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The petrology, geochemistry and implications of basalts dredged from the Rowley Terrace–Scott Plateau and Exmouth Plateau margins, northwestern Australia

Anthony J. Crawford[1] & Ulrich von Rad[2]

We report major and trace-element compositions of 14 basalts and dolerites dredged from seven sites along the outer rifted margin of northwestern Australia. Lavas from the margin of the Scott Plateau–Rowley Terrace, of interpreted Callovian–Oxfordian age, are evolved basalts and ferrobasalts with Zr/Nb from 5–17, and LREE-enriched REE patterns [(La/Yb)N from 3.4 to 8], and are T-MORB transitional to more P-MORB from the SW Indian Ridge and the Red Sea–Afar rift zone. They are significantly different from the unusually depleted N-MORB drilled less than 100 km farther west on the Argo Abyssal Plain at ODP Site 765. T- to P-MORB were also dredged at the foot of the southwestern corner of the Exmouth Plateau. This dredge site is only 80 km from ODP Site 766, which also yielded N-MORB. Basalts very similar to those drilled at ODP Site 766 were also dredged at a site only 20 km east of Site 766.

The evolved, mainly ferrobasaltic nature of the Rowley Terrace–Scott Plateau margin basalts, their T- to P-MORB compositional signatures, and their close spatial association with strongly depleted N-MORB resemble in many ways the lava pile formed during the last 4 m.y. along the southern Red Sea–Gulf of Aden–Asal–Afar region. Although the latter region is associated with the effects of the long-lived (~40 m.y.) Afar plume, a plume origin for the northwest Australian margin basalts is less easily demonstrated. Problems with the plume hypothesis for this region include (1) the remarkably rapid change from 'plume-influenced' MORB along the Rowley Terrace margin to depleted N-MORB at the foot of this margin at the eastern end of the Argo Abyssal Plain, requiring a sudden switch-off of the hypothetical plum; (2) the apparent recurrence of this same pattern of T-MORB to depleted N-MORB basalts 400 km farther south on the same margin some 20–25 m.y. later (Valanginian); and (3) the occurrence of perhaps more convincingly plume-related basalts that constitute the Wallaby Plateau, which formed as part of interpreted plume head eruptions of the Kerguelen plume around 115 Ma, and were apparently erupted onto Cuvier Abyssal Plain oceanic crust only probably 30–40 m.y. old.

Introduction

Rifting of continental crust to produce a new ocean has been considered to be either essentially amagmatic, in which case a non-volcanic passive margin results, or to involve intense basaltic magmatic activity, producing a volcanic passive margin. White & McKenzie (1989) associated volcanic passive margins with massive melt production resulting from decompression melting of a megaplume during attenuation and rifting of thinned continental crust. As one example of this, they argued that the evidence for considerable magmatism along the west Australian margin (Fig. 1), including seaward-dipping reflectors, massive volcanic plateaux, and seismic evidence for broad-scale magmatic underplating, suggested that a mantle plume ascended beneath this margin close to the time of breakup.

Breakup commenced along the volcanic passive continental margin of northwestern Australia around 155 Ma in the north, and around 20–25 Ma later farther south, in what is now the Cuvier, Gascoyne and Perth Abyssal plains (Exon et al., 1982; Powell et al., 1988; Veevers & Li, 1991; Veevers et al., 1991). This rifting began when the 'Argo Land' continental block rifted off northwestern Australia in the Callovian–Oxfordian (~155 Ma) and seafloor spreading produced oceanic crust from anomaly M26 until anomaly M16 (Berriasian). Celadonite cementing a basaltic breccia directly overlying basaltic basement at ODP Site 765 at the foot of Rowley Terrace (on the oldest oceanic crust of Argo Abyssal Plain) yielded a K–Ar date of 155.3 ± 3.4 Ma (Ludden, 1992), and provides a minimum breakup age for this region. Farther south, breakup along the Cuvier and Gascoyne Abyssal Plains began in the Valanginian, around M10 (130 Ma) to M11 (132 Ma), and around anomaly M9 (129 Ma) in the Perth Abyssal Plain. Spreading continued until anomaly M4–5 time (127 Ma), when the ridge jumped westwards, abandoning the ridge system in the Cuvier and Gascoyne Abyssal Plains (Fig. 1).

Magmatism significantly preceding breakup along this margin is known from evolved trachytic to rhyolitic lavas of mainly Rhaetian to Early Jurassic age (213–190 Ma) drilled in several Browse Basin wells landward of Scott Plateau, from the margins of the Wombat Plateau, and from the southwestern margin of the Exmouth Plateau (von Rad et al., 1992a, b; Exon & Buffler, 1992; von Stackelberg et al., 1980). These eruptions accompanied a widespread intracratonic rift phase along this margin, and were probably erupted in shallow water to subaerial conditions (von Rad & Exon, 1983; von Rad et al., 1990). Basalt flows alternate with earliest Jurassic shallow-water limestone in Scott Plateau well Scott Reef No. 1 (von Rad et al., 1992a, b). Little is known of the geochemistry of these early Jurassic volcanics.

More widely represented and voluminous than the pre-breakup Late Triassic to Early Jurassic volcanics on this margin are extensive basalts of Oxfordian–Callovian age, that Ramsay & Exon (1994 — this issue) show to cover an area of at least 25 000 km^2 beneath the northwestern Rowley Terrace. This same magmatic phase is observed as packets of seaward-dipping reflectors of interpreted Oxfordian–Callovian on the northeastern margin of the Argo Abyssal Plain adjacent to the Scott Plateau (Hinz et al., 1978). Similar reflectors, and a well-defined underplated crustal layer with velocity 7.2–7.3 km/s, occur along the western and southern margin of the Exmouth Plateau and adjacent to the Cuvier Abyssal Plain (Mutter et al., 1989; Hopper et al., 1992). The latter authors suggested that the Cuvier margin reflectors formed shortly after the Valanginian–Hauterivian breakup in this region.

During cruises 95 and 96 of the *Rig Seismic* to the northwestern Australian margin, samples of the Oxfordian–Callovian basalts were dredged from along the

[1] Dept of Geology, University of Tasmania, GPO Box 252C, Hobart, Tasmania 7001.
[2] Bundesanstalt fur Geowissenschaften und Rohstoffe, Postfach 51 01 53, Hannover 51, Germany.

