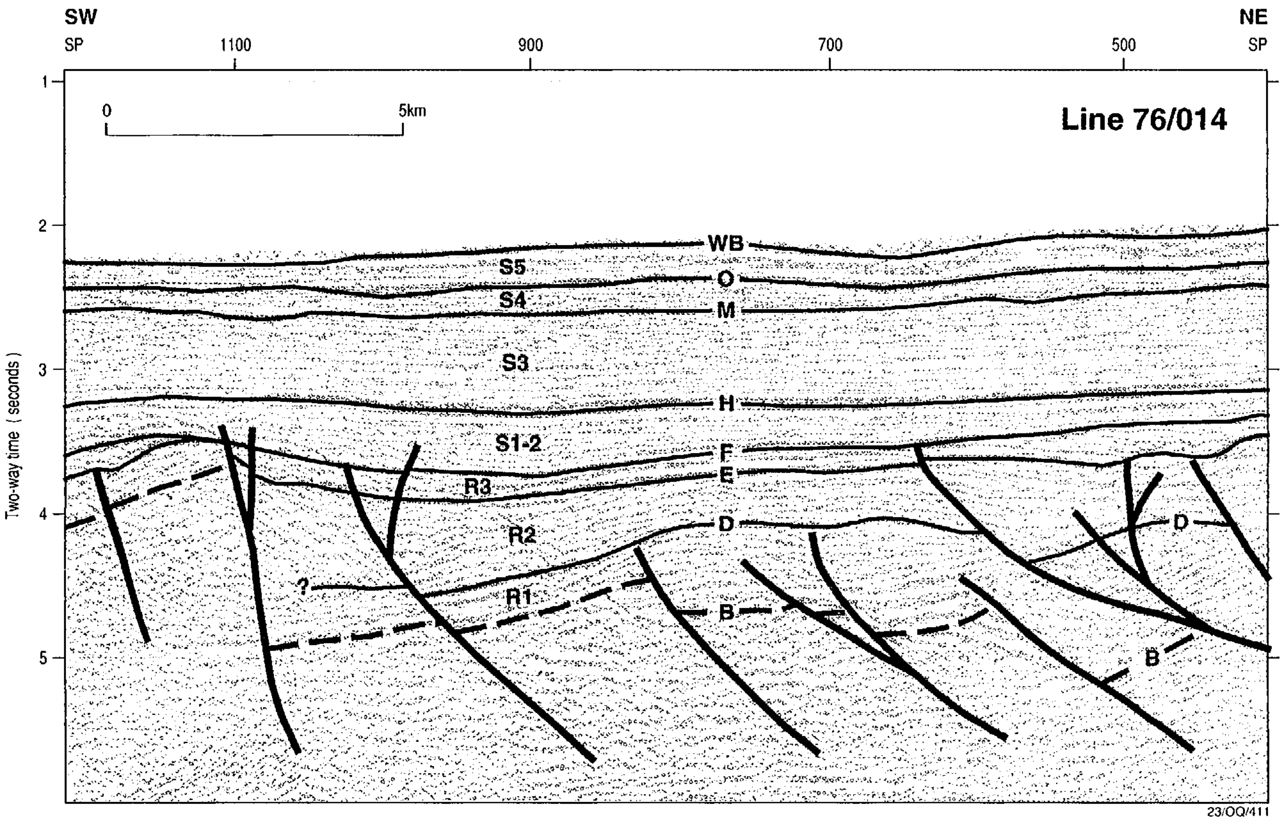

Figure 15: Portion of seismic line 76/14 showing a high-angle diffuse zone interpreted as transfer fault zone (for legend refer to Table 3; for location refer to Enclosure 2).

interpreted as accommodation zones (Rosendahl, 1987) or transfer fault zones similar to those postulated by Gibbs (1984), Etheridge et al. (1984, 1985, 1989) and Lister et al. (1986). These transfer fault zones are typically less than one, to several kilometres wide and are associated with areas of relatively shallow basement. They are generally composed of one or more high-angle faults with variable displacements (e.g. Figure 15), they mark distinct changes in basement dip, and frequently have significant heave. They are typically associated with polarity switches of faults and en echelon stepping of depocentres. In places, they are complicated by negative and positive flower structures (e.g. Enclosures 24 & 26). Mapping of the transfer fault zones proved difficult owing to their complex nature, particularly in areas of sparse data coverage; thus, to some extent, the interpreted transfer zone trends have been extrapolated across the basin using a simple orthogonal extensional model as presented by Etheridge et al. (1984) and Lister et al. (1986).

The high- to low-angle normal faults exhibit a variety of trends, but they generally strike northeast or southeast. They are frequently arcuate in plan and terminate obliquely against transfer zones. In these cases, rotation of basement appears to be directed into "corner faults" as described from the intracontinental Rakwa rift zone in East Africa (Scott, 1994). Many smaller scale faults are difficult to map, owing to inadequate line spacing, the presence of small-scale strike-slip faults and the overall complexity of the basin. Orientation of the faults could not always be constrained and trends in areas of low data coverage (Enclosure 14) are inferred from the regional structural style.

Flinders Sub-basin

In the South Flinders Sub-basin, both the northern and southern boundaries are typically delineated by northeast, east-southeast and east-trending normal faults, some of which also appear to have a strong strike-slip component. Overall, the sub-basin has a more or less symmetric graben morphology with several tilted fault blocks stepping down into the basin. In the westernmost compartment, the central graben narrows considerably and can be interpreted as a large negative flower structure (line 79-16, Enclosure 15). Towards the east, north-northwest trending transfer zones divide the sub-basin into several segments (e.g. lines 76/30 and 76/34, Enclosure 15). Over most of the South Flinders Sub-basin, normal faults typically trend east to east-southeast with northeasterly and southwesterly dips. In contrast, northeast to north-northeast striking normal faults predominate in the westernmost part of the South Flinders Sub-basin as well as in the North Flinders Sub-basin. These northeast trends more or less agree with trends interpreted by Scott (1993) for the Queensland Basin. Trends of transfer fault zones mapped in the westernmost study area are very tentative because of the structural complexity and sparse data coverage. A distinct detachment surface against which normal faults sole out was interpreted on several lines in the northwestern study area (Enclosures 15, 24 & 25).

Tregrosse Sub-basin

In the Tregrosse Sub-basin, the east to southeast-trending northern margin is typically faulted and offset southeastwards by north-northwest trending transfer fault zones. The southern margin is characterised by a hinge zone. In its western part, the Tregrosse Sub-basin appears to be composed of a northwards-plunging half-graben which is composed of several faulted tilt blocks. Interpreted normal faults typically have a south to southeasterly dip. Line 76/28 (Enclosure 23) illustrates the structural style of the western Tregrosse Sub-basin. The northern boundary fault is characterised by a feature resembling a listric fan as described by Gibbs (1984), with a low-angle master fault acting as a detachment for a number of smaller faults. In its eastern part, where it widens along a major transfer zone, the sub-basin becomes more complex and the normal faults are higher angle. Line 76/25 (Enclosure 22) is located along an intra-basinal transfer zone west of the Tregrosse Fault Zone, which has a north-northwest trend and branches into three segments at its northern end (Fig. 14; Enclosure 14). To the west of this zone, normal faults strike east to southeast and dip to the south-southwest, whereas north-northeast striking normal faults with a northeasterly dip occur east of this zone. The Tregrosse Sub-basin narrows to about 50 km at its easternmost end, between this branched fault zone and the Tregrosse Fault Zone to its east. In this compartment the flanking basement platform protrudes into the basin on both its southern and northern margins. Line 76/25 (Enclosure 22) shows the complexity of this compartment with its high-angle faults, and changes in basement rotation, polarity and displacement.

Lihou Sub-basin

The northern and southern boundaries of the Lihou Sub-basin are characterised by polarity switches between northeast-trending hinges and faults across northwest trending transfer zones. However, in a number of locations, the nature of the boundary could not be interpreted either because of a masking of much of the seismic record by reefal platforms within the younger section, or because of inadequate data coverage. Similarly, interpretations of fault trends within the central southern Lihou Sub-basin are only tentative owing to poor seismic resolution in the area of thickest sediment, where the sediment/basement interface cannot be resolved (Enclosure 3). Normal faults in the sub-basin generally trend northeast and east to southeast. The style of the sub-basin is difficult to determine as there is no true 'dip-line' across the entire basin which doesn't cross a major transfer zone. However, lines 76/21 (Enclosure 17) and 76/23 (Enclosures 16 & 21) represent good examples of the general structural style. On the southern end of Line 76/21 basement is not resolved as it is masked by a volcanic mound within the early sag-phase sequence (Fig. 11). However, this line clearly shows basement dipping steeply basinward from both the northern and southern ends to a central point masked by the volcanics. Although not shown on the structure map, the volcanics may be associated with an underlying transfer zone (Bosworth, 1985).

On Line 76/23 (Enclosure 21), the northern boundary is defined by a growth fault which consists of a moderately steep ramp in its upper part but shallows into a flat ramp at depth. The early synrift sequence (R1) thickens into the lower part of the fault and the main synrift sequence (R2) thickens into the upper part of the fault. The upper and lower parts of this growth fault have slightly differing trends, a phenomenon which is also seen for the major basin-bounding fault intersected by the northern end of line 76/11 (Enclosure 20). Here the earlier synrift section is associated with a northeasterly trending fault plane (Enclosure 4) and the later rift section is associated with a southeasterly trending fault plane (Enclosure 9). This indicates a multi-phase nature of rift-zone formation. The half-graben defined by the growth fault on line 76/23 (Enclosure 21) is bounded to the south by a number of steeper faults which may partly be a result of hanging wall collapse. However, the major antithetic fault system appears to cut the listric fault indicating that this fault is part of another, younger cross-cutting trend.

