J Geophys (1985) 56:106–120

Journal of Geophysics

Magnetic expression of the continent-ocean boundary between the western margin of Australia and the eastern Indian Ocean

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Abstract. A comprehensive review of the Early Cretaceous seafloor-spreading magnetic anomalies (M0 to M10) in the eastern Indian Ocean leads to the isolation of a distinctive magnetic anomaly at the continent-ocean boundary (COB). This anomaly is traceable 2000 km southward from the rifted margin of the magnetically smooth central Exmouth Plateau, through the transform-faulted and rifted margins of the Cuvier Abyssal Plain and Carnarvon Terrace and the set of narrow spreading segments south of the Zenith-Wallaby Fracture Zone to the area west of Perth. The anomaly corresponds to the COB as indicated by: 1. the lower part of the continental slope in a mean water depth of 3.75 km for the rifted margin and 4.5 km for the transform-faulted margin and 2. a change in seismic-reflection character from the faulted breakup unconformity on the continent to the smooth but hyperbolic oceanic layer 2. The COB anomaly at the rifted margin is modelled by modifying the magnetization of the oldest oceanic block of the seafloor-spreading sequence adjacent to the continental crust; in places, the COB anomaly is flanked by smaller anomalies modelled as rift-related dykes in the adjacent continental crust. The amplitude of the COB anomaly, commonly twice or more that of the adjacent oceanic magnetic anomalies, is due either to a thicker or a more intensely magnetized source. The COB anomaly at the transform-faulted margin is modelled by a thick vertical body that extends 10 km seaward of the COB.

The Wallaby Plateau is probably underlain by oceanic crust, as shown by the continuity of the abandoned spreading ridge of the Sonne Ridge southwestward from the Cuvier Abyssal Plain; the shape of the Wallaby Plateau and the volcanic composition of dredge-hauls indicate that it is probably a volcanic upgrowth of the oceanic crust, as exemplified by Iceland today. Furthermore, like Iceland, the Wallaby Plateau is crossed by magnetic anomalies that are possibly degraded seafloor-spreading anomalies. The Zenith Plateau lacks magnetic lineations and its crustal structure, like that of the Naturaliste Plateau to the south, remains unknown.

Key words: Seafloor-spreading magnetic anomalies – Continent-ocean boundary magnetic anomaly – Spreading pattern of the eastern Indian Ocean – Volcanic upgrowths on oceanic crust

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Introduction

The 2000-km-long western margin of Australia, from the northwestern Exmouth Plateau to the southern Naturaliste Plateau (Figs. 1 and 2), is marked by a series of marginal plateaus indented by abyssal plains. The abyssal plains are crossed by Early Cretaceous seafloor-spreading magnetic anomalies, as described by Powell (1978) and Powell and Luyendyk (1982) for the Gascoyne Abyssal Plain, by Larson (1977), Larson et al. (1979) and Johnson et al. (1980) for the Cuvier Abyssal Plain and by Markl (1974a, b; 1978a, b) and Larson et al. (1978) for the Perth Abyssal Plain. As revised here, the anomalies range from M10 (122[125] Ma) through M0 (108 [110.7] Ma) into the Cretaceous interval of normal polarity and, calibrated by DSDP drilling, define the pattern of seafloor spreading. To provide direct comparison with previous work, ages are expressed here in terms of the old radiometric decay constants and,

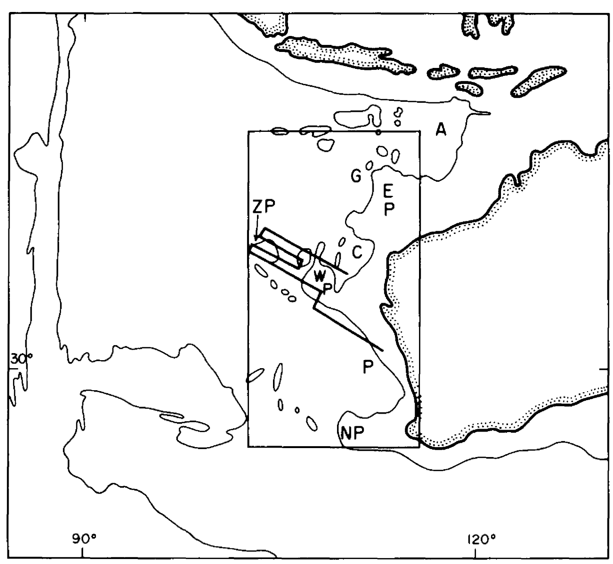


Fig. 1. Western margin of Australia, located within box that shows outline of Fig. 2. Also shown are 4-km isobaths and the track of the 1983 *Cook* cruise off the western margin. From north to south, A = Argo Abyssal Plain, G = Gascoyne Abyssal Plain, EP = Exmouth Plateau, ZP = Zenith Plateau, C = Cuvier Abyssal Plain, WP = Wallaby Plateau, P = Perth Abyssal Plain, NP = Naturaliste Plateau

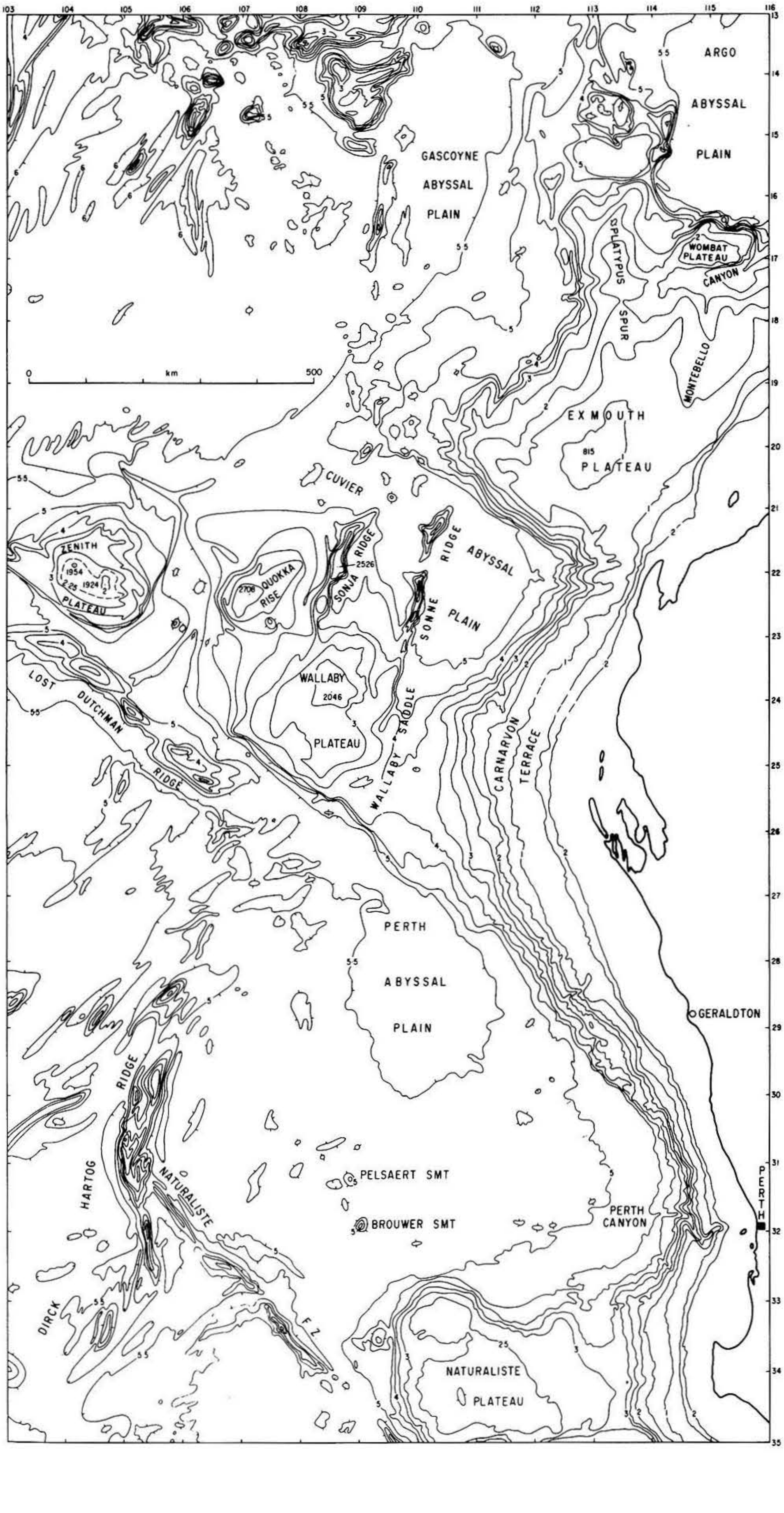


Fig. 2. Bathymetry of the western margin (0.5-km contour interval and, additionally, the 0.2-km isobath) from Fisher (1982), amended by new data: for the Zenith Plateau and the area southwest of the Wallaby Plateau from the 1983 cruise of *Cook* plotted on GEBCO sounding sheets; for the Exmouth and Wallaby Plateaus from von Stackelberg et al. (1980); for the Joey Rise from Heirtzler et al. (1978); and for the 2-km isobath of the Naturaliste Plateau from Coleman et al. (1982). *Bar* refers to scale at 19° S. Nomenclature: Heezen and Tharp (1966) named the complex of plateaus northwest of the Carnarvon Terrace the Wallaby Plateaus; Tomoda et al. (1968) called the western one the Zenith Seamount; various authors then confined the word Wallaby Plateau to the eastern one; Fisher (1982) called the western one the Wallaby Plateau and the eastern one the Cuvier Plateau. We resolve the confusion by calling the western one the Zenith Plateau (it is too big for a seamount), the eastern one the Wallaby Plateau and recognise a third as the Quokka Rise, named after a small wallaby common on islands offshore from Perth

