Development of the continent-ocean transform boundary of the southern Exmouth Plateau

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ABSTRACT

A two-stage model is proposed to explain the principal tectonic and magmatic features observed in multichannel seismic reflection and refraction data across the southern transform margin of the Exmouth Plateau (northwestern Australia): (1) The rifting stage, in which detachment surfaces developed under conditions of extension at a high angle to the future transform and were later sheared by right-lateral strike-slip faulting. Final transform rupture was attended by large fault-block rotation and mafic intrusions in conditions of pure shear. (2) In the drifting stage, as the oceanic ridge abutted the continent, the continental rim was underplated (at this location, resulting in a 10-km-thick, 7.3 km/s, 3 g/cm^3 layer), resulting in a permanent isostatic uplift of the crust and tilting of synrift sedimentary deposits. This wedge extends laterally, forming a thickened oceanic layer 3. Transient heating of the continental lithosphere induced thermal uplift and erosion of up to 3.5 km of sedimentary units over a 50-km distance from the continent-ocean contact.

INTRODUCTION

By comparison with other types of plate boundaries, paleotransform segments in passive continental-margin settings have received relatively little attention. Consequently they are not well described, and the tectonic and magmatic processes attending their evolution are poorly understood (Scrutton, 1979). In intracontinental rift settings, there are cross-structures known as accommodation zones (Rosendahl, 1987; Bosworth, 1987)—areas of complex shearing and folding—and large-scale transfer zones (Gibbs, 1984; Etheridge et al., 1985; Tankard and Welsink, 1987) that have recently received considerable attention. They represent the rift features most likely to develop into transform faults during plate separation. An accurate kinematic description of the transition between rifting and transform rupture is, however, unavailable. Only a few recent seismic studies have been made of the deep crust across continent-ocean transforms (Todd et al., 1988; Keen et al., 1989), the results of which, together with consideration of the evolving temperature and rheological structure, have recently been employed to advance preliminary models of transform-margin evolution (Reid, 1989; Todd and Keen, 1989).

We report herein the principal findings of an investigation into the deep structure of the southern margin of the Exmouth Plateau off northwestern Australia (Fig. 1); these results are part of a larger study of the margin (Mutter et al., 1989). The Exmouth Plateau is an unusually broad region of continental crust, deformed during a Jurassic rifting period that preceded Early Cretaceous sea-floor spreading in the adjacent Indian Ocean (Powell, 1976; Veevers and Cotterill, 1978; Larson et al., 1979). Recent Ocean Drilling Program (ODP) results show that the southern Exmouth is partly composed of a synrift, shallow-water, Tithonian-Valanginian(?) terrigenous sequence about 1 km thick, resting unconformably on a Triassic prerift basement (Haq et al., 1990). An erosional hiatus spanning the Barremian-Hauterivian (~10 m.y.) separates the sequence from about 1 km of postrift hemipelagic to eupelagic sediment deposits.

Our data include two-ship seismic reflection and refraction measurements. The latter resolve the presence of a high-velocity layer in the lower crust beneath a strike-slip deformation zone. We

