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Architecture of the Queensland Trough: implications for the structure and tectonics of the Northeastern Australia Margin

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The Queensland Trough is a 155°-trending bathymetric deep, located just seaward of the Great Barrier Reef of northeast Australia. The trough reaches a maximum depth of 2800 m, separating the continental shelf and the submerged Queensland Plateau. It is underlain by extended continental crust. This preliminary interpretation of the trough's deep structure uses 3700 km of 1970's vintage seismic data, supplemented by gravity and magnetic data from the same surveys. The main seismic profile grid has a spacing of approximately 50 km. However, another survey shot in a zigzag pattern provides line spacing locally as close as a few kilometers.

Acoustic basement, characterized by a chaotic and indistinct seismic signature with rare, discontinuous steeply dipping reflections, is overlain by two main acousto-stratigraphic megasequences within the trough: (1) The post-rift section comprises flat-lying, continuous reflections and extends up to two seconds two-way travel time (TWT) below the water bottom. (2) The syn-rift section consists of moderately dipping semi-continuous reflections, separated by zones of chaotic reflections and diffractions. The reflection separating the syn- and post-rift packages is quite distinct, characterized by angular discordances and truncated reflections. No wells have penetrated the syn-rift package.

Seismic profiles in all orientations reveal tilted basement fault blocks. Many bounding faults are clearly listric. Half-graben form a series of syn-rift depocenters with up to 5 km of syn-rift fill. Syn-rift depocenters appear to be elongate along the axis of the trough, suggesting rift-parallel bounding faults and orthogonal extension. However, no structures parallel or perpendicular to the trough axis have been recognized. Most of the syn-rift depocenters are composed of two or more smaller "deeps".

Two rifting models provide alternative syn-rift structural interpretations: (1) Curvilinear faults, based on a model derived from the East African Rift where the tectonic transport direction has been shown to be oblique to the rift axis, define a series of half-graben. Accommodation zones and half-graben polarity switches are identified from profile and plan-view geometries. (2) Nearly rectilinear 110°- and 020°-striking faults, based on orthogonal extension models, predominate. However, both of these trends are oblique to the rift axis contrary to predicted geometries. "Transfer faults" provide a structural basis for the apparent compartmentalization the syn-rift isopach cells into the "deeps".

The data are insufficient to unequivocally support either model, although the orthogonal extension fault geometry better explains the distribution of the depocenters. Both interpretations, combined with limited basement dip information suggest that the structure underlying the Queensland Trough is the product of oblique rifting. Extension is aligned obliquely to the trough at 110°, rather than perpendicular to the rift elongation at 065°. The proposed kinematics suggest that formation of the trough pre-dates either the Coral or Tasman Sea taphrogenesis.

Introduction

The Queensland Trough is a bathymetric deep located just seaward of the Great Barrier Reef of northeast Australia (Fig. 1). Its present-day axis trends northwest-southeast at 155°. The trough defines the boundary between the continental shelf and the submerged Queensland Plateau, considered to be continental crust (Ewing & others, 1970). The deeper northern end of the trough has a maximum depth of 2800 m, and is linked to the Coral Sea Basin to the north by the Osprey Embayment, which appears to be underlain in part by oceanic crust (Symonds & others, 1984). The southern terminus of the trough shallows to 800 m at the intersection with the approximately east-west-trending Townsville Trough, separating the Queensland and Marion Plateaux. Previous interpretations of the Queensland Trough (Falvey & Taylor, 1974; Falvey & Mutter, 1981; Falvey & others, 1990; Gardner, 1970; GSI, 1980; Karig, 1971; Mutter, 1977; Mutter & Karner, 1978; Pinchin & Hudspeth, 1975; Symonds & others, 1983; Symonds & others, 1984; Symonds & Davies, 1988; Taylor & Falvey, 1977) invoked either Early to Late Cretaceous extension associated with the creation of the Tasman Sea spreading ridge to the south, or Paleocene to Eocene extension associated with the Coral Sea spreading ridge to the north, as mechanisms for trough formation. However, no reliable dating of the deep sediments is available. Refraction data (Ewing & others, 1970; Falvey & Taylor, 1974) suggest a sediment package at least 4 km thick in the trough.

The present study complements other, largely AGSO-sponsored ongoing work, that addresses the evolution of Australia's northeast margin. The Queensland Trough is a little known major depocenter, yet its evolution and architecture is critical to understanding the long-term petroleum potential of this region. Previously unpublished data are presented. Profile-specific geometries demonstrate that both "dip" and "strike" lines exhibit substantial

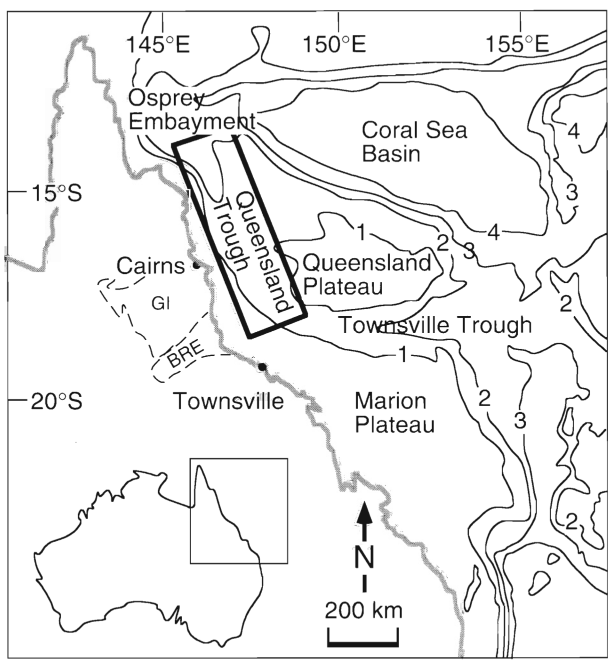

Figure 1. Location map of study area (heavy box) on the northeast margin of Australia and major physiographic features. Contours are in 1000's of meters. GI = Georgetown Inlier. BRE = Broken River Embayment.

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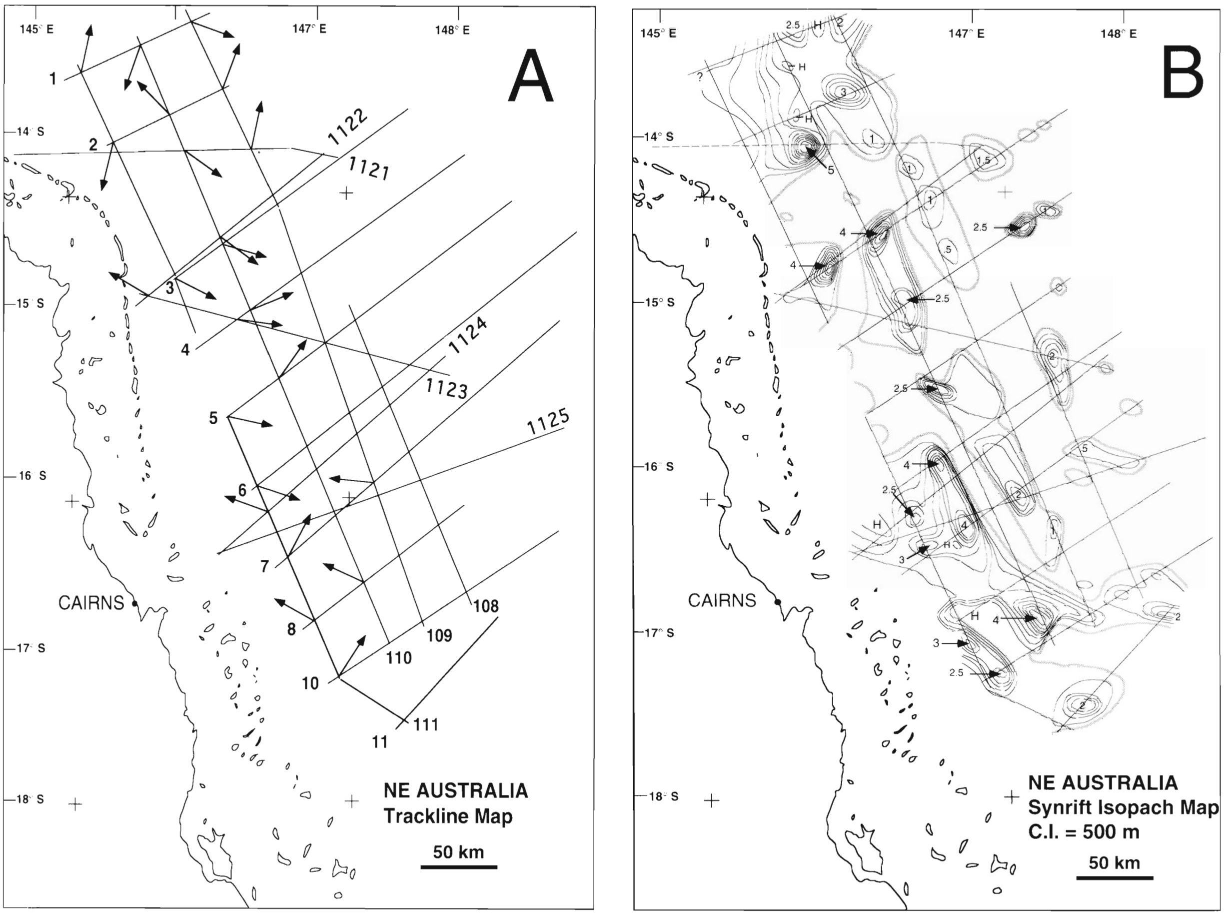