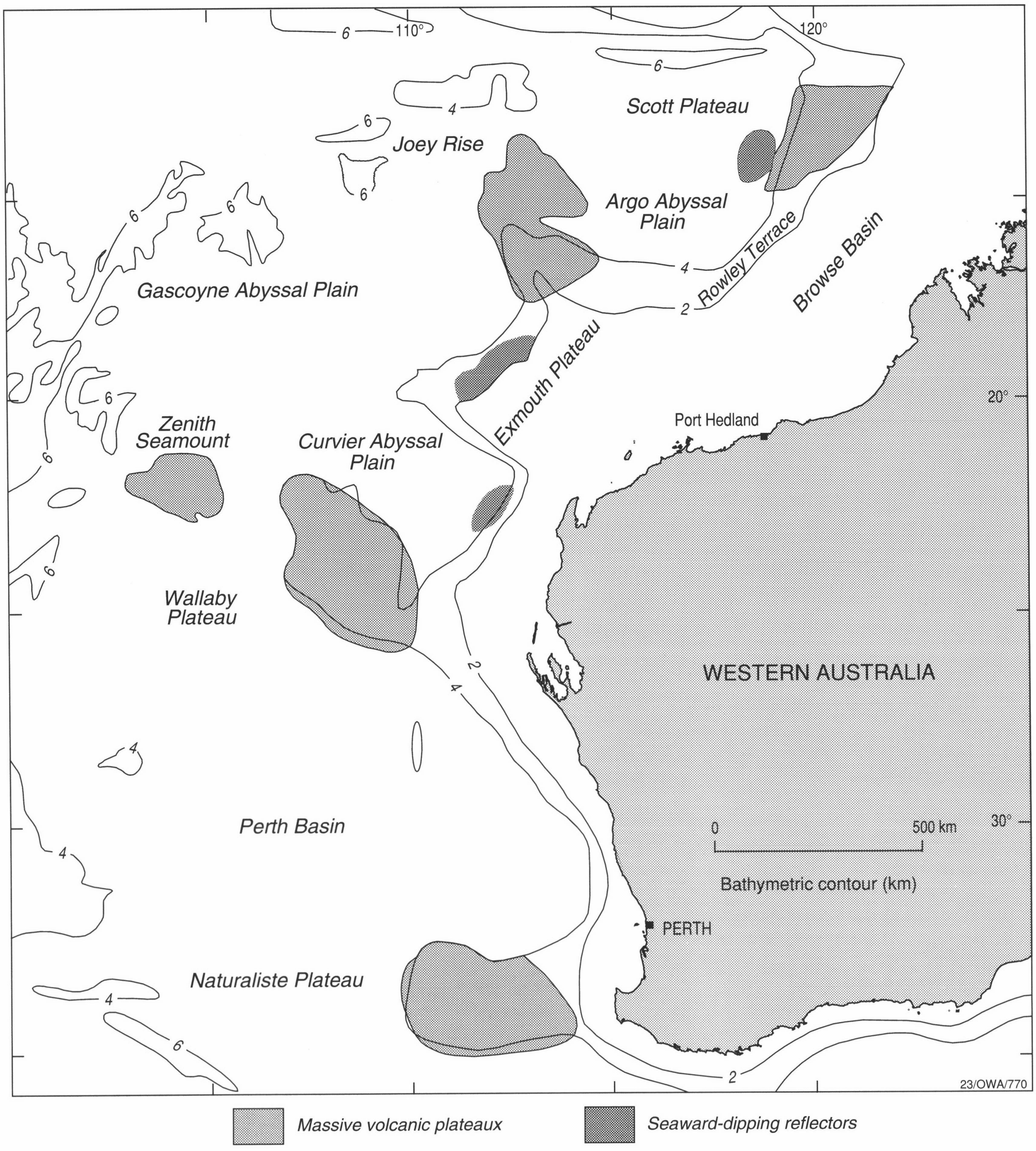

Figure 1. Map showing the the distribution of major volcanic provinces along the northwestern rifted margin of Australia, including the Exmouth and Scott Plateaux, Argo, Cuvier and Gascoyne Abyssal Plains, Wallaby Plateau and the Naturaliste Plateau and Perth Basin. Note massive volcanic plateaux argued by White and McKenzie (1989) to be related to inception of a mantle plume in this region. Note also regions of seaward-dipping reflectors. Modified from White and McKenzie (1989).

Rowley Terrace margin and the southwestern margin of the Exmouth Plateau. In this paper, we present a preliminary account of their major and trace-element geochemical features, and geodynamic implications. More detailed geochemical work, including Nd-Sr-Pb isotopic studies, are in progress (J.J. Mahoney & A.J. Crawford, in prep.).

Sampling

Precise dredge site locations are provided in the cruise final reports of AGSO (BMR) cruises 95 (Exon & Ramsay, 1990) and 96 (Colwell et al., 1990) to northwestern Australia. Those dredges which sampled volcanic rocks are described below, and dredge localities are shown on Figure 2.

Dredge 95/01: Northern slope of Taipan Canyon at water depths of 4650–3800 m. Seismic interpretation suggests that it should have recovered pre-Oxfordian rocks, and it sampled altered basaltic lavas, claystones of probable Jurassic age, a possibly Triassic red, calcite-veined claystone, and some Late Miocene and younger chalks and oozes. The basalts are mainly quite strongly altered. Most are quite evolved augite+plagioclase-phyric basaltic lavas, but 95/01–4A is a vesicular, sparsely plagioclase-phyric basalt with zeolite–smectite (chlorite) alteration; 95/01–6 is an oxidized and carbonate-altered augite+plagioclase-phyric basaltic lava breccia, and 95/01–2A is a strongly altered sparsely plagioclase-phyric hyaloclastite. Only relatively weakly-altered sample 95/0–4B was selected for analysis; it is a moderately augite+plagioclase-phyric basalt, with altered olivine microphenocrysts and common elongate ilmenite needles in a groundmass that includes slightly altered devitrified glassy mesostasis.