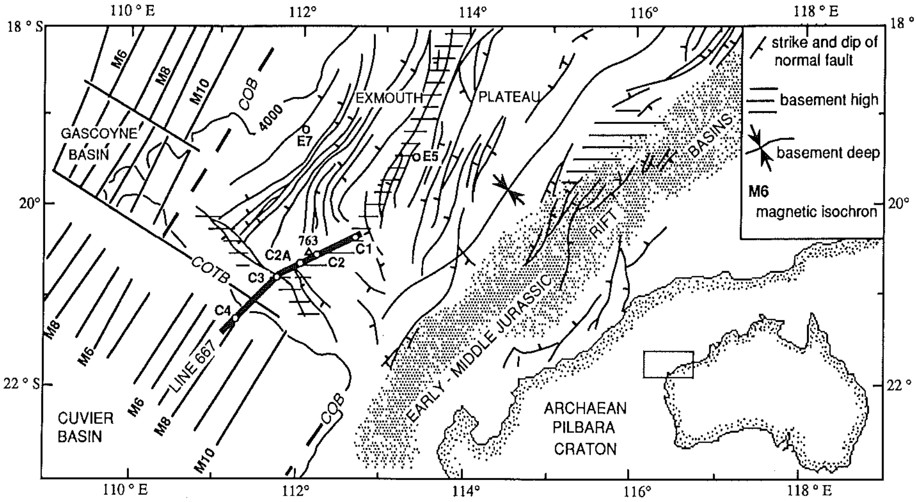

Figure 1. Central and southern Exmouth Plateau study area, outlined approximately by 4 km isobath. Ship track for CDP line 667 (thick black line) crosses fossil strike-slip deformation zone (hachured basement high) under which is 10-km-thick 7.3 km/s lower crust. Deep refraction lines were shot along 100-km tracks at right angles to line 667; only midpoint locations are shown (small circles, expanded spread profiles [ESPs] C1 through C4). Continent-ocean boundary (COB), continent-ocean transform boundary (COTB), and magnetic isochrons are from Fullerton et al. (1989). Basement faults are from Exon and Willcox (1980), and locations of ESP midpoints E5 and E7 are from Mutter et al. (1989). ODP Site 763 is principal stratigraphic tie-in point for line 667.

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infer that evolution of the transform margin was attended by intense magmatism. We use gravity data and thermal modeling to advance some models for the structural and magmatic evolution of this margin, models that we believe may have application to other transform margins.

TRANSFORM-MARGIN STRUCTURE

Figures 2 and 3 show the structure of the Exmouth Plateau along seismic line 667, which crosses the transform margin at an orientation nearly normal to the transform direction. Five expanded-spread profiles (ESPs) were acquired along the reflection profile. The velocity-depth structures derived from them, together with velocities obtained by analysis of common-depth-point (CDP) gathers, were used to migrate and convert the reflection data to a depth section. We have assigned ages to the major tectonic-seismic units using drilling results from the nearby ODP Site 763 (Fig. 1).

ESPs C3 and C4 provide a description of the whole crust; the others allow a description of the upper 5 km of sedimentary section down to an inferred extensional detachment surface. The structure of the southernmost 100 km of the profile exhibits two unanticipated features. First, the oceanic crust shows two distinct reflections that bifurcate away from a common depth of 15 km at around CDP 8500. There they define a single prominent reflection at a position comparable to the crust-mantle transition seen in other parts of the Cuvier basin (Larson et al., 1979) and other deep oceans (e.g., Spudich and Orcutt, 1980; McCarthy et al., 1988). In Figure 2, the upper event (M1) extends to less than 11-km depth. Comparison with the velocity-depth structure at ESP C4 suggests that M1 coincides with the base of a unit with an average velocity of 6.8 km/s, typical of oceanic layer 3. The lower event (M2) reaches depths in excess of 17 km.

The second unusual feature is a 10-km-thick layer with a velocity of 7.2–7.4 km/s at the base of the crust at ESP C3 beneath the outermost plateau. Deep crustal layers with velocities in this range have now been reported from a number of rifted continental margins, where they have frequently been attributed to magmatic underplating of extensionally thinned continental crust (e.g., LASE Study Group, 1986; White et al., 1987; Austin et al., 1990). A layer with similar velocity, but only 3.6 km thick (see Fig. 1, at E7), was reported beneath the rifted margin of the Exmouth Plateau by Mutter et al. (1989). Magmatism in such settings may result from decompression melting of a thinned lithosphere (Beaumont et al., 1982; Foucher et al., 1982; White and McKenzie, 1989).

To further characterize the nature of the interpreted underplated layer, we computed the gravity response of a simple density-layer model of the margin (Fig. 3), limited by the available gravity data and seismic reflection and refraction analyses. The preferred model shows a wedge with a density of about 3 g/cm^3 that thins toward the center of the plateau (where ESP E5 from Mutter et al. [1989] is used to determine the structure here) and connects with a southward-thinning wedge, the geometry of which is defined by reflectors M1 and M2 beneath the Cuvier basin.

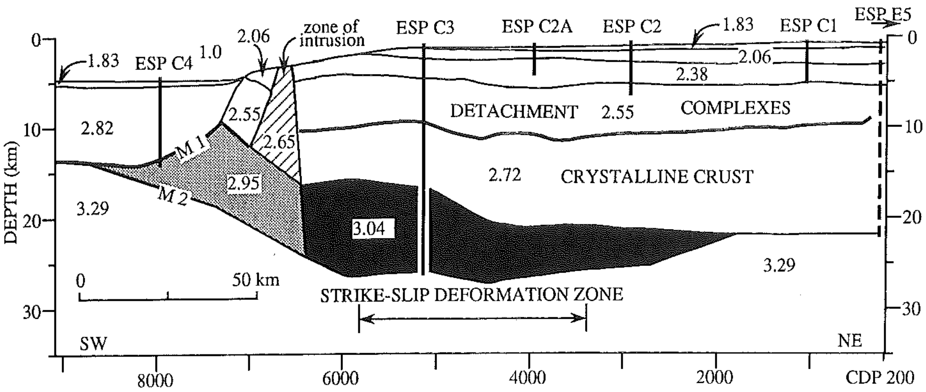

Figure 3. Estimated crustal-density distribution (g/cm^3) along line 667 derived through two-dimensional forward gravity modeling of free-air gravity anomaly data. Shallow crustal geometry was determined by deepest visible seismic reflectors (thick black lines) in CDP profile 667 (see Fig. 2). Expanded-spread-profile (ESP)–derived velocity-depth solutions (Fig. 2; Mutter et al., 1989, for ESP E5) determined deep structure.