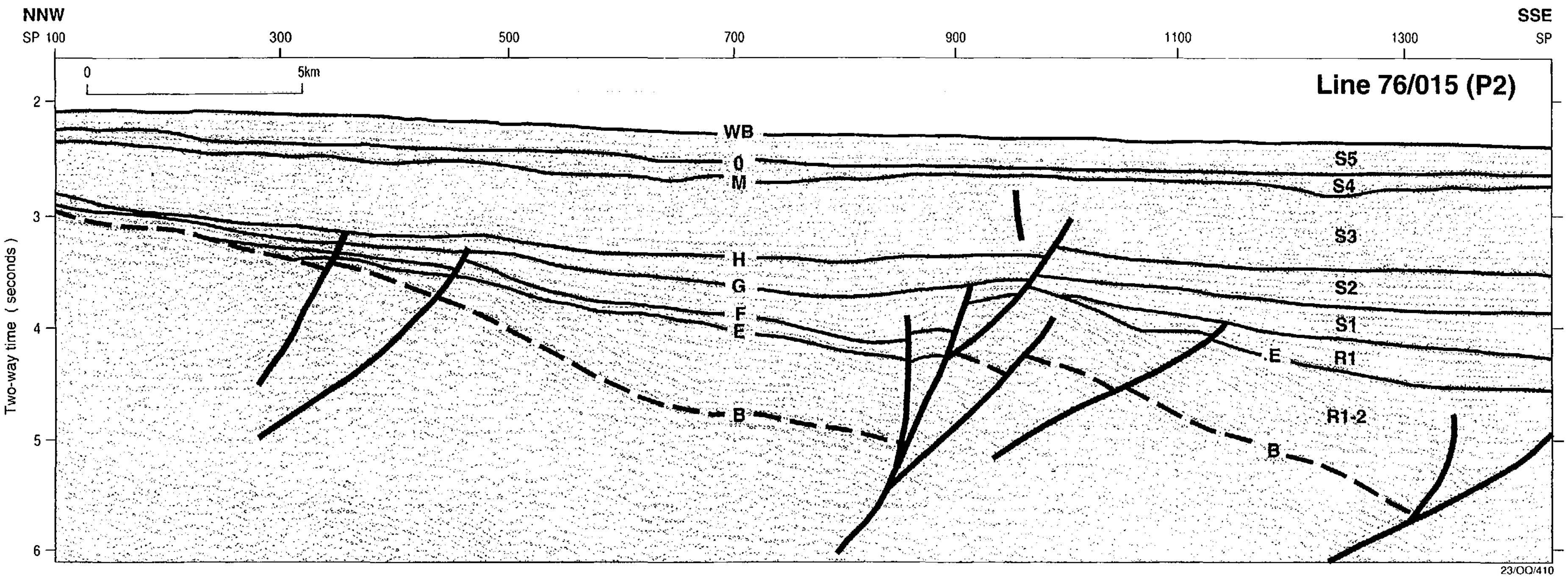

Figure 16: Portion of seismic line 76/15 showing the northern hinged basin margin and two basinward-dipping half-graben (for legend refer to Table 3; for location refer to Enclosure 2).

On Line 76/23 two major depositional centres in the Lihou Sub-basin are separated by an approximately 15 km-wide, complex horst block, the southern end of which is defined by a major northwest trending transfer zone. The polarity of the normal extensional faults changes across this transfer zone, and the southern depocentre lies in the westernmost compartment of the Lihou Sub-basin. Basement within this compartment occurs at 5.5-6.0 s TWT (≈7.5-8.5 km). South of the fault defining this half-graben, basement dip changes and there is no indication of sediment growth into the southern boundary fault, which is interpreted to represent a major transfer zone.

East of the Lihou Fault Zone, normal faults typically strike north-northeast. The northern basin margin switches from a gently dipping hinge as shown in Figure 16 to a faulted margin with several fault blocks stepping into a large graben structure illustrated in Enclosure 20. The southern margin of the easternmost Townsville Basin is not well-defined, largely due to sparse data coverage. However, line 76/11 (Enclosure 20) illustrates several half-graben of more than 10 km width dipping to the south into the Cato Trough. A basement high appears to separate the easternmost Townsville Basin into northern and southern parts (Plates 1, 3 & 4). This high is overlain by mounded features which may be either reefs or volcanics (Enclosure 20).

Cato Trough

Four seismic lines cross the boundary between the Marion Plateau and the Cato Trough. On the two southernmost lines (73-1130 and 76/07; Enclosures 18 & 19), a synrift sequence, up to 2.5 s TWT (≈ 5 km) thick, is present between two high-angle faults along the slope below the Marion Plateau. As the line spacing in this area is about 50 km, it is not clear whether these probable transfer zones correlate as shown on the structure map (Enclosure 14); however, if the correlation is correct, they have a northwest trend which is similar to trends in the central Townsville Basin. To the east of this southern graben structure, steeply eastward-dipping basement is overlain by a sequence comprising high-amplitude, disrupted, seaward-dipping reflections which are interpreted as volcanics and lava flows. This sequence correlates with flat lying oceanic basement on the eastern part of lines 76/07 and 73-1130, and on line 76/08. The graben structure is not present to the north, on line 76/09 (Enclosure 17), where the boundary between the Marion Plateau and Cato Trough is defined by an eastward dipping hinge, and only minimal rift-phase sediments are present.

The style of the continent-ocean boundary (COB) east of the Marion Plateau is illustrated on line 76/07 (Enclosure 19). Continental basement is displaced by about 2.0 s TWT along an east-dipping fault which soles out onto a deep reflector. This reflector dips westwards from about 8.5 s (≈ 15 km), below oceanic basement, to more than 9.5 s TWT (≈ 20 km), below interpreted continental basement, where seismic resolution is lost. It is likely that this deep COB reflector represents Moho dipping beneath the continent. On line 73-1130, the continent-ocean boundary appears to be more complex, but this may be the result of poor data quality. On line 76/09 oceanic basement is interpreted on the easternmost part of the line, indicating that the COB is offset along a fault zone between lines 76/09 and 76/07 (Fig. 14; Enclosure 14).

Structural Model

The relatively widely spaced data across the Townsville Basin, wide variation in interpreted fault trends, the presence of at least two reactivation events, and the overall structural complexity of the basin all impose limitations on a rigorous evaluation of the basin's kinematic history. Interpretation of structures in the Townsville Basin was partly driven by utilising a simple orthogonal model of extension (e.g. Gibbs, 1984; Etheridge et al., 1984; Lister et al., 1986). This model implies extension roughly orthogonal to the rift axis, resulting in normal faults striking parallel to, and transfer faults/accommodation zones striking perpendicular to, the rift axis. Alternatively, a simple strike-slip model requires a principle strike-slip displacement zone parallel to the basin axis and normal faults striking at angles of 60-120° with respect to the rift axis (Aydin & Nur, 1982; Mann et al., 1983; Christie-Blick & Biddle, 1985).

The main structural trends in the Townsville Basin indicate that the basin-forming mechanism cannot be simply explained by either of these end-member models.

The observed structural style in the Townsville Basin is characterised by:

- a predominance of half-graben morphology;
- significant basement dip into normal faults on profiles that are both transverse and parallel to the rift axis;
- heave on 'normal' faults on lines parallel to the rift axis;
- the presence of significant heave on major rift transverse faults;
- polarity reversals of basement dip on all lines; and
- numerous positive and negative flower structures.

Thus, contrary to predictions from the simple extensional model, profiles in all orientations exhibit dipping basement (Enclosures 15-18) and the possible "transfer faults" have significant heave. The distinct northwesterly fault trend which is interpreted to represent transfer zones is at angles of about 50-80° with the two main rift axis trends (Table 2) of the Townsville Basin. Similarly, interpreted normal faults which are constrained by more than one seismic line, rarely trend parallel to the rift axis trends. The main structures show trends which cannot be reconciled with a simple orthogonal model — the trends suggest that the basin formed by oblique northwest extension as suggested by Symonds et al., 1987, 1988). Chorowicz & Sorlien (1992) and Scott et al. (1992) made similar observations in rift basins in East Africa, and Scott (1994) concluded that the tectonic transport direction in the Queensland Basin is also oblique to the rift axis. Scott et al. (1992) defined extension that is neither perpendicular nor parallel to the rift basin axis as 'oblique extension'.

A method to better constrain kinematics in extensional terranes, particularly for basins where seismic reflection data are the sole source of information, has been proposed by Scott et al. (1994). This method, which involves calculation of true basement dip from two apparent dips at seismic line intersections, was used in the present study to further test a simple orthogonal model, to determine whether the main structural elements of the Townsville Basin are associated with distinct dip domains, and to attempt to better constrain the tectonic transport direction. However, it needs to be stressed that the use of this method for establishing tectonic transport direction in areas that have undergone multiple deformation phases should be treated with caution.

The computation of true basement dips from apparent basement dips conducted at 88 seismic profile intersections provides a direct observation of the net rotation of infra-rift blocks within the Townsville Basin. It is evident from the rose diagram and stereonet presentation of the dip data (Fig. 17) that no clear consistent basement rotation can be interpreted throughout the basin. Three main dip directions are observed, a strong north-northeast - south-southwest trend, a north-northwest - south-southeast trend and an east-southeast - west-northwest trend. Thus, these data tend to refute a simple orthogonal model of extension, in which basement rotation would be expected to align along a northwest to north-northwest azimuth. The results of the basement dip analysis are difficult to understand in terms of a consistent tectonic transport direction.