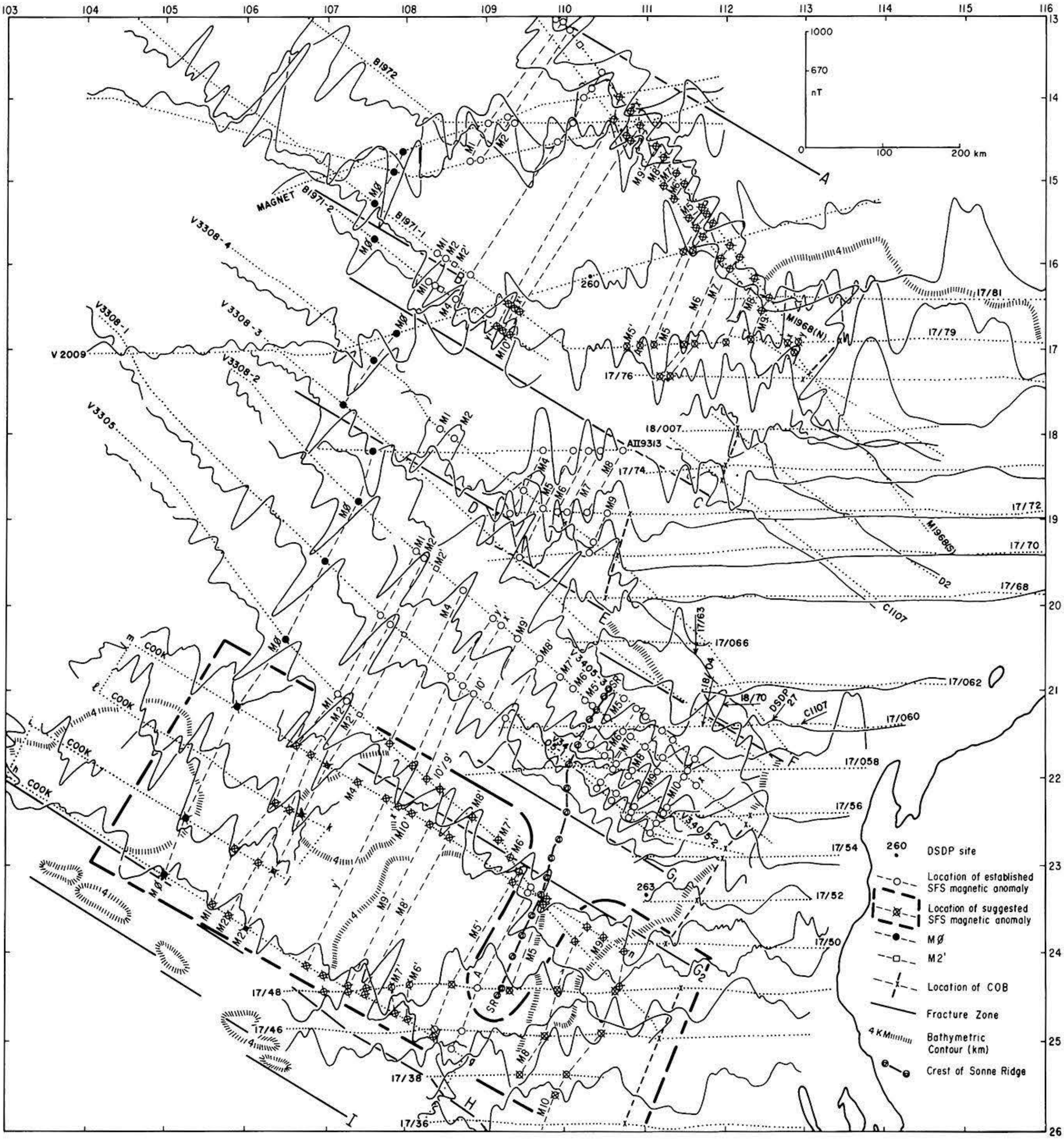
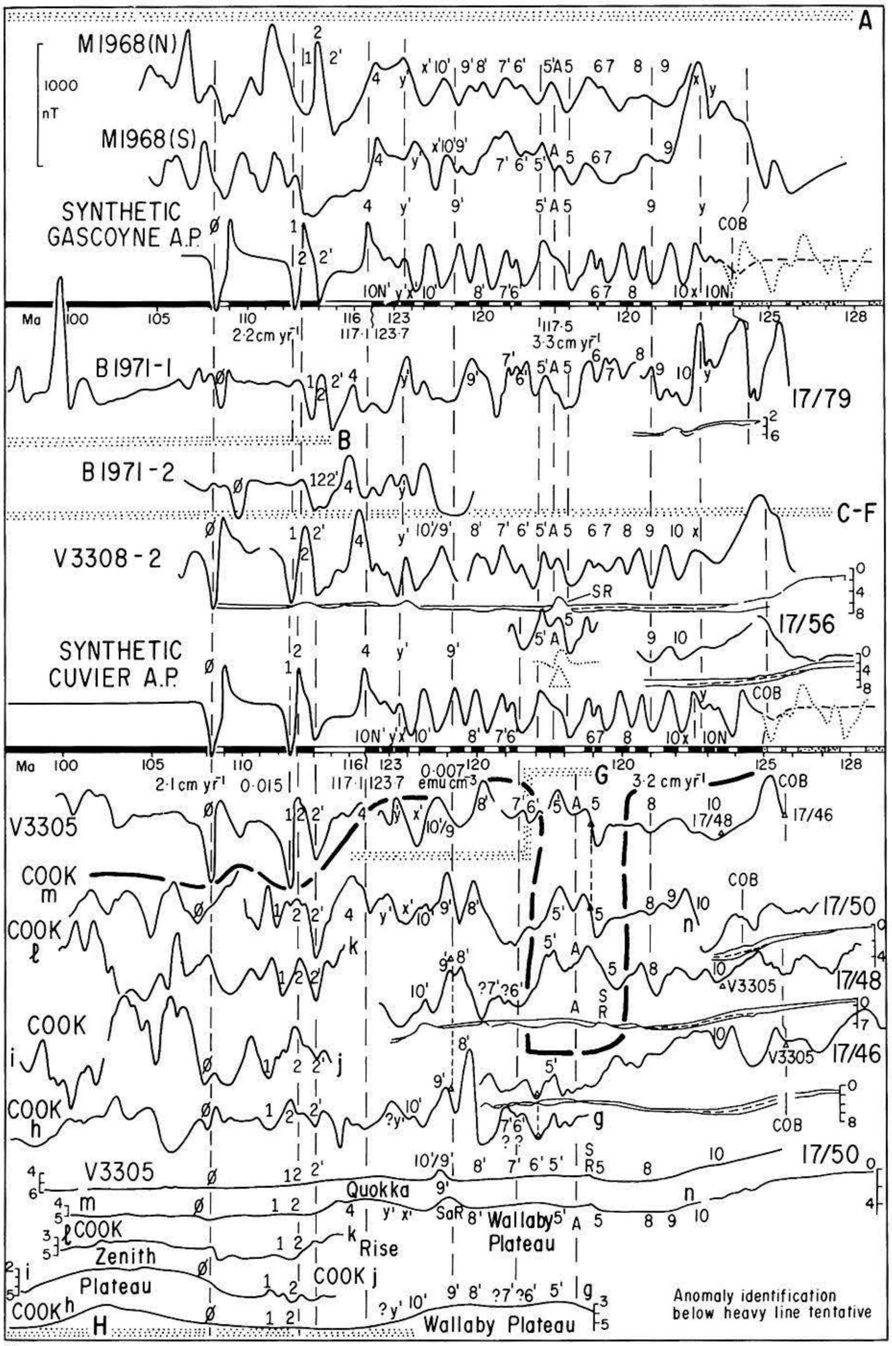


Fig. 3. Selected ships' tracks and magnetic profiles for the northern area. For the sake of clarity, ships' tracks across the Cape Range Fracture Zone (F) are indicated by *arrows*. New profiles for the Zenith Plateau area are from *Cook*, reduced by the Australian Geomagnetic Reference Field (AGRF) of Petkovic and Whitworth (1975); rest of the profiles were compiled from Powell (1978), Larson (1977), Larson et al. (1979), Falvey (1972a, b) and BMR Margins Survey, published by the Australian Government Publishing Service, Canberra. Magnetic anomaly determinations in the Cuvier Abyssal Plain from Larson (1977), Larson et al. (1979) and Johnson et al. (1980), were tentatively extended southwestward into the Wallaby-Quokka area (tentatively interpreted anomalies enclosed by *heavy broken line*) by us; while those in the Gascoyne Abyssal Plain from Powell (1978), cited in Larson et al. (1978) and also in Powell and Luyendyk (1982), were amended by us to include a reflected set M9′-A-M9 and the COB. Fracture zones determined by bathymetry are F (Cape Range FZ), H (Zenith-Wallaby FZ) and I (fitted to Lost Dutchmann Ridge); the rest are postulated from offsets in the magnetic anomaly pattern

in square brackets, converted to the new constants (Dalrymple, 1979).