The seismic profile along line 667 is almost at right angles to the major structural trends, entering the Cuvier basin along approximately the M8 isochron (128 Ma). Whereas major normal faults strike northeast on the western Exmouth, near line 667 they are subparallel to the southern boundary (Fig. 1) within a triangular region up to 100 km wide in the east. In Figure 2, two prominent, sinuous, high-amplitude reflector groups appear to be centered at depths of 5 and 8 km (e.g., Fig. 2, CDPs 800–1200); between CDPs 2000–2600 and 600–800, they dip steeply (10°). In the central and western Exmouth Plateau, similar reflectors were interpreted by Mutter et al. (1989) as extensional detachment faults and footwall ramps; i.e., large bends in detachment faults (Gibbs, 1984). Many high-angle normal faults sole out into these supposed detachments. Bedding reflectors, tilted by normal faulting only a few degrees, suggest a crustal extension of only a few percent (Wernicke and Burchfiel, 1982).

Together, the regional and local tectonic patterns indicate that a broad strike-slip deformation zone, close to a former transform boundary, was active in the later rifting stage. In intracontinental settings, such zones link oppositely dipping half-graben systems that can be up to several hundred kilometres in length and are prime candidates for transform rupture (Rosendahl, 1987). South of CDP 3400, faulting becomes more closely spaced, disrupting the lateral continuity of the detachment reflectors at depths of between 7 and 10 km. Typical strike-slip deformation features are visible, e.g., normal and reverse fault splays ("flower structures") that exhibit variable amounts of slip along the same fault. We do not see a similar faulting pattern between the continent-ocean transform boundary and CDP 5800. The strike-slip deformation has sheared the lenticular bodies as defined by the highly reflective detachment reflectors. Regional structural maps (Fig. 1; Exon and Willcox, 1980) show that faults form an en echelon right-stepping pattern, consistent with right-lateral strike-slip deformation (Christie-Blick and Biddle, 1985).

From CDP 5000 southward, the prerift and synrift sequences are thinner, erosion causing the prerift basement to crop out along the upper part of the transform slope (Fig. 2). We have estimated the amount of missing section by measuring the section between the shallowest inferred detachment reflector (d) and the sea floor at regular distances (Fig. 4). The values of denudation increase southward and reach a maximum of 3.5 km near the continent-ocean transform boundary. Just south of CDP 5000, where the amount of estimated erosion is the least and the underplated layer is thickest, the synrift reflectors are noticeably rotated. Although this may be partly a result of differential isostatic adjustment to the varying load of the sedimentary cover, 3°–4° of dip still remain after removing this effect, even in the case of local isostasy. Part of this tilt was probably acquired postdepositionally because (1) it is greater than expected for a primary depositional surface; (2) it is greater than anywhere else within the synrift section; and (3) there is no evidence for synrift reflectors onlapping the tilted reflectors. It appears that uplift occurred prior to deposition of the postrift section, which onlaps the synrift section at a much smaller angle. The

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[1] Figure 2 is a loose insert accompanying this issue.

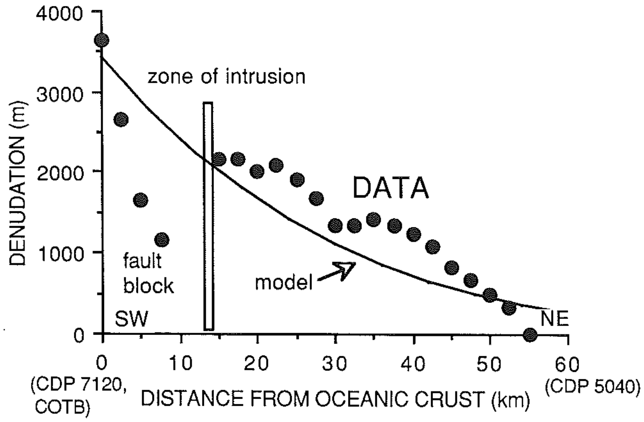

Figure 4. Estimates of missing seismic section (see Fig. 2, loose insert) on southern paleotransform margin as function of distance to continent-ocean transform boundary (COTB); missing sedimentary rocks were presumably eroded subaerially. Calculated amounts of denudation have same order of magnitude and trend as data points; erosion rates used are proportional to local height above sea level. Little erosion seems to occur more than about 50 km away from continent-ocean contact, probably because of poor thermal diffusivity of lithosphere and finite heat supply.

prerift basement appears to be raised and is beveled between CDPs 5200 and 5800, indicating that subaerial uplift and erosion may have taken place before the beginning of synrift sedimentation.