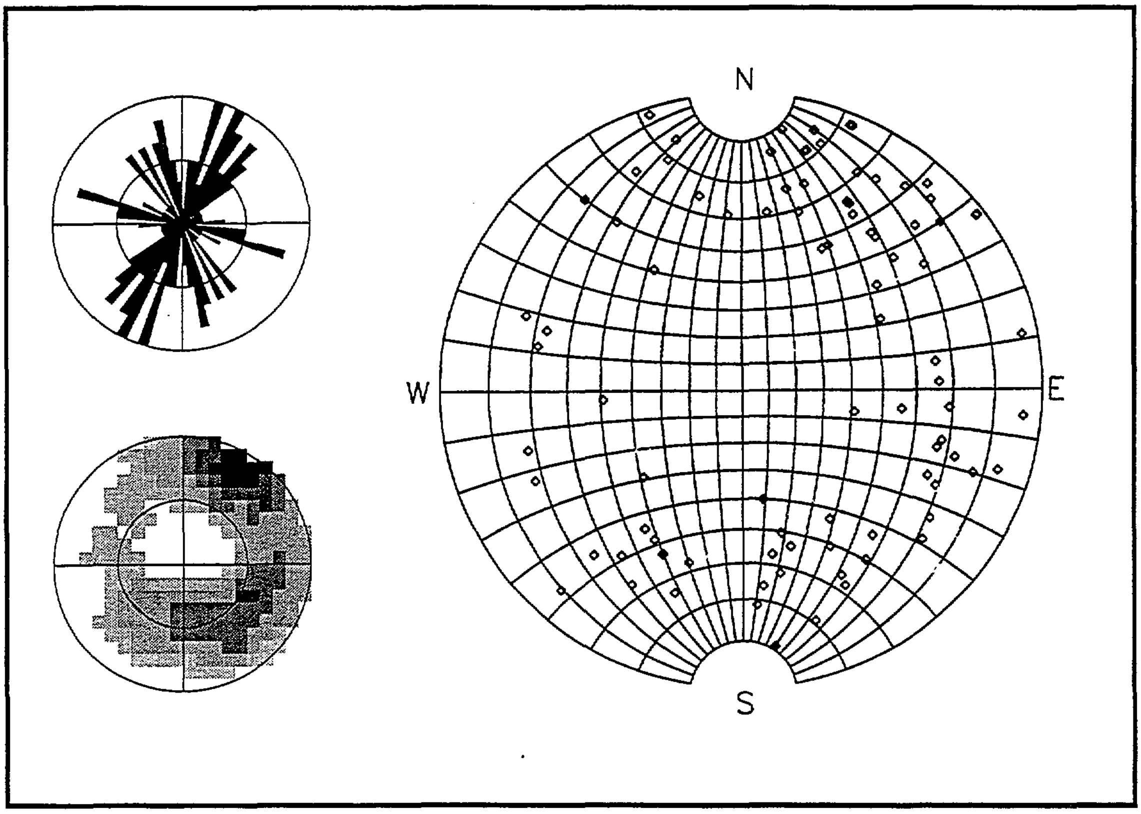

Figure 17: Rose diagram and stereonet presentation of directions of 88 true basement dips in the Townsville Basin.

When the dip data are grouped according to sub-basin (Fig. 18), it is evident that the three observed trends are dominant in different basin elements. In the North and South Flinders Sub-basins, the north-northeast - south-southwest trend is most prominent and is roughly orthogonal to the east-west - east-southeast trending basin margins and the overall east-southeast trending rift axis. In the Tregrosse Sub-basin, the most prominent basement dip is along the east-southeast trend, which is roughly parallel to the rift axis rather than orthogonal. This trend is strongest at line intersections in the eastern sub-basin, close to the Tregrosse Fault Zone and may represent basement dipping obliquely into intersections of normal and transverse faults within this complex zone. Northwest and northeast trends of basement dip occur mostly along the sub-basin margins; they are oblique to the rift axis with angles of 30-60°, and suggest oblique extension. A distinct east-southeast trend (110°) similar to that observed west of the Tregrosse Fault Zone was also described for the Queensland Basin, where it is interpreted to coincide with the oblique extension direction (Scott, 1994). In the Lihou Sub-basin, the south-southeast trend is most prominent at an angle of about 70 to 80° with the overall northeast-trending rift axis in the Lihou Sub-basin.

The presence of distinct domains of basement dip trends within the sub-basins of the Townsville Basin adds weight to the suggestion that the rift zone formed by utilising pre-existing lineaments within an anisotropic basement. Basement dips within the individual sub-basins more or less conform to a model of oblique extension, i.e. basement dips obliquely to orthogonally into normal faults which are in turn orthogonal to oblique to the rift axis trends.

In summary, it is suggested that the Townsville Basin formed by overall northwest directed oblique extension, which was accommodated and modified by the reactivation of pre-existing basement trends. The Queensland Basin is interpreted to have formed through west-northwest directed extension (Scott, 1993) and was probably part of the same extensional system. The different structural trends of the Townsville and Queensland Basins can be reconciled by them having a common pole of rotation during the extensional episode, located to the southwest of the zone of convergence between the two basins (Scott, 1994). The tectonic transport direction associated with this extensional event is nearly perpendicular to the extensional stress field which resulted in the Paleocene to

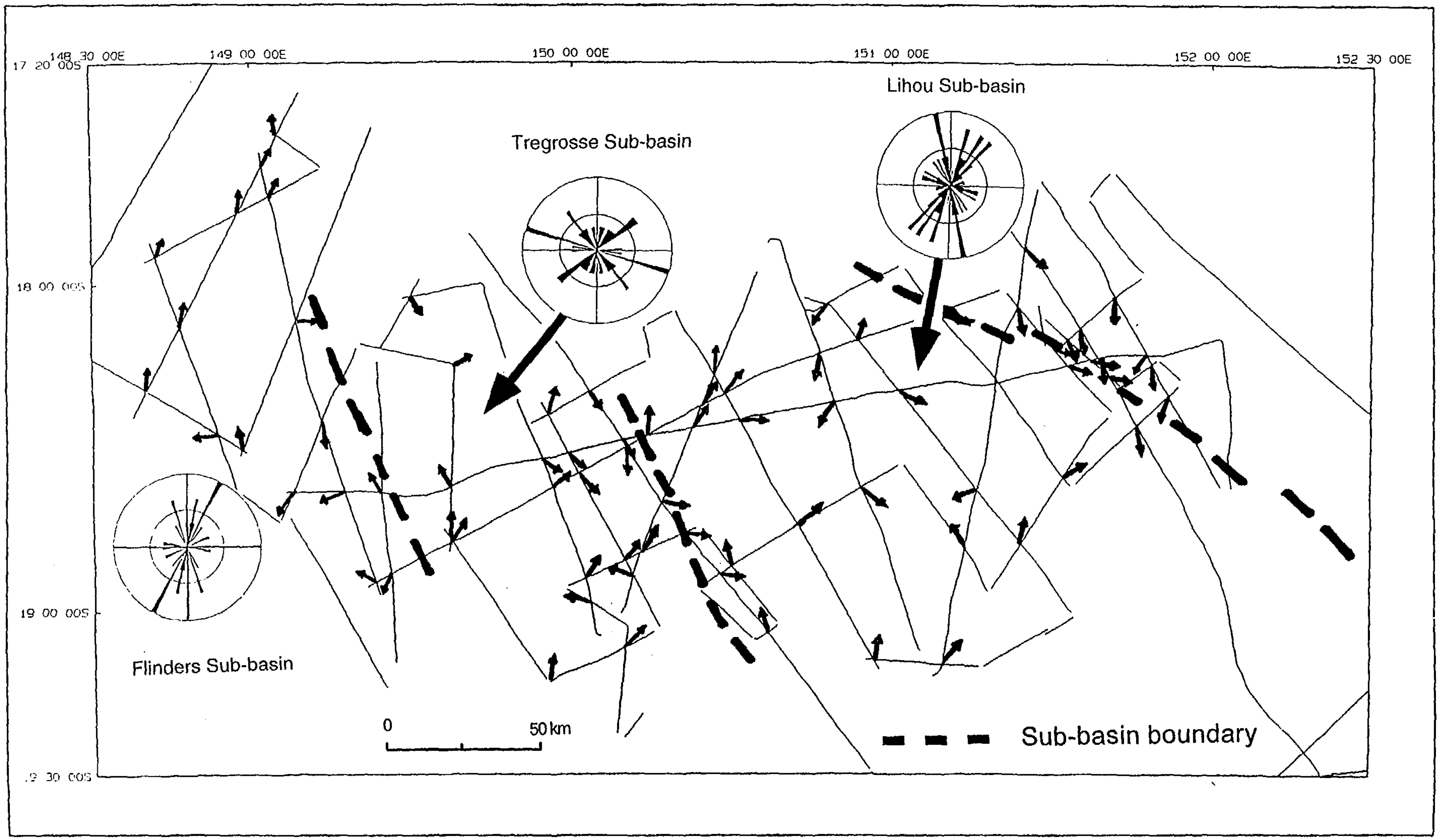

Figure 18: Trackline map of interpreted seismic lines showing areal distributions and rose diagrams of directions of true basement dips.

Early Eocene opening of the Coral Sea Basin to the north, and the northern Tasman Sea and Cato Trough to the southeast. Therefore, the formation of the Townsville and Queensland Basins is interpreted to predate and to be kinematically independent from later extensional and ocean basin forming events in the Tasman Sea and Coral Sea, as originally suggested by Symonds et al. (1987).

The origin of rift troughs and marginal plateaus within this part of the northeast Australian continental margin can be linked both spatially and temporally in terms of a detachment model (Lister et al., 1986) in which the full width of the margin is part of a complex upper-plate (Symonds et al., 1988) formed initially during northwest-southeast extensional tectonic transport. The relatively unstructured Queensland Plateau would be underlain by a mid-crustal detachment, and its northwestern and southeastern margins would be associated with branches in the detachment. Its Queensland Trough margin lies along the western edge of the extensional terrane, and would largely have formed as a side-wall feature. The "headwall" of the detachment system is undefined, but probably lay to the north of the Eastern and Papuan plateaus, and has now been incorporated into the collisional system associated with the New Guinea Orogen. Slightly oblique upper crustal extension beneath the Townsville Trough, and highly oblique extension beneath the Queensland Trough, would have been accompanied by varying degres of sub-detachment pure-shear extension of the lower crust and upper mantle of the whole extensional terrane. The latter would have led to subsidence of the whole margin province, with the Queensland Plateau subsiding more than the Marion Plateau, because of the greater lithospheric thinning beneath it. The width and character of the adjacent onshore Eastern Highlands appears to have some correspondence with margin features and provinces, and may be interpreted within the detachment model as passive margin mountains formed in part by thermally induced uplift, as well as some permanent uplift related to the deep thinning and associated igneous underplating. The reduced expression of the Eastern Highlands adjacent to the Queensland Trough, and its even lower relief adjacent to the Marion Plateau, compared to that adjacent to the Tasman Basin to the south, probably relates to the reduced aerial effect and magnitude of deep thinning associated with the northeast margin extensional event. Adjacent to the Queensland Trough the western extent of deep thinning may have been largely limited by it being the side-wall to the extensional system, and adjacent to the Marion Plateau, where deep thinning was much less than to the north, any permanent effect of uplift was even further reduced. Within this model of rift basin development, the Capricorn Basin, to the south of the Marion Plateau, can also be viewed as a side-wall feature associated with highly oblique upper crustal extension but minimal deep thinning. Later phases of basin and margin development leading to full continental breakup and seafloor spreading in places, were superimposed on the primary rift architecture associated with this initial continental extension event.