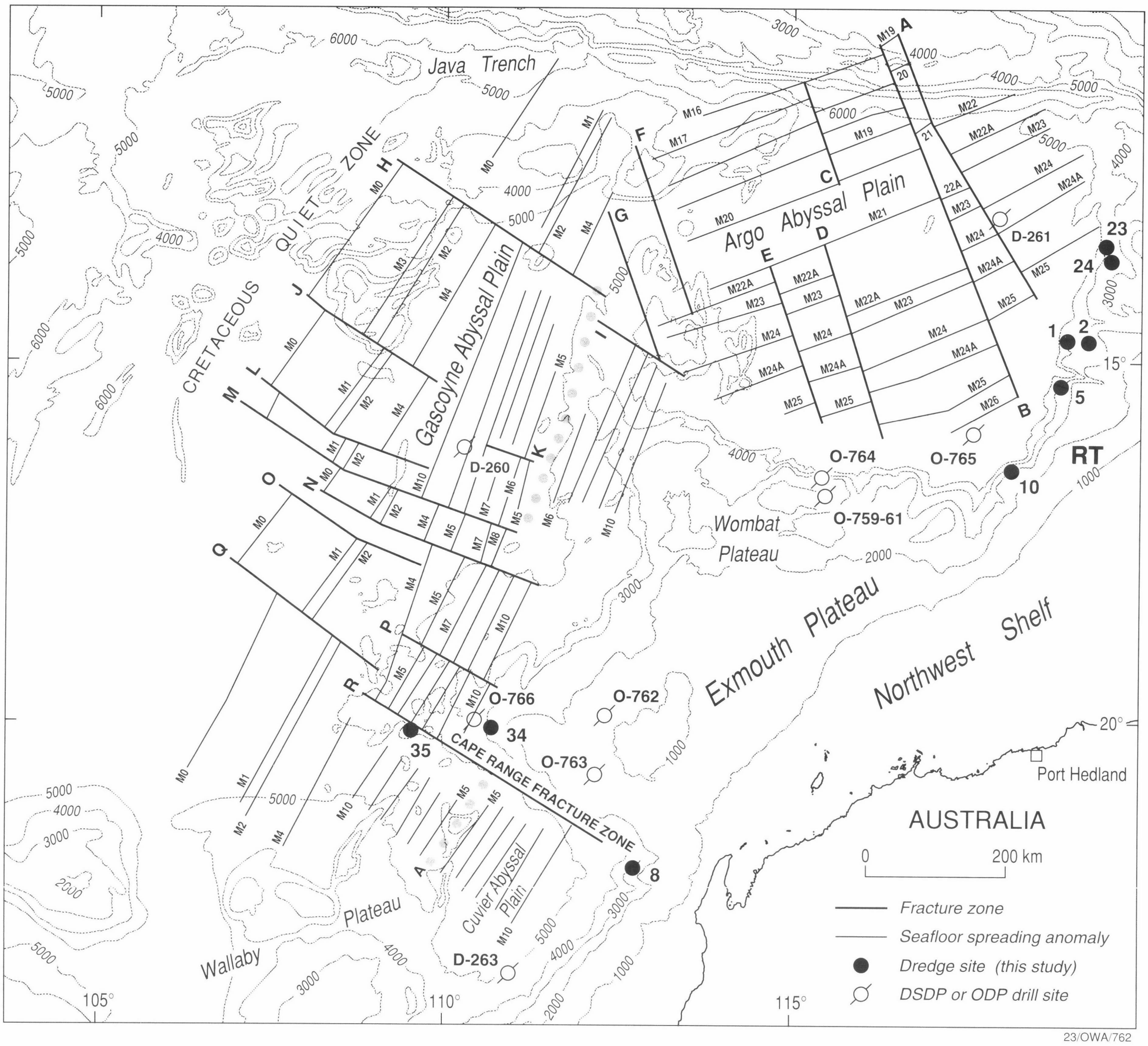

Figure 2. Map of the eastern Indian Ocean and northwestern continental margin of Australia showing Exmouth Plateau, Rowley Terrace (RT), magnetic lineations on the oceanic crust, and locations of dredge sites 95/01, 95/02, 95/05, 95/10, 96/08, 96/23, 96/24, 96/34 and 96/35. Also shown are locations of ODP Site 765 and 766. (Modified from von Rad et al., 1992.)

Dredge 95/02: Western slope of the northern arm of Taipan Canyon in water depths of 4000–3100 m. Seismic data suggest that it should have sampled similar pre-Oxfordian rocks to dredge 95/01. The dredge consisted largely of shallow-marine Oxfordian volcaniclastic grits with shelly fossil remains, minor altered basaltic volcanics, and minor foram ooze. Sample 95/02–1A is a rather altered augite+plagioclase-phyric evolved basaltic lava with altered olivine microphenocrysts, and it is essentially identical petrographically to 95/01–4B. Sample 95/02–2A is a calcite-cemented volcaniclastic grit with abundant dolerite clasts to at least 5 mm across, and common altered, devitrified glassy clasts.

Dredge 95/05: Northwest slope of Copperhead Canyon in 3850–3330-m water depth, across a section interpreted from seismic data to be mainly Jurassic–Cretaceous rocks. Palaeontological ages are Cretaceous (Colwell et al., 1994a, Table 2 — this issue). A few altered lavas were recovered in this dredge, which was dominated by ferruginous sandstones and ironstone breccias, and less abundant grey siltstones. The only sample selected for further study, 95/05–6A, is a grey, aphyric trachybasaltic to andesitic lava composed of an intersertal intergrowth of fresh plagioclase and slightly altered, granular augite and abundant FeTi oxides, with minor altered glassy mesostasis. One volcaniclastic sandstone also contained ~20 modal% terrigenous quartz clasts.

Dredge 95/10: Eastern slope of Clerke Canyon in water depths of 5325–4090 m. The dredge, which by inference from seismic data traversed a Late Triassic section, was dominated by a diverse haul of detrital marine sedimentary rocks, with common macrofossil-rich carbonates and around 30% of altered grey volcanics. Norian–Rhaetian ages have been determined palaeontologically (Colwell et al., 1994a, Table 2 — this issue). Most lavas are trachytic-textured sparsely plagioclase-phyric or aphyric basalts or trachybasalts, and two of these (95/10–14A and –15A) have been selected for detailed study; 14A has altered augite in the groundmass, whereas augite is fresh in 95/10–15A.

Dredge 96/08: Southeasternmost flank of Exmouth Plateau in water depths of 3550–3180 m. Sandstones and mudstones make up most of the dredge, but a few altered lavas were also recovered. The only rock selected for study is 96/08–10A, a microgabbroic shallow intrusive rock composed of intergrown fresh augite and calcic plagioclase, with interstitial FeTi oxide and minor chloritic alteration products.

Dredges 96/23 and 96/24: These dredge sites are from the flank of the Scott Plateau about 200 km north of dredge 95/01, and the age of one dredged rock is Toarcian (uppermost Lower Jurassic). Sample 96/23–4 is a moderately altered very sparsely plagioclase-phyric basalt with an intersertal groundmass composed of fresh augite, plagioclase, FeTi oxides and altered glass. Sample 96/24–1 is a moderately altered sparsely plagioclase-phyric basalt similar to 96/23–4.

Dredge 96/34: Southwestern corner of the Exmouth Plateau at 4000 m water depth, only 20 km east of ODP Site 766 located at the geophysical ocean–continent transition. The dredged sequence is interpreted to be of Valanginian age, based on the strong similarity of the dredged lavas to those drilled at ODP Site 766 just a short distance to the west, which occur within a late Valanginian (~134 Ma) sequence. Four samples were selected for detailed study. Sample 96/34–1 is a vesicular sparsely plagioclase-phyric trachybasalt with moderate smectite alteration. Sample 96/34–2 is a slightly altered sparsely plagioclase-phyric microlitic glassy basalt, and samples 96/34–3 and –4 are respectively finer and coarser-grained dolerites, with quite common iddingsite+calcite-altered olivine phenocrysts and either fresh or clay+zeolite-altered clusters of plagioclase phenocrysts in a holocrystalline, ophitic-textured groundmass composed of pinkish augite and fresh plagioclase, with subordinate interstitial FeTi oxides.

Dredge 96/35: Located 80 km west-southwest of ODP Site 766 on the southwestern corner of the Exmouth Plateau, at the foot of the slope at about 4000 m water depth. Dredged rocks are interpreted to be of Valanginian age (Colwell et al., 1990).The single sample selected for analysis is a strongly altered plagioclase-rich evolved dolerite, with abundant equant large FeTi oxides and altered augite; chlorite–smectite alteration is common, and veinlets of red-brown manganiferous material are not uncommon.

Whole rock geochemistry

Fourteen least-altered samples were selected for detailed geochemical study, and have been analyzed by XRF spectrometry at the Department of Geology, University of Tasmania, for major and trace elements (Table 1); nine of these were analyzed for rare earth elements (REE), Ta, Hf and Th using instrumental neutron activation analysis at Becquerel Laboratories (Sydney). As all samples were slightly to strongly altered, all analyses have been recalculated to 100% volatile-free, and loss on ignition is reported together with original totals below the recalculated major element analyses in Table 1. The high and variable ignition losses of the analyzed samples preclude evaluation of magmatic affinities using norms, and emphasis is placed on those elements (Ti, Zr, Y, Nb, Hf, Th, REE) considered to be immobile during low-grade alteration of basaltic rocks.

Compositions of the analyzed samples are shown as Harker diagrams (Fig. 3), with important oxides and trace elements plotted against the fractionation index FeO*/MgO. Two compositional groups are distinguished on the basis of trace element contents and REE patterns (see below): Group 1 comprises samples from dredges 1 2, 5, 10, 23 and 24, all from along the Rowley Terrace margin, and also samples 96/8–10A and 96/35–4 from the southeastern and southwestern corners, respectively, of the Exmouth Plateau; whereas Group 2 is represented by the four analyzed samples from dredge 34 from near the base of the southwestern escarpment of the Exmouth Plateau, 80 km east-northeast of dredge site 96/35.