At about CDP 6400, detachment reflectors are interrupted along a steep, north-dipping boundary by a region of chaotic reflection patterns, very similar to features described by Mutter et al. (1989) as internally nonreflective zones of igneous intrusion. Within a 5-km-wide region between the continent-ocean transform boundary and the zone of intrusion, the basement reflectors become more laterally discontinuous and dip northward about 15°. We suggest that they may form part of a block that was locally rotated during extension across the margin.

DISCUSSION

Crustal extension in a general transtensional tectonic regime may have contributed to thinning the southern Exmouth margin. Oblique extension may have led to the development of extensional detachment faults, which, from crosscutting relations, would have occurred previous to the strike-slip shearing. If mid-crustal detachments decouple upper- and lower-crustal extension, they could explain the discrepancy between the low crustal-extension values that can be deduced from the fault geometries along most of line 667 and the relatively thin prerift basement above the underplated wedge. However, such a simple shear process is less favorable than uniform-sense pure shear for producing significant amounts of partial melts, because it envisages a slower ascension of aesthenosphere into the base of the attenuated lithosphere during stretching (Buck et al., 1988).

We can make a first-order estimate of the extent of crustal thinning with reference to Figures 2 and 3 and assuming a prerift crustal thickness of 30 km (Mutter et al., 1989). If the underplated sequence is composed of pure igneous rocks (not a mixture of mafic igneous with original felsic crustal components), then the prerift crust over the center of the underplated body would have been extended by about a factor of two. If only half the sequence consisted of pure igneous rocks, this factor would be smaller, about 1.5. Near the continent-ocean transform boundary, just south of the strike-slip deformation, considerable thinning has produced an association of a highly rotated fault block surrounded by large igneous bodies, an association that may be more indicative of pure shear for final transform rupture.

We noted above that stratigraphic evidence is consistent with erosional thinning by a maximum of about 3.5 km, diminishing to zero ~50 km from the transform boundary (Fig. 4). After break-up, large horizontal thermal gradients across a transform zone are created as the oceanic spreading center slides past the cooler continental lithosphere (Scrutton, 1979). We postulate that if underplating does not significantly alter the average thermal structure of the continental lithosphere, lateral conduction of heat from the oceanic block may induce subaerial uplift and erosion (Todd and Keen, 1989). If the temperature-induced density changes are isostatically compensated locally by vertical displacements of the base of the lithosphere, both the greatest uplift and therefore the greatest erosion should take place nearest the oceanic crust. We can test this hypothesis by comparing the theoretically expected amount of erosion against the observations. The results show (Fig. 4) that both the trend and order of the predicted erosion are compatible with the data. Some eroded sediments may have been incorporated into the postrift sedimentary section.

The continent–ocean lithosphere transform boundary provides a large mechanical and thermal contrast for upwelling mantle during ocean-crust formation. Such large lateral thermal gradients could induce a secondary convection in the upper mantle (Mutter et al., 1988). Melt production would be expected to increase relative to passive upwelling, because of the increased flux of mantle into the shallower depths where melting can occur. A post–break-up origin for the underplated melt is advantageous because large amounts of continental thinning are not needed and the advective heat flow, in addition to any conductive transfer could further augment lithospheric expansion and uplift on the continental side. In our gravity modeling, the oceanic wedge between M1 and M2 (Figs. 2 and 3) is continuous with the underplated wedge, and both are most adequately described by densities appropriate for ultramafic rocks. In the Cuvier Basin, the M1–M2 interval may represent an expanded crust-mantle transition layer. This expanded ultramafic unit, thinning oceanward into a normal oceanic section, appears to map the region of the oceanic crust that was affected by the increased melt flux associated with the formation of the underplated layer beneath the transform margin.