Timing of Structural Events

The major structural event in the Townsville Basin was oblique northwest-southeast directed lithospheric extension which led to the formation of its predominant half-graben morphology. Later structural events are considered to be reactivation/inversion events superimposed on the initial basin forming event (Table 5). In a number of asymmetric graben structures, thickening of the later rift sediments into graben-bounding faults occurs in the opposite direction to that of the earlier synrift sediments (Lines 76/30, 76/34, 76/35). This "teeter-totter" effect (Rosendahl, 1987), in conjunction with differing trends of lower and upper fault planes, indicates that there were at least two significant phases to the extensional event. In places, the main synrift section overlying the earlier synrift sediments onlaps erosional fault scarps, indicating that these faults were inactive during the later stage of rifting. In other locations, clearer structural growth patterns are observable along faults for the same sequence. On many sections the boundary between sequences R1 and R2 is a distinct angular unconformity indicating that the second rifting phase was associated with differential uplift and erosion. Separate mapping of the events and a resolution of potentially differing trends was not possible with the present data set in the study area.

As discussed previously, the initial basin-forming event is thought to be of Jurassic to Early Cretaceous age and independent of events which led to the formation of the Coral and Tasman Sea Basins. However, the second extensional stage interpreted for the Townsville Basin could possibly be related to the rifting/extensional event that led to the development of the Coral Sea Basin and the Tasman Basin. Apart from the Early Cretaceous rift-related volcanic province interpreted by Ewart et al. (1990, 1992) and the presence of a Cretaceous volcaniclastic sequence in the Capricorn Basin (Ericson, 1976), there is no good constraint on the age of rifting in the Townsville and Queensland Basins. The pre-rift sedimentary section (sequence PR) interpreted for parts of the Townsville Basin may represent remnants of an older Palaeozoic basin system, which extends onshore into the Townsville hinterland (Swarbrick, 1976; Arnold & Fawckner, 1980; Wyatt & Jell, 1980), or it may consist of continental to marginal marine sediments of Jurassic age similar to those described for the Laura (Pinchin, 1974; Smart & Rasidi, 1979), Styx (Benstead, 1976) and Maryborough Basins (Ellis, 1976; Hill, 1994).

AGSO seismic line 76/07 (Fig. 12, Enclosure 19) images a distinct structural event which influenced sedimentation during the early sag-phase in the Cato Trough, with thickening of the sequence into a major fault. West of the continent-ocean boundary, this sequence (horizons BB to GB) thins rapidly and onlaps oceanic basement and rift-phase sediments. The top of this early sag-phase sequence (S1a, S1b) is strongly faulted and a number of reverse faults can be observed (Line 76/09 - Enclosure 17). Enclosure 19 indicates that the faulting probably occurred by wrench reactivation of older normal faults. Horizon GB in the Cato Trough is interpreted to approximately correlate with Horizon G in the Townsville Basin (Table 2), which is also affected by a reactivation event, albeit to a lesser extent. The structural trend resulting from this wrenching event is difficult to establish, particularly in the Cato Trough where it is most prominent. However, the available data suggest a northwest trend, more or less parallel to the Marion Plateau margin and the interpreted continent-ocean boundary. Interpreted ages of mapped horizons indicate that this structuring event is of probable Paleocene to Eocene age and may correlate with the period of seafloor spreading in the Coral Sea Basin and northern Tasman Sea Basin/Cato Trough.

A fourth, minor structuring event, which affected sedimentation of sequences S3 to S5 is evident on many seismic sections. It is characterised by numerous small-throw faults which are frequently associated with older normal faults and transfer

Table 5: Event History for the Townsville Basin.

AGE	EVENT	STRUCTURAL STYLE - TOWNSVILLE BASIN
Palaeozoic - Early Mesozoic	Regional intracratonic basin development	Possibly gentle structuring in intracratonic downwarps along sites of future rifting;
Jurassic to Early Cretaceous	Extension in Townsville, Queensland & ?Capricorn Basins	Half-graben development; significant normal and strike slip faulting;
mid- to Late Cretaceous	Extension preceding seafloor spreading in Coral and Tasman Sea Basins	Uplift and differential erosion along basin margin; continued movement on normal faults; development of antithetics; asymmetric graben formation;
Paleocene-Eocene	Seafloor spreading in Coral and northern Tasman Sea Basins, and ?Cato Trough	Major wrench reactivation on normal and transfer faults; differential uplift and erosion of synrift section;
Oligocene-Miocene	Collision along northern Australian margin - changes in intraplate stress	Minor reactivation structuring, particularly along major basin-forming faults;

zones. They occur preferentially in the vicinity of major basin-forming faults, offsetting reflectors mostly within sequence S3. Some of this faulting may have been caused by deformation of unconsolidated sediment and differential compaction, but may also relate to changes in intraplate stress resulting from collisional events along the northern Australian margin during the Neogene (Hamilton, 1979; Johnson, 1979; Pigram & Davies, 1987; Struckmeyer et al., 1993).

TECTONOSTRATIGRAPHIC EVOLUTION

Systematic interpretation of the regional seismic grid across the Townsville Basin has produced an improved understanding of the structural style and sedimentary fill of the basin. The Townsville Basin formed part of a complex intracratonic rift system of probable Mesozoic age along Australia's northeastern margin. This system formed through overall oblique northwest-southeast extension which utilised pre-existing Palaeozoic structural trends of the Tasman Fold Belt. Comparison with interpreted structural trends of the adjacent Queensland Basin supports the suggestion that formation of both basins predated, and was independent of the tectonism related to seafloor spreading in the Tasman and Coral Sea Basins.

The structural style and sequence geometries interpreted from the seismic sections are consistent with the following tectono-stratigraphic history. During most of the Palaeozoic, the tectonic setting of the eastern and northeastern margins of Australia was that of a convergent margin, with periods of oblique subduction represented by northwest trending, parallel belts of volcanic arc, forearc basin and subduction complex successions (e.g. Harrington & Korsch, 1985a, b; Henderson, 1987; Murray et al., 1987; Totterdell et al., 1991). Basement underlying the present-day offshore northeastern margin is thus likely to comprise an amalgamation of Palaeozoic intrusions and lithified sediments of probably mostly forearc assemblages (Murray et al., 1987). North-northwest to northwest-trending lineaments, which separate distinct gravity provinces on the Queensland and Marion Plateaus (Plate 10), parallel those of the Tasman Fold Belt onshore and may represent terrane boundaries between these old convergent margin belts. A distinct northwesterly gravity trend on the eastern Marion Plateau may in fact be an old Palaeozoic suture. It appears to be offset to the west in the vicinity of the Tregrosse Fault Zone which is interpreted to be a major structural boundary in the younger Townsville Basin. There is an indication that gravity trends change from north-northwesterly on the Marion Plateau and the southeastern Queensland Plateau, to northwesterly and west-northwesterly trends on the western Queensland Plateau (Plate 10). These two trends correspond to the trends of transverse structures in the Townsville and

Queensland Basins, again indicating that formation of the two basins was probably controlled by older basement trends.

In the Jurassic to Early Cretaceous, the eastern Australian continental margin, incorporating the present marginal plateaus, lay adjacent to the Pacific Plate. The overall tectonic setting of the margin was still convergent, with the continent-ocean-boundary lying to the east of Lord Howe, Dampier and Mellish Rises (e.g. Veevers et al., 1991; Struckmeyer et al., 1991), which were later detached from the Australian continent in the Late Cretaceous to Paleocene through the opening of the Tasman Sea/Cato Trough by seafloor spreading. The northern Australian margin in New Guinea is thought to have been a passive margin during the Mesozoic with a major extensional episode occurring in the Late Triassic to Early Jurassic (Pigram & Davies, 1987; Home et al., 1990; Struckmeyer et al., 1990, 1993). It is possible that these two opposing margin settings, i.e. convergent in the east and passive in the north, were connected via a strike-slip fault system along the northeastern margin of Australia (Symonds et al., 1984), which included possible subsidiary fault systems along the site of the present Queensland-Townsville-Capricorn Basin system.

In the Jurassic to Early Cretaceous, overall northwest-southeast directed, oblique extension occurred along this northeastern strike-slip margin and resulted in low- to high-angle normal faulting and block rotation which initiated the Townsville and Queensland Basins. Major northwest to north-northwest trending transverse structures, which compartmentalise the Townsville Basin into distinct structural elements, align with lineaments of the onshore Tasman Fold Belt indicating that extension in the basin was accommodated by the utilisation of pre-existing, Palaeozoic structural trends; as discussed above, these trends are likely to represent major basement terrane boundaries. Gravity trends, structure contour maps and sediment thickness maps all indicate that at least the earlier phases of sedimentation in the Townsville Basin were controlled by these major old structural trends.

The transtensional tectonism in the Townsville Basin was accompanied by volcanism and differential uplift in adjacent regions. Coarse to fine-grained clastics derived from adjacent and intra-basin basement highs, and volcanics were deposited in a variety of terrestrial environments ranging from alluvial fan deposition along steep fault scarps to fluvial and, possibly, lacustrine environments in the deeper parts of the basin. In the mid- to Late Cretaceous, a northeast-southwest directed extensional event, which later culminated in breakup and opening of the Coral and Tasman Sea Basins, may have been superimposed on the older rift system, resulting in reactivation and overprinting of the primary basin-forming structures, and uplift and differential erosion in the Townsville Basin. Some of the tilt blocks were capped and buried by the late rift-phase sedimentation. Deposition occurred in similar, alluvial, fluvial and fluvio-lacustrine environments, but marginal marine environments probably existed during this latest rift stage in the deeper, eastern part of the basin.