Figure 2. (A) Trackline map of data coverage over the Queensland Trough used in this study. Shaded segments are shown in the line drawings in Figures 4 through 7. Arrows indicate computed azimuth of basement dip. (B) Syn-rift isopach map of the Queensland Trough. Syn-rift depocenters appear to occur in elongate trough-parallel depressions. However, each depocenter appears to be composed of a number of deeps.

rotation of extended basement blocks.

The wide grid spacing of the presently available data makes it impossible to precisely constrain the structural geometry of the Queensland Trough. However, two extension models can be fitted to the observed structures, thus providing insights into the underlying rift architecture. Both alternative fault patterns, combined with measured basement rotation directions, indicate that the Queensland Trough formed by oblique rifting. Further, the proposed direction of extension appears to be incompatible with plate motion vectors involved in the seafloor-spreading phases responsible for opening either the Coral or Tasman Seas. It is suggested that the extension which produced the Queensland Trough pre-dates the extension episodes preceding the opening of both the Coral or Tasman Seas. A similar suggestion by earlier workers (Mutter & Karner, 1980; Symonds & others, 1987) is supported by this analysis.

The data

Figure 2A shows the location of approximately 3700 km of multi-channel seismic data collected by (GSI, 1974, 1979). The 1979 rectilinear grid over the trough has a spacing of approximately 50 km. The 1974 grid was shot in a zigzag pattern, thus providing line spacing locally as close as a few kilometers. The seismic data were processed using standard industry parameters of the time. The interpretation presented here is supplemented by gravity and magnetic data collected during the same surveys (GSI, 1980). Profiles perpendicular to the trough axis are conventionally referred to as "dip" lines and profiles parallel to the trough axis as "strike" lines and this usage is retained here. However, as will be demonstrated, these terms are misleading in the context of oblique rifting.

Two acousto-stratigraphic megasequences can be recognized in the seismic data (Fig. 3). The post-rift section comprises flat-lying, very continuous reflections and extends up to two seconds (TWT) below the water bottom. The syn-rift section is characterized by semi-continuous, moderately dipping, diverging reflections that are separated by zones of chaotic reflections and diffractions. The megasequence boundary separating the syn- and post-rift packages is distinct, characterized by onlap above and angular truncation below. The pre-rift or basement section is commonly chaotic or incoherent, but steeply dipping, discontinuous reflections are recognizable locally, especially in areas of high-standing basement within the rift and on the adjacent plateau. The boundary between the syn-rift and underlying basement is sometimes quite distinct, but is more commonly defined by a gradual loss of seismic character and/or a velocity jump. No wells have penetrated the syn-rift package, but 1000 m of the post-rift section were cored in the central Queensland Trough during Leg 133 of the Ocean Drilling Program (Davies & others, 1991). The hole was drilled near the intersection of Lines 7 and 111 (Fig. 2A). Its total depth corresponds to 3.2 TWT, well above the interpreted boundary between the post- and syn-rift megasequences interpreted herein (Fig. 3), and the oldest sediments intersected have been dated at Early Miocene.

Line drawings of the "dip" lines are shown in Figure 4. In each case, the dashed line is the seafloor. The majority of these profiles trend northeasterly (Fig. 2), but profile trends range from northeast, to due east, to southeast. The dotted line is the boundary between the flat-lying reflections of the post-rift megasequence and the dipping reflections of the syn-rift megasequence. The syn-rift reflection configuration can vary substantially. They are sometimes quite continuous, as in the half-graben on the right end of the profile in Figure 3, but also can be semi-continuous dipping reflections or diffractions as in the half-graben imaged on the left. As the focus of this article is the syn-rift megasequence and its tectonic significance, none of the flat-lying post-rift reflections have been digitized in the line drawings for clarity.

As noted earlier, water depths increase to the north along the axis of the Queensland Trough. However, there is no similar systematic increase in the thickness of the post-rift sediments; rather, they thicken over areas underlain by the dipping reflections of the syn-rift section and thin over basement highs. This may indicate either increased subsidence due to greater sedimentary loads or later fault movement in some places. Where there is no evidence of an underlying syn-rift section or where basement shallows, profile sections have been omitted from the line drawings.

Structural style

A striking feature of the profiles is the predominance of half-graben morphology along the entire rift. The majority of the half-graben deepen to the east and are bounded by west-dipping faults. Exceptions are the isolated half-graben deepening westward on the right end of Line 1122 (Fig. 4A) and a system of likewise westward-deepening half-graben in the southern-central portion of the rift on the right end of Lines 1124, 1125 & 7 (Fig. 4B). The northern profiles (Lines 1 & 2, Fig. 4A) image distinctly more chaotic and less coherent reflections below the post-rift megasequence. To the south on Lines 1121, 1122 & 3 (Fig. 4A), the deep structure of the trough is characterized by one or two half-graben, separated by apparently undeformed high-standing basement blocks. Farther south still, most profiles show a series of tilt-blocks that define larger composite half-graben (Lines 1123, 4, 5, 6, 1124, 1125, 7, & 8, Figs 4A & B). Finally, in the southernmost profile (Line 10, Fig. 4B), extensional strain is manifested by two widely separated half-graben which lie on both sides of the bathymetric trough. Examining each of these zones in more detail and including some "strike" or rift axis parallel profiles, one can establish the geometry of the syn-rift structure.

The three most northern dip lines (Fig. 4A) are tied by strike lines shown in Figure 5. Similarly to the two most northern profiles (Lines 1 and 2), the left end of the strike profiles have very discontinuous and chaotic reflection character beneath the post-rift megasequence. The sense of half-graben polarity and the presence of tilted fault blocks is ambiguous, although some dipping reflections

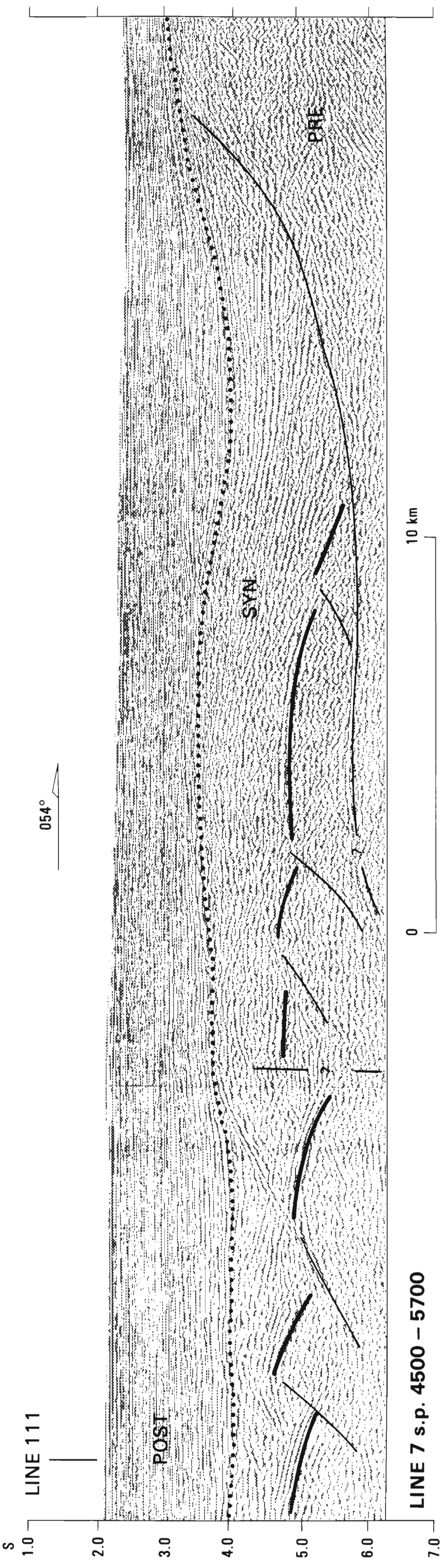


Figure 3. An example of the seismic data from the Queensland Trough. Two megasequences (referred to as the pre- and syn-rift) overlying acoustic basement (post-rift) are recognizable throughout the data set. Dotted line represents the boundary between flat-lying continuous reflections of the post-rift section and the dipping, semi-continuous reflections, separated by chaotic zones and diffractions of the syn-rift section. Solid line separates the base of the syn-rift from the chaotic, discontinuous reflections of the pre-rift basement. Note the variable rotation of tilted fault blocks on this NE trending "dip" line. For location see Figures 2A and 4B.

do extend deep into the section. The next line to the south (1121) records a clear, albeit isolated, half-graben that is manifested on the strike profiles (Lines 110 and 111, Fig. 5) by a thickening of the post-rift section in this locale.

