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The nature of the Wallaby (Cuvier) Plateau and other igneous provinces of the west Australian margin

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Seismic reflection data and dredged rocks confirm that the Wallaby (Cuvier) Plateau off western Australia is underlain by a volcanic basement consisting of complex packages of dipping reflectors similar to those of other large, oceanic, igneous provinces (LIPs) of the eastern Indian Ocean, such as the Kerguelen Plateau. Wedges of seaward-dipping reflectors underlie the Wallaby Saddle, which separates the plateau from the adjacent upper continental slope. These are interpreted to be interbedded subaerial lava flows and volcaniclastics similar to those obtained by ODP drilling of like features beneath the margins of the North Atlantic Ocean. Volcanic rocks dredged from the Wallaby Plateau are altered transitional tholeiitic basalts with immobile element contents and ratios similar to basalts from the Naturaliste Plateau, eastern Broken Ridge, and the Bunbury Basalt of southern western Australia. Basalts from all of these regions show compositional features indicative of the involvement of sub-continental lithospheric mantle in their petrogenesis, and appear to have been erupted between 120 and 100 Ma as a result of an anomalous post-breakup heating event. A consistent explanation for the origin of the Wallaby Plateau, and similar large, post-breakup volcanic features (LIPs) of the eastern Indian Ocean, is that they are the product of a single, large hotspot (Kerguelen hotspot or mantle plume). However, for the Wallaby Plateau and its associated Sonne and Sonja Ridges there is another possible origin, that they are the products of convective partial melting following a ridge crest jump in the Cuvier Abyssal Plain. The distribution of other volcanic features of the western Australian margin can be readily explained by magmatism associated with dynamic rift processes rather than proximity to a plume.

Introduction

The Wallaby (Cuvier) Plateau[3] is one of several marginal plateaux that lie off the continental margin of western Australia (Fig. 1). It is separated from the western Australian continental shelf by the Wallaby Saddle (Fig. 2). The plateau ranges in water depth from approximately 2100 m at its crest on its northern part to about 4000 m at the base of the bounding slopes (Fig. 3), and has an areal extent within the 4000 m isobath of ~70 000 km^2.

The origin of the feature has been the subject of debate for many years. Prior to 1978, the plateau was regarded as a thinned continental fragment, similar to other marginal plateaux (e.g. Exmouth and Scott Plateaux) off the west Australian coast (Heezen & Tharp, 1965, 1966; Laughton et al., 1970; Symonds & Cameron, 1977). Subsequently, Veevers & Cotterill (1978) suggested that it is a thick accumulation of oceanic volcanics ('epilith') formed on oceanic crust after the start of spreading in the Cuvier Abyssal Plain area in the Early Cretaceous (Larson et al., 1979; Fullerton et al., 1989). The oceanic hypothesis for the plateau's origin was supported by dredging of a 1000 m thick sequence by the R/V *Sonne* on its eastern and southern flanks in 1979, which recovered lavas and volcaniclastic sediments apparently from a layered basement sequence beneath the main Neocomian unconformity (von Stackelberg et al., 1980). However, as noted by von Stackelberg et al. (op. cit.), volcanics from the plateau margins may simply represent marginal volcanism rather than reflecting the true nature (continental or oceanic) of the central part of the feature.

In this paper, we present previously unpublished seismic reflection profiles, as well as petrological–geochemical analyses of samples collected in 1990 during an AGSO program focussed on the plateau's central western flank. This latter work was aimed at sampling dipping basement reflectors in an area away from the plateau's 'volcanic' margins (Colwell et al., 1990). The results obtained (including the recovery of basalts, and basaltic conglomerates and sandstones) support a volcanic origin for the core of the feature and provide, for the first time, evidence of a genetic link to other large, oceanic, igneous provinces (LIPs; see Coffin & Eldholm, 1991) of the eastern Indian Ocean.

Regional setting

The physiography of the Wallaby Plateau was first systematically described by Falvey & Veevers (1974). The plateau consists of two main bathymetric highs. A large southeastern high, which was called the Wallaby Plateau by Veevers et al. (1985), forms the main part of the feature and contains two closures of the 2500 m isobath (Fig. 3). The largest closure occurs in the north and shallows to about 2100 m water depth. A smaller bathymetric high occurs in the northwest and was named the Quokka Rise by Veevers et al. (1985). The plateau is bounded in the north by the Cuvier Abyssal Plain (Basin), and to the south by the Perth Abyssal Plain. Its southern margin is formed by the steep, 2000 m high, NW-trending scarp of the Wallaby–Zenith Fracture Zone (Fig. 3). In the west, the Wallaby Plateau is separated from the Zenith Seamount (Plateau) (Fig. 1) by a 100–150 km wide, NNE-trending bathymetric trough. In the east, it is separated from the upper continental slope of the Australian margin (the Carnarvon Terrace) by the NNE-trending Wallaby Saddle (Figs 2 and 3).

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3 Although the term Wallaby Plateau is widely used in the Australian geoscience literature, on many bathymetric charts and on the AAPG tectonic map series the feature is referred to as the Cuvier Plateau. To add further to the confusion, on the AAPG maps the name Wallaby Plateau is applied to a feature farther to the west referred to by other workers (e.g. Tomoda et al., 1968; Veevers & Cotterill, 1978) as the Zenith Seamount and later by Veevers et al., (1985) as the Zenith Plateau. Part of this confusion stems from the original application of the term Wallaby Plateau(s) by Heezen & Tharp (1965, 1966) to a composite feature here taken to consist of the Zenith Plateau in the west and the Wallaby Plateau (the subject of this paper) in the east. Veevers et al. (1985) further subdivided the Wallaby Plateau into two features — a northwestern high that they called the Quokka Rise (Fig. 3) and a larger southwestern high, which they defined as the Wallaby Plateau. In this paper, we use the term Wallaby Plateau in its more general sense as referring to both of these features, unless otherwise specified.

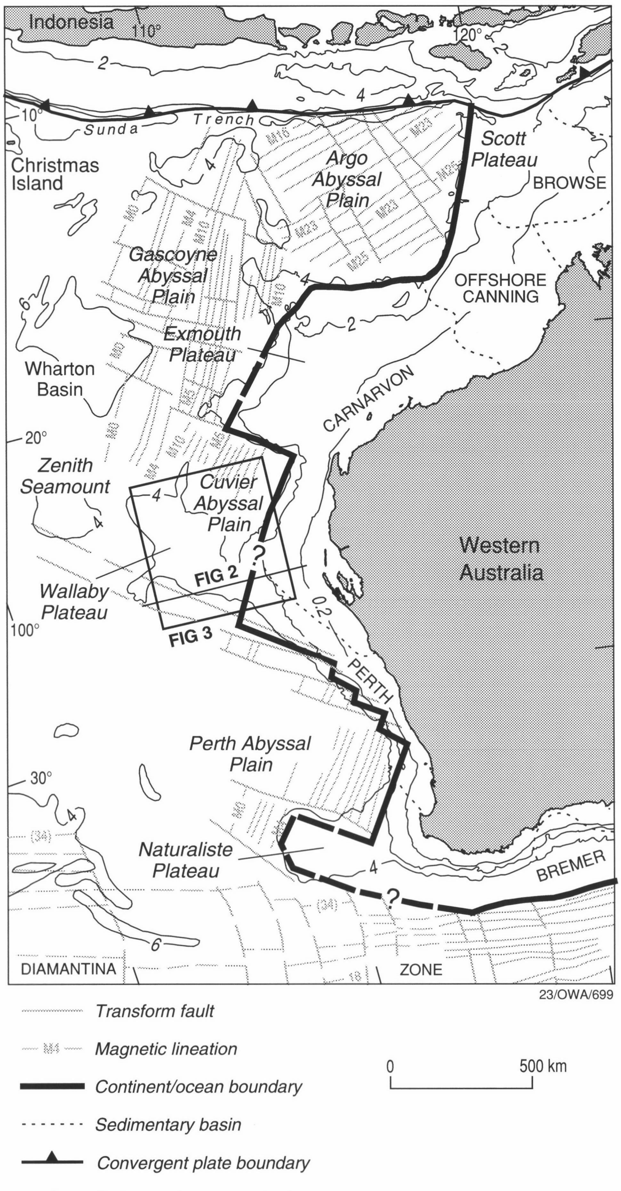


Figure 1. General location of the Wallaby Plateau and other features off the western Australian margin (after Falvey et al., 1990).

Two ridges trend NNE into the Cuvier Abyssal Plain from the northern margin of the Wallaby Plateau (Figs 1 and 3). The eastern ridge — the Sonne Ridge — is composed of several highs, which shallow to about 3500 m, and is generally considered to be an abandoned spreading ridge formed at about magnetic anomaly M4–5 time (Veevers et al., 1985; 126 Ma using reversal time scale of Kent & Gradstein, 1985). The western ridge — the Sonja Ridge — is composed of several highs which shallow to 2700 m, and is associated with anomaly M8–9 near the western edge of the early seafloor spreading episode (M10–M4) that formed the eastern Cuvier Abyssal Plain.

The stratigraphy and depositional history of the Wallaby Plateau/Cuvier Abyssal Plain area are poorly known and are based on one Deep Sea Drilling Project (DSDP) hole (Site 263), one petroleum exploration well just to the south on the adjacent continental shelf (Pendock ID-1), and scattered dredge and core samples (Fig. 3). Site 263 (Veevers et al., 1974) bottomed 100–200 m above the oceanic basement of the Cuvier Abyssal Plain in possibly allochthonous Early Cretaceous sediment (Veevers & Cotterill, 1978). Pendock ID-1 intersected mid-Cretaceous sedimentary rocks unconformably overlying Carboniferous to Devonian sedimentary rocks (Genoa Oil NL, 1970). Dredging undertaken by the German Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in 1979 in three areas on the southern and eastern flanks of the plateau (Fig. 3) recovered volcanic rocks and volcaniclastic sediments including variably altered tholeiitic basalts, tuffs, basalt breccias, and volcaniclastic sandstones and breccias (von Stackelberg et al., 1980; Table 1). A minimum Late Cretaceous K/Ar age of 89 Ma was obtained on a sample of altered basalt from site 170KD on the southern margin of the plateau. Sampling on the northern Sonne Ridge yielded basalt, volcanic breccia and tuffs (von Stackelberg et al., op. cit.).

Seismic reflection data in the region are sparse (Fig. 3). Two major unconformities have been identified throughout the region — one, 'C', corresponding to the base of the Santonian Toolonga Calcilutite, and the other, 'D', thought initially to be an intra-Neocomian unconformity separating Aptian–Cenomanian Winning Group sediments from Palaeozoic rocks (Symonds & Cameron, 1977; Fig. 2). The 'D' unconformity is now known to be the top of volcanic basement (von Stackelberg et al., 1980; this paper).

A NE-trending magnetic anomaly pattern encompassing anomalies M10–M5 has been identified in the Cuvier and adjacent Gascoyne Abyssal Plains (Larson, 1977; Larson et al., 1979; Johnson et al., 1980; Veevers et al., 1985; Fullerton et al., 1989). Breakup in the region began at M10 (about 130 Ma; Fullerton et al., 1989) or perhaps M11 (about 132 Ma; Veevers & Li, 1991), in the Valanginian, and a little later at anomaly M9 (about 129 Ma) in the Perth Abyssal Plain to the south (Veevers et al., 1991). Breakup is thought to be contemporaneous across the Cape Range Fracture Zone that separates the Cuvier and Gascoyne Abyssal Plains, and seafloor spreading is interpreted to be continuous to anomaly M4–5 (about 127 Ma — Hauterivian), when a westward jump in the Cuvier and northern Gascoyne Abyssal Plains left behind abandoned spreading ridges and associated symmetric anomaly patterns in these areas (Fig. 1).

New insights into the extensional and magmatic development of the region have arisen from the interpretation of two-ship seismic reflection and refraction data across the western and southern margins of the Exmouth Plateau, and the Cuvier margin of the Carnarvon Terrace. Mutter et al. (1989) examined the western rifted margin of the Exmouth Plateau and suggested that rifting occurred over a prolonged period and was initially dominated by detachment faulting, that passed laterally and temporally into an outer 100 km wide zone of pure shear deformation characterised by high-angle normal faults and magmatic underplating. Lorenzo et al. (1991) presented results for the Exmouth Plateau's southern transform margin indicating that the final rupture was associated with fault-block rotation and mafic intrusion. Significant underplating of the margin occurred only during the drift phase, and extended laterally to form a thickened oceanic layer 3 beneath the northern margin of the Cuvier Abyssal Plain. Hopper et al. (1992) interpreted a seaward-dipping reflector sequence beneath the lower slope of the Cuvier margin on a single deep seismic line, suggesting that this margin is a so-called "volcanic rifted margin". Veevers

TABLE 1. Details of 1979 *Sonne* SO-08 Wallaby Plateau Dredge Hauls (after von Stackelberg et al., 1980).