During the Paleocene to Eocene episode of seafloor spreading in the Coral Sea Basin to the north and possibly in the Cato Trough to the southeast, wrench movement on reactivation faults continued and ?subaerial volcanism occurred in the eastern Townsville Basin. Partially restricted shallow marine conditions probably existed in the basin, with paralic to shallow shelf environments on the basin margins. In post-middle Eocene time, slow regional subsidence during the post-breakup sag-phase of continental margin development resulted in shallow marine conditions being established on the Queensland and Marion Plateaus, although parts of both of these features were probably still emergent until at least the Oligocene. During the Middle to Late Eocene, the Townsville Basin received neritic to deepwater, high and low energy deposits which probably consisted mainly of terrigenous and calcareous turbidites. Minor reactivation events occurred in the mid-Oligocene to Late Miocene/Early Pliocene, probably as a result of collisional tectonism along the northern Australian margin. This mid-Oligocene event was enhanced by a global fall in sealevel and is reflected by a major regional unconformity. A Late Oligocene sealevel rise followed, resulting in the gradual flooding of the adjacent basement platforms and eventual establishment of carbonate platforms and reef growth. Minor volcanic activity persisted probably into the Early Miocene. In post- Early Oligocene times, as the water depth over the plateaus increased, pelagic ooze, turbidites and slump deposits, in part derived from the flourishing carbonate platforms, became the major components of sedimentation in the basin.

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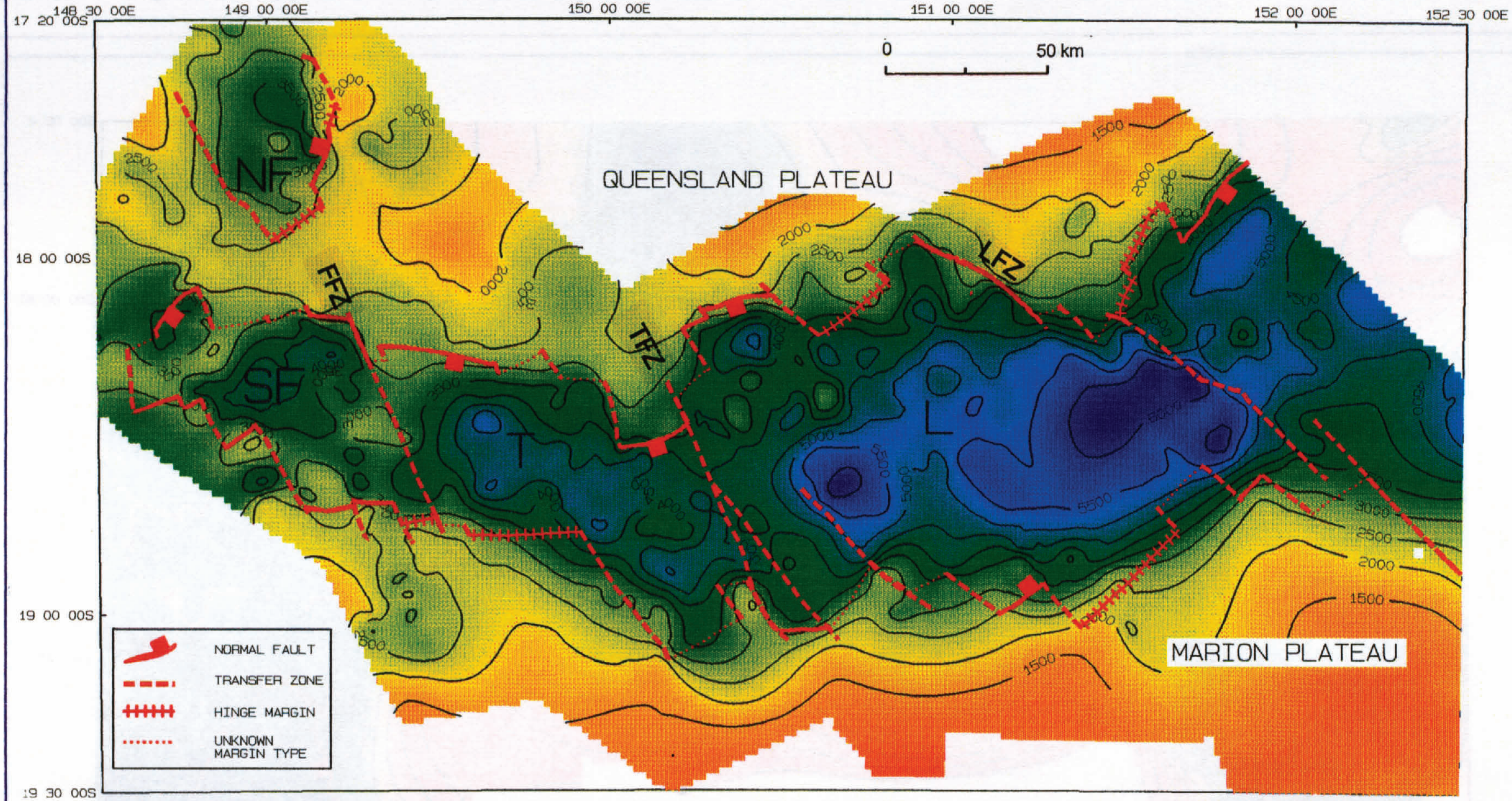

Plate 1: Contours of basement structure in milliseconds TWT, showing interpreted major structural elements of the Townsville Basin; NF = North Flinders Sub-basin, SF = South Flinders Sub-basin, T = Tregrosse Sub-basin, L = Lihou Sub-basin; FFZ = Flinders Fault Zone, TFZ = Tregrosse Fault Zone, LFZ = Lihou Fault Zone.

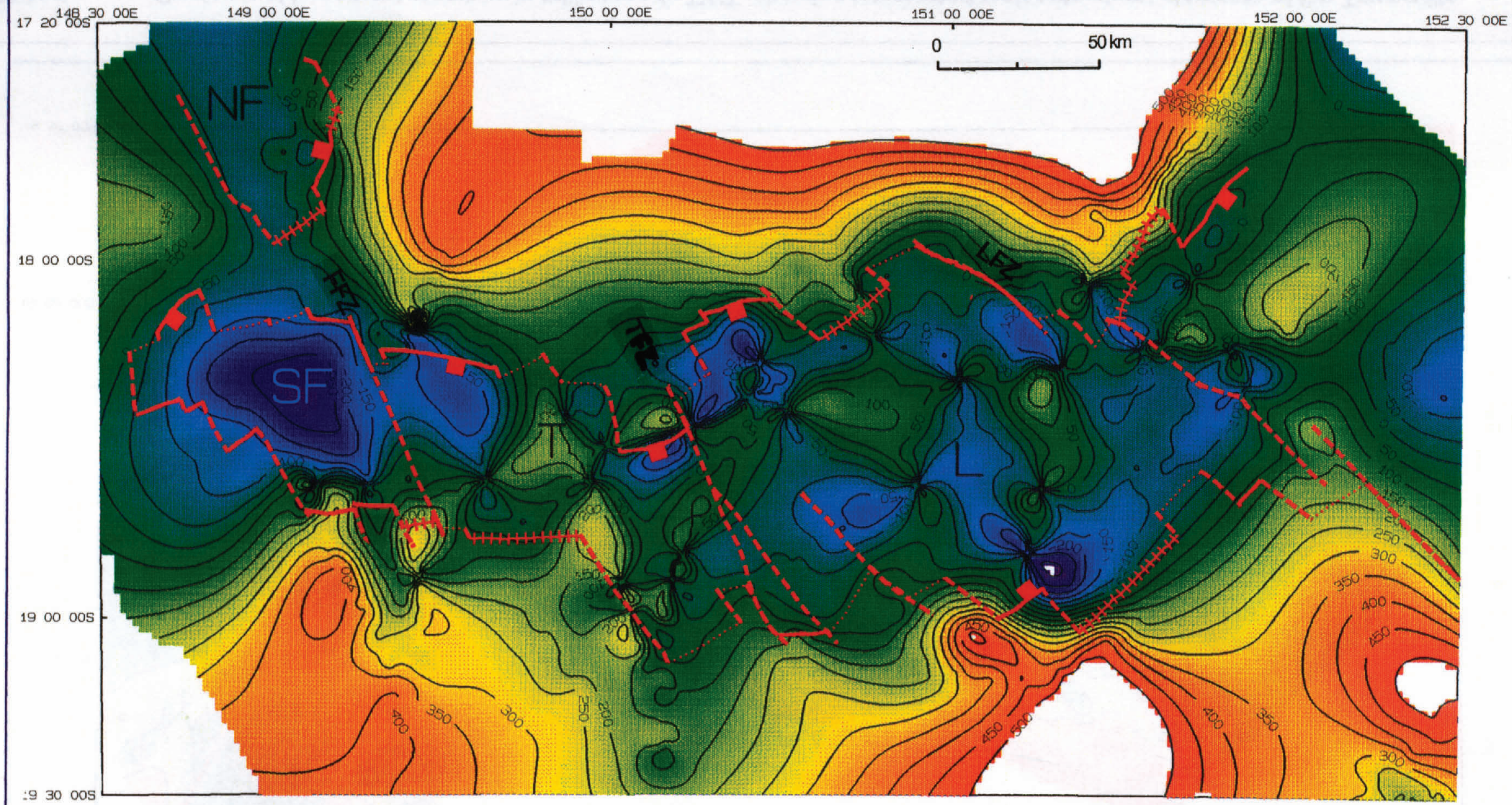

Plate 2: Contours of free-air gravity collected during AGSO Surveys 50 & 76, showing interpreted major structural elements of the Townsville Basin; NF = North Flinders Sub-basin, SF = South Flinders Sub-basin, T = Tregrosse Sub-basin, L = Lihou Sub-basin; FFZ = Flinders Fault Zone, TFZ = Tregrosse Fault Zone, LFZ = Lihou Fault Zone.