Rowley Terrace Margin lavas and dredges 96/8 and 96/35

The Rowley Terrace margin (herein RT) and southern Exmouth Plateau dredged lavas and dolerites are of evolved basaltic–ferrobasaltic compositions with FeO*/MgO values greater than 1.78, and correspondingly high TiO_2 (3.0–6.0%) and P_2O_5 (0.36–1.6%) contents. In general, these rocks fall within the compositional fields defined by basalts dredged from the SW Indian Ocean ridges (Le Roex et al., 1983; Melson et al., 1977), an exception being the depletion of CaO and strong enrichment of Na_2O in 95/10–14B, which are obviously secondary alteration effects. The K_2O (and related elements Rb and Ba) contents of the RT lavas vary in an irregular manner, although still broadly following the trend defined by the Indian Ocean MORB; this possibly reflects the significant alteration of these rocks, as shown by their high and variable loss on ignition values (3.1–8.2%).

SW Exmouth Plateau

The four analyzed rocks from dredge 96/34 are less evolved, significantly less enriched in TiO_2, P_2O_5 and Na_2O, and have higher CaO contents at any value of FeO*/MgO than the RT margin samples. As for the RT lavas, the K_2O contents of dredge 96/34 rocks are high and rather variable (0.4–1.8%), posssibly reflecting alteration.

Strongly altered basalt 96/35–4 has very high LOI (13.5%), and shows massive enrichment of MnO (reflected petrographically in the amorphous brown–black manganiferous oxide–hydroxide material throughout the matrix of this basalt), with coupled enrichment of Ni (1000 ppm) and Ce and Pb (520 and 510 ppm, respectively, measured by XRF), and a pronounced depletion of CaO (2.7%). Despite this strong seafloor alteration, the immobile elements show that it is a ferrobasalt with high TiO_2 (3.7%), V (695 ppm), P_2O_5 (0.65%), Zr (476 ppm), and Nb (28.7 ppm), and is very similar to the ferrobasalts from farther north along the RT margin. An important point to note is that Th is remarkably enriched to 37 ppm (measured by XRF) in this sample; this is discussed further on.

Significant compositional differences are shown by the high field strength element (HFSE; e.g. Ti, Zr, Y, Nb, Hf) contents and ratios of the RT lavas and 96/35–4 relative to the rocks from SW Exmouth Plateau dredge 96/34. This is shown, for example, on the Zr/Nb versus Zr/Y(Fig. 4a) and (La/Yb)N (Fig. 4b) diagrams in which the 96/34 rocks fall at notably higher Zr/Nb values and lower Zr/Y and (La/Yb)N values than the RT margin and 96/35 lavas. This difference is also reflected in their respective rare earth element (REE) patterns (Fig. 5), with the dredge 96/34 rocks having broad, LREE-depleted patterns with slight HREE depletion, contrasting with the

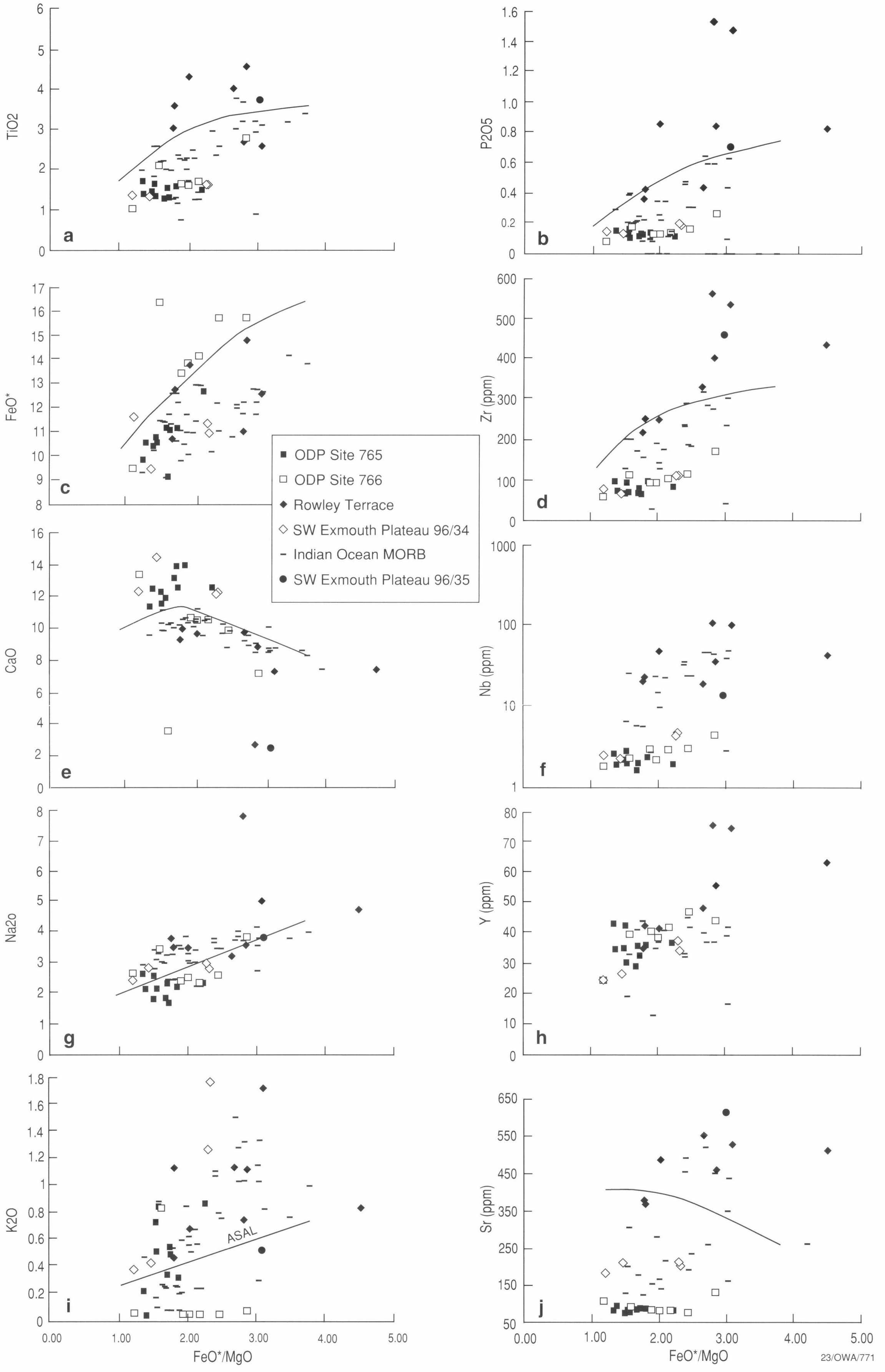

Figure 3. Harker diagrams for dredged samples from the northwestern Australian margin. Also shown are selected basaltic glasses from the Indian Ocean (Melson et al., 1977) and basalts from the plume-affected SW Indian Ridge (Le Roex et al., 1983; 1989). A best-fit line for data for the Asal Rift in the Horn of Africa region is also shown (from Piccirillo et al., 1979).

Table 1: Wholerock analyses of dredged basalts from the Rowley Terrace and SW Exmouth Plateau margin. LOI = Loss on Ignition; BDL = below detection limit.