Although it is not clear from these line drawings, the northern syn-rift reflections tend to be of higher amplitude than those to the south. The highly diffractive character of the reflections suggests the presence of volcanics; this is supported by the proximity to interpreted oceanic crust to the north in the Osprey Embayment (Symonds & others, 1984). Likewise, very high-amplitude events within the post-rift section, such as the example on the right end of Line 1 (Fig. 4A; labelled "V") between the intersections with Lines 110 and 109, may be interpreted as flows.

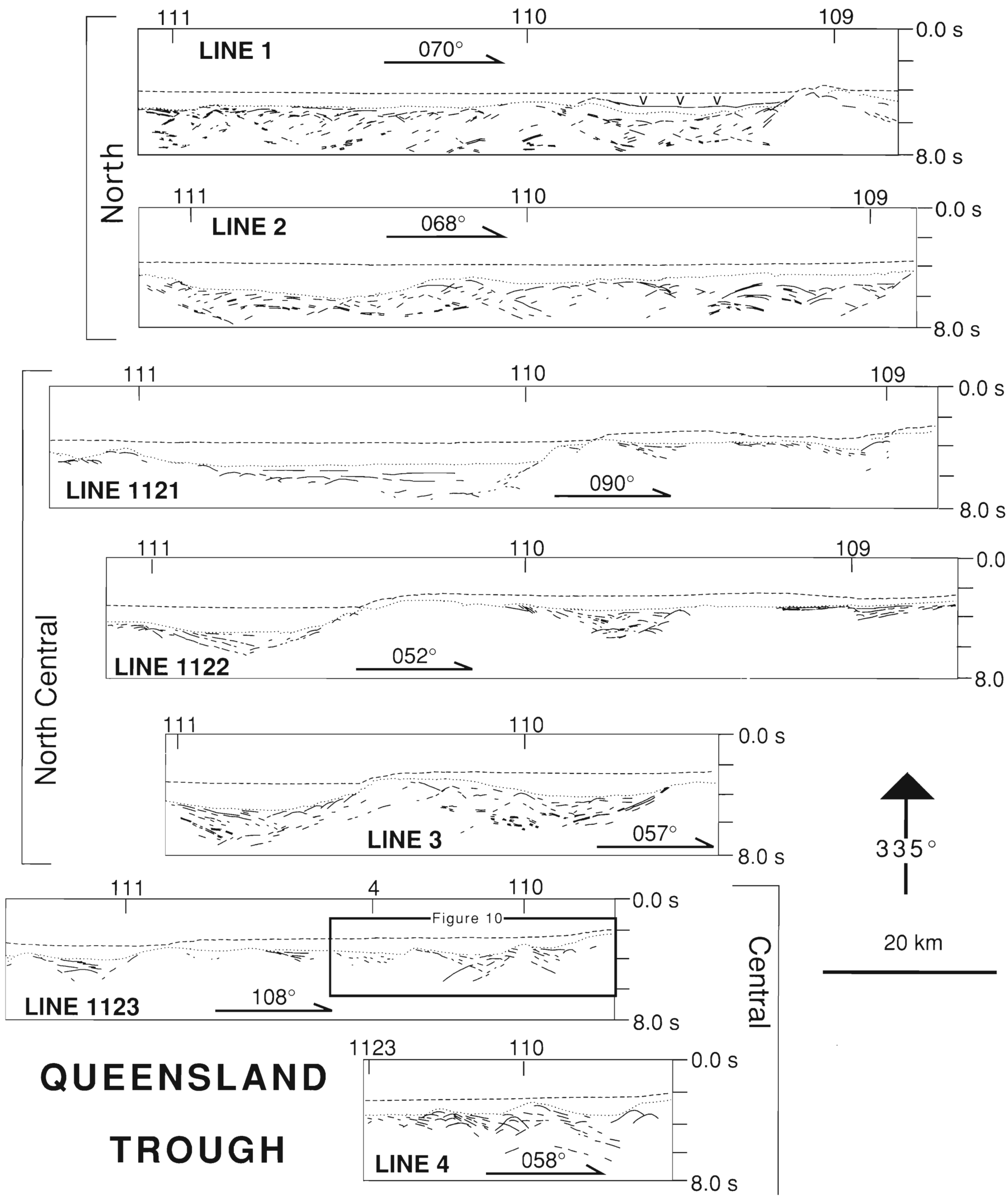
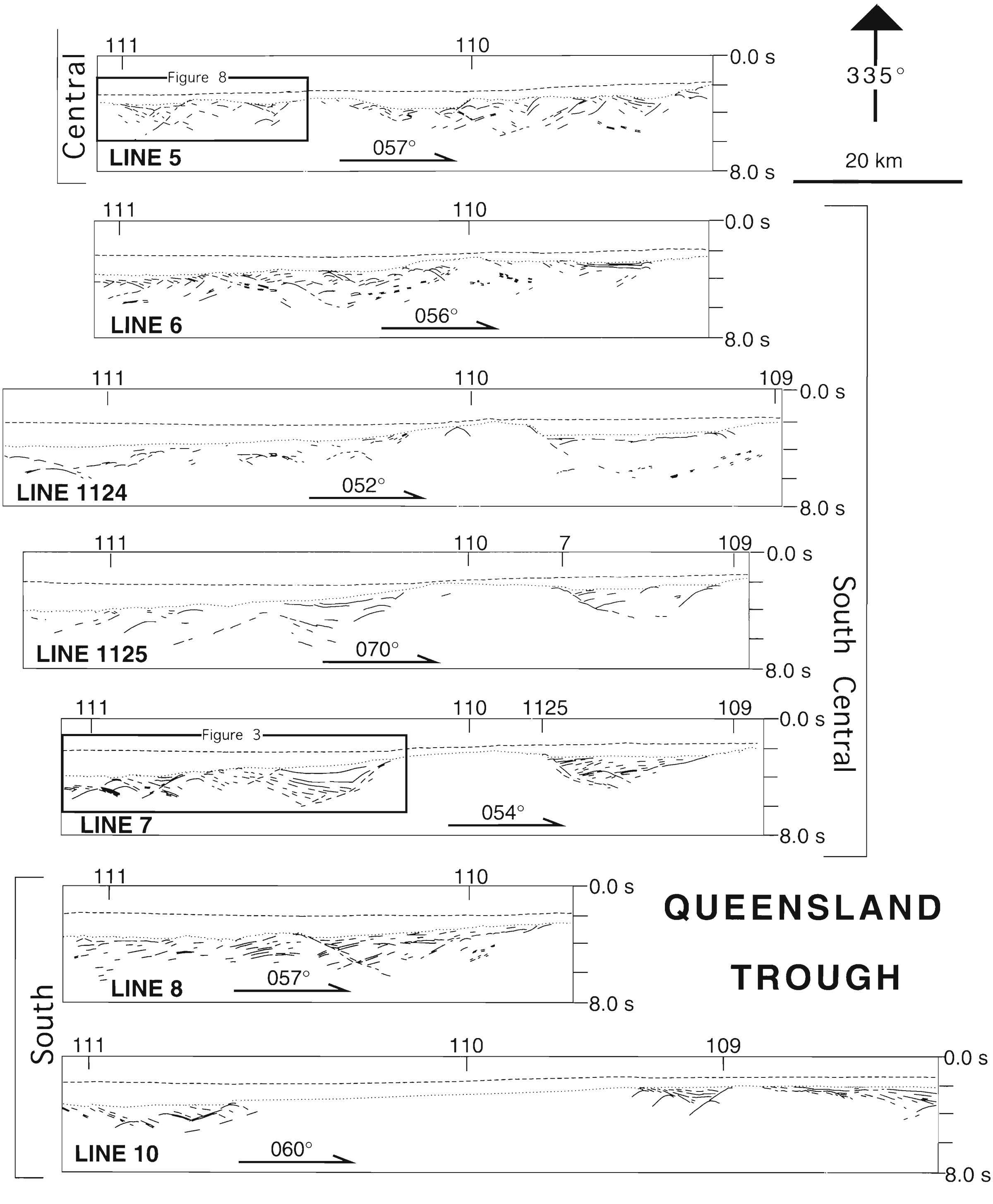


Figure 4. Line drawings of the (A) northern "dip" lines and the (B) southern "dip" lines in the Queensland Trough. Orientations of profiles are indicated by arrows and azimuths. Profiles are "hung" on the strike Line 110 and view is NW (335°). Profile ties are indicated. Boxes indicate portions of seismic profiles shown in Figures 3, 8 and 10 for comparison of seismic character to line drawings. Dashed lines represents the water/sediment interface. Dotted lines represent the boundary between the post- and syn-rift megasequences. See Figure 2A for locations.