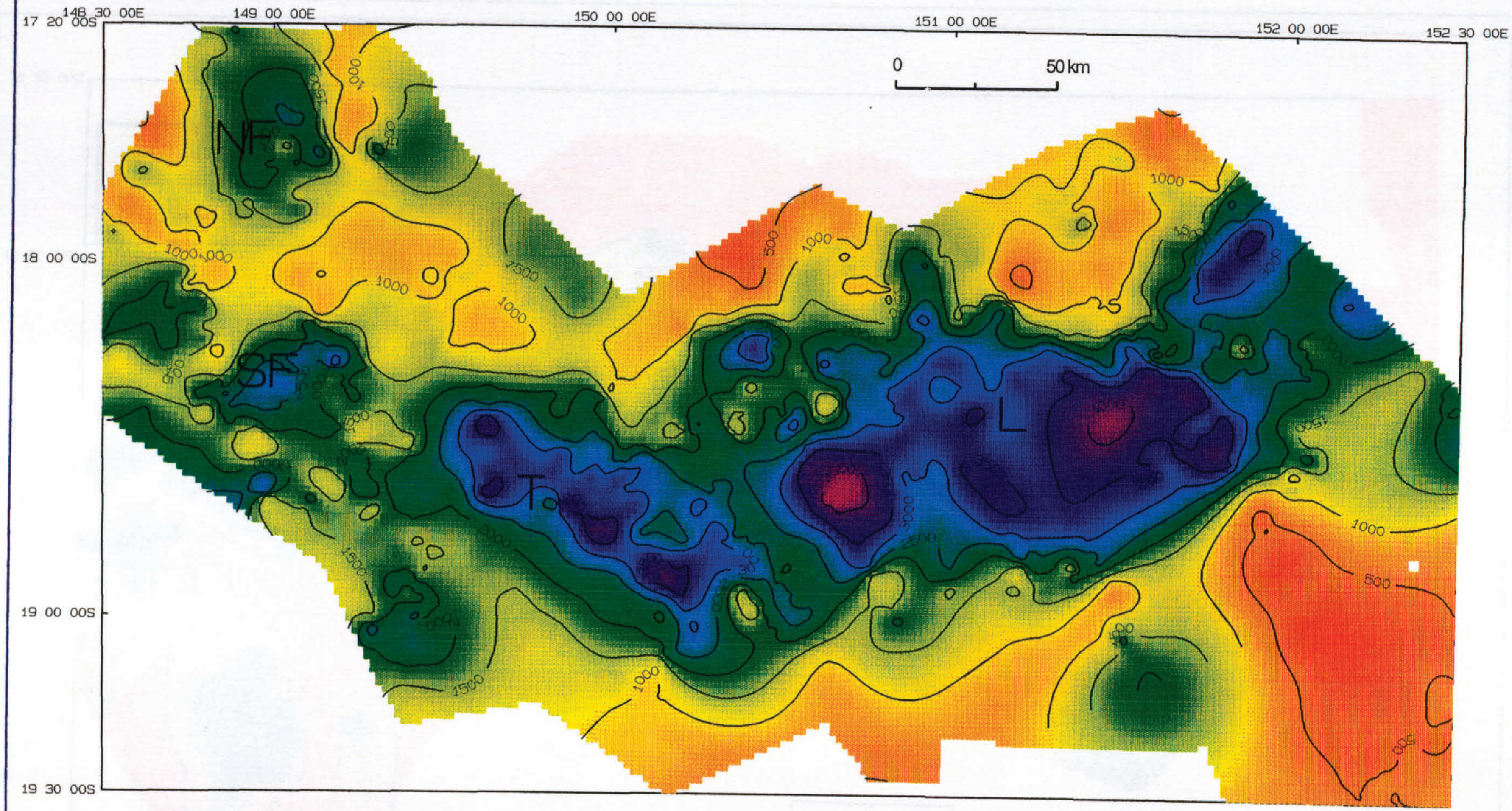

Plate 3: Contours of total sediment thickness in milliseconds TWT; NF = North Flinders Sub-basin, SF = South Flinders Sub-basin, T = Tregrosse Sub-basin, L = Lihou Sub-basin.

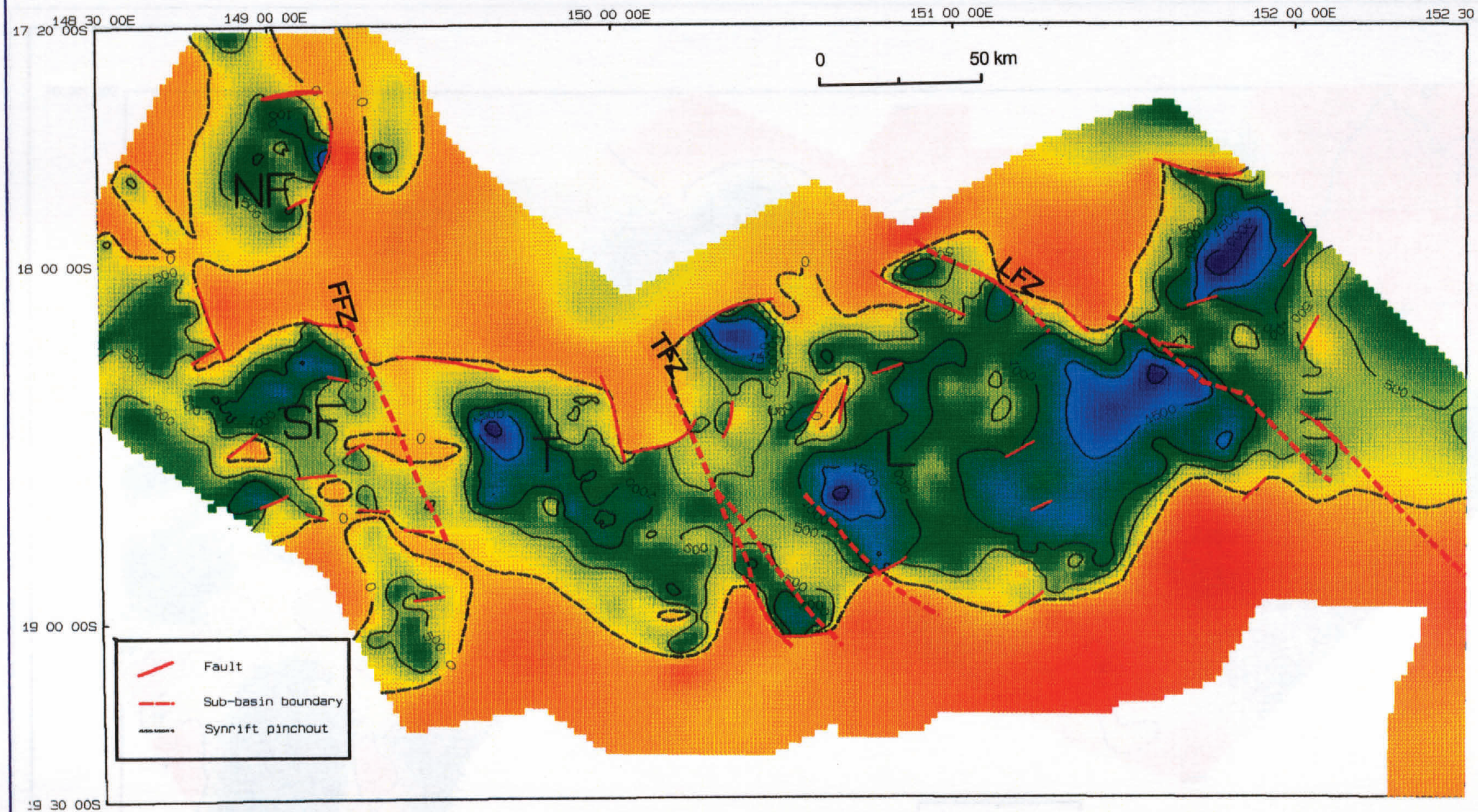

Plate 4: Contours of synrift thickness in milliseconds TWT; NF = North Flinders Sub-basin, SF = South Flinders Sub-basin, T = Tregrosse Sub-basin, L = Lihou Sub-basin; FFZ = Flinders Fault Zone, TFZ = Tregrosse Fault Zone, LFZ= Lihou Fault Zone.

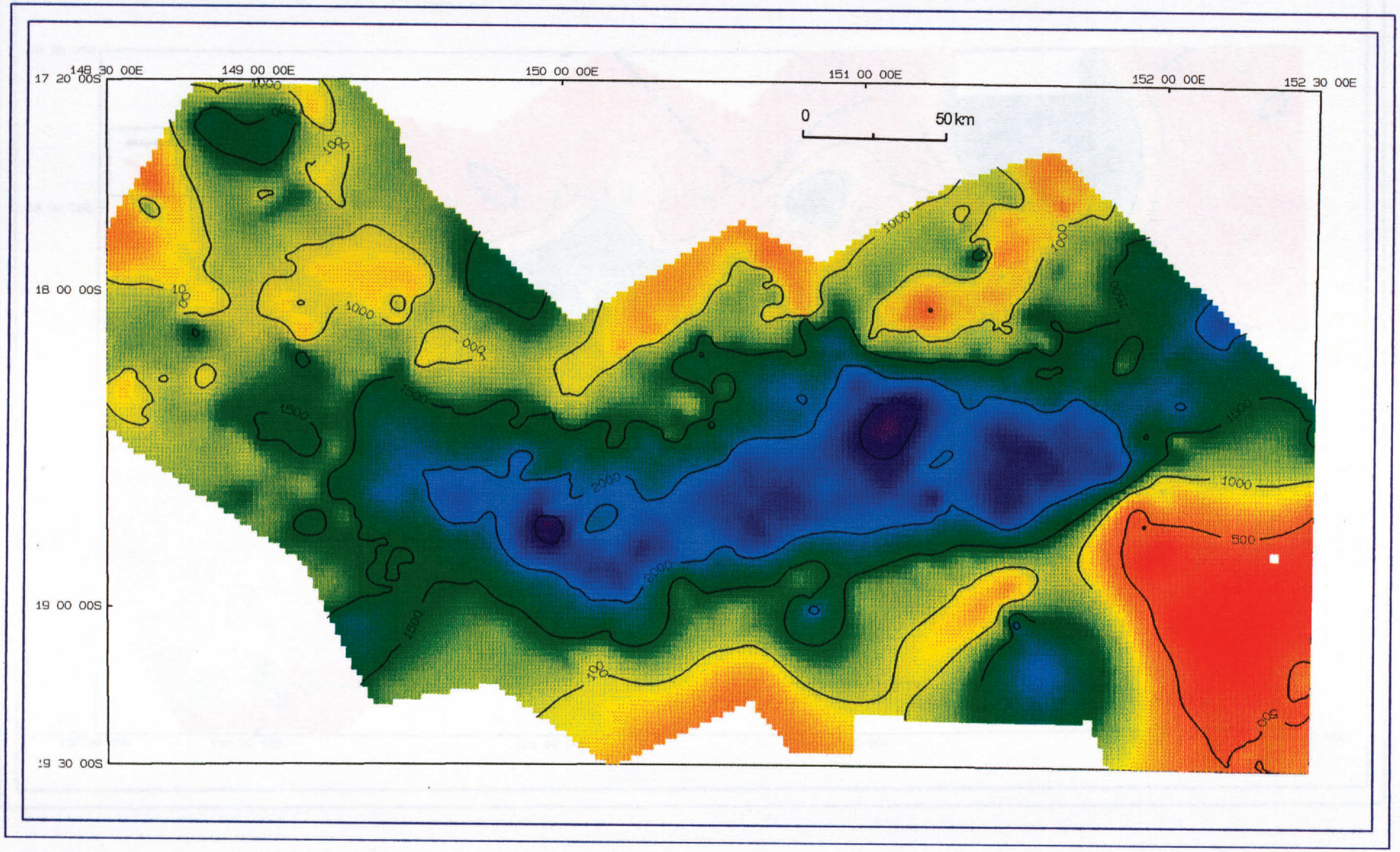

Plate 5: Contours of sag-phase thickness in milliseconds TWT.