Identification	*95/01–4B*	*95/05–6A*	*95/10–13A*	*95/10–14B*	*95/10–15A*	*96/8–10A*	*96/23–4*	*96/24–1*	*96/34–1*	*96/34–2*	*96/34–3*	*96/34–4*	*96/35–4*
SiO_2	51.66	51.50	46.73	54.08	52.28	48.58	49.76	49.30	50.49	51.66	47.36	50.70	42.45
TiO_2	3.03	6.00	4.33	2.67	2.55	4.02	4.57	3.57	1.60	1.61	1.34	1.31	3.72
Al_2O_3	17.06	19.46	16.55	17.70	17.47	15.91	14.49	15.69	17.32	17.96	16.06	17.99	14.47
Fe_2O_3	11.79	9.97	15.29	12.12	13.84	13.70	16.35	14.03	12.03	12.47	12.83	10.43	19.13
MnO	0.17	0.09	0.25	0.23	0.31	0.19	0.28	0.20	0.19	0.21	0.32	0.17	6.25
MgO	5.97	1.99	6.84	3.88	4.03	4.63	5.16	7.00	4.69	4.92	9.56	6.46	6.29
CaO	9.22	7.38	9.64	2.55	7.28	9.71	8.85	9.95	12.17	11.99	12.23	14.36	2.74
Na_2O	3.76	4.68	3.45	7.77	4.97	3.17	3.54	3.45	2.76	2.94	2.41	2.78	3.72
K_2O	1.14	0.84	0.69	0.75	1.73	1.15	1.13	0.46	1.77	1.27	0.38	0.43	0.54
P_2O_5	0.36	0.82	0.85	1.52	1.46	0.44	0.84	0.43	0.19	0.20	0.14	0.13	0.65
LOI	4.64	5.85	4.13	5.15	3.13	6.75	3.82	4.65	5.06	3.57	5.86	3.93	13.46
FeO*/MgO	1.78	4.51	2.01	2.81	3.09	2.66	2.85	1.80	2.31	2.28	1.21	1.45	2.74
Ni	80	15	61	10	8	10	37	82	64	74	173	138	1178
Cr	222	39	131	2	2	3	7	274	351	345	365	359	331
V	349	539	405	93	93	433	363	361	340	366	320	315	695
Sc	45	55	45	25	22	34	32	42	45	47	36	40	47
Zr	219	434	248	563	536	329	402	250	110	109	76	72	476
Nb	20.8	44.0	48.8	108.1	101.9	18.9	36.2	23.7	4.8	4.4	2.5	2.3	28.7
Y	35	63	42	75	74	48	56	43	34	37	25	26	114
Sr	375	507	484	932	523	547	457	362	201	212	182	209	607
Rb	37	9	11	18	37	50	27	10	36	27	8	9	16
Ba	182	285	227	139	625	329	274	126	54	43	38	27	497
La	14.20	31.36	29.94		69.60	27.21	30.92	16.50		6.36		3.22	
Ce	35.07	76.70	70.91		159.53	64.14	75.94	40.43		17.05		9.03	
Nd	22.07	47.53	40.54		86.87	39.23	48.08	28.41		12.78		7.87	
Sm	6.34	12.78	9.89		17.70	9.68	12.67	7.74		4.02		2.88	
Eu	2.17	4.45	3.43		5.88	2.97	4.38	2.71		1.58		1.15	
Tb	1.08	1.99	1.42		2.56	1.44	1.99	1.46		0.92		0.67	
Ho	1.27	2.13	1.56		2.51	1.75	2.16	1.75		1.22		0.90	
Yb	2.25	3.93	3.22		5.74	3.93	3.52	3.22		2.98		2.00	
Lu	0.27	0.55	0.42		0.85	0.52	0.46	0.39		0.38		0.27	
Hf	5.02	10.30	5.02		11.04	7.34	9.24	6.15		2.53		1.79	
Ta	1.20	3.07	3.17		6.80	1.53	3.07	1.63		0.67		0.66	
Th	1.44	3.32	2.10		5.38	7.48	2.26	1.72		0.83			
(La/Sm)N	1.37	1.50	1.85		2.40	1.71	1.49	1.30		0.96		0.68	
(La/Yb)N	4.17	5.26	6.13		8.01	4.57	5.80	3.38		1.41		1.06	
Zr/Nb	10.53	9.85	5.08	5.21	5.26	17.40	11.12	10.55	22.95	25.00	30.43	31.43	

strongly LREE-enriched RT margin basalts. REE were not determined by INAA for sample 96/35–4; however, XRF analyses yielded the following values: La 134 ppm, Ce 520 ppm and Nd 142 ppm. These data indicate a strongly LREE-enriched pattern for this sample, with a prominent positive Ce anomaly resulting from oxidative seafloor alteration. The significance of these differences in HFSE and REE contents between the 96/34 rocks and the evolved, LREE-enriched basalts and ferrobasalts from the RT margin and dredge site 96/35 is discussed below.

Affinities of the dredged basalts

In the Harker diagrams in Figure 3, the dredged basalts from the northwestern margin of Australia are compared with basalts drilled at ODP Sites 765 and 766 in the same region, and with a selected suite of basalts and basaltic glasses from Indian Ocean spreading centres (Le Roex et al., 1983; 1989; Melson et al., 1977). Also shown