M10 lies within the Jurassic-Cretaceous M-series of mixed polarity so that, unlike the central North Atlantic which is bounded by the Jurassic quiet zone, a continuous set of anomalies extends up to the continental margin. The central and southern parts of the Exmouth Plateau are underlain by continental crust, as shown most clearly by the



a

Fig. 4. **a** Selected magnetic, seismic and bathymetric profiles, located in Fig. 3, projected on an azimuth of 302°. Fracture zones A–H shown by *stippled lines*. Block model of M-series (Larson and Hilde, 1975) with normal polarity *in black*, reversed polarity *clear*- note that ages are expressed in the old K/Ar decay constants for direct comparison with previous work – and synthetic magnetic anomalies, involving reflection of blocks about axis (A), after Larson (1977), Larson et al. (1979) and Johnson et al. (1980) for the Cuvier Abyssal Plain, extended by us to the Gascoyne Abyssal Plain and tentatively to the Wallaby/Quokka region, distinguished from area of established anomalies by a *heavy broken line*. Model parameters not shown on the figure are: model source is 5.5–6.0 km below sea level and trend is 030°; present-day magnetic field parameters are inclination 55° up and declination 2° west. Remanent-magnetization parameters are inclination 55° up and declination 40° west. Remanent-magnetization intensity is expressed in old units of emu/cm^3 ($=10^{-3}$ A/m) to provide direct comparison with previous work. The positive anomaly at 122.4 Ma is labelled *x*, and the negative anomaly at 122.7 Ma, *y*. Lines through modelled anomalies afford direct comparison with observed anomalies; note offset of M7′, A and M8 on V3305 and southward. SR = Sonne Ridge, whose magnetic anomaly is modelled by adding the magnetic response of a ridge with intensity 0.00075 emu/cm^3 to the block model (*dotted line*). Sa R – Sonja Ridge. The COB is located at 123.7 Ma in the Gascoyne Abyssal Plain and at 124.9 Ma in the Cuvier Abyssal Plain. The block model is extended (*dotted blocks*) past 125 Ma, and its magnetic profile shown by a *dotted line*. Track crossings are shown by *triangles*. Depths of seismic profiles in seconds of reflection time. Bathymetric profiles (km) of tracks across Zenith Plateau, Quokka Rise and Wallaby Plateau are concentrated at the bottom. Scales: 150 km are equivalent to 1000 nT. **b** Block model and synthetic magnetic anomalies in segment CE, extended from determinations by Larson (1977). Depth of seismic profiles in seconds of reflection time. Model parameters not indicated in the figure are as in Fig. 4a

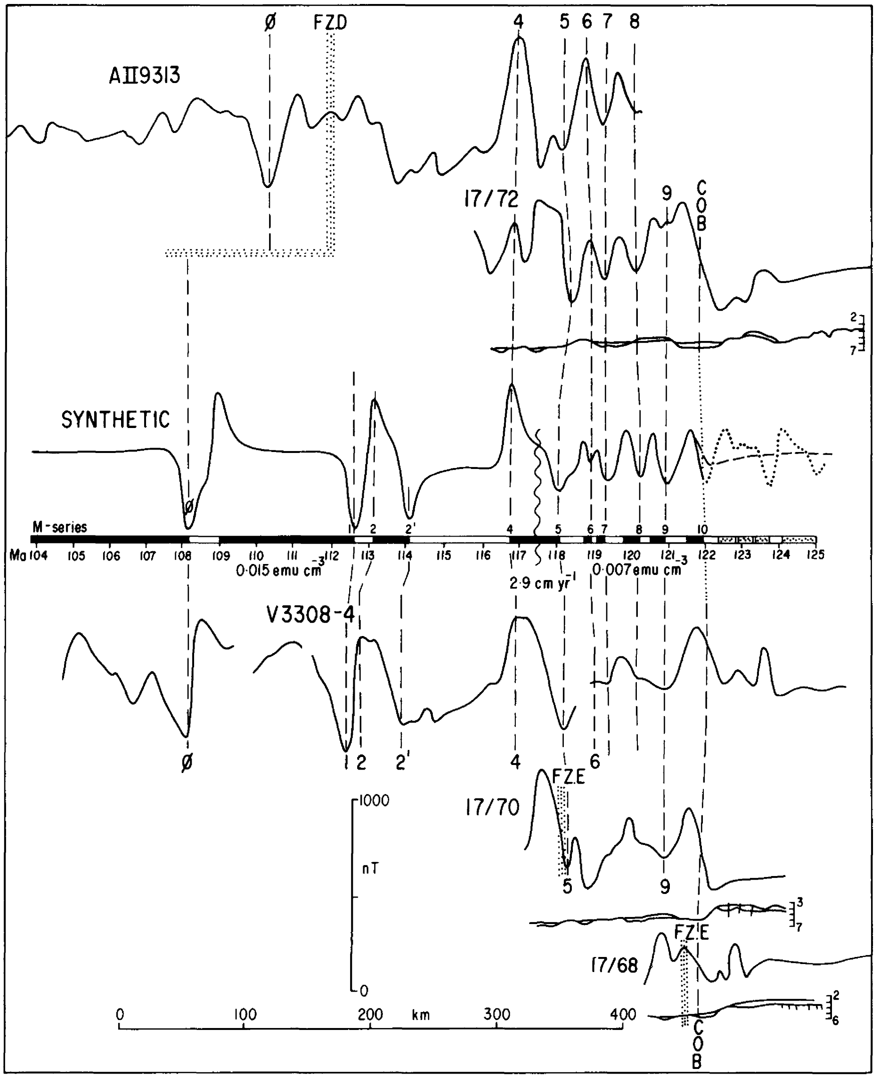


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Fig. 4b

occurrence of Triassic (200–230 Ma) sediment (Barber, 1982) in drill-holes. These parts of the Exmouth Plateau are magnetically featureless or smooth so that the boundary between the central rifted and southern sheared Exmouth Plateau and the adjacent ocean floor is marked by a continent-ocean boundary (COB) magnetic anomaly that can be modelled as the edge of an oceanic magnetic body, associated in places with rift-related dykes in the adjacent continental crust. South of the Exmouth Plateau, at the edge of the Cuvier and Perth Abyssal Plains, a similar anomaly is found but it is less distinctive because the continental crust is not magnetically smooth. Hence, all the seafloor-spreading magnetic anomalies must be identified so that the COB anomaly can be isolated.

In contrast, Veevers et al. (1985) show that in the region to the northeast, along the COB between the northwestern margin of Australia and the Jurassic Argo Abyssal Plain (Heirtzler et al., 1978), a prominent magnetic anomaly is due to a 40–80-km-wide body, most of which lies beneath the continental margin.

During the first cruise of HMAS *Cook* round Australia, measurements of the total magnetic field and bathymetry, supplemented in places by seismic reflection profiles, were made along the western margin and across the poorly known Zenith and Wallaby Plateaus and provide critical data for a review of the magnetic pattern.

Bathymetry (Fig. 2)

The main change to the recently published GEBCO sheet (Fisher, 1982) and earlier charts (Falvey and Veevers, 1974; Veevers and Cotterill, 1978) is in and about the Zenith Plateau, which is now seen to be some 35 km wider, as defined by the 4.5-km isobath. We found a deeper (5.5 km) trough between the Zenith Plateau and the Quokka Rise, which is seen to be more elongate along a north-east trend. Sonja Ridge, detached from the Quokka Rise by a 4.5-km-deep trough, and its companion, Sonne Ridge, continue southward into the Wallaby Plateau.

The bathymetry of the region has two trends: 1. a trend of 300°, expressed by the southwest flank of Zenith and Wallaby Plateaus, Lost Dutchman Ridge and the southwest flank of Exmouth Plateau, which are recognised as fracture zones; other fracture zones are inferred from the offsetting of magnetic anomalies; the Naturaliste Fracture Zone

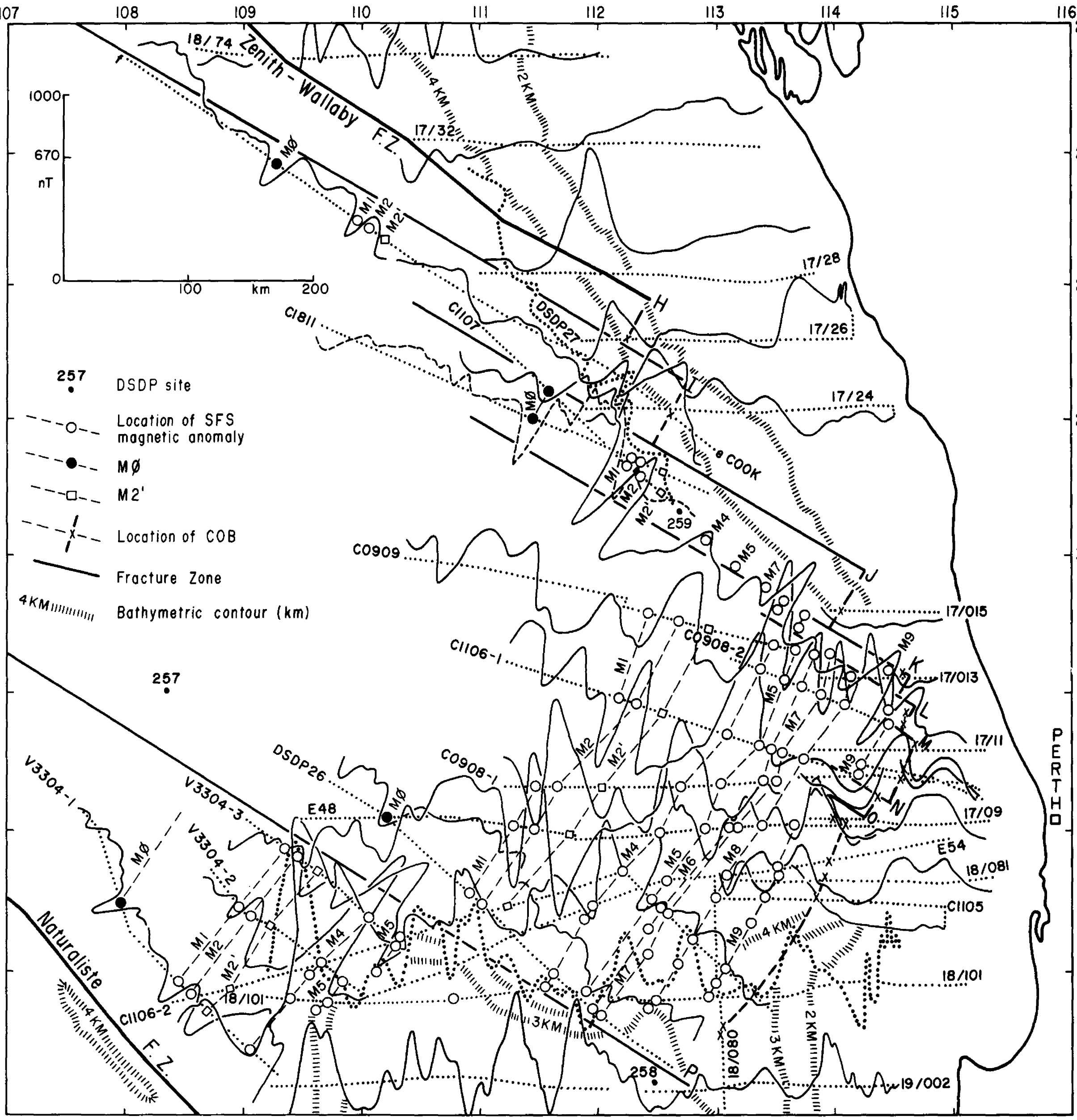


Fig. 5. Selected ships' tracks and magnetic profiles for the southern area. New profile for segment IJ from *Cook*; rest of profiles compiled from Markl (1974a, b; 1978a, b), Davies et al. (1973), Veevers et al. (1974), Hawkins et al. (1965) and BMR Margins Survey. Magnetic-anomaly determinations south of latitude 31°S slightly amended from Markl; north of 31° S, in segments J to M, amended after Larson et al. (1978). Determinations in IJ and of COB anomaly by us

(Markl, 1978b) intersects this trend at an angle of 20°; and 2. at right-angles, a trend of 030°, expressed by the continental slope at the southeast margin of the Cuvier Abyssal Plain, the northwest Exmouth Plateau, the northwest flank of the Wallaby Plateau and Sonja Ridge and the northern part of Sonne Ridge; athwart this are the trends of the southern Sonne Ridge (010°) and Dirck Hartog Ridge 020°).