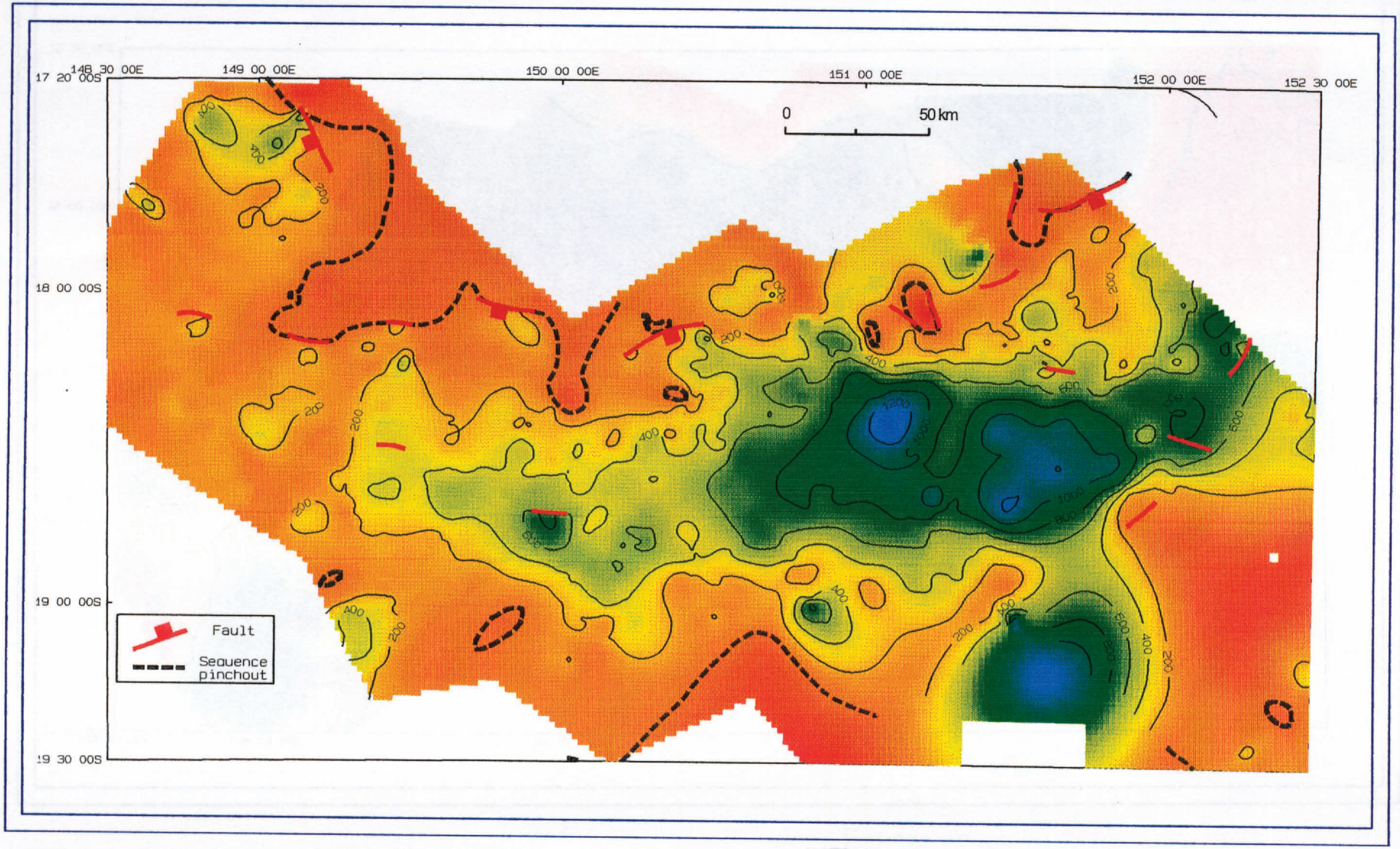

Plate 6: Contours of sequences S1 & S2 thickness in milliseconds TWT.

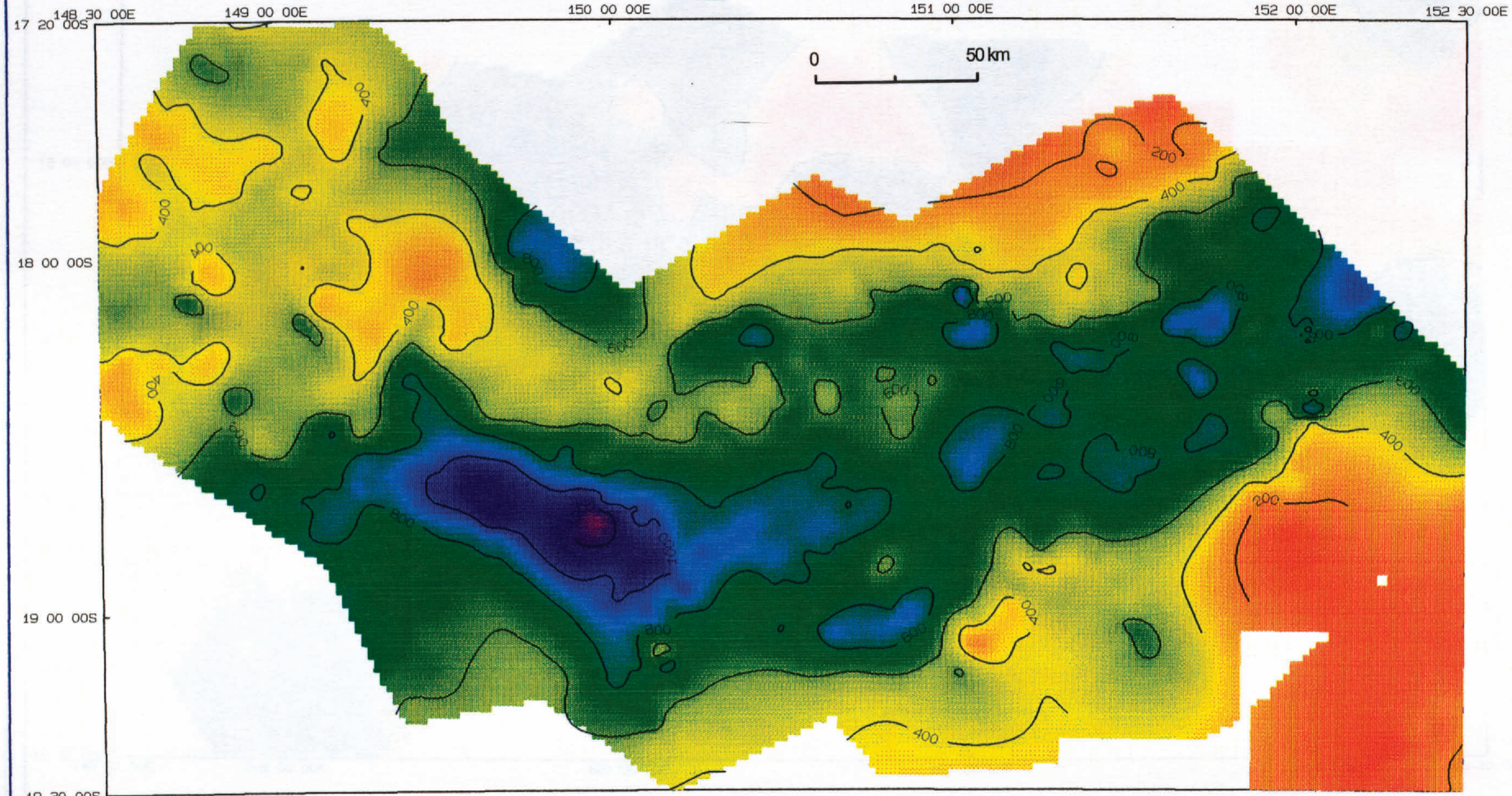

Plate 7: Contours of sequence S3 thickness in milliseconds TWT.