Dredge	*Position*		*Water Depth*	*Recovery*	*Lithology*
	S	*E*	*(m)*	*(kg)*	
159KD	24°23.5′ 24°22.8′	109°43.1′ 109°41.8′	4470–4130	100	C. gr. volc. sst. with clay matrix and volc. & rare glauc. phosph. clasts
161KD	24°24.0′ 24°23.9′	109°45.0′ 109°44.3′	4470–4230	2	C. gr. volc. sst. with clay matrix, weathered and Mn crusted
165KD	24°23.7′ 24°23.7′	109°42.4′ 109°44.0′	4415–4240	5	Pebbly volc. sst., clasts mainly alt. glass; Mn polynodules
167KD	25°39.0′ 25°35.4′	108°36.5′ 108°35.1′	5340–4750	2	Pink-grey br. ?volc. clayst.; grey f.-c. vitric-lithic volc. breccia & qtz-rich silty tuff with glassy matrix; silicified volc. breccia; pale br. v.f. basalt or tuff; Mn polynodules
168KD	25°34.9′ 25°33.4′	108°34.3′ 108°35.0′	5100–4050	200	Alt. ± amyg. basalt; volc. siltst.; fissile f. tuff; volc. clayst.
170KD	25°31.6′ 25°31.0′	108°31.9′ 108°32.4′	4620–3970	120	Tholeitic basalt; basaltic breccia; volcanogenic mudst.; v.c. poorly sorted volc. sst.; volc. breccia; Mn polynodule
173KD	25°57.8′ 25°55.3′	109°05.8′ 109°04.4′	4980–3885	0.2	Reddish br. ferrug. (?rad.) vitreous qtz chert; highly altered tuff-volc. clayst.

et al. (1985) previously inferred a volcanic, 'epilithic' origin for this margin on the basis of the unusually shallow water depth of the magnetically defined continent/ocean boundary. Hopper et al. (op. cit.) suggested that rapid rifting in the Cuvier area resulted in the limited development of extensional structures and a larger volume of magma at the initiation of sea-floor spreading, and thus the initial emplacement of thicker oceanic crust.

The marked difference in the style of margin development between the Exmouth Plateau and Cuvier margins reflects differences in the rifting and magmatic history, and has important implications for tectonic evolution of the Exmouth–Cuvier–Wallaby region.

Seismic character of the Wallaby Plateau and Saddle

The one single-channel seismic line recorded by *Glomar Challenger* across the plateau in 1972 (Fig. 3) showed a number of thin, transparent-to-weakly-bedded sequences overlying 'acoustic basement' (Veevers & Heirtzler, 1974). Using the higher-quality data recorded by the AGSO Continental Margins Survey and Shell Petrel's multichannel-systems, Symonds & Cameron (1977) described variations in seismic character beneath the main Neocomian 'breakup' (D) unconformity, i.e. within the previously defined 'acoustic basement', which they ascribed to folding and faulting of Palaeozoic rocks, similar to the situation underlying the adjacent Carnarvon Terrace (Fig. 2). They also described a regional, Late Cretaceous 'C' unconformity in the overlying sedimentary sequence.

A re-examination of the seismic data reveals considerable variation in the seismic character beneath the main 'D' unconformity. Beneath much of the southern and central Wallaby Plateau it consists of sets of dipping, commonly diverging reflectors (see Figs 3–6). Individual reflectors are commonly over ten kilometres in length. In places, the dipping reflector packages are clearly offset by faulting (e.g. Figs 4A and 5). In other areas, the packages appear to splay out in different directions from an area of acoustic basement, or dip towards the centre of a 'basin' (Figs 3 and 4). These features are very similar to dipping reflectors seen within the basement complexes of large, oceanic, hotspot-related volcanic buildups such as the Kerguelen and Ontong Java Plateaux (Rotstein et al., 1990; Coffin et al., 1990; Hagen et al., 1993; Fig. 7). They also appear similar to features on Iceland, where the complex dipping sequences have been related to frequent shifts (jumps)

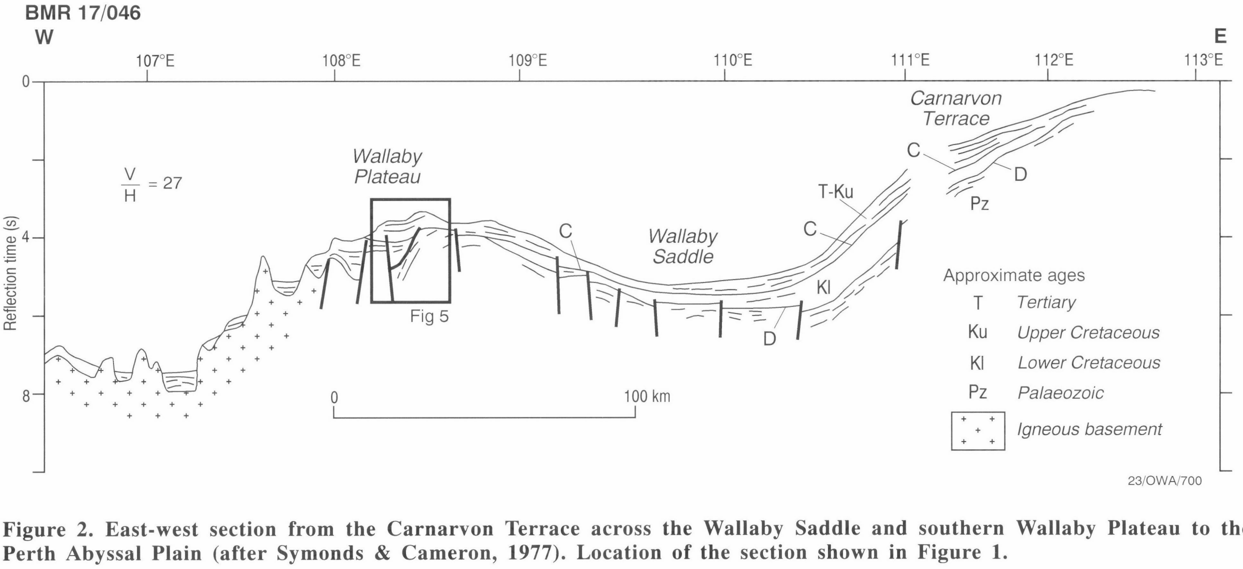


Figure 2. East-west section from the Carnarvon Terrace across the Wallaby Saddle and southern Wallaby Plateau to the Perth Abyssal Plain (after Symonds & Cameron, 1977). Location of the section shown in Figure 1.

of the active volcanic zone (Helgason, 1984). Drilling of basement beneath the Kerguelen and Ontong Java Plateaux as part of the Ocean Drilling Program (ODP) has recovered interbedded basalt flows and volcaniclastic sediments (Barron et al., 1989; Schlich et al., 1989; Kroenke et al., 1991). In the case of the Kerguelen Plateau, individual

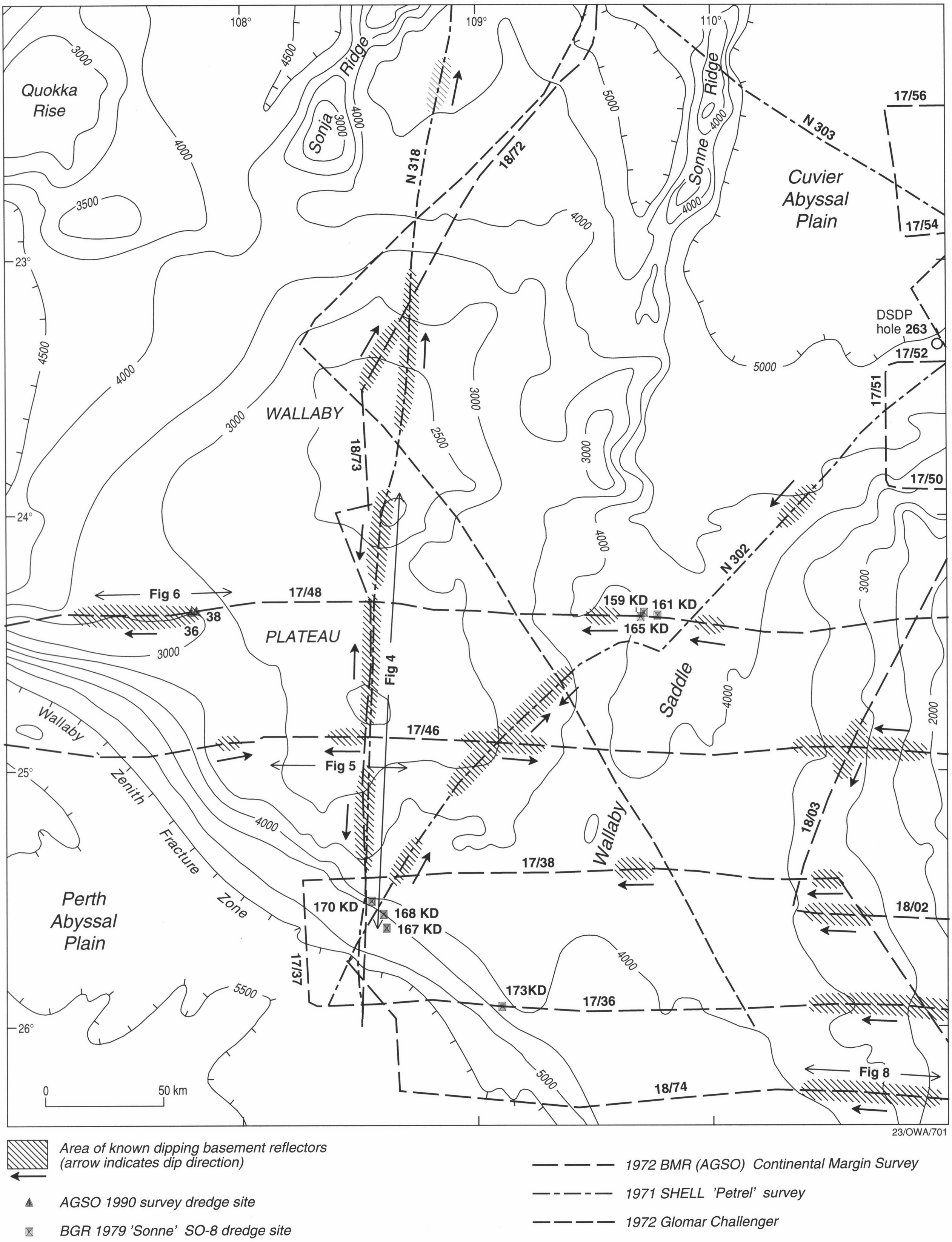


Figure 3. Bathymetric map of the Wallaby Plateau (after Jongsma et al., 1990, and GEBCO data) showing the location of seismic lines, dredge sites, DSDP drill Site 263, and areas of dipping, basement reflectors. Location of the map shown in Figure 1.

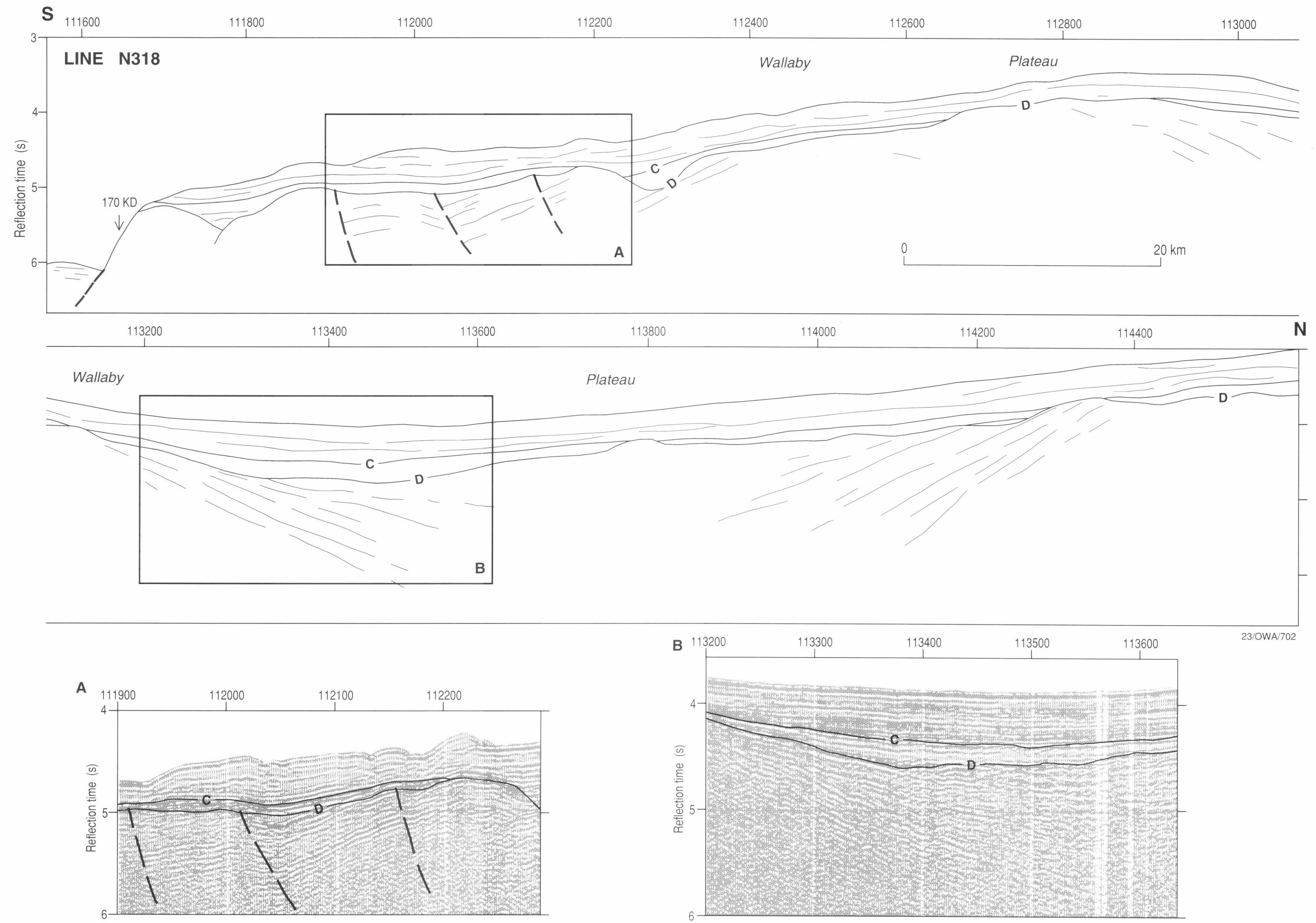


Figure 4. Line drawing of part of Shell *Petrel* Line N318 across the Wallaby Plateau showing dipping reflectors below the major, top basement, D unconformity. Note the switch in dip directions and the faulting affecting the dipping events. Inserts show parts of the single-channel seismic records. Location of the figure shown in Figure 3.