A consequence of underplating is a permanent crustal isostatic rise, as the mantle is replaced by less dense igneous rocks. The amount and timing of tilting displayed by the synrift stratigraphy are in agreement with the emplacement of the wedge-shaped underplated body, possibly during early sea-floor spreading, although time resolution is lacking because of the missing sedimentary section, represented by the postrift erosional hiatus.

MARGIN EVOLUTION

Figure 5 illustrates a two-stage scenario to explain the main structural and magmatic features of the southern Exmouth margin. During the early part of rifting (stage 1), detachment faults developed in the middle to upper crust in response to extension at a very high angle to the direction of future transform motion. Oblique right-lateral strike-slip faulting then dominated along subaerially eroding deformation zones that linked oppositely dipping half-graben systems up to several hundreds of kilometres in extent. Final transform rupture occurred offset from the strike-slip deformation zone and may have been attended locally by considerable crustal thinning and magmatic intrusions, perhaps under conditions of pure shear.

During drifting (stage 2), sea-floor spreading proceeded, and large lateral thermal contrasts were established after the ridge abutted the continental block. Igneous melt resulted from the decompression of ascending aesthenosphere and may have been augmented through induced secondary convection, thus (1) creating an expanded crust-mantle transitional wedge and (2) underplating and intruding the lower crust. Underplating locally produced a permanent isostatic uplift of the synrift sedimentary units. Conductive heating by the hotter oceanic block may have induced transient thermal uplift of the

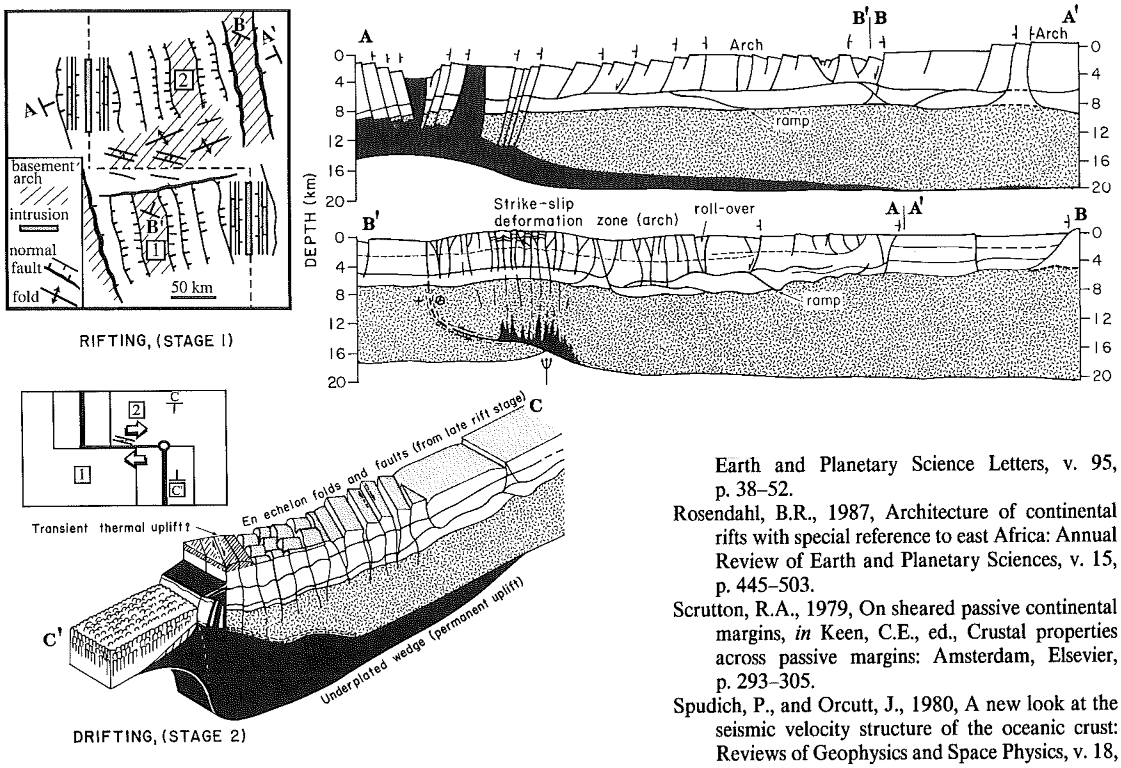

Figure 5. Evolutionary model for development of southern Exmouth margin described in text. For comparison, profile A-A' shows pure rifted western Exmouth margin during late rifting- early drifting (from Mutter et al., 1989). Profile B-B', through paleotransform margin, is based largely on interpretation of line 667 (see Fig. 2).

continental side, accompanied by ensuing subaerial denudation (hachured region).

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