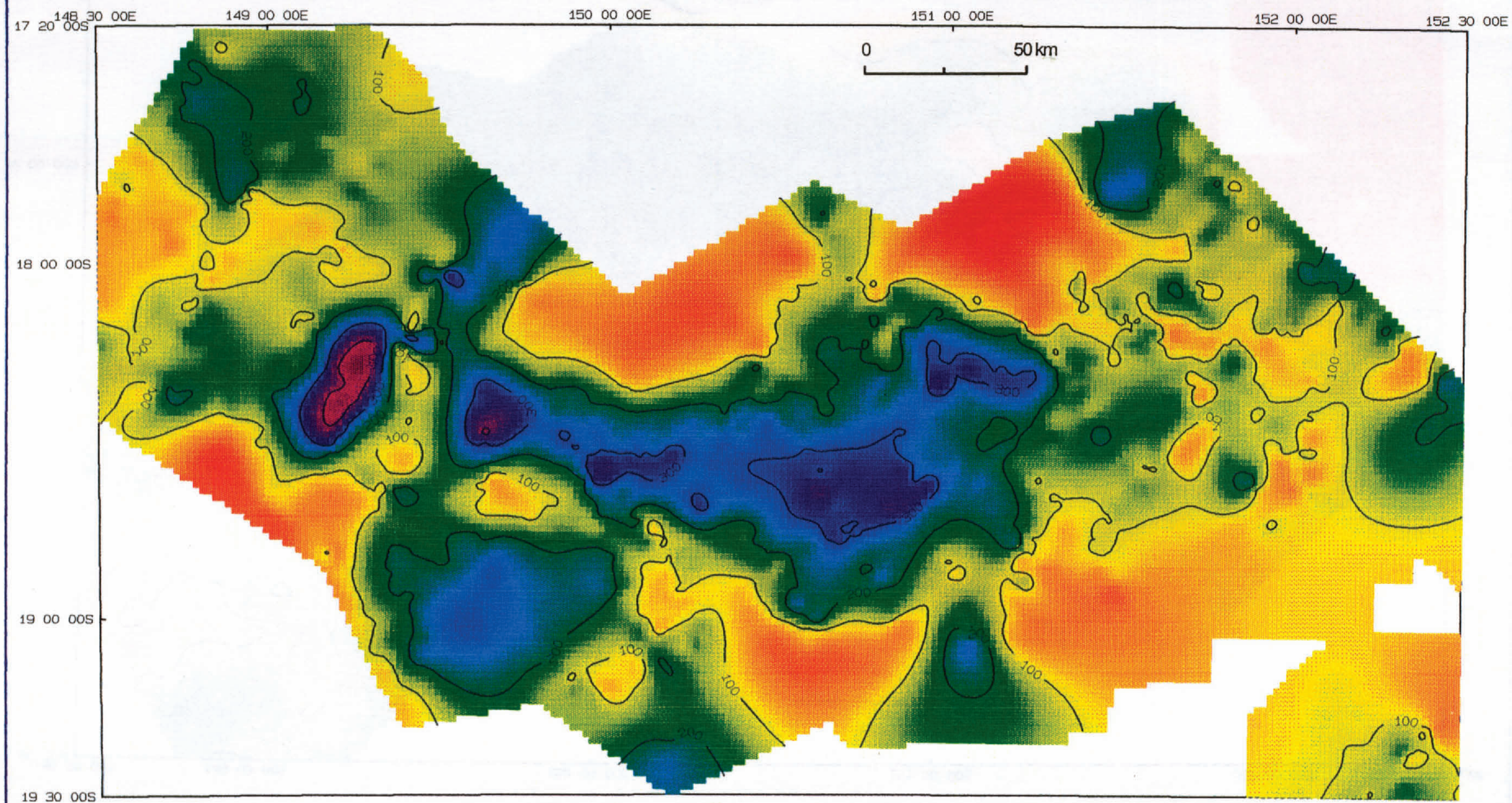

Plate 8: Contours of sequence S4 thickness in milliseconds TWT.

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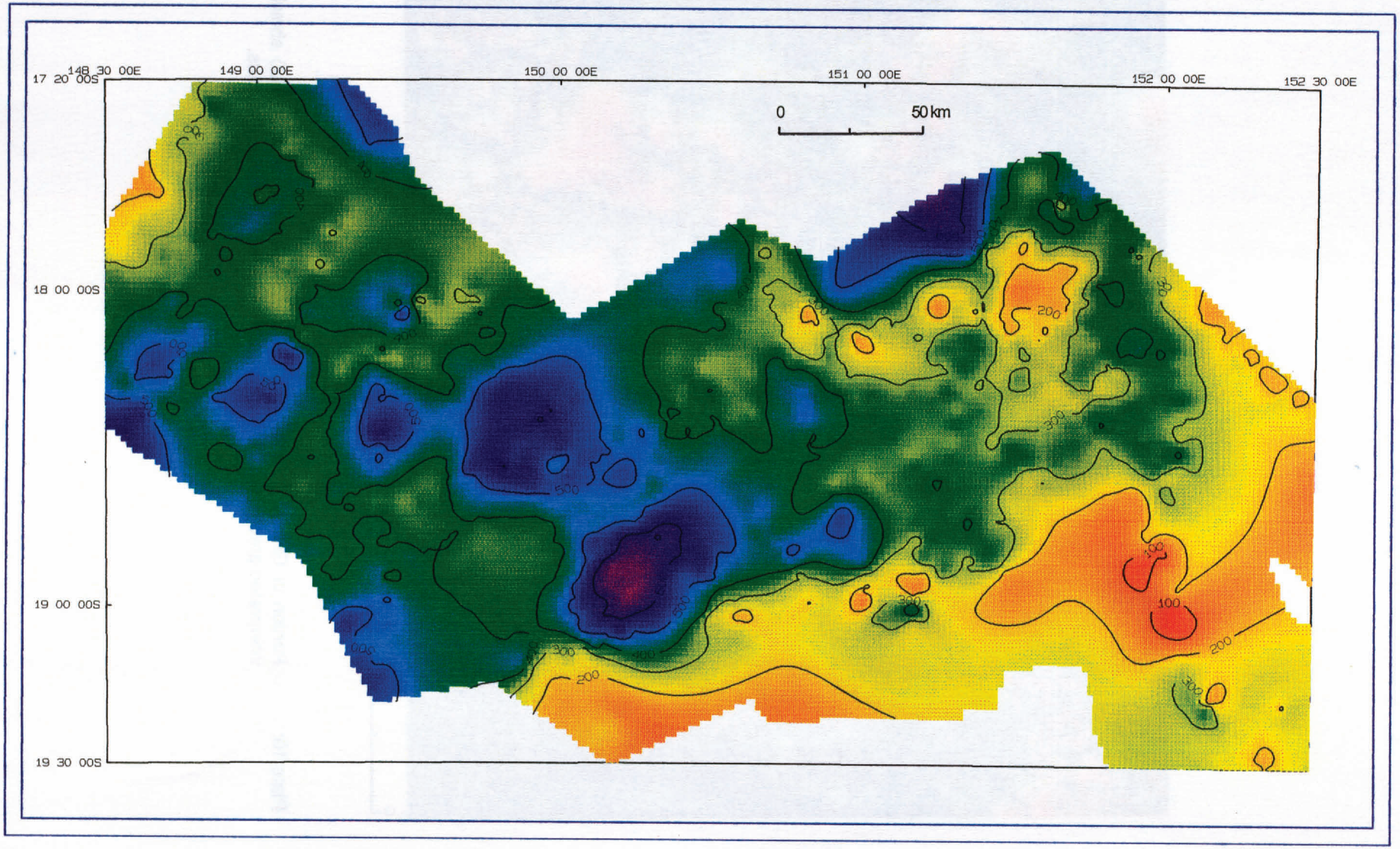

Plate 9: Contours of sequence S5 thickness in milliseconds TWT.

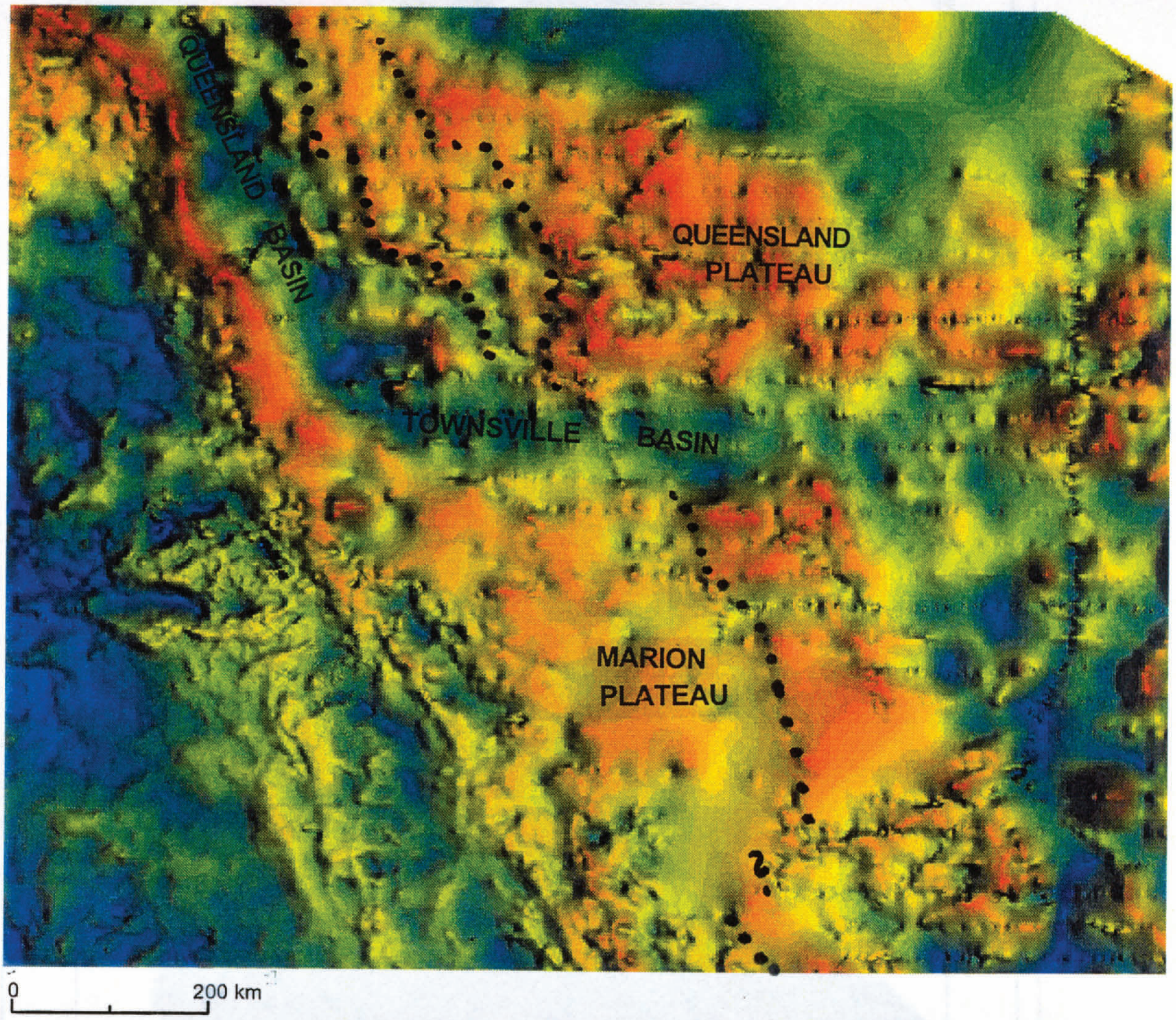

Plate 10: Portion of Gravity Anomaly Map of Australia (Morse et al., 1992) showing interpreted gravity provinces on the Queensland and Marion Plateaus.