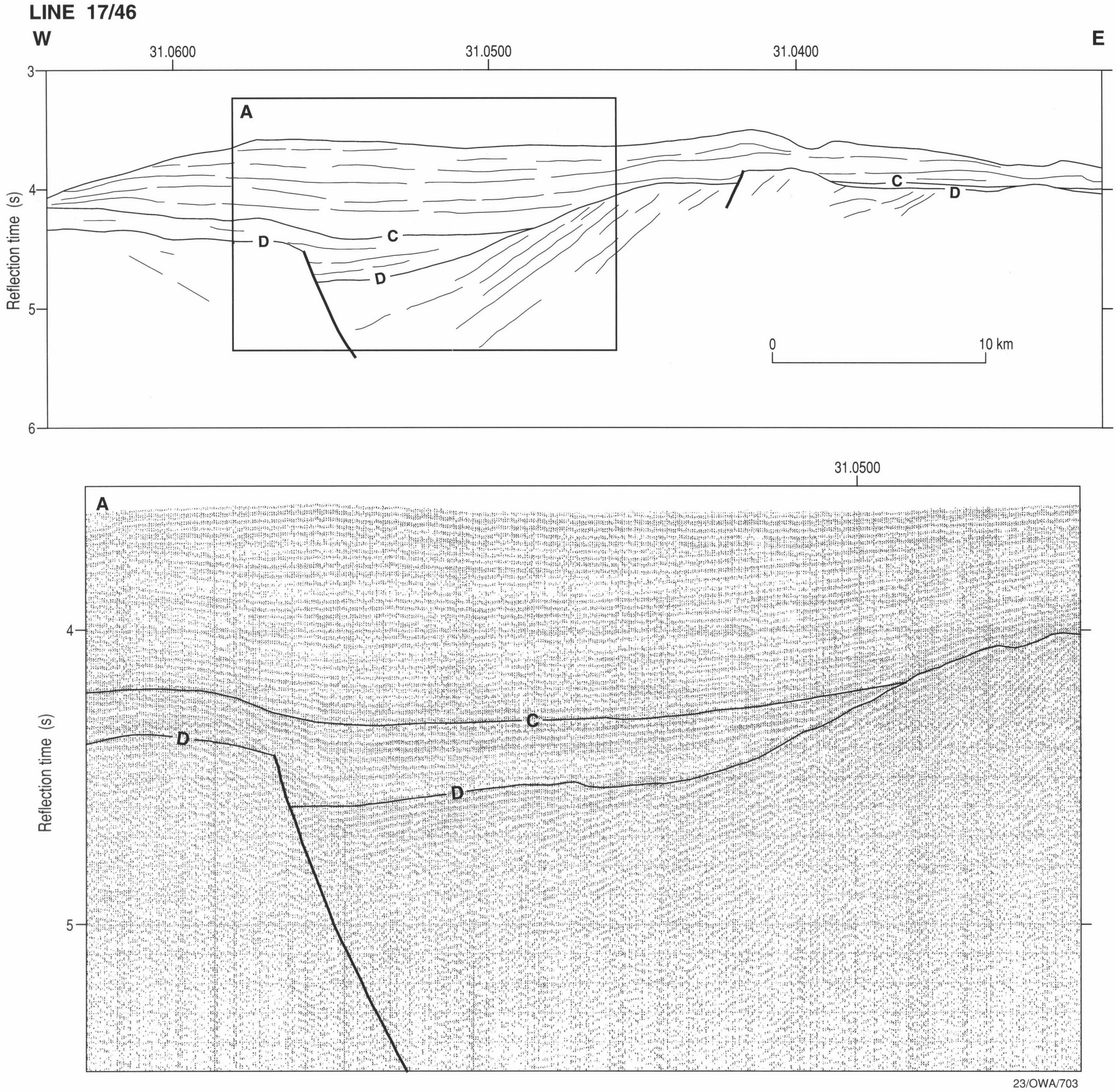


Figure 5. Line drawing of part of AGSO Line 17/46 from the southern Wallaby Plateau showing basement reflectors dipping west into a major fault. Insert shows part of the single-channel monitor record. To the west of the fault, basement displays little in the way of internal layering. Location of the figure shown in Figure 3.

basalt flows have a maximum thickness of several metres and commonly show evidence of subaerial eruption. At three of the Kerguelen Plateau 'basement' sites, isotopic data on basalts provide some evidence of continental lithospheric mantle involvement, whereas at a fourth, on the southernmost part of the plateau, lead isotope data strongly suggest contamination from underlying attenuated continental crust (Alibert, 1991; Storey et al., 1992). Geochemically, the Kerguelen Plateau lavas are transitional between mid-ocean ridge basalt (MORB) and ocean island (Kerguelen–Heard hotspot) basalt, whereas the Ontong Java lavas are high-degree tholeiitic melts similar to those occurring today around Iceland (Storey et al., 1992; Mahoney et al., 1993).

Wedges of seaward-dipping reflectors are common beneath eastern portion of the Wallaby Saddle (Figs 3 and 8). These are similar to those described from beneath several of the world's continental margins by Hinz (1981) and from beneath the outer Vøring Plateau off Norway by Talwani et al. (1981) and Mutter et al. (1982). Where drilled, for example during DSDP Leg 81 on the Rockall Plateau and ODP Leg 104 on the Vøring Plateau, such seaward-dipping complexes consist of subaerially erupted basalt flows and thin interbedded sediment layers (Roberts et al., 1984; Eldholm et al., 1987).

Dredge results

The 1990 AGSO geological program on the central west part of the plateau set out to sample the only known exposure of dipping basement reflectors within the plateau itself, i.e. not on its margins. Two dredge hauls were taken on an east-facing escarpment in 3120–2850 m of water using a chain-bag dredge (Figs 3 and 6; Colwell et al., 1990). Major rock types recovered were altered basaltic lavas, and basaltic conglomerates and sandstones (Table 2). The basaltic sediments are generally poorly sorted and contain rounded clasts up to 2 cm across. The petrology of the dredged rocks is discussed in detail in the Appendix. All samples are strongly altered. Consequently, geochemical analyses have been restricted to the two least-altered samples: samples 36/3 and 38/1 (Table 3). Sample 36/3 is an altered, trachytic-textured, sparsely plagioclase-phyric evolved basaltic to trachyandesitic lava, and sample 38/1 is an altered olivine+augite+plagioclase-phyric basaltic lava.

The intense seafloor alteration of the samples analysed is expressed compositionally by their very high loss on ignition values (around 8.5%). However, with due caution, several important conclusions can be drawn about the affinities and correlations of these lavas. For sample 36/3, despite its broadly basaltic levels of CaO (9%), Ni (98 ppm) and Cr (144 ppm), and its basaltic Ti/Zr (92) value, its SiO_2 content is 41.5%, and MgO is reduced to only 1.07%, whereas Fe_2O_3, P_2O_5 and Y contents are exceptionally high (20.7%, 2.35% and 75 ppm, respectively). This implies extensive depletion of MgO and SiO_2 from the abundant groundmass glass in this sparsely plagioclase-phyric lava, and addition of Fe_2O_3, P_2O_5, and Y. Identical compositional features are recorded in strongly altered basaltic lavas dredged from the Naturaliste Plateau (e.g. sample 12/3 of Coleman et al., 1982). The latter authors showed that the high P_2O_5 levels reside in altered groundmass glass, and the enhanced Y abundances are

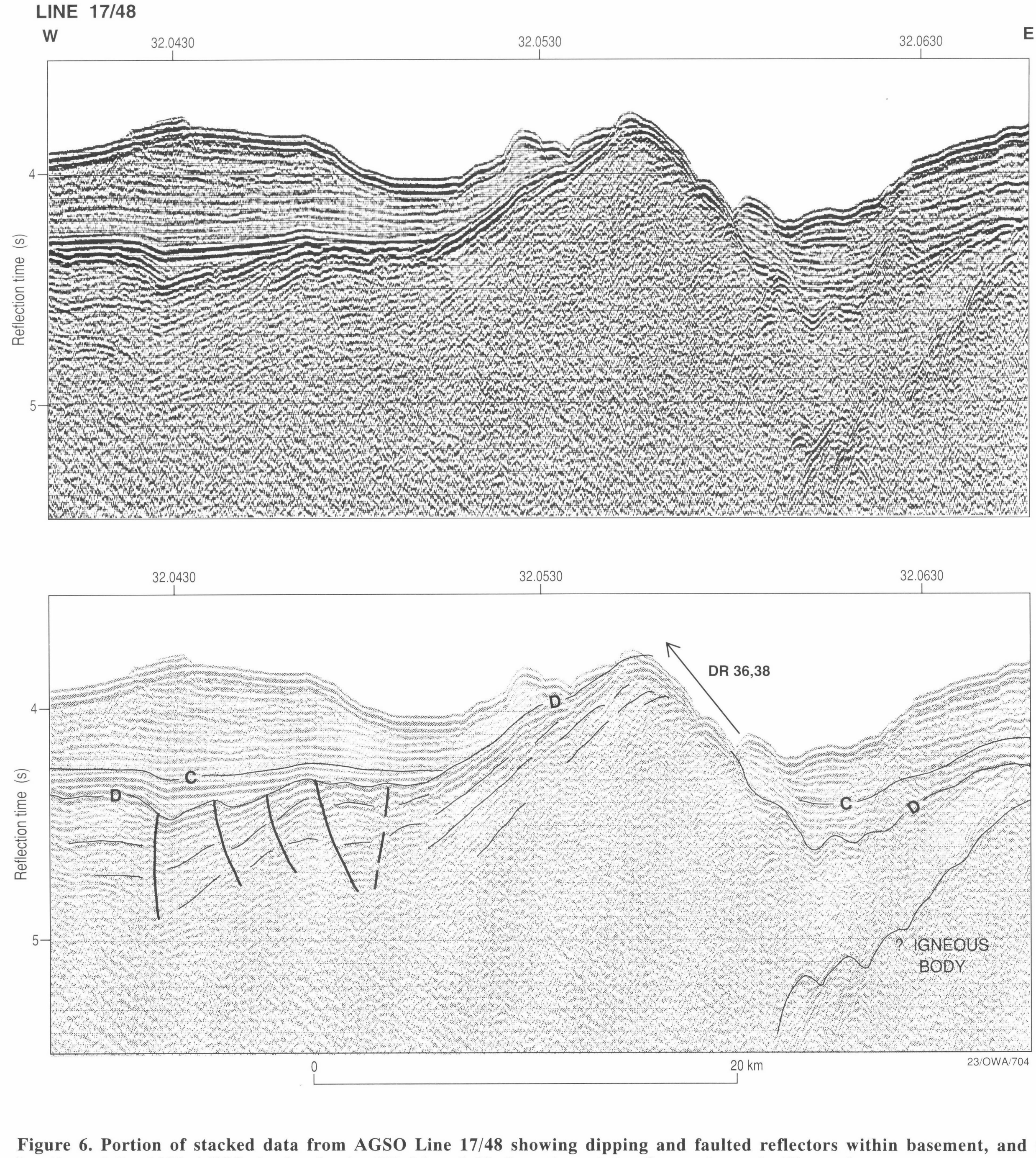


Figure 6. Portion of stacked data from AGSO Line 17/48 showing dipping and faulted reflectors within basement, and the location of the 1990 AGSO dredge hauls, DR 36 and 38. Location of the figure shown in Figure 3.