As shown by the seafloor-spreading magnetic anomalies, the 030°-trend is the strike of the spreading and the 300°-trend the orthogonal strike of the fracture zones. This can be modelled by a pole of rotation at 56.5° S, 2.7° W of India from Australia, relative to Australia, for the interval 125 [128]–92.7 [95.0] Ma ago (Johnson and Veevers, 1984). The linear features athwart these trends – the Naturaliste Fracture Zone, Dirck Hartog Ridge and the southern part of the Sonne Ridge – are anomalous.

Seafloor-spreading magnetic anomalies (Figs. 3–7)

West and south of the Exmouth Plateau

Following Powell (1978) and Larson (1977), we identify the anomalies in the area west and south of the Exmouth Plateau as shown in Figs. 3 and 4. The best-mapped set of anomalies in the region is that in the Cuvier Abyssal Plain (Larson, 1977; Larson et al. 1979; Johnson et al. 1980) which, as shown by V3308-2 (Fig. 4a), comprises M10 through M5 reflected about the axis(A) of an abandoned spreading ridge marked by Sonne Ridge, succeeded by M4 through M0. The magnetic effect of Sonne Ridge, which rises 2 km above the level of layer 2 along V3308-2 (dotted lines in Fig. 4a), is small compared with the sea-floor-spreading magnetic anomalies and suggests that ridges and depressions in the oceanic basement contribute only a small part of the total magnetic anomaly in this region.

The same model is compared with two pairs of profiles in the northernmost spreading segment, between fracture zones A and C. All profiles have a broad and deep magnetic depression northwest of M4: M1968(N) and B1971-1 contain M1, M2 and the adjacent trough, designated M2′; all contain y′ (a characteristic anomaly between M10′ and M10N′); and M1968(N) contains an almost complete set of M5 through M9 reflected about an axis (A). Correlation of the other complete profile [M1968(S)] with the model is weak, except for M4, y′, y and M5′-A-M5. In isolation, few of these determinations are acceptable and the pattern of the poorly correlated profiles of the Gascoyne Abyssal Plain only palely reflects the good correlation of observed and modelled anomalies in the Cuvier Abyssal Plain, but it satisfies the other constraint on the spreading pattern: the comparable width of separation of M0 and the COB (600 km), which is not explicable without duplication.

In the intervening segment, between fracture zones C and D (Fig. 4b), in which the distance from M0 to the COB is only 400 km, the magnetic-anomaly sequence is modelled from V3308-4 (after Larson, 1977) as a clear M0 through M4, and on AII9313 and 17/72 as tentatively M5 through M9 so that the difference of 200 km in the width from M0 to the COB is accommodated by an unreflected set. Larson (1977) remarked that the positive anomaly we identify on V3308-4 as M4 "is probably not M-4, but an anomaly associated with the edge of the Exmouth Plateau". We disagree because the anomaly matches the model and the edge of the Exmouth Plateau, as indicated by the lower continental slope seen in 17/70, is about 250 km away. We differ with Powell and Luyendyk (1982) in identifying their M4 as y′ in B1971-1 (Fig. 4a), and M6 as M9′.

In the Cuvier area (Fig. 4a), the COB anomaly is isolated as the large anomaly shown in V3308-2 and 17/56 that corresponds to the position of the COB as independently determined by Roots et al. (1979) from the contrast in seismic character and by modelling the free-air gravity anomaly. The COB-anomaly straddles an extrapolated spreading age of 125 [128] Ma ago and would be modelled by an expanded (higher intensity or thicker) source block of normal polarity between 124.07 and 124.9 Ma ago. The spreading block model and its anomalies (dotted lines) are extended to the east in Fig. 4a to show the non-correlation with the observed anomaly beyond 125 Ma ago. The oldest modelled age in the reflected set to the west of Sonne Ridge is 123.7 Ma, so that we must postulate removal westward of M0 of the reflected block between 123.7 and 125 Ma ago, there being no indication of a symmetrically arranged set of this age to the east of Sonne Ridge. In the Gascoyne Abyssal Plain (Fig. 4a), as shown by M1968(N), the COB anomaly is isolated as a large anomaly with a modelled age of 123.7 Ma, corresponding to an expanded (higher intensity or thicker) block between y (122.7 Ma) and M10N (123.7 Ma), which coincides with the age of the reflected set on the west. In both the Cuvier and Gascoyne Abyssal Plains the age of A is 117.5 Ma and the oldest isochron in the resumed spreading after the ridge jumped to the west

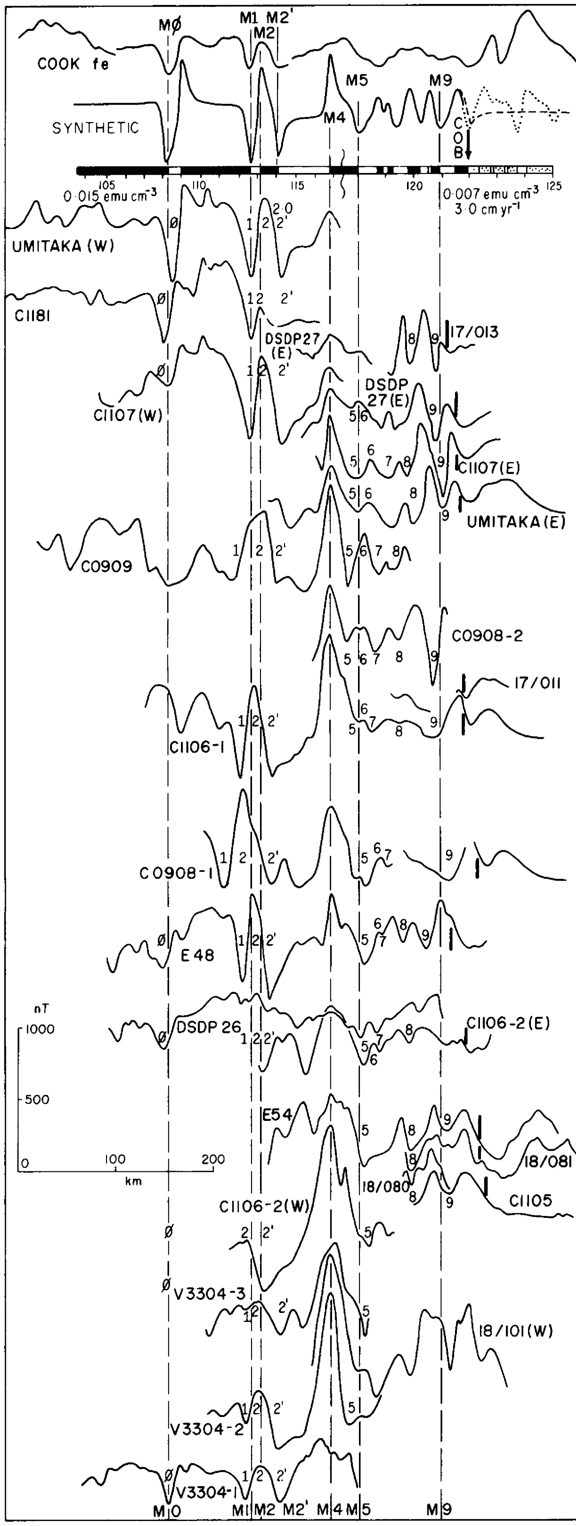


Fig. 6. Selected magnetic profiles, located on Fig. 5, projected on an azimuth of 302° and aligned on M4, compared with a synthetic model extended past the COB (*dotted blocks and dotted line*). Lines through modelled anomalies afford direct comparison with observed anomalies. COB anomaly indicated by heavy *broken line on right*. Model parameters not shown in the figure are as for Fig. 4

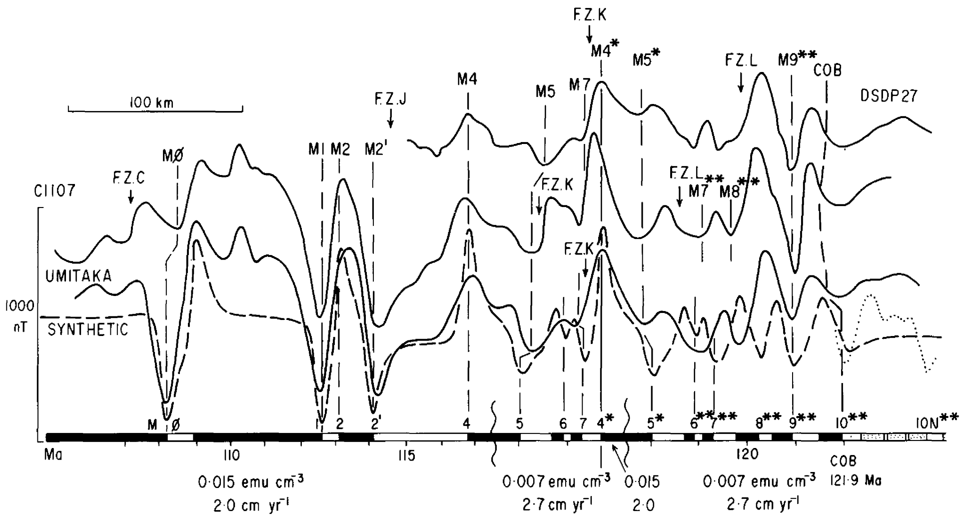


Fig. 7. Magnetic profiles of Leg 27 and C1107, located on Fig. 5, and *Umitaka* aligned on M9 across the segments between J and M, projected on 302°, and synthetic model (*broken line*) incorporating a repetition of M4 and M5 (*asterisked*) in segment KL, and M6 through M10 (*double asterisked*) in LM. COB at 121.9 Ma. Block model extended beyond 121.9 Ma by *dots*. Model parameters not shown in the figure are as in Fig. 4

is 117.1 Ma, immediately before M4. In the segment between fracture zones C and D (Fig. 4b), the COB anomaly is isolated as the western flank of a negative anomaly (M10) at a modelled age of 121.9 Ma, best seen on 17/70, with the smooth zone of the Exmouth Plateau beyond. On the other profiles, some smaller anomalies at the edge of the Exmouth Plateau are later modelled (Fig. 10) as due to dykes.