Dip Lines 1121 and 1122 (Fig. 4A) show well-defined half-graben, isolated from each other by seemingly undeformed, planated basement. These isolated half-graben average 10–15 km in width. On Line 3, there is some evidence for a series of tilted fault blocks joining the two half-graben on either end of the profile. On the eastern end of Line 1122 on the Queensland Platform, the half-graben which deepens to the west does not extend to either undeformed so is not shown in the line drawings. An isolated half-graben with the opposite polarity is imaged on Line 1121 to the north, suggesting that an unrecognized structure (?transfer fault) must be present between the two profiles to allow for the different rotation of basement.

Strike profiles (Fig. 6) that tie dip Lines 1122 and 3 record dipping reflections, but individual half-graben are not well



adjacent profile and is apparently totally isolated from the main trough. To the south on Line 3, no half-graben is present, and plateau basement to the east appears to be defined. On Line 110, a full-graben morphology is suggested by inward-dipping faults and outward-dipping syn-rift reflections at either end of the profile. These

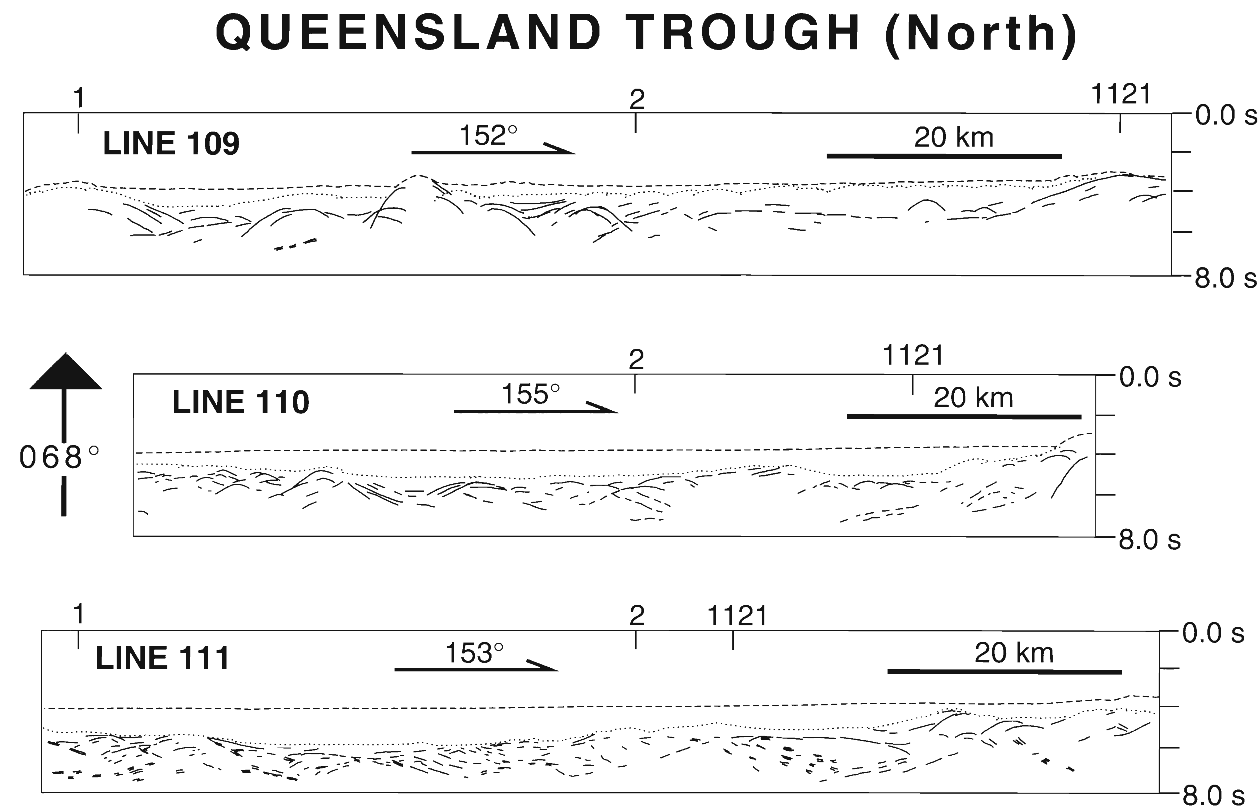


Figure 5. Line drawings of the northern "strike" lines of the Queensland Trough. Notations and locations as in Figure 4.

reflection/fault geometries are consistent with our traditional view of "dip" versus "strike" lines. That is, the data record higher rotation of syn-rift reflections, and more clearly imaged extensional features, such as tilted fault blocks, on dip profiles rather than on strike profiles. This relationship is predicted if extension has been aligned perpendicular to the rift axis or northeast–southwest. However, to the south, this relationship does not hold up and is not consistent throughout the rift zone.

In the central part of the trough, dip Lines 1123, 4 and 5 (Figs 4A & B) image series of tilted fault blocks combining to form composite half-graben rather than the single isolated half-graben that characterized the northern part of the trough. The composite half-graben morphology is typical of rifted basins elsewhere (e.g. Florensov, 1969; de Charpal & others, 1978; Ramberg & Neumann, 1978; Chenet & others, 1982; Logatchev & others, 1983; Bally, 1984; Ramberg & Morgan, 1984; Skilbeck & Lennox, 1984; Etheridge & others, 1985; Rosendahl, 1987). The size of tilted fault blocks is smaller, averaging 5–10 km. The post-rift section thins and thickens over each fault block. The only strike line through this part of the trough with recognizable syn-rift section is the one that runs down the axis of the trough (Line 110, Fig. 7A). It has all the characteristics one expects to see: that is, reflection packages with a variety of dips separated by sub-vertical reflection disruptions. The post-rift section undulates near the ties with Lines 4 and 1123, but is fairly constant in thickness and depth south of the tie with Line 5. The thickness of the post-rift section along this strike line does not vary as diagnostically as on the dip lines, where changes in thickness reflect the asymmetry of deeper structures.

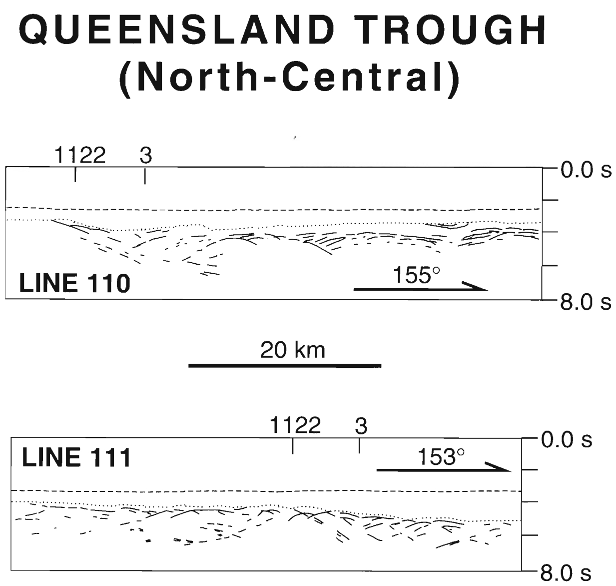


Figure 6. Line drawings of the north-central "strike" lines of the Queensland Trough. Notations and locations as in Figure 4.

Seismic profiles over the half-graben on the western end of Line 5 and the section of a strike line that it crosses are shown in Figure 8. Although there is apparent rotation of basement into a west-dipping fault on the western end of Line 5, there is clearly as much — if not more — rotation and higher subsidence to the south along Line 111. Likewise, the relationship of the post-rift thickness and underlying structure noted above is clearer on the strike line (111) than on the dip line (5). This example highlights the fact that seismic profiles of all orientations in the data set reveal tilted basement fault blocks, and there does not seem to be a consistent relationship between basement rotation and orientation of the profiles as one might expect in simple extensional regimes (see later discussion section).