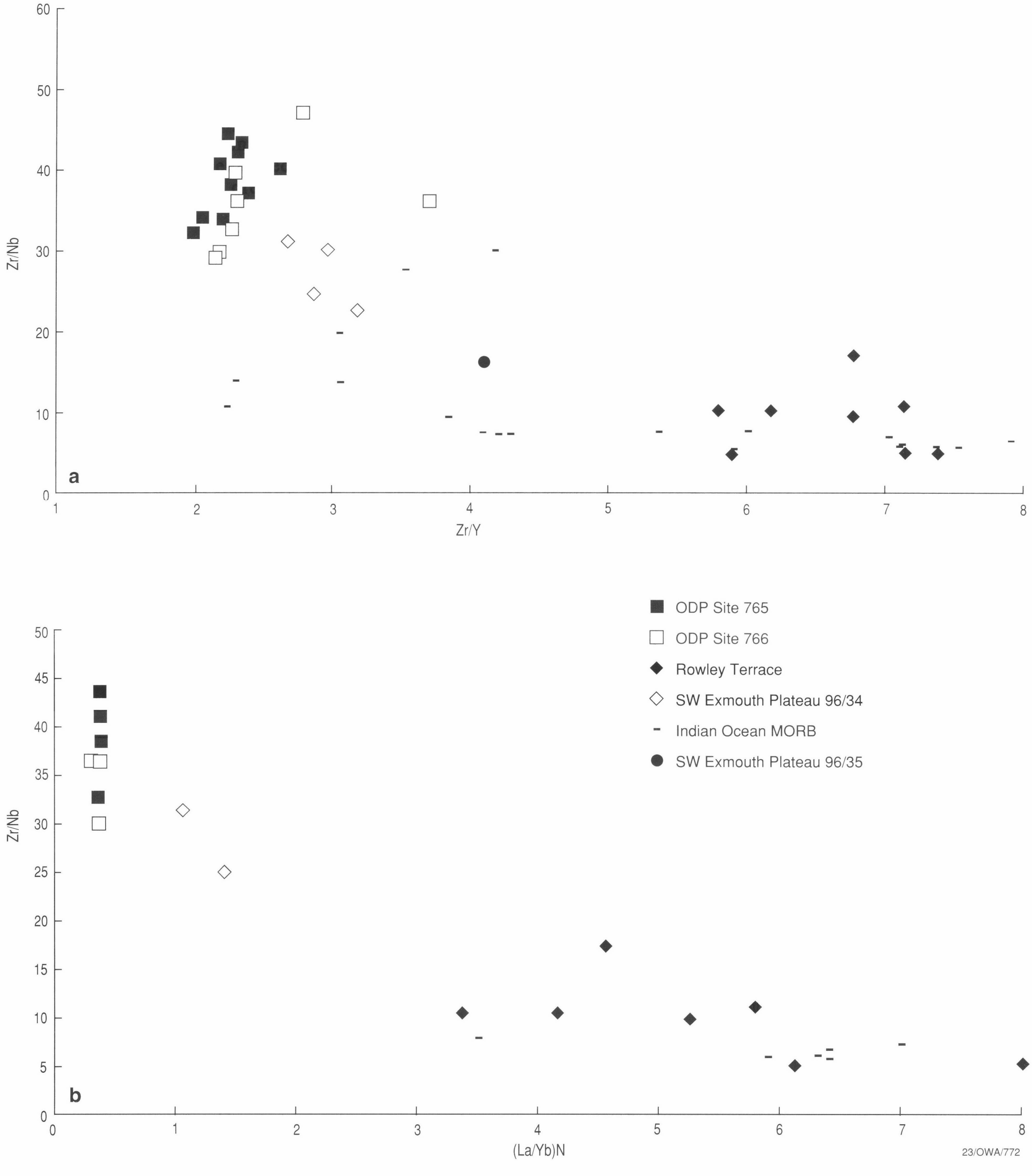

Figure 4. Plots of Zr/Nb versus (a) Zr/Y and (b) (La/Yb)N for basalts from Rowley Terrace and the southwestern corner of the Exmouth Plateau, from ODP Sites 765 and 766, selected basaltic glasses from the Indian Ocean (Melson et al., 1977) and basalts from the plume-affected SW Indian Ridge (Le Roex et al., 1983, 1989).

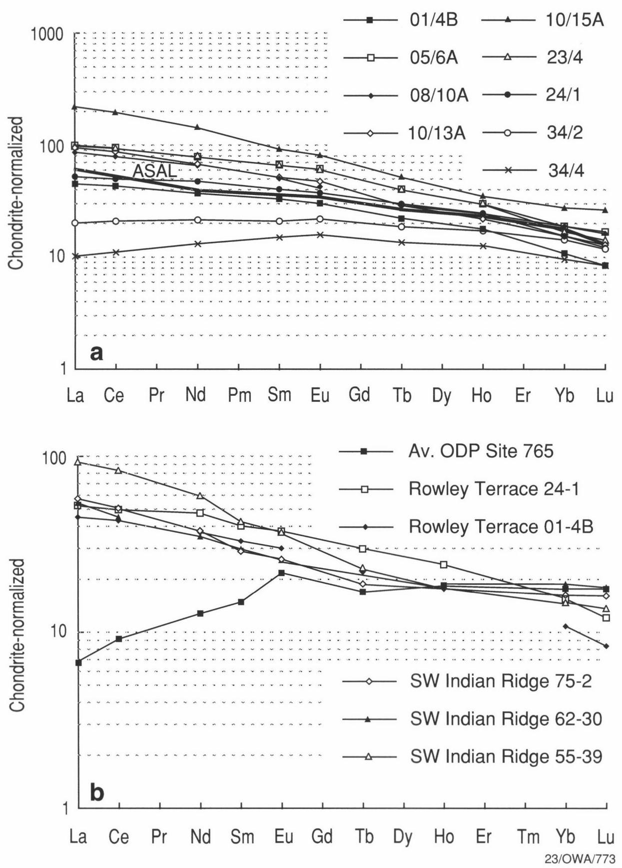

Figure 5. Chondrite-normalized REE patterns for (a) basalts from the SW Exmouth Plateau (34/2 and 34/4) and the Rowley Terrace; also shown is an average pattern for the Asal rift ferro-tholeiites from the Afar region on the Horn of Africa (Schilling et al., 1992), and (b) representative Rowley Terrace least-evolved basalt REE patterns compared with an average pattern for the depleted N-MORB drilled at ODP Site 765 (Ludden and Dionne, 1992), and three representative patterns for T- to P-type tholeiitic basalts from the SW Indian Ridge (Le Roex et al., 1983).

is a best-fit line for the well-defined magmatic trends (Piccirillo et al., 1979) for modern basalts from the Asal Rift in the Afar triangle, adjacent to the southernmost Red Sea. Selection of the SW Indian Ridge basalts for plotting on these Harker diagrams, many of which are from spreading ridge segments along the SW Indian Ridge that are significantly influenced by the Bouvet mantle plume (Le Roex et al., 1983, 1989), was deliberately biased towards more fractionated lavas that are comparable in terms of extents of fractionation with the evolved samples that form the focus of this study. Important points to be noted from the Harker diagrams are that the RT margin basalts are more strongly enriched in TiO_2, P_2O_5 and Zr at any FeO*/MgO value than even plume-related basalts from the SW Indian Ridge, although other major elements fall within the fields defined by the Indian Ocean MORB. Also, the SW Exmouth Plateau ferrobasalt 96/35–4 is directly comparable with the RT ferrobasalts, and notably unlike the N-MORB lavas drilled at nearby ODP Site 766. Compared with the drilled basaltic lavas and sills from ODP Sites 765 and 766, the RT lavas and 96/35–4 are strongly enriched in TiO_2, P_2O_5, Zr, Nb and especially Sr, and depleted in CaO.

Key element ratios unaffected by fractionation, such as Zr/Nb, La/Nb, Ta/La and Th/La are useful in distinguishing the affinities of these lavas. According to the classification scheme for oceanic basalts (MORB) proposed by Le Roex et al. (1983), normal (N-) MORB have Zr/Nb> 17, Y/Nb> 8 and chondrite-normalized La/Yb values (herein (La/Yb)N) <1.1. Enriched, or plume (P-) MORB have Zr/Nb< 8, Y/Nb values from 0.9–1.2, and (La/Yb)N> 4.8. Compositions falling between these extremes are classified as transitional (T-) MORB.

On the basis of their low Zr/Nb (~5) and Y/Nb (0.69–0.85) values and strongly LREE-enriched REE patterns (Figs 4, 5), RT basalts from dredge 95/10 are P-MORB. The remainder of the Group 1 basalts (Zr/Nb 9 to 17, Y/Nb 1.4 to 2.5, and (La/Yb)N values from 3.4 to 4.1 are T-MORB, as is the altered ferrobasalt 96/35–4. Two REE patterns of the least evolved analyzed RT basalts are compared in Figure 5 with patterns for plume-influenced basalts from the SW Indian Ridge, and an average pattern for the Asal Rift basalts (Schilling et al., 1991), and a strong similarity is evident. In contrast, Group 2 basalts, with Zr/Nb from 23 to 31, Y/Nb from 7 to 11 and (La/Yb)N values of 1.06 and 1.4 for the two analyzed