Southwest of the Cuvier Abyssal Plain: Wallaby Plateau, Quokka Rise, Zenith Plateau

The magnetic lineation in the Cuvier Abyssal Plain (Fig. 3) cannot be traced south of V3305. Fracture zone G2 marks a discontinuity in the regularity of magnetic anomalies, from the set of good anomalies exemplified by V3308-2 to the irregular anomalies of *Cook* mn, 17/48, 17/46, and *Cook* hg. The only link between the oceanic structure of the Cuvier Abyssal Plain and the Wallaby-Quokka region is the continuity of the Sonne Ridge as seen in seismic profiles (Figs. 3 and 4a), with its characteristic magnetic signature of M5′-A-M5 in V3305, *Cook* mn and 17/48. A possible link in the western part of the region is a positive magnetic anomaly on *Cook* mn, lk, ij and hg, tentatively identified as M2, flanked by M1 and M2′. The irregular magnetic anomalies of this region are interpreted in Figs. 3 and 4a as a degraded extension of the set of seafloor-spreading magnetic anomalies of the Cuvier Abyssal Plain, but a detailed magnetic survey would be required to establish the validity or not of this interpretation. Accordingly, the interpreted anomalies are distinguished in Figs. 3 and 4a from the established ones to the north. Later, in the discussion, we suggest a mode of spreading for the Wallaby-Quokka region like that in the area between the Reykjanes Ridge and the southern shelf of Iceland. The only possible COB anomaly is that on V3305 and 17/46, which cross at this point; a model age of 125 [128] Ma, as in the Cuvier Abyssal Plain, is indicated.

West of Perth

In the region northwest of Perth (Fig. 5), a broad segment between fracture zones L and P is defined by a set of sub-parallel anomalies that range from M0 through M9 (Fig. 6). Between latitude 31° and 28° S, parts of this set are offset progressively to the northwest to define three narrow spreading segments and a fourth, between I and H (the Zenith-Wallaby Fracture Zone), is postulated to account for the offset in the COB. South of P, which marks the northeast flank of the Naturaliste Plateau, a set of anomalies (M0 through M4) discovered by Markl (1978a), and possibly also M5, lie northwest of the Naturaliste Plateau; as noted by Markl (1978a), M4 in V3304-1 and -3 is perturbed by the topography of the plateau margin.

All these anomalies are aligned along M4 in Fig. 6 and are modelled with the same parameters as apply in the north. Except northwest of Naturaliste Plateau, where M5 is the oldest recognised anomaly, the anomaly set starts with M9 and the COB anomaly is isolated as a modified M10 at 121.5 [124.7] Ma in segment JK, 121.3 [124.3] Ma in KL and 122.5 [125.5] Ma in LP, the same age as in CD. By extrapolation, the COB anomaly in IJ is 125 [128] Ma. The strong parts of the interpretation are: 1. the near-parallelism of the anomalies along an azimuth of 032°, 2. the well-defined M0 through M4, and 3. a well-defined M9.

In segment IJ, M0 through M2′, hinted at in the profile collected on *Umitaka Maru* by Tomoda et al. (1968), are identified along the track of *Cook*. In JK, KL and LM, the tracks of C1107, DSDP Leg 27 and *Umitaka*, whose track (not shown) is close to that of the others, are interpreted as crossing the three segments (Fig. 7) as first mapped for JK by Larson et al. (1978). Within this segment, DSDP site 259 lies midway between M2′ and M4 with a predicted magnetic age of 115.5 [118.3] Ma. The oldest fossils recovered from this site were dated as late Neocomian by Morgan (1980, p. 63) and more precisely by Dr. R. Helby (1983, personal communication) as middle-late Valanginian to early-middle Hauterivian, which has a mid-point of 115 [117.8] Ma, thus marking a precise tie of the magnetic and biostratigraphic time-scales.

The tracks of the three profiles shown in Fig. 7 lie close to each other in compartment JK, and that of C1107 diverges slightly from the others in KL. The anomaly sequence in segment JK is interpreted as extending to M7 on Leg 27 and *Umitaka*, and to M5 on C1107, and in segment KL (anomalies asterisked in Fig. 7) from M4* to M5* on Leg 27 and C1107. M7** and M8** on C1107 and M9** on Leg 27 and C1107 are in segment LM. The short offset along L is expressed in these profiles by the much broader anomaly between M8** and M9**.

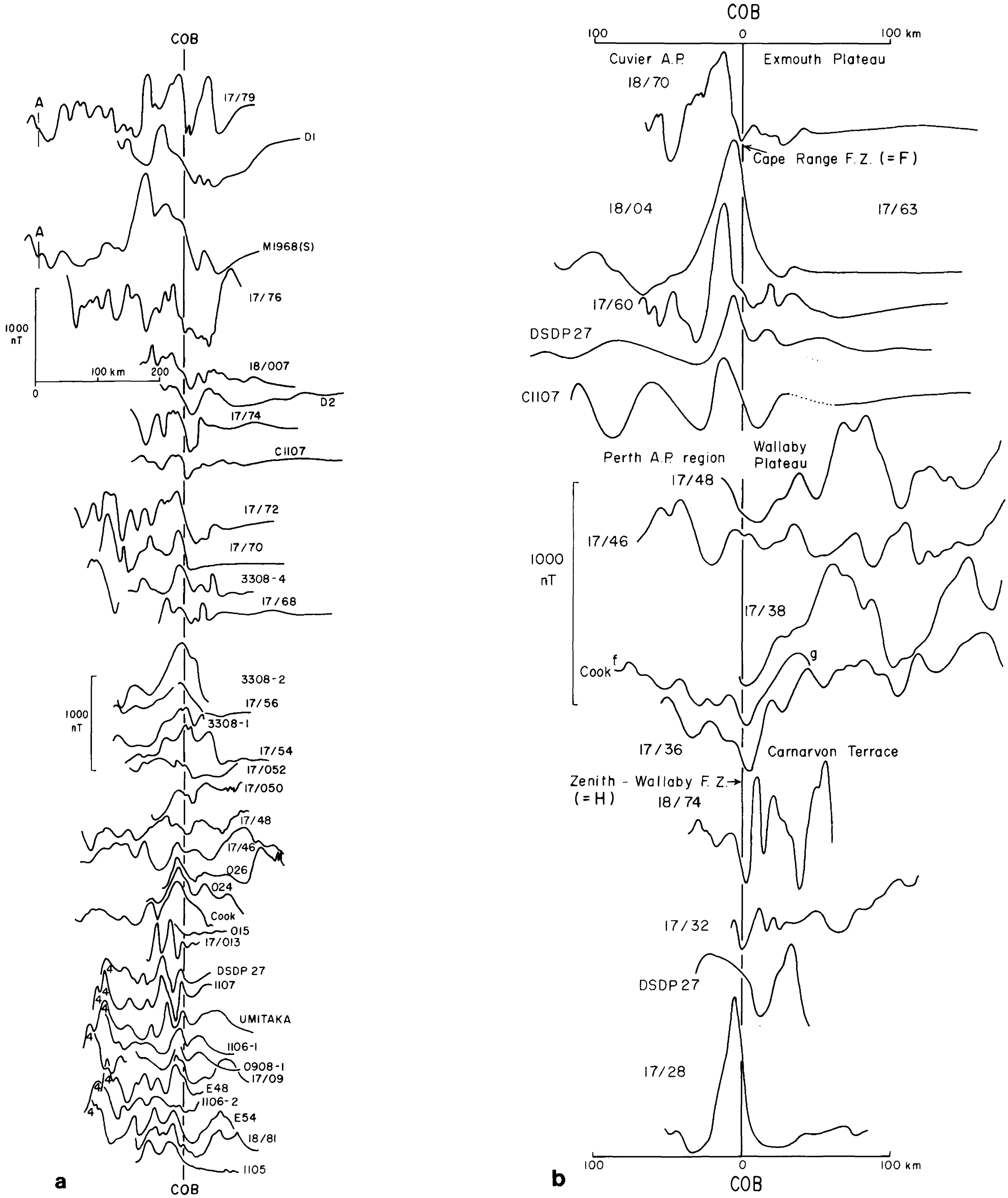
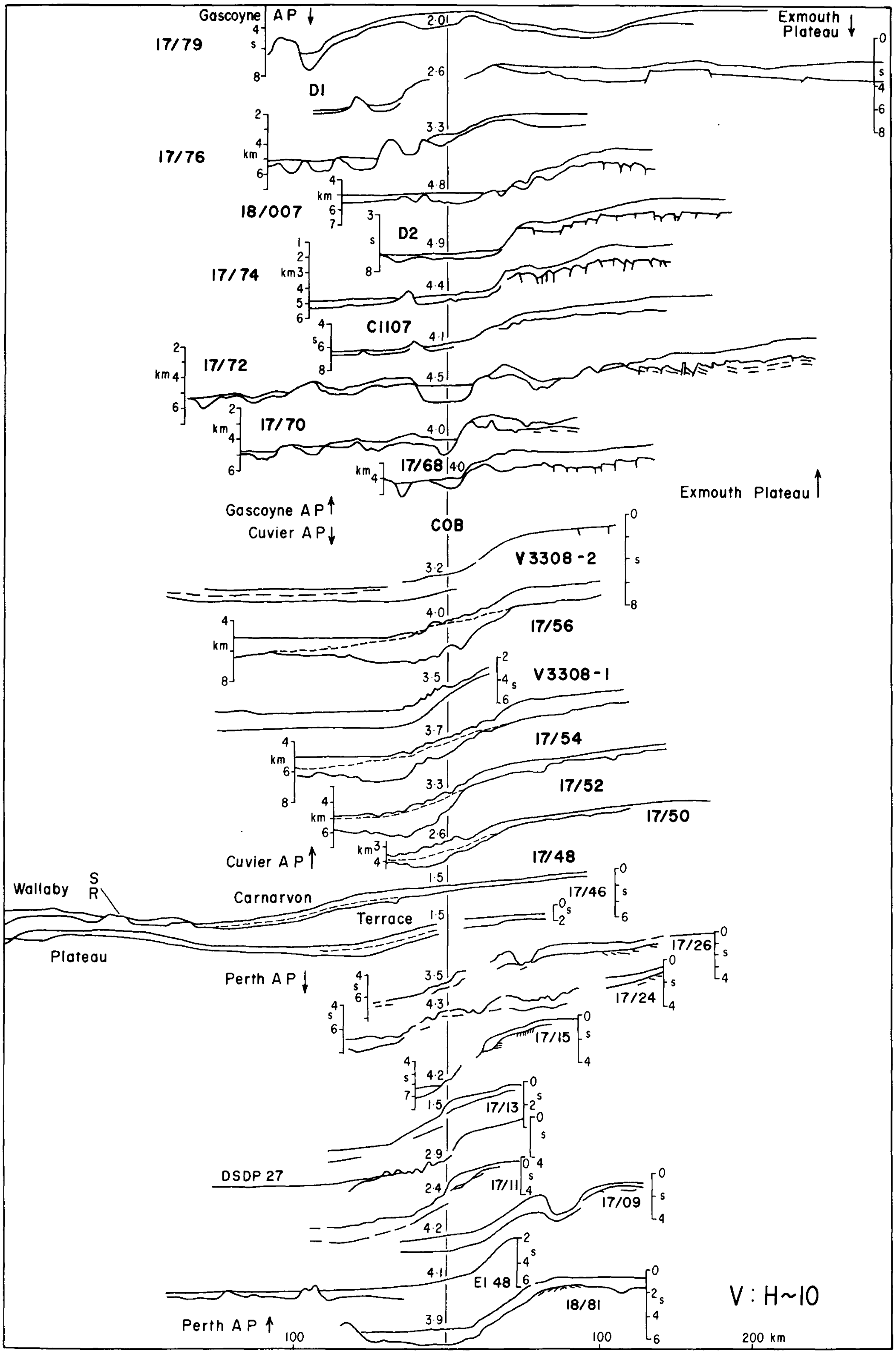