In the next "dip" profile to the south (Line 6, Fig. 4B), tilted fault blocks are locally as small as 1 to 3 km across. Lines 1124, 1125 and 7 to the south image the only observed linked polarity switch along the rift axis. On these three adjacent profiles, a basement horst separates opposing polarity half-graben, both deepening toward the horst. The westernmost strike profile (Line 111, Fig. 7B) also

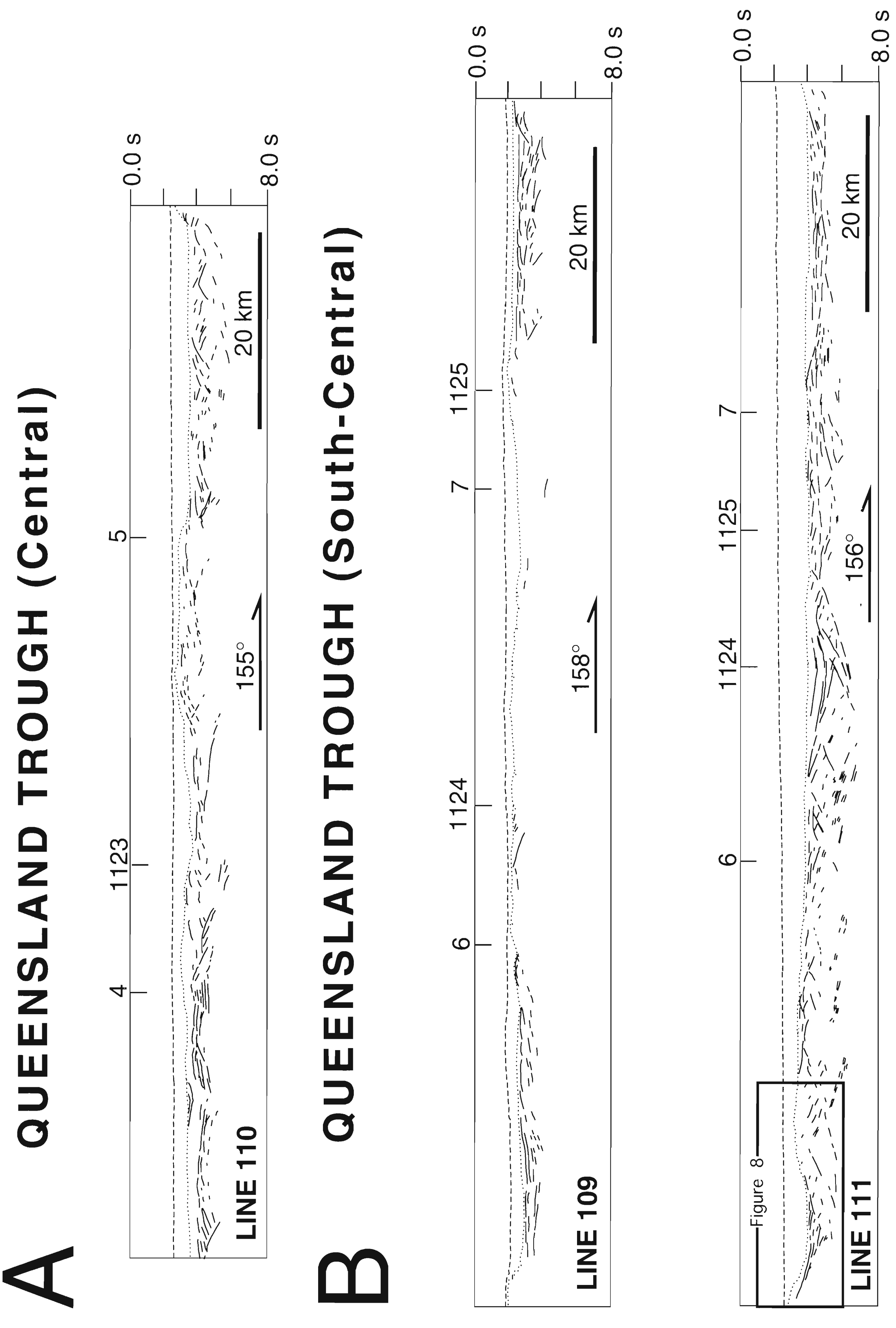


Figure 7. Line drawing of the (A) central and (B) south-central "strike" lines of the Queensland Trough. Notations and locations as in Figure 4.

images both tilted fault blocks and diverging syn-rift reflections, in contrast to what is expected from a "strike" line in simple rift-perpendicular extension. In fact, the half-graben imaged at the tie with Line 1124 is clearly more highly rotated on the strike profile (Line 111). The easternmost strike line (Line 109, Fig. 7b) sits almost entirely on the western edge of the Queensland Plateau. However, where the syn-rift section is imaged to the right of the tie with the dip profile (Line 1125), it also has a significant dip. The middle strike profile is not shown, because it images only the apparently undeformed basement horst seen in the "dip" lines. Although the horst appears to be a continuous feature, crossing Lines 1125 and 7 near their intersection and continuing north a distance of approximately 40 km to Line 1124, it is not seen on Line 6 farther north. Likewise, the horst is not imaged on Line 8 to the south. On the western end of Line 8 (Fig. 4B), westward-dipping syn-rift reflections and eastward-dipping fault plane reflections, continue through the intersection of Line 110 where one expects to see the continuation of the horst. Eastward of the expected location of the horst, a platform begins and continues seemingly undeformed to the eastern end of the line, where one might expect to see evidence of the half-graben imaged on Line 7 or the opposite polarity half-graben on Line 10.

On Line 10 (the southernmost profile, Fig. 4B), a large block of apparently undeformed basement is substantially broader than the horst described above. The absence of either the horst or this broad expanse of undeformed basement on Line 8 is evidence that they are not continuous. Well-defined half-graben on either side of the undeformed block on Line 10 are of the same polarity, in contrast to the opposite polarity half-graben adjacent to the