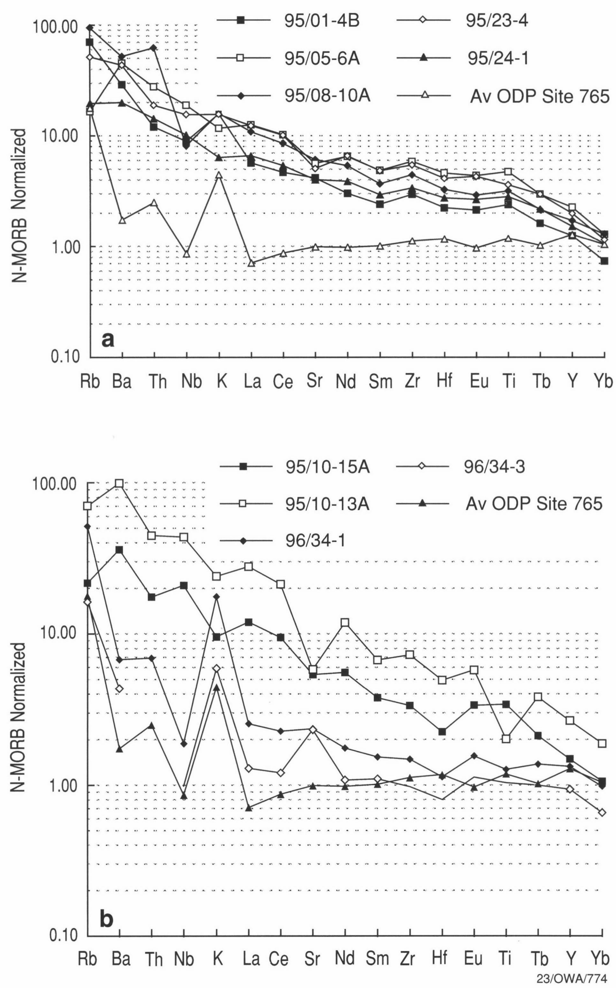

Figure 6. N-MORB normalized patterns (normalizing values from Sun and McDonough, 1989) for (a) T-MORB from the Rowley Terrace margin, and (b) P-MORB from the Rowley Terrace margin (95/10) and N-MORB from dredge 96/34 on the southwestern corner of the Exmouth Plateau. In both diagrams, the average ODP Site 765 N-MORB are shown for comparison.

samples, are best classified as N-MORB. Figure 6 shows N-MORB-normalized element variation patterns for analyzed samples from each of the above groups, a pattern for the average N-MORB drilled at ODP Site 765, and an average pattern for the Asal Rift basalts (Piccirillo et al., 1979; Schilling et al., 1991). Whereas the P- and T-MORB from the RT region are clearly distinguished from the Site 765 N-MORB on the basis of their pronounced enrichment in LREE and incompatible elements, those N-MORB dredged at 96/34 are very similar to the Site 765 basalts, the only difference being slightly more depleted LREE in the latter. This similarity extends to identical anomalous enrichments in Rb, Th and K in the 96/34 lavas and those from ODP Site 765; the same style of anomalous enrichment is evident in RT basalt 96/08–10A and highly altered ferrobasalt 96/35–4. Without isotopic data, it is difficult to determine with confidence whether these unusual patterns reflect some crustal contamination (or involvement of crustally contaminated subcontinental mantle lithosphere), or whether they are simply alteration effects. Although Th is regarded as an immobile element during seafloor alteration of basalts, recent work by Bienvenu et al. (1990) showed clearly that Th is strongly enriched in the alteration products of glassy oceanic basalts. In this light, and the fact that anomalously high K, Rb and Th contents occur in the most altered samples (as based on petrographic examination and LOI contents), we suggest that the positive spikes for Rb, K and Th in the patterns shown in Figure 6 are alteration-related.

We draw attention to the strong compositional similarity between the RT ferrobasalts and samples 96/8–10A and 96/35–4 from the southeastern and southwestern corners, respectively, of the Exmouth Plateau, some 400 km farther south. In a similar manner that the RT P- and T-MORB are located close to the Oxfordian N-MORB drilled at ODP Site 765, so is 96/8–10A (dredged from the southeastern margin of the Exmouth Plateau, southeast of dredge 35) and 96/35–4 (from less than 80 km from the Valanginian N-MORB drilled at ODP Site 766). Either the southern Exmouth margin samples are from an extensive continuation of the RT lava pile stepped some 400 km farther south and 400 km west (see Fig. 1), or more plausibly perhaps, the same magma generation processes led to production of P- and T-MORB followed by N-MORB during the Valanginian along the Cuvier Abyssal Plain margin, and during the Oxfordian some 30 m.y. earlier on the RT margin.

Discussion

The extensive Oxfordian–Callovian basaltic sequences along the Rowley Terrace margin of northwestern Australia are composed of quite strongly fractionated basalts and ferrobasalts that vary in key element signatures from T-MORB to P-MORB, with the former being dominant if the dredge volumes of each magma type are representative of their proportions in the volcanic pile. These basalts were produced immediately prior to breakup along this margin, and magma compositions changed rapidly at breakup towards the strongly depleted N-MORB compositions drilled at ODP Site 765, less than 100 km to the west.

This rapid change in magma composition accompanying break-up is clearly shown by plots such as Zr/Nb versus Zr/Y (Fig. 4a) and Zr/Nb versus $(La/Y)_N$ (Fig. 4b). A simple explanation of the data is mixing between melts derived from a depleted asthenospheric N-MORB mantle source, and melts derived from a more enriched 'plume-type' source (e.g. Le Roex et al., 1983, 1989). Earlier-formed melts related to the pre-breakup magmatism are derived from a source with more 'plume' component [i.e. high $(La/Y)_N$, low Zr/Nb], which is 'switched off' or absent by the time the Site 765 N-MORB are erupted.

A mantle plume origin for the NW Australian margin?

The pronounced similarity in the compositional characteristics of the RT margin lavas with the plume-affected T- and P-MORB from the SW Indian Ridge supports the claim that a mantle plume may have been involved in the lithospheric stretching, rifting and breakup along this margin. The low $(La/Nb)_N$ values for the RT lavas (<1) are unlike those (>1.5) for basalts in which involvement of subcontinental lithospheric mantle is postulated (Mahoney et al., in press; Colwell et al., 1994b — this issue). Thus, if a plume did generate the RT basalts, it apparently did not interact with the subcontinental lithosphere along this margin, but yielded the RT basalt parental magmas by direct partial melting of the plume (plus entrained asthenosphere?) itself. However, a key point is that *by the time of breakup*, voluminous basaltic magmatism such as that sampled at ODP Site 765 and 766 shows no plume signature at all. Rather, it bears the signature of strongly depleted N-MORB that appear to have been generated by relatively high degrees of partial melting compared to even typical N-MORB (Ludden & Dionne, 1992). No apparent plume trace extends from this margin, and the plume seems to have abruptly shut down at this time.

An alternative to the plume scenario for the generation of the Late Triassic–Jurassic basalts along the northwestern Australian margin involves passive mantle ascent and melting, in response to lithospheric stretching and extension in this area starting around 155 Ma, and jumping southward to commence at ~130 Ma on the Cuvier margin.. In this model, which incorporates aspects of the Mutter et al. (1988) and Hopper et al. (1992) models, early magmatism derives from the 'low melting temperature' enriched component in the asthenospheric mantle, possibly present as veins in more refractory depleted mantle (Altherr et al., 1990). The binary mixing (two components) evident from trace element data for the RT basalts would involve depleted asthenospheric mantle as one end-member, and the low-melting veins as the other. Once strong extension begins, a short burst of more rapid upwelling and convection leads to more extensive melting of (residual, refractory?) mantle, producing strongly LREE-depleted N-MORB (Mutter et al., 1988), before magmatism settles into the steady-state N-MORB generation mode recorded by the magnetic anomalies in both the Argo and Cuvier–Gascoyne–Perth abyssal plains. This scenario broadly supports the model proposed by Mutter et al. (1988) and Hopper et al. (1992) in which the earliest stages of breakup along this margin are characterized by rapid rifting and extension, leading to establishment of strong lateral temperature gradients in the subjacent upper mantle. This forced small-scale convection, increased mantle upwelling and increased amounts of partial melting, and a significant increase in the volume of magma generated during this decompression by partial melting. The 'more depleted than normal' N-MORB basalts at both ODP Sites 765 and 766 have more extreme compositional characteristics [higher CaO/Na_2O, lower $(La/Sm)_N$, and Ti/Zr values (av. 110) than in typical SW Indian Ridge or

Mid-Indian triple junction MORB] expected of relatively high-degree melts of an N-MORB mantle source, as pointed out by Ludden & Dionne (1992).