TABLE 2. Details of AGSO Survey 96 Dredge Hauls (after Colwell et al., 1990).

Dredge	*Position* S	E	*Water Depth* (m)	*Recovery* (kg)	*Lithology*
DR36	24°21.81′ 24°22.13′	107°49.7′ 107°46.85′	3120–2850	30	(1)Basaltic conglomerate/sst.-mod. yellow. br.,poorly sorted, most clasts well rounded (2)Mn crusts; (3)trachyandesite/basalt- dk.yellow. altered, (4)?amygdaloidal basalt- mod. br., mod. altered.
DR38	24°21.9′ 24°21.6′	107°49.6′ 107°49.3′	3120–2980	5	(1)Basaltic conglomerate- dk. yell. orange-lt. br., bimodal, clasts subround, mod. consol.; (2)basalt- dk. yell. orange-grey, altered.

also probably located in this altered glass. They suggested that the ultimate source of the "excess" P_2O_5 was likely to have been biogenic.

Sample 38/1 is slightly less altered than 36/3, with the alteration being expressed petrographically as abundant black–brown clayey material in the groundmass, and compositionally as an abnormally high MnO content (2.7%) and perhaps a rather high Fe_2O_3 (16.1%), and low SiO_2 (46.0%) contents. Most other compositional features of 38/1 appear reasonable for a tholeiitic basaltic lava, except for the exceptionally high Pb (220 ppm) and Ni (511 ppm) contents, which almost certainly reflect adsorption of these metals onto the manganese oxides–hydroxides that make up most of the altered groundmass.

Geochemistry and implications

Mantle plume model

Over the years, a number of workers have suggested that certain large bathymetric features of the eastern Indian Ocean, such as the Kerguelen Plateau and Broken Ridge (Fig. 9), are the products of volcanic activity associated with a Kerguelen–Heard mantle plume or hotspot (e.g. Luyendyk & Rennick, 1977; Duncan, 1978, 1981; Morgan, 1981; Duncan & Storey, 1992). It has recently been pointed out that at the time of the main outpouring of lavas that formed the Kerguelen Plateau, the Indian Ocean was probably less than 700 km wide (Storey et al., 1989, 1992; Duncan & Storey, 1992). If the plume head

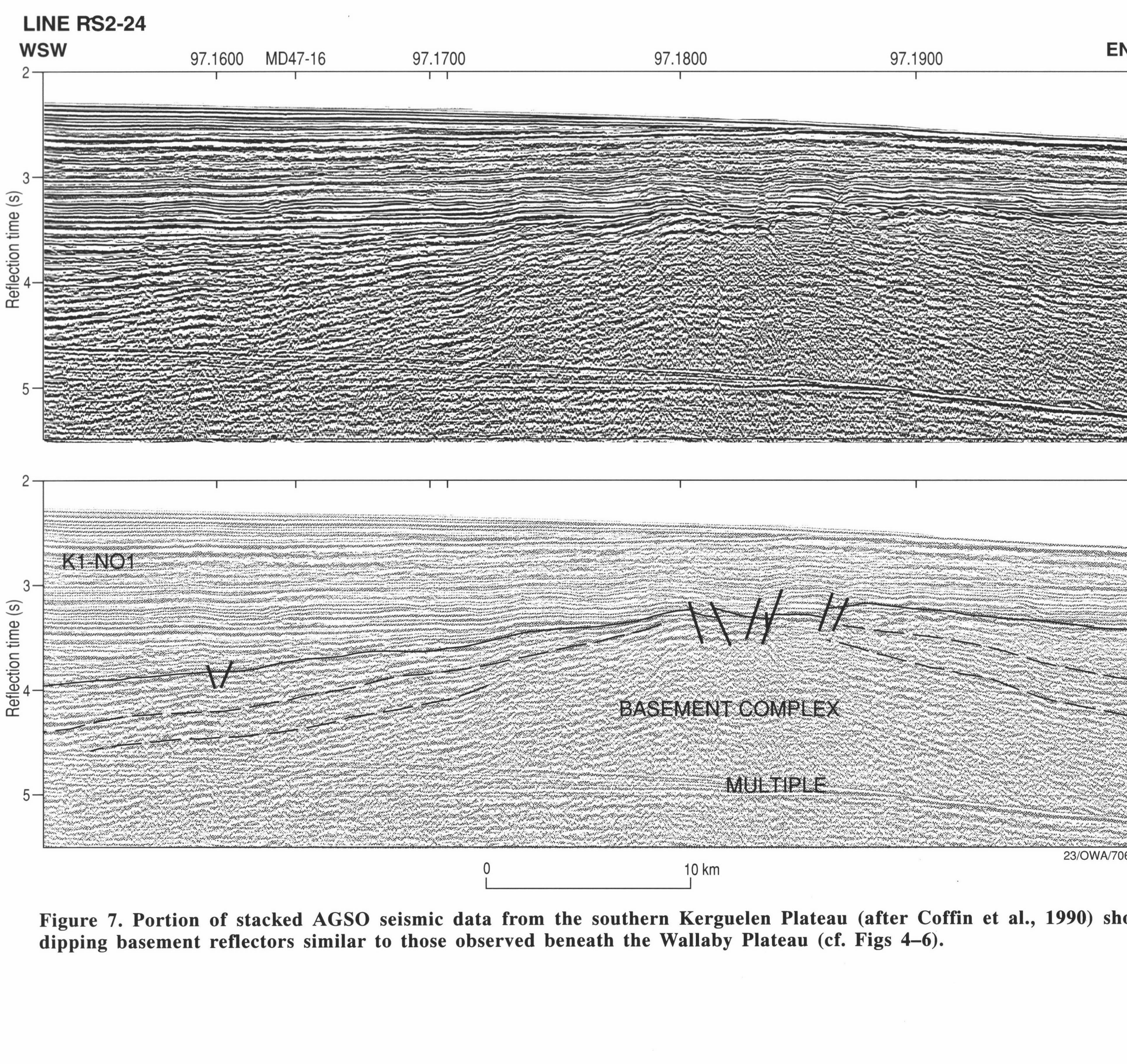


Figure 7. Portion of stacked AGSO seismic data from the southern Kerguelen Plateau (after Coffin et al., 1990) showing dipping basement reflectors similar to those observed beneath the Wallaby Plateau (cf. Figs 4–6).

associated with the Kerguelen plume was as large as has been hypothesized for major plumes (1000–2000 km, White & McKenzie, 1989; see also Duncan & Richards, 1991), then it is likely that some continental lithosphere from beneath Gondwana was mobilized, and involved in the immediately pre-breakup and breakup magmatism during the birth of the eastern Indian Ocean (Storey et al., op. cit.; Duncan & Storey, op. cit.; Mahoney et al., in press). Given the significant isotopic and key trace-element differences between sub-continental and sub-oceanic lithospheric mantle, it is possible to test for the involvement of sub-Gondwana continental lithospheric mantle in the generation of lavas during the early stages of Indian Ocean opening.

It has been convincingly argued by Mahoney et al. (in press) and Storey et al. (1992) that sub-Gondwana continental lithospheric mantle was involved in the petrogenesis of tholeiitic lavas from the Naturaliste Plateau (*Eltanin* Cruise 55), eastern Broken Ridge (*R.D. Conrad*, Cruise 27, Dredge 8), and southernmost Kerguelen Plateau (ODP Site 738). Petrogenesis of the latter suite may have involved contamination by underlying attenuated continental crust. These areas were all located close to continental blocks at the time of their formation. In contrast, the distinctive trace-element and isotopic compositions associated with a continental lithospheric mantle component (see below) are less well-developed in lavas from the main body of the Kerguelen Plateau and Broken Ridge, which were generated at greater distances from continental margins.

On this basis, it might be predicted that the Wallaby Plateau formed in an analogous manner to the Naturaliste Plateau, being a pile of 120–100 Ma tholeiitic basalts with key isotopic and trace-element fingerprints indicating involvement of sub-continental lithospheric mantle [in this case, of the West Australian Archaean craton(s)]. Storey et al. (1989, 1992) and Mahoney et al. (in press) have argued that a key compositional feature of subcontinental lithospheric-derived magma is a significant depletion in Nb (and Ta) relative to LREE, so that primitive mantle-normalized ratios of La/Nb [herein $(La/Nb)_N$] are significantly greater than 1. Values of this ratio for N-MORB and OIB (Sun & McDonough, 1989) are typically 1.1 and 0.8, respectively. Mahoney et al. (in press) show that the $(La/Nb)_N$ values for the eastern Broken Ridge Dredge 8 lavas are 1.4–1.6, for the Naturaliste Plateau 1.9–3.4, and for ODP Site 738 at the southern tip of the Kerguelen Plateau, $(La/Nb)_N$ values are ~2. These data provide strong evidence for the involvement of sub-Gondwana continental lithospheric mantle in the petrogenesis of these lavas.

Isotopic data for Pb-Nd-Sr provide even stronger support for continental lithospheric mantle involvement in the

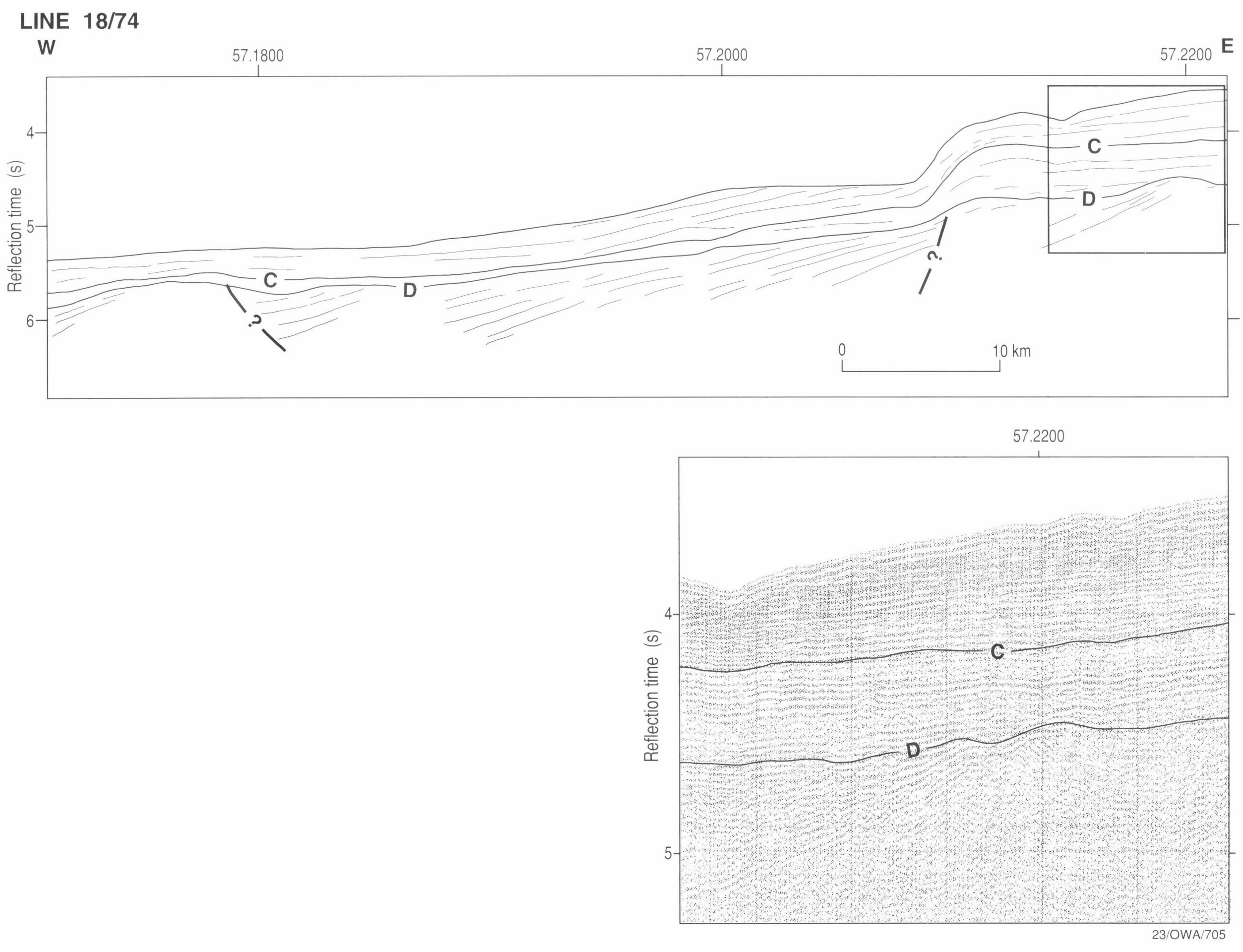


Figure 8. Line drawing of part of AGSO Line 18/74 showing seaward-dipping reflectors beneath the eastern Wallaby Saddle adjacent to the Carnarvon Terrace. Location of figure shown in Figure 3.