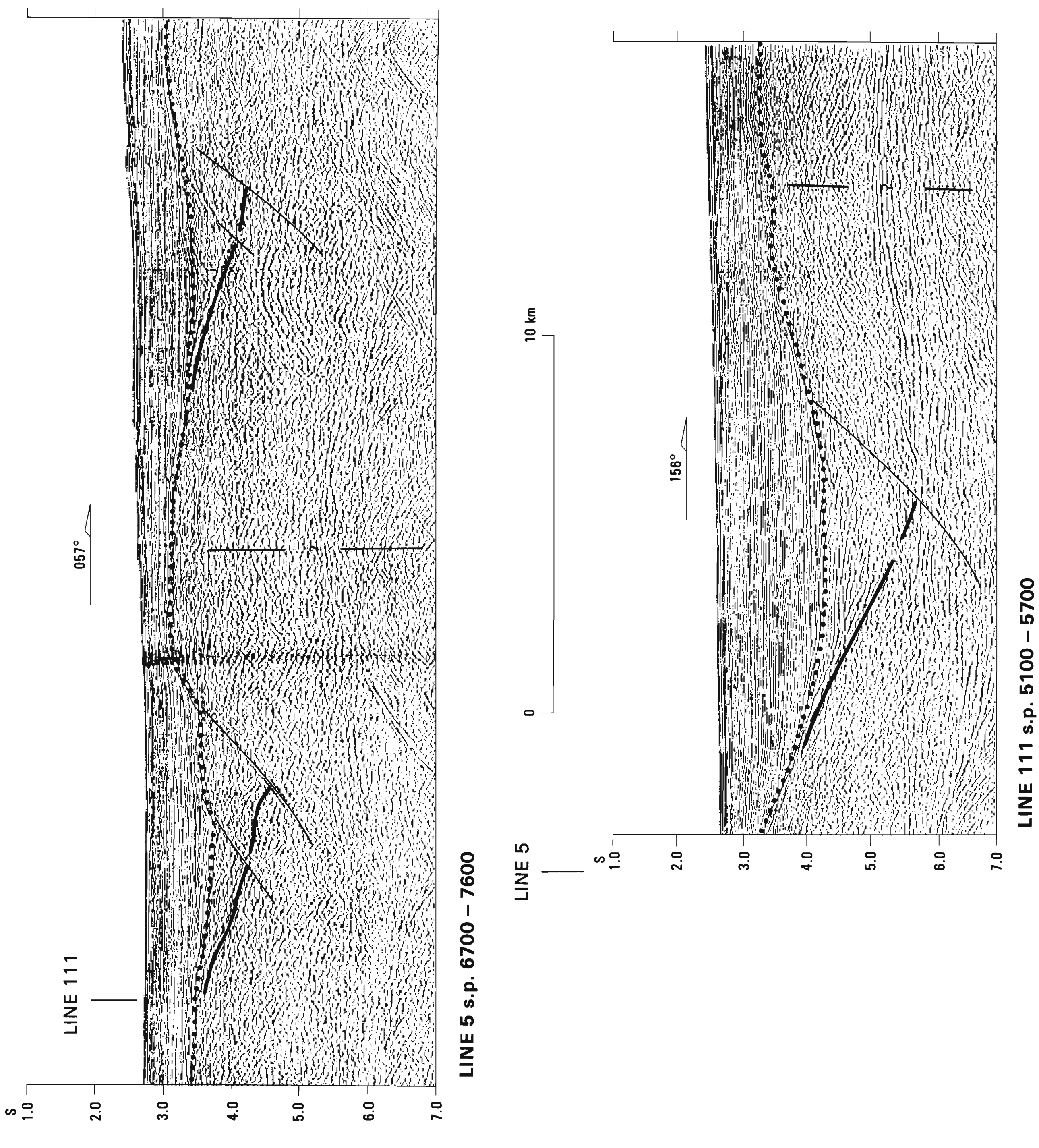


Figure 8. Tying seismic profiles. Line 5 is a "dip", or trough perpendicular profile. Line 111 is a "strike", or trough parallel profile. Apparent rotation of the half-graben near the profiles intersection is greater on the "strike" line than on the "dip" line. Note also the thicker post-rift section on the "strike" line indicating greater subsidence adjacent to the bounding fault. Notations and locations as in Figure 3.

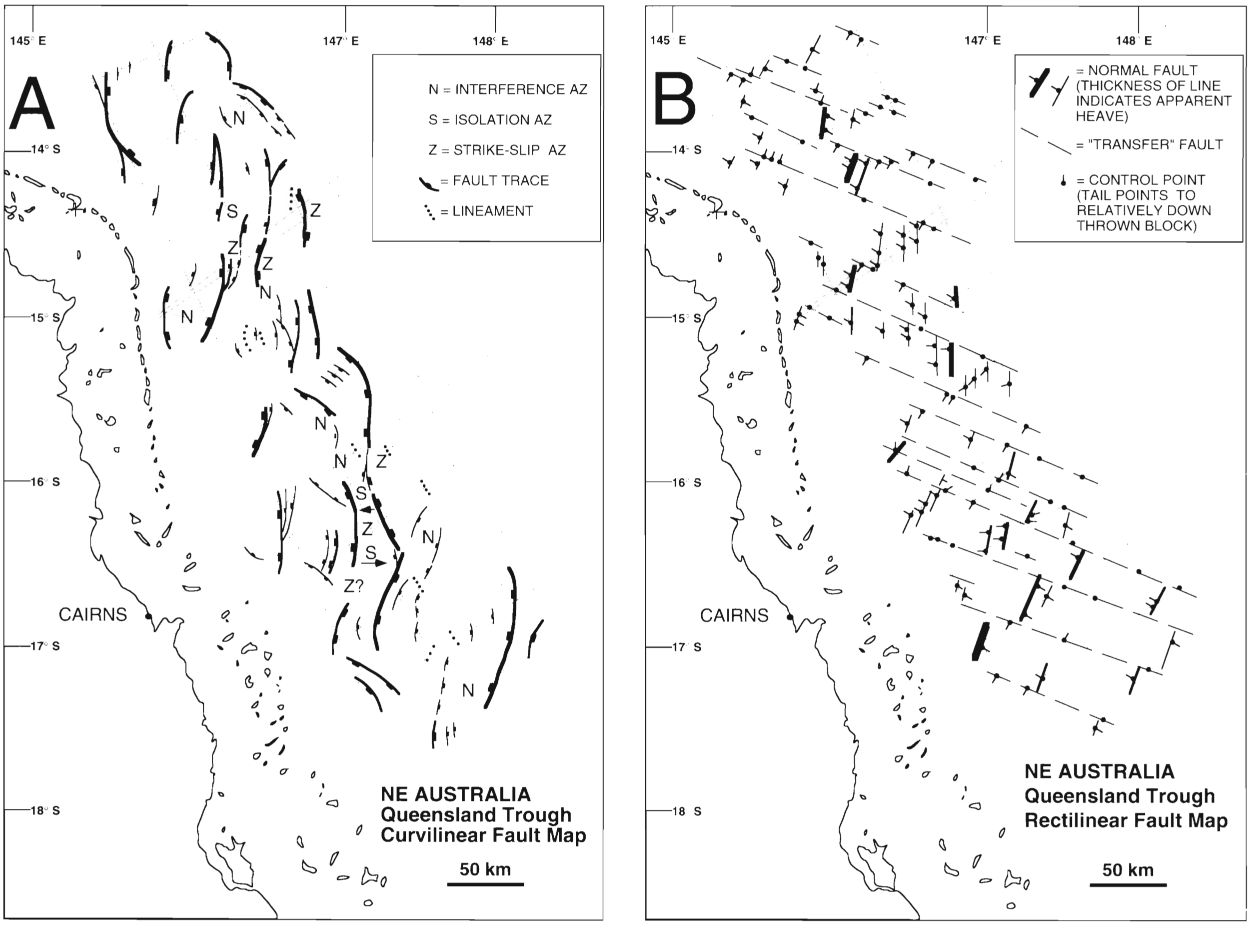


Figure 9. (A) Curvilinear fault map of the Queensland Trough using model concepts from the East African Rift (Rosendahl, 1987). Shaded strip indicates a possible zone of required structures for rift-perpendicular extension and to decouple mapped normal faults of varying orientation or opposing polarity. Structures of this orientation are not recognized in the available data. AZ = accommodation zone. (B) Rectilinear fault map of the Queensland Trough after concepts of the model presented by Lister & others (1986). Note that in both interpretations fault correlations adjacent to profile intersections are oblique to the axial trend of the rift.

horst to the north. The half-graben are widely separated, suggesting that the extensional strain has been more widely distributed. At this location, the trough is merging with the nearly east–west Townsville Trough, and the half-graben on the right end of the profile may be continuous with this system.

Architecture models of the Queensland Trough

The curvilinear interpretation. The above data show that seismic profiles of all orientations contain tilted basement fault blocks. Many bounding faults are clearly listric (Fig. 3), but there seems to be no consistent "dip" versus "strike" line relationship. The dip inconsistency is analogous to data collected from the East African Rift (EAR), where half-graben are thought to be bounded by arcuate or curvilinear faults connected by various types of accommodation zones (Rosendahl, 1987) into a sinusoidal system. In fact, the crustal scale analogy between the Tanganyika/Rukwa/Malawi Rift bending around the Tanzanian Craton and the Queensville/Townsville Trough system bounding the continental block of the Queensland Plateau was, in part, the motivation for this study. In the EAR, field measurements of slip on rift faults (Chorowicz & Sorlien, 1992) and dip analysis (Scott & others, 1990; Scott & others, 1992) indicate that extension is oblique to the rift axis. In addition, the horst in the south-central part of the Queensland Trough (Lines 1124, 1125 & 7, Fig. 4B) has a profile geometry described as an isolation accommodation zone by Rosendahl (1987).

With the EAR sinusoidal geometry as a model, the curvilinear fault interpretation shown in Figure 9A was derived from the available data. The half-graben bounding faults form a series of syn-rift depocenters with up to 5 km of fill, as shown in the isopach map of syn-rift section (Fig. 2B), that appear to be elongated along the axis of the trough at 155°–160°. This apparent structural grain suggests rift parallel bounding faults and orthogonal extension. However, the available data yield no evidence for major linear structures parallel or perpendicular to the trough axis. The series of arcuate half-graben north of 14° S in the Queensland Trough (Fig. 9A) are elongate more or less parallel to the trough trend; that is, the tangent to their point of maximum curvature is parallel to the rift trend. However, farther south fault patterns become more rhombohedral, indicating a strike-slip mechanism for the formation of the half-graben. Note also that most of the syn-rift depocenters are composed of two or more smaller "deeps" (Fig. 2B) that cannot be explained by the curvilinear fault model interpretation presented in Figure 9A.