Fig. 8. **a** Magnetic profiles projected on 302° across the rifted margin from north to south and aligned along the COB. **b** Magnetic profiles projected on 032° across the transform-faulted margin from north (Cape Range Fracture Zone) to south (Zenith-Wallaby FZ) and aligned along the COB, except the northern part of the Zenith-Wallaby FZ (17/48 to 18/74) which we believe to be a boundary between normal and epilithic oceanic crust



a

Fig. 9. a Seismic profiles (reflection time in seconds), some converted to depth (km) sections, projected on 302° across the rifted margin from north to south and aligned along the COB, all corresponding to the magnetic profiles of Fig. 8a. Water depth at COB in km. *Lower line* is layer 2 on the oceanic side and the breakup unconformity on the continental side; *broken line* is boundary between clay below and carbonate above. **b** Seismic profiles (reflection time in seconds), projected on 032° across the transform-faulted margin from north (Cape Range FZ) to south (Zenith-Wallaby FZ). We believe the boundary between the Perth Abyssal Plain and the Wallaby Plateau to be that between normal and epilithic oceanic crust. Water depth at COB in km

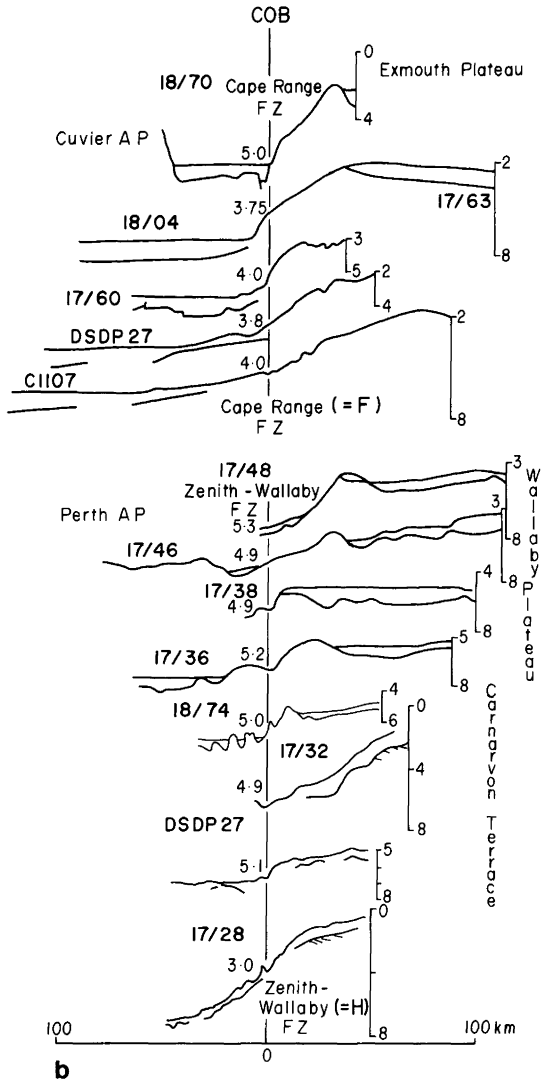


Fig. 9b

Magnetic anomaly at the COB

The COB anomalies, isolated from the seafloor-spreading anomalies, are aligned in Fig. 8a for profiles projected along an azimuth of 302°, i.e. normal to the isochrons and the trend of the rifted margin; and in Fig. 8b for profiles projected along 032°, i.e parallel to the isochrons, across the transform-faulted margins of the Cape Range Fracture Zone (F) and part of the Zenith-Wallaby Fracture Zone (H). Corresponding seismic profiles (Fig. 9a and b) show that, with the few exceptions discussed later, the COB anomaly lies at or within 40 km of the foot of the lower continental slope at water depths of 2.4–4.9 km (mean 3.75 km) for the rifted margin and of 3.0–5.3 km (mean 4.5 km) for the transform-faulted margin, corresponding to a change in seismic-reflection character from the faulted breakup unconformity on the continent to the smooth but hyperbolic oceanic layer 2 (Veevers and Cotterill, 1978).

From the few available profiles, Falvey (1972b) identified the magnetic anomaly at the lower slope as the COB anomaly and modelled it by assuming magnetic induction and remanence in both oceanic and continental "high susceptibility 'basement' at an intermediate crustal depth". Here, we follow the assumption of Talwani and Eldholm (1973) that the COB anomaly is due to the contrast between the remanently magnetized oceanic crust and the non-magnetic continental crust. The most distinctive magnetic anomaly across the COB of the rifted margin is in 17/70, a simple downslope that meets the smooth field of the Exmouth Plateau at a shallow magnetic trough. This anomaly is modelled (Fig. 10) as a normal remanently magnetized oceanic block (at M10) that terminates at the COB against the non-magnetic continent. The amplitude of 430 nT requires the oceanic block to have an intensity or thickness double that of the other blocks. The neighbouring profiles in segment CD (17/72, V3308-4, 17/68) have anomalies of similar shape except for two small peaks that rise above the smooth Exmouth Plateau flank. These peaks, in 17/68, are modelled (Fig. 10) by the same contrast between the oceanic block and the adjacent continental crust with, in addition, three dykes of reversed polarity and each 0.2 km wide in the basement of the outer Exmouth Plateau, following a general suggestion by Exon and Willcox (1980, p. 40). North and south of segment CD, the COB anomaly maintains the same shape on the southeast flank of a downward-sloping anomaly. As shown by the 35 complete COB profiles in Fig. 8a, the amplitude of the COB anomaly has a mean and mode of 300 nT. The model of the COB anomaly in 17/70, with an amplitude of 430 nT, represents those profiles with an amplitude greater than the mean and that in 17/68 represents those less than the mean.

Across the COB at the transform fault of the Cape Range Fracture Zone (F in Fig. 3), between the Cuvier Abyssal Plain and the southwest Exmouth Plateau, the magnetic anomaly (upper part of Fig. 8b) is a nearly symmetrical positive feature of variable width and amplitude, with the COB on the northeast-sloping flank. Across the Zenith-Wallaby Fracture Zone (lower part of Figs. 8b and 9b), the COB anomaly again corresponds to a down-sloping flank but with an irregular shape except in 17/28, which resembles the anomaly across the Cape Range Fracture Zone.

The COB anomaly across the Cape Range Fracture Zone is modelled along 18/04–17/63 (Fig. 10) by a two-dimensional magnetic body 10 km wide, extending from the surface to the base of the oceanic crust. The landward edge of the body lies along the transform fault, which marks the COB. This body also satisfies the FAA (Willcox, 1977). The COB magnetic anomaly across the Cape Range Fracture Zone is everywhere positive and the body must have been intruded after the Cuvier Abyssal Plain was generated and during an interval of normal polarity. If the body were simply a thick marginal phase of the normal and reverse polarized ocean floor, then it would have changed polarity along the Cape Range Fracture Zone to produce an alternation of positive and negative anomalies.