Table 3. Wholerock major and trace element analyses of Wallaby Plateau dredged basalts 36/3 and 38/1, and Bunbury Basalts BB1 and BB3 (this study), with comparative analyses from the Bunbury Basalt (BB2, 4, 5 and 7, from Storey et al., 1992), Naturaliste Plateau LREE-enriched basalts from Eltanin Dredge 55 (Mahoney et al., in press), eastern Broken Ridge basalts from Conrad Dredge 8, and two basalts from ODP Leg 119 Site 738 at the southeastern tip of the Kerguelen Plateau (Mahoney et al., in press).

	Rig Seismic	*Rig Seismic*	*Bunbury Bas.*	*Bunbury Bas.*	*Bunbury Bas.*	*Bunbury Bas.*	*Bunbury Bas.*	*Bunbury Bas.*	*Eltanin*	*Eltanin*	*Eltanin*	*Eltanin*	*Eltanin*	*Conrad*	*Conrad*	*Conrad*	*ODP Leg119*	*ODP Leg119*
	Cruise 96 36/3	Cruise 96 38/1	Bunbury Beach BB1	Gelorup Quarry BB3	Storey et al. BB2	Storey et al. BB4	Storey et al. BB5	Storey et al. BB7	Cruise 55 12–2	Cruise 55 12–8	Cruise 55 12–1	Cruise 55 12–21	Cruise 55 12–24	27–08 D8–B–4	27–08 D8–B–9	27–08 D8–E1b	738–33 R–2 65–68	738–34 R–4 30–33
SiO_2	41.5	46.0	51.8	52.1	52.2	51.7	52.7	53.1	59.9	54.7	50.3	51.3	50.6	49.4	49.1	49.9	52.3	51.5
TiO_2	2.34	1.18	1.64	1.97	2.05	1.77	1.96	1.31	1.8	1.88	0.63	0.74	0.99	2.22	3.11	1.6	1.97	1.69
Al_2O_3	17.7	16.1	15.8	14.4	14.6	15.6	15.2	14.7	15	18	20.6	19.8	19.6	13.9	14	13.8	15.8	15.4
Fe_2O_3	20.7	16.1	11.3	12.2	12.5	11.7	12.1	11.8	9.86	13.2	7.9	9.01	10.7	17.7	15.3	14.8	11.8	11.6
MnO	0.16	2.69	0.16	0.18	0.19	0.18	0.19	0.20	0.12	0.20	0.11	0.12	0.14	0.37	0.42	0.24	0.10	0.13
MgO	1.07	4.41	5.70	5.55	5.71	5.71	5.57	6.54	4.04	4.98	5.24	4.86	4.32	2.48	5.16	6.04	5.70	6.18
CaO	9.03	9.54	10.20	9.45	9.67	10.10	9.77	10.50	4.02	3.87	10.65	9.51	8.90	7.45	9.33	10.40	7.73	9.21
Na_2O	3.31	2.75	2.88	3.35	3.12	3.09	3.22	2.83	3.25	2.75	3.74	3.31	3.40	3.61	2.90	2.49	3.23	3.09
K_2O	1.89	0.98	0.25	0.45	0.38	0.33	0.39	0.40	2.31	1.01	0.46	1.21	1.07	1.30	0.39	0.47	1.41	0.99
P_2O_5	2.35	0.23	0.18	0.24	0.22	0.18	0.21	0.13	0.59	0.24	0.06	0.08	0.11	1.01	0.38	0.18	0.22	0.19
Total	100	100	100	100	100.6	100.4	101.3	101.5	101	100.8	99.7	100	99.8	99.5	100	99.9	100.3	100
LOI	8.46	8.59	1.18	0.57							2.87	2.04	2.22	0.34	0.55	0.1	2.11	1.26
Ni	98	511	70	41	38	69	41	58	111	128	72	72	106	17	34	53	30	28
Cr	144	141	338	274							366	338	356		15	23	61	101
V	743	401	241	262							145	149	209		472	375	254	256
Sc	75	55	34	34	33	31	31	41	22	28	26	28	33	38	44	48	37	37
Zr	152	147	104	136	141	115	133	98	203	140	27	32	46	241	176	138	195	159
Nb	8.0	10.5	6.1	6.0	6.7	5.1	5.9	3.0	8.8	5	0.58	0.84	1.2	19.4	13.8	7.3	11.1	8.3
Y	75	47	35	41	39	35	37	32.2	27	28	12.7	14.7	16.4	48	31	38	27	28
Sr	243	272	228	227	235	231	247	163	132	141	187	151	163	338	297	127	271	301
Rb	27	25	4	8	4.3	5.6	5.7	8.9	61.2	38	5.4	13.7	20	9.7	3.5	6.7	34	13.1
Ba	113	251	55	102							14	58	30	471	160	125	213	303
Pb	3.3	220																
La	18.0	31.9		8.6	10.2	7.2	10.0	8.5	28.6	12.4	1.3	1.5	2.5	29.0	19.5	10.0	19.6	14.6
Ce	30.1	122.4		22.4	25.6	21.4	26.3	18.4	59.0	36.0	3.5	4.5	5.8	80.4	50.0	26.0	53.2	37.2
Nd	22.6	35.8		16.8					29.9	14.9	3.3	3.7	5.4	43.6	26.1	15.3	25.0	19.3
Sm		6.76		5.13	5.28	4.15	4.98	3.53	6.30	4.76	1.34	1.61	2.08	9.93	5.89	4.16	6.06	4.94
Eu		2.14		1.74	1.45	1.42	1.58	1.55	1.99	1.51	0.64	0.73	0.90	3.90	2.08	1.40	2.03	1.70
Tb		1.14		0.97					1.36	1.11	0.30	0.40	0.45	1.62	0.86	0.97	1.17	1.03
Ho		1.60		1.25														
Yb		4.08		3.10	3.50	2.86	3.21	2.84	4.41	2.87	1.26	1.42	1.60	4.38	2.87	3.97	2.72	2.62
Lu		0.61		0.44	0.46	0.38	0.37	0.42	0.52	0.28	0.20	0.22	0.23	0.63	0.43	0.65	0.37	0.36
Th		4.75		1.31	1.60	1.20	1.50	1.50	6.40	1.87				4.95	2.63	2.19	2.82	2.11
Ta		<0.5		0.59					0.62	0.34	0.06	0.09	0.09	1.19	0.80		0.61	0.50
Hf		2.76		3.40	4.50	3.80	5.00	3.20	5.50	3.70	0.71	0.84	1.23	5.91	4.07	3.21	4.53	3.79

Footnote: Major and trace elements excluding REE, Hf, Ta and Th by XRF analysis in Dept of Geology, University of Tasmania. Other elements by INAA at Becquerel Labs., Lucas Heights.

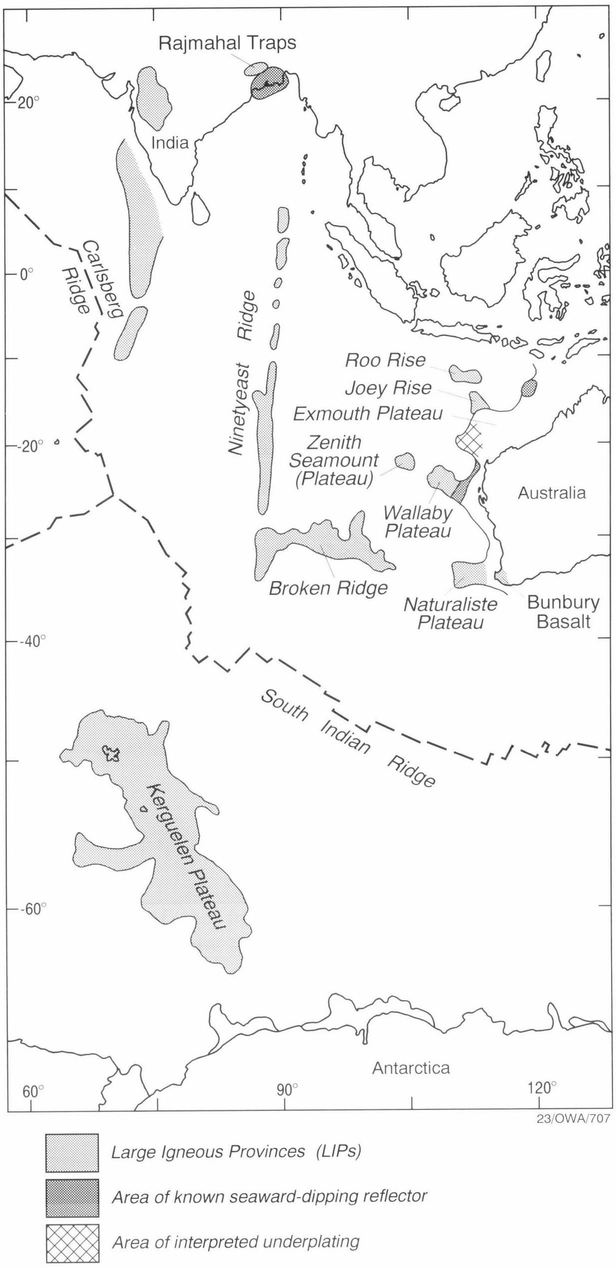


Figure 9. Distribution within the eastern Indian Ocean of areas of: (i) interpreted underplating; (ii) large igneous features (LIPs), and (iii) known seaward-dipping reflectors. Areas of underplating from Mutter et al. (1989) and Lorenzo et al. (1991); LIP distribution from Coffin & Eldholm (1991); and areas of seaward-dipping reflectors from this paper, Hinz (1981), Storey et al. (1992) and Hopper et al. (1992).

petrogenesis of lavas forming the eastern Broken Ridge, Naturaliste Plateau and the southernmost Kerguelen Plateau (Storey et al., 1989, 1992; Alibert, 1991; Mahoney et al., in press). These lavas show more extreme isotopic variations than recorded for the post-45 Ma Kerguelen plume magmas, with substantially more negative ε_{Nd}values, $^{87}Sr/^{86}Sr$ values extending to notably more radiogenic values, and lower $^{206}Pb/^{204}Pb$ values than the modern Kerguelen plume lavas.

Wallaby Plateau lavas

Abundances of the immobile elements Zr, Nb and the REE (Table 3) show that samples 38/1 and 36/3 from the Wallaby Plateau are probably evolved tholeiitic basalts. Both samples have Zr/Nb values (14–20) similar to most analyzed lavas from the eastern Broken Ridge and ODP Site 738 on the southern Kerguelen Plateau, and are just below values (23–28) for the non-plagioclase accumulative basalts from the Naturaliste Plateau reported by Storey et al. (1989). Similarly, sample 38/1 shows a strongly LREE-enriched REE pattern (with a pronounced alteration-induced positive Ce anomaly), very close to those reported by Storey et al. (1989) and Mahoney et al. (in press) for basalts from the other eastern Indian Ocean locations (Figs 10b, c, d). In the absence of isotopic data for the Wallaby Plateau samples, the high $(La/Nb)_N$ values of 3.1 for 38/1 and 2.33 for sample 36/3 (coupled with the <0.5 ppm Ta measured for 38/1), and the pronounced negative Nb anomalies on the multi-element variation diagrams in Figure 11a-d, provide substantial support for a broad correlation of the Wallaby Plateau basalts with those from the other eastern Indian Ocean locations (Naturaliste Plateau, southernmost Kerguelen Plateau, and eastern Broken Ridge).

Bunbury Basalt

Petrographic descriptions of two samples of the Bunbury Basalt, which has been suggested to be a continental flow basalt related to the Kerguelen plume (Davies et al., 1989; Storey et al., 1992), are given in the Appendix. They are plagioclase+sparsely augite-phyric rather coarse-grained basalts that show only very minor alteration of the glassy mesostasis. Data given in Storey et al. (1992) and our new data (Table 3) show that the Bunbury Basalt has $(La/Nb)_N$ values ranging from 1.46–2.94. REE patterns are less LREE-enriched (Fig. 10c) than those for the enriched lavas from the Naturaliste Plateau (Fig. 10b), from the eastern end of Broken Ridge (Fig. 10d), and from ODP Site 738 on the southern tip of Kerguelen Plateau (Fig. 10c), but normalized element variation patterns (Fig. 11b-d) still show pronounced negative Nb–Ta anomalies.

We provide here the first isotopic data for the Bunbury Basalt (Table 4). Data are plotted on Figure 12a-e (note initial ratios are plotted for Nd and Sr isotopes, but

Table 4. Isotopic data for Sr, Nd and Pb for Bunbury Basalts BB1 and BB3 (this paper). Initial Nd and Sr values recalculated for 110 Ma. Analyses performed by Ruth Lanyon at the Research School of Earth Sciences, Australian National University.