The main criticism of the sinusoidal rift model (Reynolds,

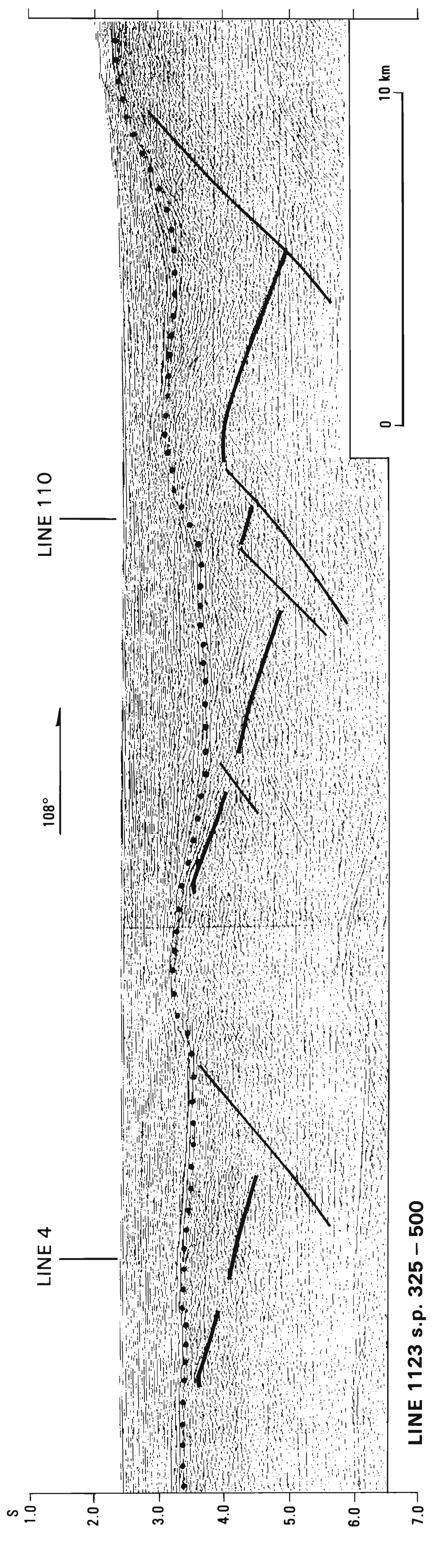


Figure 10. Southeast trending seismic profile 1123 exhibiting similar rotation of three tilted fault blocks. Compare this geometry with the variable rotation of tilted blocks imaged on northeast trending Line 7 shown in Figure 3. Notation and location as in Figure 3.

1984; Rosendahl, 1987) proposed for the EAR is that it does not provide structures whereby consistent regional kinematics can occur and has no predictive value for tectonic reconstructions. In other words, linking structures aligned approximately parallel to the extension direction are required to "release" blocks bounded by variably oriented faults along the rift-axis strike to allow tectonic transport of the blocks. The sinusoidal model predicts at least two directions for half-graben linking structures, which do not have a consistent relationship with the direction of extension. Scott & others (1992) and Chorowicz & Sorlien (1992) both addressed this problem by analysing the kinematics from two different data sets both concluding that such structures must exist. It is possible that either intracontinental rifts do not extend sufficiently to develop these structures or are ill-defined in early stages of rifting. However, sufficient evidence exists in both the East African Rift and the Queensland Trough that the structures are present and provide a consistent regional kinematic history.

The rectilinear interpretation. In a simple, ideal orthogonal extension model, a "dip" line shot parallel to the direction of extension images a series of tilted fault blocks with similar rotation and recoverable fault/base syn-rift relationships. Likewise, a "strike line" images flat-lying to shallowly-dipping syn-rift reflections and vertical faults. Profiles in any other orientation are predicted to image complex geometries which cannot be reconstructed in the plane of the profile simply by movement along the imaged faults. The rift axis will align perpendicular to the direction of extension, although deeps may shift their lateral position from the axis or switch polarity across extension parallel, rift perpendicular transfer faults.

Line 1123 (Fig. 10) most closely resembles the series of "balanceable" tilt blocks within a single profile that is predicted to be on a dip line in an orthogonal extension system. Note the morphology of the base of the syn-rift section. Block dips are consistent with each other. Profile orientation, however, is southeast at 108° rather than northeast as are the majority of the trough-perpendicular "dip" lines (Fig. 2A). The southeast direction is compatible with the basement rotation dip azimuths in Figure 2A. Line 4, which intersects Line 1123, also images tilted fault blocks, but they are not as clear, and there is considerable disruption of syn-rift reflections within each apparent fault block. Changes in the thickness of the post-rift section indicate that both profiles consist of three tilted fault blocks starting at their intersection and proceeding eastward. However, correlation of the bounding faults does not produce parallel structures. The easternmost block on Line 1123 appears to be smaller than the middle block, but the reverse relationship seems to be the case in Line 4. Any attempt at correlating faults on these two intersecting profiles requires at least two fault trends. The strike line that intersects these profiles (Line 110, Fig. 7A) images flat to dipping reflectors, which are truncated on a 1 to 3 km scale versus the 5 to 10 km scale of blocks in the "dip" lines. Interpretation of these profiles suggests that the normal faults accommodating extension in the rift trough are aligned roughly perpendicular to Line 1123 or at about 018° and that tilted blocks are separated from each other by "transfer" or oblique- to strike-slip faults aligned sub-parallel to the profile. This interpretation can accommodate all the observed faults as well as explain the chaotic nature of reflections within the half-graben imaged in Line 4.

It is also instructive to examine the geometry of the two opposing half-graben and the horst block located on Lines 1124, 1125 and 7 (Fig. 4B) interpreted as an isolation accommodation zone in the previous section. Line 110 (not shown) is trough axis-parallel and images continuous elevated basement from just south of Line 7 to just north of Line 1124. Given the similarity in profile morphology, and the proximity and orientations of the lines, the interpretation of a trough parallel elongate horst shown in the curvilinear fault map (Fig. 9A) seems reasonable. However, attempting to correlate the rest of the faults within either of the adjacent half-graben leads to a variety of interpreted fault trends, as was the case for structures imaged on Lines 4 and 1123. Also, the opposing polarity half-graben on Line 6 (Fig. 4B) requires an intervening structure between the profiles to allow the asymmetry reversal.

Close inspection of the morphology of the horst reveals that basement dips atop the horst vary from profile to profile. In Line 7, the apex of the horst is east of the intersection with Line 110, with a wider westward-dipping surface. On Line 1125, the apex has shifted to the west of the intersection with Line 110 and has a distinctly wider eastward-dipping surface. The relationship of the apex to Line 110, and between the widths of the dipping surfaces, again reverses on Line 1124. In addition, a strong diffraction to the west of the intersection of Line 1124 with Line 110 suggests a possible structure or structures running through the horst at an angle with Line 110 rather than parallel to it. Correlation of these horst features yields a zigzag pattern whose segment trends are both oblique to the rift axis and suggests that this basement high is not a continuous unbroken feature but may be cut by sub-vertical strike-slip faults.

Where half-graben or tilted fault blocks are discernable, and where correlations of faults very near the profile ties is possible, faults trend NNE–SSW striking between 010° to 025° or WNW–ESE with strikes between 100° to 120° (Fig. 9B). These strikes are compatible with those predicted by the reflector dip/fault geometry interpretation done on Lines 1123, 4 and 110 (Figs 4A and 7A) based on orthogonal extension models, even though these trends are both oblique to the rift axis trend as in Figure 9B.

Discussion

The oblique relationship between the fault trends in the rectilinear fault map (Fig. 9B) and the rift axis are nearly identical to an interpretation of the western branch of the EAR system (Scott & others, 1992). Determination of the tectonic transport direction, based on dip analysis in the African basins, confirms that oblique rifting has been operative in the EAR. This conclusion is supported by landbased fault-slip analysis by Chorowicz & Sorlien (1992). A similar dip analysis on the Queensland Trough data is limited due to the small number of profile intersections (Fig. 2A). However, of the 22 profile ties where underlying basement rotation can be measured with reasonable confidence, 15 yield a true dip direction of WNW–ESE implying that tectonic transport direction or extension direction is aligned along this azimuth. The seven northeast–southwest dips are either found in the north, where the presence of volcanics obscures rift-related structures, or are adjacent to proposed northeast–southwest trending "transfer" faults which may affect subsidence locally.

It is likely that the structural pattern in the Queensland Trough is neither as regular and rectilinear, nor as perfectly arcuate and unlinked, as that shown in the two alternative interpretations in Figure 9. Rather, it is more likely that the actual structural style lies somewhere in between as modelled for the EAR by Chorowicz & Sorlien (1992), wherein extensional rift-bounding normal faults are arcuate and are compartmentalized by transfer faults aligned approximately in the direction of of extension, which is oblique to the rift axis (Fig. 11).

By incorporating arguments based on predicted orthogonal extension geometries and observations of geometries within the data, it is possible to construct an interpretation which provides a linked fault system consistent with a stable stress regime (Fig. 11). The underlying syn-rift extension of the Queensland Trough appears to have been accommodated by somewhat variably-trending NNE–SSW normal, possibly curvilinear, faults. The normal faults are truncated by pervasive WNW–ESE oblique- to strike-slip, steeply dipping faults in this interpretation. The structural architecture presented in Figure 11 also fits with the compartmentalization of the syn-rift isopach cells into smaller "deeps". Further, the interpretation is consistent with our current understanding of strain distribution in extensional systems, with the enigmatic qualification that both normal and transfer faults are aligned oblique to the trough axis.