Talwani and Eldholm (1973) and Rabinowitz (1976) modelled the COB positive anomaly across the Agulhas Fracture Zone off South Africa as due to the unadorned edge of oceanic layer 2, but did so only by assigning it a high intensity (a susceptibility of 0.04 cgs units for magnetic induction; and substantially the same for remanent magnetization, according to Rabinowtz [1976]). This kind of interpretation, involving a high-intensity source, is not applicable to the Cuvier Abyssal Plain, whose floor has a modelled remanent intensity of 0.007 emu/cm^3 (Larson, 1977).

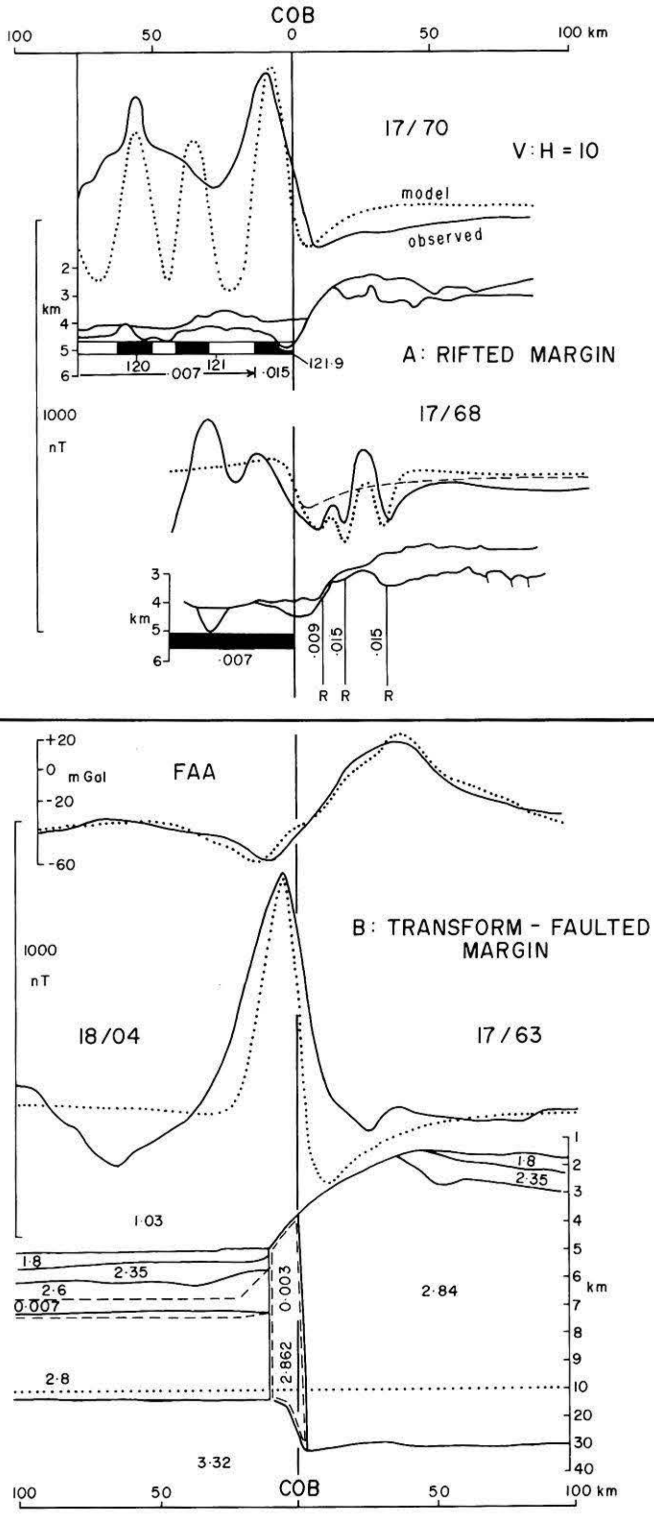


Fig. 10. *A*, models of the COB anomaly along the rifted margin on the western side of the Exmouth Plateau (17/70 and 17/68) projected on an azimuth of 302° and *B*, across the transform-faulted southern side (18/04-17/63) projected on an azimuth of 032°. The simple COB anomaly in 17/70 at the rifted margin is modelled (with the field parameters as given in Fig. 4) by modifying the magnetization of the oldest oceanic block of the seafloor-spreading sequence so that it has double the remanent-magnetization intensity of the others (as shown) or double the thickness. In 17/68, also at the rifted margin, a simple oceanic magnetic block of uniform intensity against non-magnetic continental crust produces the anomaly shown by the *dotted line* on the oceanic side and the *broken line* on the continental side; the addition of magnetic dykes of reversed polarity (R) near the edge of the continent simulates the complete set of anomalies. In 18/04-17/63, at the transform-faulted margin, a dense (2.862 t/m^3) vertical body at the COB is required to account for the free-air gravity anomaly (FAA) (Willcox, 1977; Roots et al. 1979; Exon and Willcox, 1980), implying a vertical body emplaced along the Cape Range FZ, interpreted from seismic diffractions at the foot of the slope (Exon and Willcox, 1980). Vertical exaggeration is x 10 above 10 km depth, x 1 below. Other densities from refraction velocities found by Larson et al. (1979). The magnetic anomaly is modelled by two bodies, outlined by *broken lines:* (1) part of oceanic layer 2 (density = 2.6 t/m^3, remanent-magnetization intensity = 0.007 emu/cm^3) and (2) a nearly vertical body (density = 2.862 t/m^3, intensity = 0.003 emu/cm^3). Other parameters as in Fig. 4. The width of the model anomaly is less than that observed, but is close to that of the other crossings of the Cape Range Fracture Zone

With the exception of the symmetrical positive anomaly in 17/28 (Fig. 8b), the magnetic anomaly across the Zenith-Wallaby Fracture Zone cannot be modelled as for the Cape Range Fracture Zone. Four crossings of the Zenith-Wallaby Fracture Zone – across the COB along the Carnarvon Terrace (18/74, 17/32) and across the boundary between the normal oceanic and thick (presumed epilithic) crust along the Wallaby Plateau (*Cook* fg, 17/36) – are marked by a negative magnetic anomaly, which implies an oceanic block of reversed polarity at the boundary. This is the only hint of a reversely polarized block along the COB of the western margin.

The dominantly, if not exclusively, normal polarity of the oldest oceanic block at the COB of the western margin is unexpected because the magnetic reversal sequence in the range of interest, from 120 to 130 Ma, contains an equal number of short (< 1 Ma) normal and reverse polarity intervals.

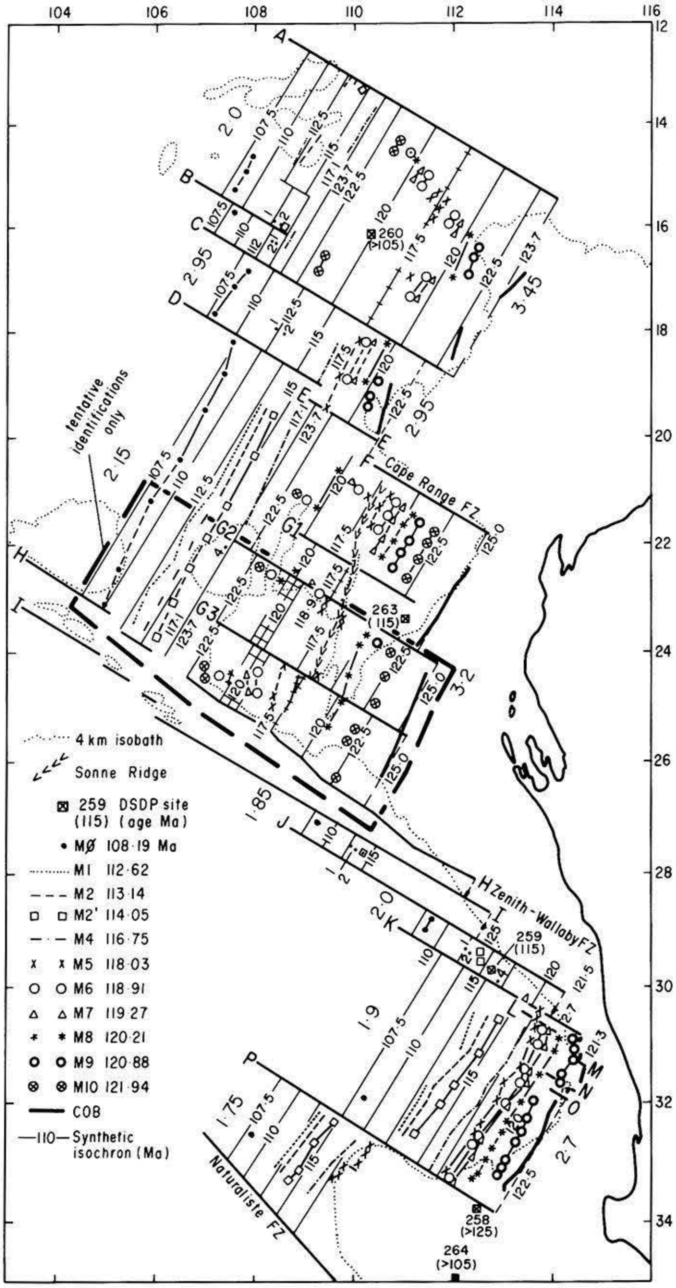


Fig. 11. Observed and inferred seafloor-spreading isochrons, including the COB anomaly, modelled by the motion of India from Australia relative to Australia for the interval 125 [128]–92.7 [95.01] Ma ago about a pole at 56.5°S, 2.7°W (Johnson and Veevers, 1984). Half-rates (cm/yr) of the first phase (up to 117.5 Ma ago) shown on east and of the second phase (after 117.5 Ma ago) on the west. *Cross-hatching* at 24° S, 108° E about the 120-Ma isochron indicates area of rapid spreading. The identification of seafloor-spreading magnetic anomalies in the region south of the Cuvier Abyssal Plain (Quokka Rise/Wallaby Plateau), enclosed by a *heavy broken line*, is tentative only

We have noted already that the COB anomaly lies at or within 40 km of the foot of the lower continental slope. The only exceptions are: a. across Platypus Spur, at the northwest tip of the Exmouth Plateau (Fig. 9a: 17/79, D1, 17/76) at depths of 2.0–3.3 km and at 85–45 km inboard of the foot of the lower slope; b. along the Carnarvon Terrace (Fig. 9a: 17/48, 17/46) very tentatively interpreted at a depth of 1.5 km; and c. at the upper slope northwest of Perth (Fig. 9a: 17/13), also at a depth of 1.5 km. Exon et al. (1982) suggest that the outer part of the Platypus Spur is a Neocomian epilith. Our recognition of the COB anomaly across the Platypus Spur confirms this view. We attribute the shallow COB along the Carnarvon Terrace to the same cause. The equally shallow COB northwest of Perth is due to the oblique intersection of the seafloor-spreading strike of 030° with the 330° trend of the continental slope, so that the COB along the northeast part of each short spreading segment is much shallower than elsewhere.