	Bunbury Beach BB1	*Gelorup Quarry BB3*
87Sr/86Sr	0.704128±27	0.70482±18
(87Sr/86Sr)i	0.704045	0.704741
143Nd/144Nd	0.512882±6	0.512741±7
(143Nd/144Nd)i	0.512604	0.512463
206Pb/204Pb	17.967	17.905
207Pb/204Pb	15.551	15.584
208Pb/204Pb	37.946	38.22

Footnote: Sr, Nd and Pb isotopes were collected using conventional ion exchange techniques and analysed using a Finnigan MAT 261 Mass Spectrometer operated in static multicollector mode. $^{87}Sr/^{86}Sr$ values are normalised to $^{86}Sr/^{88}Sr = 0.1194$; $^{143/144}Nd$ values are normalised to $^{146}Nd/^{144}Nd = 0.7219$. Sr and Nd 2σ precision refers to within-run statistics. Pb isotopes were analysed using the ^{207}Pb-^{204}Pb double spike technique (Hamelin et al., 1985). Mean ($\pm 2\sigma$) standard values obtained over this period of analysis include: NBS 987(n=39) - $^{87}Sr/^{86}Sr = 0.710209\pm35$; La Jolla (n=54) - $^{143}Nd/^{144}Nd = 0.512189\pm19$; NBS 981 (n=8) - $^{206}Pb/^{204}Pb = 16.939\pm10$, $^{207}Pb/^{204}Pb = 15.494\pm11$, $^{208}Pb/^{204}Pb = 36.712\pm31$.

measured values are plotted for Pb isotopes). It is evident from these plots that the Bunbury Basalt samples fall

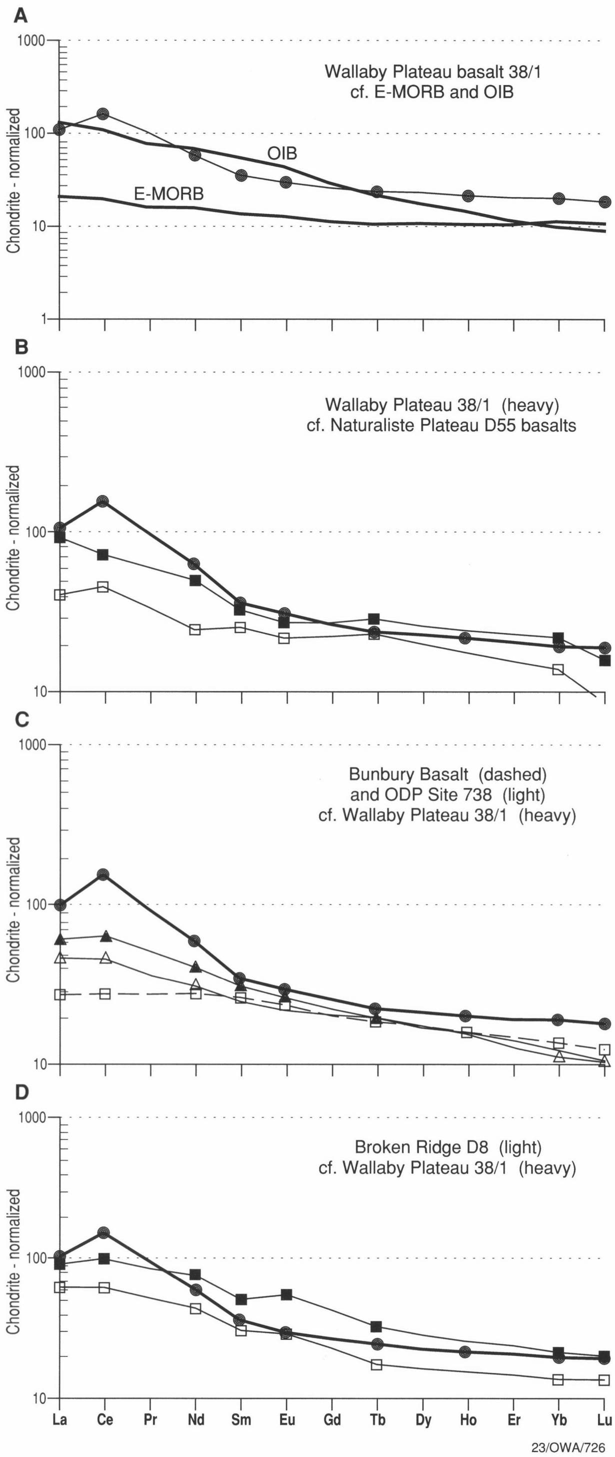


Figure 10. Chondrite-normalized REE pattern of dredged Wallaby Plateau basalt 38/1 (filled circles in Fig. 10a, heavy line in b, c, d) compared with those for: (a) the average E-MORB amd OIB (from Sun & McDonough, 1989); (b) two basalts dredged from the northern margin of the Naturaliste Plateau by USNS *Eltanin* at dredge site 55 (filled and open squares; data from Mahoney et al., in press); (c) Bunbury basalt (open squares, this paper) and two basalts from ODP Site 738 on the southeastern tip of the Kerguelen Plateau (filled and open triangles; data from Mahoney et al., in press); and (d) two basalts from the eastern end of Broken Ridge (filled and open squares; data from Mahoney et al., in press).

along the same broad trends in Pb–Sr–Nd isotopic space as do those samples from the Naturaliste Plateau and eastern Broken Ridge analyzed by Storey et al. (1992) and Mahoney et al. (in press). The enriched radiogenic

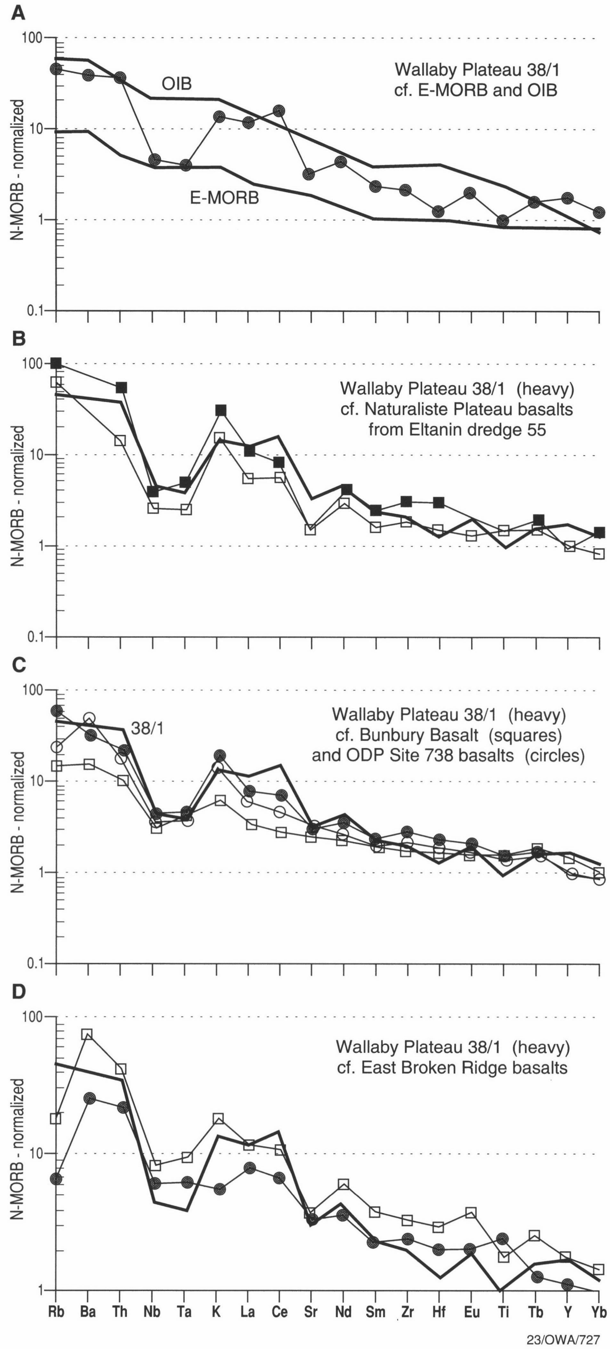


Figure 11. NMORB-normalized multi-element variation patterns of dredged Wallaby Plateau basalt 38/1 (filled circles in Fig. 11a, heavy line in b, c, d) compared with those for: (a) the average E-MORB and OIB (from Sun & McDonough, 1989); (b) two basalts dredged from the northern margin of the Naturaliste Plateau by USNS *Eltanin* at dredge site 55 (filled and open squares; data from Mahoney et al., in press); (c) Bunbury basalt (open squares, this paper) and two basalts from ODP Site 738 on the southeastern tip of the Kerguelen Plateau (filled and open circles; data from Mahoney et al., in press); and (d) two basalts from the eastern end of Broken Ridge (filled circles and open squares; data from Mahoney et al., in press).

mantle end-member involved in the petrogenesis of these lavas may be subcontinental lithospheric mantle, as hypothesized by the above authors. However, for the Bunbury Basalt, further study is required to determine whether the less-enriched mantle source component of these lavas was Kerguelen plume mantle, or typical Indian Ocean MORB asthenosphere.

In summary, key trace-element features, notably the very low Nb and Ta contents coupled with quite LREE-enriched REE patterns, suggest that two analyzed, altered basalts from the Wallaby Plateau are evolved tholeiites very similar to those sampled from the Naturaliste Plateau, the eastern part of Broken Ridge, and the southernmost part of the Kerguelen Plateau. Perhaps not surprisingly given their present positions with respect to the cratonic crust of Australia, the basalts sampled from the Wallaby Plateau, Bunbury and Naturaliste Plateau have compositional fingerprints suggesting the involvement of subcontinental lithospheric mantle in their petrogenesis.

Large igneous provinces off western Australia

The above analysis of seismic data and the new dredge samples from the Wallaby Plateau add new weight to previous studies that have suggested that the Wallaby Plateau is a volcanic feature, probably underlain by oceanic crust, and formed during or following breakup (Veevers & Cotterill, 1978; von Stackelberg et al., 1980; Veevers et al., 1985). This raises the question of how the Wallaby Plateau relates to other volcanic provinces that either once lay relatively near the west Australian margin at, or not long after breakup, or that now actually form part of the margin.

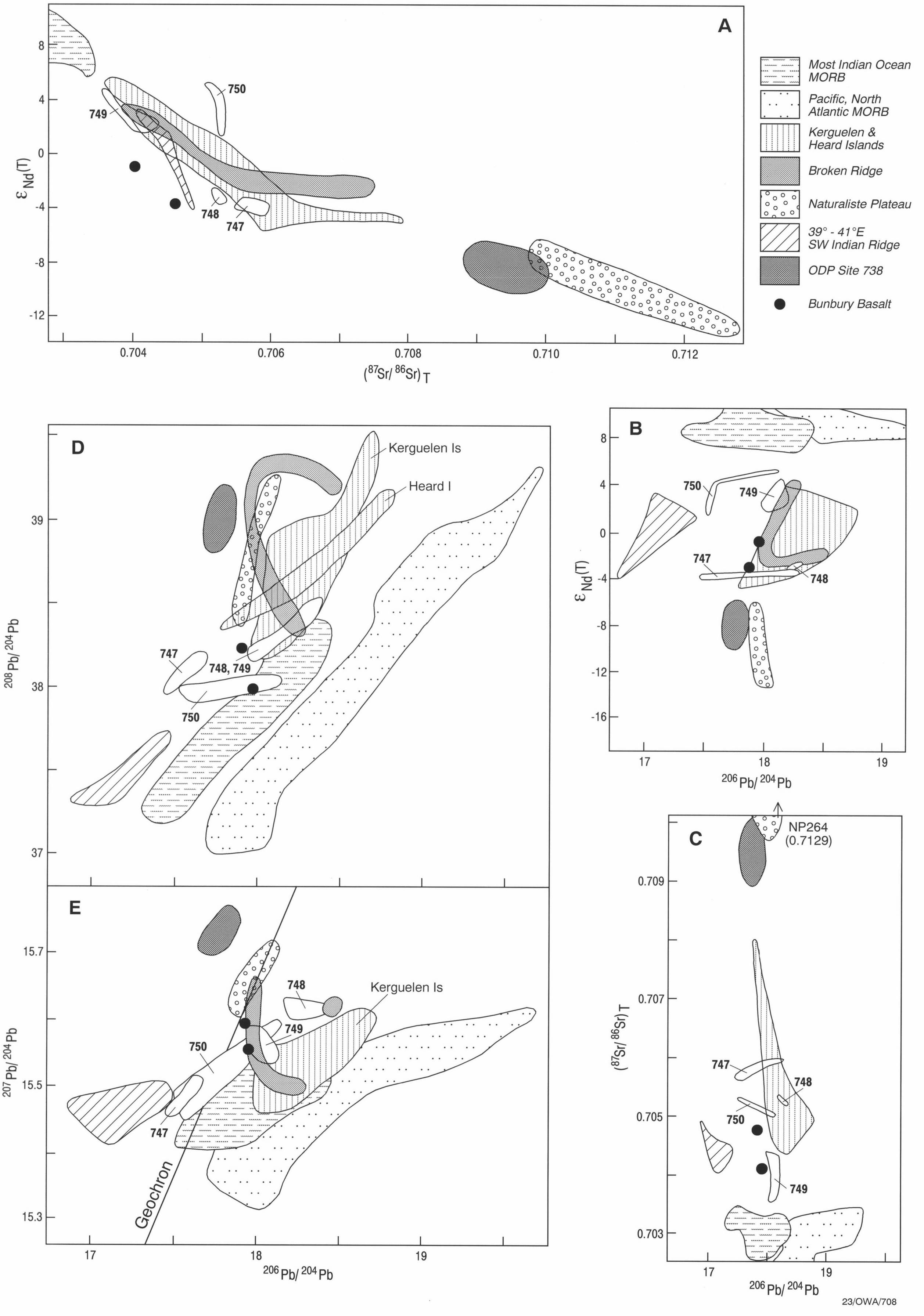
It is now well recognised that voluminous emplacement of mafic igneous rock via processes other than 'normal' seafloor spreading can produce features such as continental flood basalts (CFB) and associated intrusives; so-called 'volcanic passive margins'; oceanic plateaux (OP); submarine ridges (SR); ocean basin flood basalts; and seamount chains (Coffin & Eldholm, 1991, 1992). These large igneous provinces (LIPs) contain enormous volumes of lava that were emplaced very rapidly, and have many similarities in their temporal, spatial, and compositional characteristics (Coffin & Eldholm, op.cit.). Coffin & Eldholm (1991, 1992, in press) illustrate the distribution of LIPs in the eastern Indian Ocean, and summarise a variety of information on these features. Plate reconstructions, such as those of Davies et al. (1989) and Royer & Coffin (1992), indicate that six LIPs lay within or relatively close to the west Australian margin up until about 110 Ma, following breakup of Gondwanaland and the westward drift of Greater India. These are the Joey and Roo Rises (OP's); the Zenith and Wallaby Plateaux (OP's); the Bunbury Basalt (CFB — southwest Australia); the Naturaliste Plateau (?OP); the Rajmahal Traps (CFB — northeast India); the Kerguelen Plateau (OP); and Broken Ridge (SR) (Fig. 9). Several of these features have now been imaged with modern seismic data, and have been sampled during various DSDP and ODP legs in the Indian Ocean. The formation of most of these LIPs is interpreted to be related to volcanic activity associated with the Kerguelen–Heard mantle plume or hotspot. Davies et al. (1989) and Storey et al. (1992) include the Naturaliste Plateau and its possible on-land equivalent, the Bunbury Basalt, among the earliest products of the Kerguelen hotspot. This results in a hotspot track which Davies et al. (1989) hypothesized may date back to about 135 Ma and includes, in chronological order, the Bunbury Basalt, Naturaliste Plateau, Rajmahal Traps (India), Kerguelen/Broken Ridge, Ninetyeast Ridge, and finally the northeasternmost Kerguelen Plateau and the associated Tertiary–Recent volcanism of Kerguelen and Heard/McDonald Islands. Storey et al. (1992) in their figure 1 also suggest that volcanics of the Sylhet province (India), a seaward-dipping reflector sequence on the adjacent continental margin, the Damodar and Darjeeling Lamprophyres (India), and the Prince Charles Mountains Lamprophyres (Antarctica) are some of the early products of the Kerguelen hotspot.