In Figure 11, there is a noticeable change in the trend of the normal faults at 15° 15′ S from NNE–SSW in the north to north-south in the south. The normal faults appear to revert to a NNE–SSW trend at latitudes south of Cairns. The northwest–southeast-trending structures that separate the variable normal fault trends are approximately aligned with changes in the continental shoreline trend from north–south to northwest–southeast. Further, north–south-trending residual negative bouger gravity anomalies onshore are truncated by northwest–southeast-trending relative highs which align with these bounding structures (Murray & others, 1989; his fig. 1). It is proposed that these trends are major crustal anisotropies that have partitioned the strain along the axis of the Queensland Trough.

Tectonic implications

It is proposed that extension in the Queensland Trough was directed WNW–ESE at an oblique angle to the northwest–southeast (155°) trend of the rift axis. The axis of the trough may be so aligned in response to the regional grain of the Paleozoic Tasman Fold Belt (Mutter, 1977). The structural pattern of NNE-trending normal faults and WNW-trending transfer faults is broadly consistent with interpretations of recently collected seismic data from the Townsville Trough (Falvey & others, 1990; Symonds & others, 1987; 1988). Analysis of the Townsville Trough data suggests northwest-trending extension resulting in a ENE set of normal faults with northwest-trending transfer faults. As an alternative to the WNW-extension direction proposed above, it may be that northwest-trending extension indicated by Townsville Trough structural interpretations, reactivated a WNW crustal anisotropy suggested by the strain partitioning along the Queensland Trough and onshore gravity signatures (Murray & others, 1989).

As mentioned earlier, the regional crustal morphology of rift zones wrapped around a craton is similar to both the Tanganyika/Rukwa/Malawi Rift and the Queensland/Townsville Trough. However, the large-scale similarity ends there. The Tanganyika and Malawi rift zone axes are sub-parallel and do not intersect; rather, they are joined by the strike-slip Rukwa rift zone (e.g. Rosendahl & others, 1992). The Queensland and Townsville Troughs intersect at their southern and western termini, respectively. Further, the troughs strike radially from their point of intersection at an angle of approximately 115° to each other. This configuration is very suggestive of an incipient triple junction (McKenzie & Morgan, 1969). There is some evidence that a third arm of the system extends inboard of the Marion Plateau. White (1961; 1965) first proposed that northeast-trending structures bounding the Broken River Embayment (Fig. 1) represent an intra-continental rift. Mutter & Karner (1980) also hypothesize a possible Paleozoic three-branch system of which only the Queensland and Townsville branches were reactivated in the Mesozoic. As evidence, they cite prominent structural lineaments of the appropriate trend in the Broken River Embayment and the Georgetown Inlier (Fig. 1). Arnold & Fawkner (1980) argued that these half-graben structures were active during deposition of Ordovician and Silurian sediments. However, their figure 4 suggests that the structures existed in pre-Silurian time. If this is true, then southeastward movement of the Queensland and Marion Plateaus is consistent with the creation of a possible incipient "triple junction" and explains the relationship between the Queensland and Townsville Troughs. Given the corroborating structural patterns mapped in the Townsville Trough, this seems to be the most plausible explanation for the creation of these troughs and resolves the kinematic difficulties of opening them with Mesozoic plate motion vectors determined from spreading centers in the Coral and Tasman Seas.

This interpretation differs radically with the many previous structural interpretations of the northeast margin of Australia with regards to implications for large-scale tectonic evolution. Whether or not extension within the Queensland/Townsville Trough was directed northwest or WNW, the structural interpretations presented herein and from the Townsville Trough (Symonds & others, 1987; 1988) imply that extension at basement levels in this system is not kinematically consistent with either the spreading direction of the Coral Sea to the north or the Tasman sea to the south as is commonly stated in other studies. Since we have no age constraints on the extension for the Queensland/Townsville Troughs system, it is possible, or probable, that extension here predates tectonism in either of the adjacent spreading centers. A (?pre-) Paleozoic triple junction, reactivated in the Mesozoic, is supported by the kinematics suggested here by the structural interpretation of the Queensland Trough as being the product of oblique rifting.

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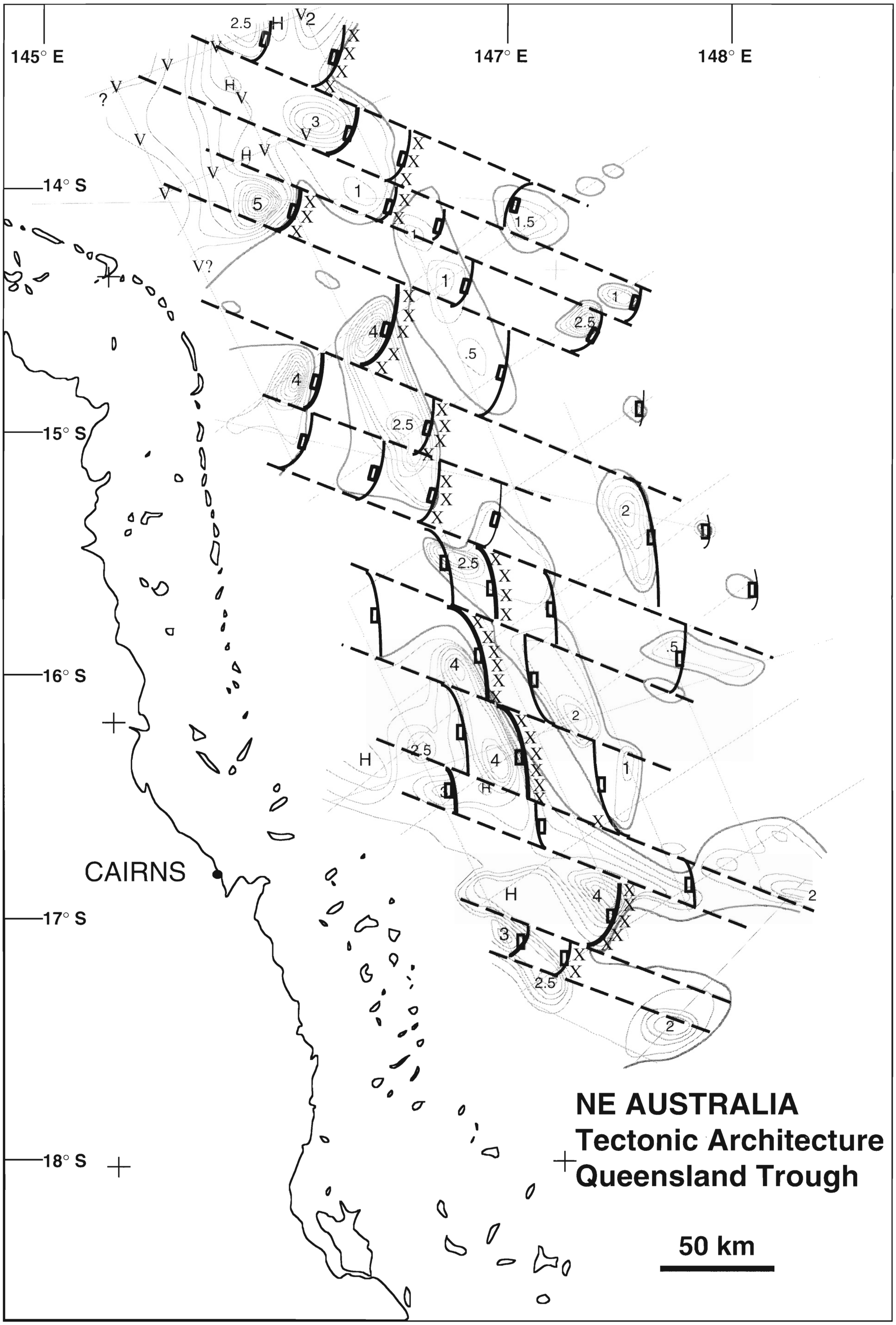
Figure 11. Interpreted tectonic architecture of the Queensland Trough. Grayed contours are the syn-rift isopachs shown in Figure 2B. Note the change in the orientation of the normal faults just south of 15° S latitude. This interpretation is consistent with the syn-rift isopach data, the dips of basement rotations (Fig. 2A), profile geometries discussed in the text and correlated structural trends close to profile intersections. XXX = westward extent of relatively highstanding basement blocks. V = volcanic seismic signature.


145° E
147° E
148° E
14° S
15° S
16° S
17° S
18° S
CAIRNS
NE AUSTRALIA
Tectonic Architecture
Queensland Trough
50 km

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