Summary of seafloor-spreading pattern

Figure 11 shows the seafloor-spreading isochrons observed from magnetic anomalies (and from the tentatively interpreted anomalies in the Wallaby-Quokka region, enclosed by a heavy broken line) and synthetic isochrons fitted to the pole of opening of India and Australia (56.5° S, 2.7° W), updated by Johnson and Veevers (1984) from an earlier determination by Johnson et al. (1980). All segments, except CD, have two sets of half-rates of spreading: fast (3.45–2.7 cm/yr or 3.136°/Ma–2.557°/Ma) between 125.0 [128.0] and 117.5 [120.4] Ma ago and slow (2.15–1.75 cm/yr or 1.965°/Ma–1.665°/Ma) between 117.5 [120.4] and 108.2 [110.9] Ma ago. Segment CD has a uniform rate of 2.95 cm/yr or 2.668°/Ma between 122.5 [125.5] and 108.2 [110.9] Ma ago. The length of a degree of longitude along a small circle about the rotation pole varies by a factor equal to the cosine of the latitude; this factor is cos 0° = 1.0 in segment AB (at the equator to the pole) and cos 16° = 0.96 in the segment between P and the Naturaliste Fracture Zone. The observed rates from north to south exceed this variation and are attributed to variable rates of spreading due to asymmetrical spreading.

The onset of spreading is indicated by the oldest synthetic isochron at the COB, which is 125.0 [128.0] Ma in segments FH and IJ, this age being confirmed by the age of the breakup unconformity near Perth (Veevers and Cotterill, 1978). Isochrons younger than 125 [128] Ma at the COB, as in the other segments, are taken as indicating ridge jumps to Australia (Johnson et al. 1980).

Between fracture zones A and C, and F and H, the change from fast to slow spreading at 117.5 [120.4] Ma was accompanied by (1) a ridge jump to India so that an abandoned ridge with symmetrical flanks was left on the Australian Plate and (2) a doubling of the remanent intensity.

Discussion

Comparison of Wallaby Plateau and Iceland

The Wallaby Plateau is a volcanic upgrowth of oceanic lithosphere (or an epilith), as suggested:

– by Veevers and Cotterill (1978) from its contrast with the Exmouth Plateau in seismic character and basement relief,

– by Larson et al. (1979) by an extrapolation of seafloor-spreading isochrons southwestward from the Cuvier Abyssal Plain ("Fig. 6b. Spreading continues... after a ridge jump occurred in the Cuvier Basin and the Wallaby Plateau forms synchronously as a large, Early Cretaceous volcanic outpouring"),

– by von Stackelberg et al. (1980) by sampling of seismic sequences.

On the eastern and southern Wallaby Plateau, and on the Sonne Ridge which extends northward into the Cuvier Abyssal Plain, the layered sequence [seen in processed seismic profiles to be at least 3000 m thick] beneath the main Neocomian unconformity consists of interbedded weathered tholeiitic and differentiated alkali basalts, tuffs, basalt breccias and thick volcaniclastic sandstones and conglomerates. A minimum mid-Creaceous age (K/Ar age: 89 m.y.) was determined for a somewhat altered basalt from the southern Wallaby Plateau. This suggests that intense volcanism and associated deposition of volcaniclastic debris flows formed the plateau, during or after the Neocomian breakup of the region.

Von Rad and Exon (1983) note further that the composition of the basalt supports an oceanic origin. This work countered the interpretation of Symonds and Cameron (1977) that the Wallaby Plateau has a basement of Palaeozoic rocks, implying a continental crustal structure, but did not rule out the possibility that the volcanic pile was a thick superstructure on continental crust. This possibility is now questioned by: (a) the continuity in seismic and magnetic profiles of the Sonne Ridge southward from the Cuvier Abyssal Plain along the eastern flank of the Wallaby Plateau; (b) the possible magnetic lineation of M1–M2–M2′ traced southward from the Cuvier Abyssal Plain into the trough between Quokka Rise and Zenith Plateau; and (c) the further interpretation from (a) and (b) of a reflected set of magnetic anomalies, as in the Cuvier Abyssal Plain, in the Wallaby-Quokka region which satisfies the geometrical constraints of spreading. The degraded shape of the anomalies compared with the regularly shaped anomalies in the Cuvier Abyssal Plain requires explanation.

A similar transition from clear to degraded seafloor-spreading magnetic anomalies is found from the normal oceanic crust of the Reykjanes Ridge and Kolbeinsey Ridge segments of the mid-Atlantic Ridge to the thick (Icelandic-type) oceanic crust of Iceland (Nunns et al. 1983). The aeromagnetic survey of the region by Serson et al. (1968) (who only showed the vertical component) – see Rutten (1975) for the total-field anomalies of this survey – has parameters similar to those of the marine survey of the Wallaby Plateau region (a line spacing of about 40 km and a separation of 3–5 km between the source and receiver) and affords a direct comparison with the Wallaby region. The present latitude of Iceland (65°) compares with the Early Cretaceous palaeolatitude of the Wallaby Plateau of 40°–50° (Embleton, 1984). Talwani et al. (1971) and Nunns et al. (1983) trace the prominent axial Reykjanes Ridge anomaly northeastward into a degraded anomaly along the axial rift zone of the Reykjanes Peninsula. Von Stackelberg et al. (1980) envisage the Early Cretaceous environment of the Wallaby Plateau as similar to that of Iceland, including shallow-water to subaerial extrusion of amygdaloidal basalt. Volcanism ceased with the jump of the spreading ridge westward and the plateau submerged below sea level. The volcaniclastic sediments were probably deposited either as sediment wedges that built out the volcanic island shelf or as deep marine deposits on the proto-abyssal plain. In this environmental setting, the transition from the northern part of Sonne Ridge progressively offset eastward into the Wallaby Plateau corresponds to that of the Reykjanes Ridge into Iceland. In the magnetic setting, the central anomaly of the northern Sonne Ridge (M5′-A-M5) is traceable southward into the Wallaby Plateau, as the central anomaly (Al) of the Reykjanes Ridge is traceable to the shelf of Iceland, with the central anomaly continuing northeastward into the neovolcanic zone of Iceland. According to Nunns et al. (1983), "In view of the many unusual features of the Icelandic spreading environment (such as multiple and shifting axes, laterally extensive lava flows, prevalent central volcanoes and modifications due to erosion and alteration) the absence [outside the neovolcanic zone] of persistent, identified linear anomalies is not surprising", and this is the probable explanation of the blurred anomalies of the Wallaby Plateau. The only other parts along the margin with inferred epilithic structure are the adjacent outer Carnarvon Terrace and the outer Platypus Spur. It will require further work to ascertain if these areas are examples of the thick oceanward-dipping layers described by Hinz (1981) and of the subaerial seafloor spreading of Mutter et al. (1982).

Thick oceanic layer at the COB

According to Roots et al. (1979), the oceanic crust in the Cuvier Abyssal Plain (and elsewhere) thickens from 6 or 7 km to 16 km at the COB. Some of the profiles in the Cuvier Abyssal Plain and elsewhere on the western margin contain a COB anomaly with an amplitude as much as double that of the adjacent seafloor-spreading magnetic anomalies, suggesting double the intensity or thickness of the magnetic source layer. If, on the one hand, the magnetic source layer includes the entire oceanic crust then such a thick crust at the COB would produce the large observed anomaly. If, on the other hand, only the uppermost 500 m or so of the oceanic crust are significantly magnetic, then the bigger anomaly would be attributable to a surface layer with an increased intensity. COB anomalies of smaller amplitude, common in the region northwest of Perth, suggest thin or weakly magnetized crust.

Crustal structure of Zenith and Naturaliste Plateaus

Magnetic lineations were not found over either of these plateaus, so their crustal structure, whether oceanic or continental, remains unknown. From a study of dredged material, Coleman et al. (1982) view the Naturaliste Plateau as probably oceanic, but conclusive evidence is lacking, as it is from the Zenith Plateau.

Acknowledgements. We thank: Dr. I.S.F. Jones, R.A.N. Research Laboratory, for the opportunity of taking part in the R.A.N. Research Laboratory cruise on HMAS *Cook*; Cmdr P. Cooke-Russell, captain, and the crew of *Cook* for unstinting cooperation; our colleague Mr K.S. Gibbons for help in collecting the geophysical data; the R.A.N. Hydrographic Office for sounding sheets; the N.S.W. Geological Survey for the use of their magnetometer; Mr R. Whitworth and Dr D.A. Falvey of the Bureau of Mineral Resources for a copy of the AGRF routine; Dr D.A. Falvey, Mr T.S. Powell and Dr R.G. Markl for a copy of their theses; and Dr H.A. Roeser, Dr D.K. Smythe and Mr P.A. Symonds for critical reviews of the manuscript. This work was supported by a grant from the Funding Advisory Panel of the Australian Marine Sciences and Technologies Advisory Committee and Marine Sciences and Technologies Grants Scheme of the Department of Science and Technology.

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Received May 14, 1984; revised version November 12, 1984
Accepted November 26, 1984