We note here that an unpublished ^{40}Ar-^{39}Ar age of 115±2.0 Ma (R.A. Duncan, *pers. comm.*, 1994) for one of the Bunbury Basalt samples described in this paper puts formation of the Bunbury Basalt at the same time as the bulk of the Kerguelen Plume, and possibly the other compositionally similar, volcanic plateaux off western Australia (Naturaliste and Wallaby Plateaux and Broken Ridge). The Rajmahal Traps of eastern India have also commonly been linked to Kerguelen plume activity, and have yielded an ^{40}Ar-^{39}Ar age of 117±1 Ma (Baksi, 1986; Duncan & Storey, 1992). This whole volcanic province would have had a diameter of about 1500–2000 km, with the bulk of magma production occurring within the interval from about 120 Ma (earliest Kerguelen plume activity?) to about 110 Ma (Duncan & Storey, 1992). Such an extensive magmatic province fits with the 'mega plume' model of White & McKenzie (1989), in which massive igneous activity (volcanism and underplating) results from enhanced decompression melting of hot asthenospheric mantle related to a mantle plume, as it rises passively beneath stretched and thinned lithosphere. However, it is important to emphasize that the timing of the early Kerguelen plume activity appears be too young for the plume to be involved in the initiation of the passive margin of northwestern Australia, where breakup and accretion of oceanic crust occurred at ~155 Ma along the Argo Abyssal Plain and around 130 Ma on the Gascoyne and Cuvier Abyssal Plain sections.

Other magmatic provinces of the west Australian margin

Whereas the Naturaliste and Wallaby Plateaux are commonly referred to in discussions of LIPs of the eastern Indian Ocean (White & McKenzie, 1989; Coffin & Eldholm, 1992), it is not generally appreciated that seismic data, dredging and ODP sampling have also defined other large areas of magmatism (intrusives, extrusives and underplating) along the west Australian continental margin. Volcanics are commonly sampled along the margin and are described in numerous papers, for example by von Rad & Exon (1983), Veevers (1984), Mutter et al. (1988), Mutter et al (1989), von Rad et al. (1992), Exon & Buffler (1992), Hopper et al. (1992), Colwell et al. (1994 — this issue), and Crawford & von Rad (1994 — this issue). The styles of magmatism basically fall into four types:

1. Rift-related volcanics of possible Early Triassic (Scythian) to Middle Jurassic (Aalenian–Bathonian) age, but probably mainly focussed in the Late Triassic (Rhaetian; K–Ar age: 213 Ma) to Early Jurassic (Toarcian–Hettangian; K–Ar age: 190–206 Ma) sampled in several of the Browse Basin wells (landward of the Scott Plateau; Fig. 1), from the margins of the Wombat Plateau (northern part of the Exmouth


A
Most Indian Ocean MORB
Pacific, North Atlantic MORB
Kerguelen & Heard Islands
Broken Ridge
Naturaliste Plateau
39° - 41°E SW Indian Ridge
ODP Site 738
Bunbury Basalt
750
749
748
747
$\varepsilon_{Nd}(T)$
$(^{87}Sr/^{86}Sr)_T$
0.704
0.706
0.708
0.710
0.712
8
4
0
-4
-8
-12
B
$^{206}Pb/^{204}Pb$
17
18
19
-16
C
NP264
(0.7129)
0.709
0.707
0.705
0.703
D
Kerguelen Is
Heard I
748, 749
$^{208}Pb/^{204}Pb$
39
38
37
E
Kerguelen Is
Geochron
$^{207}Pb/^{204}Pb$
15.7
15.5
15.3
23/OWA/708

Plateau, Fig. 1), and as dredged (but as yet un-dated) and interpreted from seismic data from the southwest margin of the Exmouth Plateau east of ODP Site 766 (Exon & Buffler, 1992). This suite of volcanics ranges from highly differentiated K-rich rhyolitic to trachytic rocks erupted under subaerial to very shallow-marine conditions (von Rad & Exon, 1983) to basaltic dykes and sills of broadly MORB composition (Buffler et al., 1992).

'Intrabasement' reflectors visible on deeper penetration seismic data from large areas of the Exmouth Plateau have been interpreted as detachments related to Permo-Triassic or Carboniferous–Permian extension (Mutter et al., 1989; Williamson et al., 1990); however, Exon & Buffler (1992) interpreted some of these features, particularly beneath the western plateau, as Middle–Late Jurassic sills intruded during the latest stage of margin rifting.

2. Probable Late Jurassic to Early Cretaceous volcanics (Hauterivian–Valanginian; K–Ar minimum age of 128–133 Ma) dredged from the margin of the Scott Plateau (Hinz et al., 1978; von Rad & Exon, 1983). These rocks are alkali basalts (?hawaiite) and are rather anomalous because, assuming that the K–Ar dating is not too inaccurate, they appear to have been emplaced some 20 million years after Argo Abyssal Plain breakup, dated at ~155 Ma (Ludden, 1992). In fact, the age of the Scott Plateau basalts corresponds better with the 130 Ma breakup age of the Gascoyne and Cuvier Abyssal Plains some 1000–1500 km to the southwest.

   Further evidence for widespread volcanism of this age is provided by the sampling of Berriasian–Valanginian bentonites (i.e. smectite-dominated, altered volcanic dacitic to rhyolitic ash layers) at ODP sites on the northern, western and southern margins of the Exmouth Plateau, and the southern Argo Abyssal Plain (von Rad & Thurow, 1992). Potential sources for the explosive volcanic activity that resulted in the deposition of proximal ash turbidites in the Wombat Plateau area include the Joey and Roo Rises (volcanics have been sampled, but are un-dated, and magnetic anomaly picks imply a Late Jurassic or younger age for these features — Fullerton et al., 1989), the Scott Plateau and the Wallaby Plateau/Cape Range Fracture Zone area.

   On the basis of dredging and seismic data, Ramsay & Exon (1994 — this issue) mapped a 'volcanic layer' beneath the northwestern Rowley Terrace, adjacent to the offshore Canning Basin (Fig. 1), covering an area of 25 000 km^2. They interpret this feature to be volcanic flows and volcaniclastics of possible Callovian–Oxfordian age, and suggested it was emplaced just prior to breakup in the Argo Abyssal Plain.

3. Seaward-dipping reflector sequences have been identified from seismic data beneath the northeast margin of the Argo Abyssal Plain (Hinz, 1981) adjacent to the Scott Plateau, and beneath the lower slope of the northern Carnarvon Terrace (Cuvier margin; Hopper et al., 1992) adjacent to the Cuvier Abyssal Plain (Figs 1 and 9). These sequences are interpreted as basaltic flows emplaced as a result of unusually voluminous subaerial volcanism around the time of breakup, i.e. of Callovian–Oxfordian age in the Argo Abyssal Plain, and Valaginian–Hauterivian age in the Cuvier Abyssal Plain. Hopper et al. (op. cit.) suggested that in the Cuvier area the seaward-dipping reflectors were formed during the early stage of oceanic crust formation (i.e.post-breakup) and resulted in an exceptionally thick oceanic crust adjacent to the margin.

4. Underplated crust defined by a layer with velocity 7.2–7.3 km/s on expanded spread seismic profiles beneath the western (Mutter et al., 1989) and southern (Lorenzo et al., 1991) Exmouth Plateau (Fig. 9). Mutter et al. (op. cit.) related the underplating beneath the western plateau to Middle to Late Jurassic lithospheric thinning, resulting in plutonic underplating, accompanied by large-scale normal faulting without a detachment. Lorenzo et al. (op. cit.), however, assigned the southern Exmouth Plateau underplating to melt generation during Early Cretaceous seafloor spreading in the Cuvier Abyssal Plain, and consequent transform motion along the Cape Range Fracture Zone.

Discussion

The distribution of volcanics along the western Australian margin appears to consist of two types. A zone of Triassic to Early Cretaceous volcanics occurs along the margin and includes areas of seaward-dipping reflectors, flows, sills and possible underplating. These features lie within a zone that parallels the margin, implying that igneous emplacement was controlled by dynamic rift/breakup processes and not necessarily by proximity to a plume. Such distributions can be explained by the convective partial melting model of Mutter et al. (1988), in which the lateral temperature contrasts caused by rifting and asthenospheric upwelling drive convection in the upper mantle. The resulting "convective melt" production supplements that available from the passive upwelling of the asthenosphere related to lithospheric extension and thinning. Another similar non-plume model was recently proposed by Holbrook & Kelemen (1993) to explain the widespread, margin-parallel zone of seaward-dipping reflectors observed on deep seismic data beneath the USA Atlantic margin. They argue that dynamic mantle upwelling during rifting can produce the melts that result in the accumulation of thick igneous crust when the

Figure 12. (a) Initial ε_{Nd} vs $^{87}Sr/^{86}Sr$ for two Bunbury Basalts (filled circles: this study, Table 4) compared with fields from Mahoney et al. (in press) for ODP Sites 738, 747, 748, 749 and 750 on the Kerguelen Plateau, LREE-enriched Naturaliste Plateau basalts, Broken Ridge basalts, modern Kerguelen-Heard plume basalts, and MORB from the Indian Ocean, excluding those from 39°–41°S on the SW Indian Ridge (field shown separately) and the central and western SW Indian Ridge.
(b) Initial ε_{Nd} vs present day $^{206}Pb/^{204}Pb$ for two Bunbury Basalts (filled circles: this study, Table 4) compared with fields from Mahoney et al. (in press) for suites noted in Figure 12a, plus part of field for Pacific–North Atlantic MORB.
(c) Initial $^{87}Sr/^{86}Sr$ vs present day $^{206}Pb/^{204}Pb$ for two Bunbury Basalts (filled circles: this study, Table 4) compared with fields from Mahoney et al. (in press) for suites noted in Figure 12a, plus part of field for Pacific- North Atlantic MORB.
(d) Present day $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ for two Bunbury Basalts (filled circles: this study, Table 4) compared with fields from Mahoney et al. (in press) for suites noted in Figure 12a, plus part of field for Pacific–North Atlantic MORB.
(e) Present day $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ for two Bunbury Basalts (filled circles: this study, Table 4) compared with fields from Mahoney et al. (in press) for suites noted in Figure 12a, plus field for Pacific–North Atlantic MORB.

asthenospheric upwelling rate exceeds the lithospheric extension rate. Presumably, the volcanics produced from the above processes, particularly in the immediate pre-breakup phase, could contain a strong signature of sub-continental lithospheric mantle, as appears to be the case for the Wallaby and Naturaliste Plateaux, and Bunbury Basalt. However, unlike these latter features, the volcanism would be expected to occur around the time of breakup.