Red Sea–Gulf of Aden–Afar analogy

A very similar array of basalt compositions to that documented along the northwestern Australian margin is recorded from the Red Sea–Gulf of Aden–Gulf of Tajoura region. In this area, an extended period of crustal attenuation and rifting was accompanied by extensive flood basalt magmatism around 20–25 Ma (Sebai et al., 1991); these flood basalts are correlated by White & McKenzie (1989) with arrival beneath the region of a plume head on the order of 1000 km across. Volcanism waned from 20 Ma until around 4.5 Ma, when renewed extension and an accompanying burst of basaltic magmatism led to breakup and the opening of the Red Sea and the western end of the Gulf of Aden, both of which are still actively spreading, and erupting P-, through T-, to N-MORB where extension is greatest.

Considering only the latter stages (last 10 m.y.) of crustal extension and magmatism in the Horn of Africa region, some impressive similarities with the Late Jurassic–Early Cretaceous northwestern Australian margin are evident. The dominant basalt compositional variant erupted in the southern Red Sea–Gulf of Tajoura region since 4 Ma is T-MORB, many of which are transitional to E-MORB, with Zr/Nb ranging from 11.2 to 7.0, averaging 8.1, and (La/Yb)N in the range 1.3 to 5.3, averaging around 3 (Barrat et al., 1990; Schilling et al., 1992). However, in the axial valley of the Red Sea, typical N-MORB basalts are recorded, and significantly, some are strikingly depleted in LREE, akin to the ODP Site 765 and 766 basalts from the northwestern Australian margin. Basalts from the extensive on-land ridge segment of the Asal (Ardoukoba) rift zone show pronounced compositional similarities to the RT margin basalts (Figs 3, 4, 5), and are dominated by evolved basalts and ferrobasalts with high TiO_2, P_2O_5 and HFSE abundances, and moderately to strongly LREE-enriched REE patterns (Barrat et al., 1990; Schilling et al., 1992).

Schilling et al. (1992) have presented a case, based on extensive trace element and isotopic studies of basalts from the Red Sea–Afar area, that production of the post-40 Ma magmatism in this region involved both passive lithospheric extension (60–40 Ma) and impingement and flattening of a torus-like mantle plume on the base of the lithosphere around 30 Ma. Prior to plume arrival, diffuse lithospheric extension was accompanied by only minor magmatic activity, derived from the asthenosphere. Arrival of the plume at the base of the lithosphere, and flattening of the plume head, produced the Ethiopian–Yemen plateau basalts, which appear to require involvement of some component from the continental lithospheric mantle incorporated into the plume during thermal erosion along the base of the lithosphere. The tail of the plume is now dragged northwards by movement in that direction of the African plate, and asthenospheric mantle incorporated into the plume centre provides N-MORB basalts to the developing Red Sea and Gulf of Aden rifts, while the plume conduit itself provides alkaline magmas that form small islands in the southern Red Sea. This clearly requires important lateral and vertical heterogeneity in the Afar plume at the present time.

For the northwestern Australian margin, an extensive plateau basalt formation correlated with the Ethiopian flood basalts either remains undiscovered, or does not exist. Strong geological evidence exists for crustal stretching and block faulting along this margin before onset of the main Callovian–Oxfordian magmatic event recorded by the RT basalts. The compositions and significance of the limited volumes of Late Triassic–Jurassic volcanics accompanying this block faulting are still to be determined. The main magmatic event at around 155 Ma along this margin involves a significant 'plume' input, and shows no evidence of input from thermally eroded subcontinental lithospheric mantle. It might be argued that the voluminous RT basalts are the northwest Australian analogue of the Ethiopian plateau basalts, and record the arrival beneath the region of the plume head. However, the rapid (<5 Ma) switch from 'plume'-dominated basalts to depleted N-MORB (ODP Site 765) demands, as for the current Afar setting, massive heterogeneities in the plume, and in the case of northwestern Australia, the plume appears to have shut off abruptly at this stage.

A second complicating factor with the Afar plume analogy for northwestern Australia's Mesozoic magmatic evolution is that the sequence of magmatism that produced the RT lavas followed by highly depleted MORB at Site 765 around 155 Ma appears to have repeated itself along the Cuvier margin 500 km to the south at around 130 Ma. Furthermore, as discussed in Colwell et al. (1994b — this issue), it appears that the flood basalts of the Wallaby Plateau were superimposed, possibly around 115 Ma, on relatively new oceanic crust of the Cuvier Abyssal Plain following impact of the massive Kerguelen plume head on the base of the lithosphere in this region (and extending for more than 2000 km southwards and to the west). This represents a complicated (albeit hypothetical) scenario, in which two major mantle plumes affect the northwestern Australian margin within 40 m.y. The first evolved rapidly into a setting in which strongly depleted N-MORB are produced, then typical N-MORB, and plume-tail related alkali basalts are unknown; the second shows no such evolution, and evolved into the well-mapped Kerguelen plume.

Isotope studies on the northwest Australian margin basalts described herein are still in progress, and should better constrain the nature and composition of the source of these extensive lavas. If a mantle plume was not involved in the genesis of these basalts, we need to investigate a problem common to all models denying the role of a mantle plume in rifting and breakup leading to ocean opening, namely, why the RT (and other continental rift) lavas bear a compositional imprint essentially identical in major and trace element terms to plume-affected MORB. Future ODP drilling of massive seaward-dipping reflector sequences along the north Atlantic margin may provide key evidence to choose between these models.

Conclusions

Callovian–Oxfordian (~155 Ma) basalts form a massive welt along the Rowley Terrace–Scott Plateau margin of northwestern Australia. They are evolved basalts and ferrobasalts with affinities extending from T-MORB through to plume-influenced P-MORB, and on available evidence show no sign of involvement of the subcontinental lithospheric mantle in their petrogenesis. A rapid change to strongly depleted N-MORB is recorded along this margin by the basalts recovered at ODP Site 765 only 100 km west of the Rowley Terrace margin.

A single dredge at the foot of the southwestern corner of the Exmouth Plateau yielded highly altered ferrobasalts with immobile element signatures identical to those of the Rowley Terrace margin basalts 500 km farther north. Some 80 km farther east, and still on the foot of the southwestern Exmouth Plateau scarp, one dredge station, and also ODP Site 766 produced N-MORB basalts and sills of interpreted Valanginian age (~130 Ma).

Two quite different classes of models for the development of this continental margin might be considered. The first class, as proposed by White & McKenzie (1989) involves, as a major 'enforcer', a mantle plume that probably affected more than 1000 km of this margin. Problems with this model are the apparent absence of plume head-related plateau flood basalts, the rapid switch-off of the plume shortly after generation of the RT basalts, and the jump to strongly depleted N-MORB compositions during earliest breakup magmatism. A second class of model does not involve a mantle plume, and implies that lithospheric extension leads asthenospheric mantle to passively ascend beneath the developing rift. Earliest erupted lavas are hybrids between an enriched, easily fusible component probably present as veins, and the more typical depleted asthenospheric reservoir that hosts these veins. The convective partial melting model of Mutter et al. (1988) and Hopper et al. (1992) can be accommodated within the latter model. In addition, recent documentation by Holbrook & Kelemen (1993) of extensive seaward-dipping reflectors along the Atlantic coast of USA, with no associated plume trace, suggest that mantle plumes may not be required to produce the extensive basaltic magmatism associated with several of the Earth's major volcanic passive margins.

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