The second style of volcanic distribution is reflected by the irregular volcanic buildups that form part of the margin, such as the Wallaby and probably Naturaliste Plateaux. These features have many of the characteristics of other eastern Indian Ocean LIPs that are distant from continental margins, such as Kergulelen Plateau and Broken Ridge. All appear to have formed some 10–20 million years after the 130 Ma breakup of the Gascoyne, Cuvier and Perth Abyssal Plains, by voluminous outpourings of plume-related magmas onto pre-existing, relatively young, oceanic crust.

Broad plume head models in which mantle plumes can impact on and heat the base of the lithosphere over a 2000 km diameter zone (e.g. White & McKenzie, 1989; Duncan & Richards, 1991) could explain the LIPs of eastern India, the southeast Indian Ocean (Kerguelen Plateau and Broken Ridge) and western Australia (the Wallaby and Naturaliste Plateaux, and Bunbury Basalt) as all of these lay within a 1500–2000 km diameter circle at this time. Plate reconstructions (e.g. Veevers et al., 1991; Royer & Coffin, 1992; Royer et al., 1992) indicate that from 120–110 Ma Greater India and Antarctica /Australia were separated by a 300–800 km wide zone of newly formed oceanic crust, and therefore the LIPs are all post-breakup features. Thus, the Wallaby and Naturaliste Plateaux are unlikely to have been formed by decompression melting associated with the stretching of continental lithosphere above a plume as suggested by White & McKenzie (1989).

The 119 Ma plate reconstruction of Royer et al. (1992) shows the spreading ridge between India and Antarctica/Australia intersecting the site of the future Kerguelen/Broken Ridge LIP, and passing by the sites of the future Naturaliste and Wallaby Plateau LIPs along major transform offsets. This implies that the distribution and form of the LIPs above a single plume head is controlled by processes occurring in the overlying lithosphere. That is, the plume is an essential pre-condition for the LIP as it provides the excess heat, but it is the thinning of the lithospheric cap that controls their location. As discussed by Saunders et al. (1992), plume heat may be channelled towards zones of thin lithosphere associated with features such as active spreading ridges and continental rifts. We speculate that the Wallaby and Naturaliste Plateau LIPs may have formed when the ridge tip associated with seafloor spreading between India and Antarctica/Australia passed along major transforms that separated it from recently accreted oceanic crust to the north. This would have resulted in re-heating, and perhaps rifting and thinning, of the pre-existing oceanic crust producing an episode of voluminous magmatism. If this model is correct, volcanism associated with the Wallaby Plateau LIP would have commenced at about 118 Ma (chron M0), some 10 Ma after the formation of the adjacent Cuvier Abyssal Plain crust. The Royer et al. (1992) plate reconstruction indicates that the Kerguelen/Broken Ridge LIP may have begun at the intersection of the spreading ridge with either a major transform, or the western end of the incipient spreading ridge between Antarctica and Australia. This location may have also been a locus of re-heating and rifting of pre-existing oceanic crust leading to the formation of a LIP.

The above discussion raises the question of when the postulated mantle plume responsible for the eastern Indian Ocean LIPs may have first begun to impact on the base of the lithosphere. Perhaps the ridge jump at about chron M4 time (123 Ma) in the Cuvier and Gascoyne Abyssal Plains was related in some way to this phenomenon.

Another intriguing possibility for the origin of the Wallaby Plateau may lie in the convective partial melting model of Mutter et al. (1988). They show an example of convective melting following an oceanic spreading ridge crest jump (Fig. 13 of Mutter et al., op. cit.) resulting in an oceanic upgrowth which is later split apart by normal seafloor spreading to form two parallel aseismic ridges. Such a model may explain both the Sonja and Sonne Ridges in the Cuvier Abyssal Plain, and their bracketing of the Wallaby Plateau. If a ridge jump occurred in the region at about magnetic anomaly M4 time, an oceanic upgrowth resulting from re-rifting of pre-existing oceanic crust and associated convective partial melting could have formed the Wallaby Plateau complex. North of a possible transform, the initial upgrowth was split by 'normal' seafloor spreading to form the Sonne and Sonja ridges, whereas to the south convective melting continued for some time, resulting in the Wallaby Plateau volcanic province. For this model to be valid, it would require some re-identification of the magnetic anomalies west of the Sonne Ridge. This would not appear to present a significant problem as, although the anomalies are clear, their form is not so distinctive that other options are not possible. Such a model could also explain several other observations concerning the Sonne and Sonja Ridges:

- The Sonja Ridge is normally associated with the western limb (about chrons M8–9) of the M10–M4 spreading episode that formed the eastern Cuvier Abyssal Plain; however, there is no comparable feature associated with the equivalent eastern limb.
- The Sonja Ridge is at least as significant a feature as the Sonne Ridge, which is normally considered to be an abandoned spreading centre.
- Both the Sonja and Sonne Ridges trend at 15–20°, whereas the seafloor spreading magnetic anomaly pattern that they are normally associated with is generally shown as trending about 30°. This difference in trends may reflect different episodes of seafloor spreading.

Conclusions

The Wallaby Plateau is underlain by a "basement" containing complex dipping seismic reflector sequences similar to those of large, oceanic, plume-related volcanic features (LIPs), such as the Kerguelen and Ontong Java Plateaux. ODP drilling at both the latter locations has confirmed that these sequences are composed of interbedded, subaerial basalt flows and volcaniclastic sediments. The Wallaby Saddle, which lies between the Wallaby Plateau and the upper continental slope, and the lower continental slope adjacent to the Cuvier Abyssal Plain, are underlain in places by seaward-dipping reflectors which appear similar to those drilled by the ODP on the

Rockall and Vøring Plateaux. These sequences were also shown to consist of subaerial basalt flows and interbedded sediments, and are thought to be the result of voluminous magmatism around the time of continental breakup.

Dredging of the margins and central part of the Wallaby Plateau obtained altered tholeiitic basalts, and basaltic conglomerates and sandstones, and supports a volcanic origin for the entire feature. Immobile element compositions of two Wallaby Plateau basalts provide strong support for a correlation with those from the Naturaliste and southernmost Kerguelen plateaux, and the eastern Broken Ridge. All these features have been suggested to have formed by plumehead-related volcanism, and all involved, to some degree, Gondwanan sub-continental lithospheric mantle in their petrogenesis. However, it is critical to note that both the basaltic marginal plateaux (the Wallaby and probably the Naturaliste plateaux), and related eastern Indian Ocean LIPs, all appear to be aged from 120-100 Ma, and therefore significantly post-date breakup and accretion of the earliest oceanic crust along the west Australian margin (155–130 Ma). Thus, the plumehead assumed responsible for the formation of these plateaux (and adjacent continental flood basalts, such as the Rajmahal traps and the Bunbury Basalt) cannot be implicated in the rifting and eventual breakup of this margin in the manner proposed by White & McKenzie (1989).

The extensive rift and breakup-related volcanism that occurs in a zone that parallels the west Australian margin appears to have been controlled by dynamic rift processes. It can be readily explained by models involving convective partial melting (Mutter et al., 1988) or dynamic mantle upwelling (Holbrook & Kelemen, 1993) without recourse to mantle plumes. Convective partial melting following a ridge crest jump in the Cuvier Abyssal Plain can also explain the formation of the Wallaby Plateau and probable related features, i.e. the Sonne and Sonja Ridges. However, although such an explanation can account for some of the details in the Wallaby Plateau area, it does not produce a consistent model for all the petrologically and seismically similar post-breakup LIPs of the eastern Indian Ocean.

We believe that the most likely explanation for the temporally and spatially complex arrangement of volcanic features along the west Australian margin and in the adjacent eastern Indian Ocean, involves a combination of non-plume, dynamic, rift-related volcanism leading up to and including breakup, and plume-related, plateau-forming, post-breakup volcanism.

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Appendix

Petrography of the dredged Wallaby Plateau volcanic/volcaniclastic rocks and of samples from the Bunbury Basalt.

Wallaby Plateau samples

Sample 36/4 (i.e. Dredge 36 rock type 4; Table 2) is a very strongly altered and oxidised, formerly plagioclase+olivine+augite-phyric, moderately vesicular basaltic lava. The most abundant phenocrysts are large, subhedral to euhedral, labradoritic plagioclase phenocrysts up to 7 mm long, often partially or totally altered to a very fine-grained clayey aggregate. Former olivine phenocrysts are slightly rounded and up to about 1 mm across, and make up only 1–2 modal % of the rock. They are now altered to colourless chlorite-serpentine with black rims of very fine-grained magnetite(?). Colourless augite phenocrysts and microphenocrysts to about 1 mm across are not uncommon (<5 modal %); the augite is still largely fresh, although many grains show marginal smectite–chlorite alteration. The sample's groundmass displays a highly-altered seriate–intergranular texture composed of small plagioclase laths and subordinate granular, anhedral fresh and altered augite crystals; interstitial glass and glassy mesostatsis are altered to almost-isotropic smectite–clay aggregates, mixed with black manganiferous oxides–hydroxides. Vesicles are lined by a narrow rim of analcime, mantled, in turn, by banded black manganiferous oxide–hydroxides.

Sample 36/3 is an altered, trachytic-textured, sparsely plagioclase-phyric evolved basaltic to trachyandesitic lava containing a few small former olivine phenocrysts altered to iddingsite, and <2 modal % of small (<0.5 mm long) euhedral intermediate plagioclase (An_{30-60}) phenocrysts. The groundmass of this sample was originally glass, charged with tiny plagioclase laths and microlites, but the glass has now been thoroughly altered to a murky, heterogeneous brown material, almost isotropic in places, that is probably composed largely of ultrafine-grained smectite/clay aggregates.

Sample 36/1 is a coarse-grained, framework-supported, volcaniclastic sandstone composed mainly of 1–3 mm sized well-rounded clasts of highly altered, dominantly basaltic lavas. A remarkably diverse array of textural types is present among the lava clasts, many of which are glassy and are now altered. The most common clasts in this rock are plagioclase + (former) olivine-phyric basalts, although aphyric lavas are also well represented. Olivine is always altered to iddingsite, and groundmass augite is always replaced by the same smectite–clay material that replaces glass. The matrix of this sandstone makes up approximately 20–30 modal % rock, and is a very fine-grained, recrystallized mud.

Dredge 38 yielded only one rock suitable for detailed study. Sample 38/1 is a conglomerate made up of clasts of an olivine+augite+plagioclase-phyric basaltic lava. Small former olivine phenocrysts (<4 modal %) are totally iddingsitized. Elongate tabular plagioclase phenocrysts (An_{50-70}) make up less than 2 modal % of the rock. Augite phenocrysts are small and fresh, but show marginal subophitic intergrowth with groundmass plagioclase laths. The groundmass is seriate-intergranular in texture, and dominated by laths of plagioclase separating subordinate small, granular, anhedral augite crystals. Small Fe Ti oxide crystals are common through the groundmass, and interstitial glassy mesostasis has been totally replaced by dark brown, clay–smectite aggregates.

Bunbury Basalt samples

Two samples of the Bunbury Basalt were studied, one (BB1, Table 3) from Bunbury Beach, and the other (BB3) from Gelorup Quarry. The rock is dark-grey, non-vesicular, and porphyritic with a glomeroporphyritic texture. Phenocrysts of plagioclase and occasional augite, and glomerocrysts of both plagioclase and clinopyroxene or both, are set within a finer-grained groundmass which comprises plagioclase, granular augite and Fe-oxides. Elongate plagioclase phenocrysts (An_{64-47}), up to 5 mm long, are both twinned and zoned and have occasional inclusions of fine-grained magnesian pigeonite ($Mg\#_{69-73}$), devitrified melt and groundmass material. Glomerocrysts range from 0.5 to 7 mm across. Some also contain patches of yellow clay (possibly after olivine), which also occurs as discrete anhedral to subhedral patches throughout the rest of the rock.

Clinopyroxene phenocrysts vary from elongate simply twinned crystals up to 2 mm long to euhedral crystals ~1 mm across, and they occasionally contain inclusions of plagioclase (An_{60}). They range in composition and may be predominantly either augite ($Mg\#_{69-78}$) or magnesian pigeonite ($Mg\#_{70-73}$, although one probed crystal has a core of subcalcic-augite ($Mg\#_{71}$) and a rim of augite ($Mg\#_{74}$).

The groundmass comprises elongate plagioclase laths (An_{61-58}) with an average length of 0.01 to 0.1 mm, many of which contain inclusions of clinopyroxene, twinned subhedral to euhedral clinopyroxene crystals (augite $Mg\#_{68-71}$) 0.1 to 0.05 mm in length, and skeletal to dendritic ilmenite and titaniferous magnetite grains, plus abundant interstitial devitrified brown glassy mesostasis.