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Petrochemistry of the lavas from Proterozoic Dalma volcanic belt, Singhbhum, eastern India

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With 10 figures and 3 tables

Zusammenfassung

Der Vulkangürtel von Dalma liegt in der präkambrischen Region Singhbhum in Ostindien. Aufgeschlossen ist der Dalma-Gürtel im mittleren Bereich eines geradlinigen Beckens, das im Süden durch Basement des Archaikums begrenzt wird. Die Laven befinden sich in einer geringmetamorphen Umgebung und weisen eine bimodale Zusammensetzung auf. An der Basis sind Magnesium-reiche und darüber Kalium-arme Basalte entwickelt, die repräsentativ für den Durchschnitt der Laven sind. Die ultrabasischen Laven enthalten niedrige Konzentrationen an immobilen nicht kompatiblen Elementen, deren Verhältnis wahrscheinlich von den Eigenschaften der Lavaquelle gesteuert wird. Der geochemische Charakter der mafischen Dalma-Vulkanite entspricht weitgehend den heutigen Basalten der ozeanischen Rücken (MORB). Dabei dominieren leicht abgereicherte REE-Basalte sowie eisenreiche Basalte. Vergleicht man allerdings Elementverhältnisse wie das von Th/Ta, wird eine Abweichung von dem typischen MORB-Charakter hin zu Inselbögen-Tholeiten deutlich. Berücksichtigt man diese Beobachtungen, scheinen die Dalma-Basalte eine modifizierte MORB-Zusammensetzung zu haben, die in ihrem Chemismus am ehesten den Basalten von Back-Arc-Becken, z. B. in einem Gebiet einer Supra-Subduktionszone, zu entsprechen. Die Bimodalität der ultrabasischen und mafischen Laven erinnert an archaische komatiitische Regionen. Die geochemische Zusammensetzung der Dalma-Laven sowie der geologische Rahmen des Gebietes deuten auf ein randliches Becken hin, das sich während des Proterozoikums entwickelt haben könnte.

Abstract

The Dalma volcanic belt of the Singhbhum Precambrian terrain in eastern India is developed along the median zone of a linear basin flanked by Archaean cratonic basement to the south. The lavas, in a low grade metamorphic environment, preserve a strong compositional bimodality, with highly magnesian picritic volcanics developed at the base and low-K basalt flows above, constituting the bulk of the lava pile. The ultrabasic lavas have low concentrations of immobile incompatible elements, ratios of which are probably controlled by the source character. Dalma mafic flows are closely comparable in geochemical character to modern day mid-oceanic ridge basalts (MORB) with a dominance of light-REE-depleted basalts and ferrobasalts. However, in terms of certain element ratios (Th/Ta), deviation from MORB characteristics toward island arc tholeiites is apparent. In this respect the Dalma basalts appear to have a modified MORB composition and the closest chemical analogy may be basalts from back-arc basins, i. e. a supra-subduction zone environment. The bimodality of ultrabasic and mafic lavas is reminiscent of Archaean komatiitic provinces. The geochemical signature of the Dalma lavas, and the geological framework of the terrain, strongly point to a marginal basin domain developed in this crustal segment during the Proterozoic.

Résumé

La ceinture volcanique de Dalma, dans le Précambrien de Singhbhum (Inde Orientale) est située dans la partie médiane d'un bassin linéaire bordé au Sud par un socle cratonique archéen. Les laves se trouvent dans un environnement de faible degré de métamorphisme et présentent une composition nettement bimodale: volcanites picritiques très magnésiennes à la base, surmontées de coulées basaltiques pauvres en K, qui constituent l'essentiel de l'ensemble. Les laves ultrabasiques montrent de faibles concentrations en éléments immobiles incompatibles dont les rapports sont probablement déterminés par le caractère de la source. Les coulées basiques de Dalma sont très comparables, dans leurs propriétés géochimiques, aux basaltes récents des rides océaniques (MORB), avec une dominante de basaltes pauvres en terres rares légères et de ferro-basaltes. Toutefois, les rapport de certains éléments (Th/Ta) font apparaître, par rapport au MORB, une déviation vers les tholéiites d'arcs insulaires. A ce point de vue, les basaltes de Dalma montrent une composition de MORB modifée et une analogie avec les basaltes de bassins d'arrière-arc, c'est-à-dire en situation de supra-subduction. La bimodalité laves ultrabasiques/laves basiques est une réminiscence des provinces komatiitiques archéennes. Le signalement géochimiques des laves de Dalma et leur situation géologique plaident en faveur d'un domaine de bassin marginal développé dans ce segment central au cours du Protérozoïque.

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Краткое содержание

Вулканический пояс Дальма залегает в докембрийском регионе, восточная Индия. В среднем участке прямолинейного бассейна, ограниченного на юге архейским фундаментом, имеются обнажения этого пояса. Породы, окружающие лавы бимодального состава, проявляют следы слабого метаморфизма. У основания залегают богатые магнием, а над ними бедные кадмием базальты, являющиеся типичными для обычных лав. Ультрабазические лавы характеризуются низким содержанием неподвижных несовместимых элементов, соотношение которых обусловлено свойствами источника лав. Геохимический состав мафических вулканитов Дальма соотвествует сегедняшним базальтам океанических хребтов : MORB. При этом доминируют базальты слегка обогащенные Редкими Землями, а также железосодержащие базальты. Но, если же сравнить соотношение элементов, как напр.: тория/тантала, но ясно вырисовывается их отклонение от типичного состава MORB толеитов островных дуг. Если принять во внимание это наблюдение, то, кажется, что базальты Дальма обладают модифицированным составом MORB, который по своему химизму скорее всего приближается и базальтам тыловых дуговых бассейнов, напр.: в области супрасубдукции. Бимодальность ультрабазических и мафических лав напоминает архейские коматиитские зоны. Геохимичецкий состав лав Дальма, как и геологическое обрамление области указывают на краевой бассейн, который мог образоваться во время протерозоя.

Introduction

Studies of Precambrian volcanic rocks are of particular importance to the understanding of crustal evolution, because the bulk of the Earth's crust was probably generated during that time. Furthermore, comparisons of Proterozoic and Archaean volcanism are critical when evaluating the changing eruptive and chemical styles at the Archaean-Proterozoic boundary, a time considered to be a major turning point in crustal and mantle evolution (e.g. WINDLEY, 1984). The configuration of, and the style of interaction between, the lithospheric plates during Archaean times is poorly understood. The occurrence of highly magnesian, komatiitic lavas predicts a high geothermal gradient and possibly a relatively rapid rate of mantle convection. By Proterozoic times, however, the early crust attained sufficient mechanical stability and rigidity, aided by the development of a thickening lithosphere, to respond to plate-tectonic processes similar to those recorded during the Phanerozoic. Apart from examples such as the Cape Smith komatiitic belt (NESBITT & SUN, 1980), however, little is known of the trace element character of Proterozoic volcanism.

The present investigation was carried out in the eastern Indian shield, a terrain which provides an excellent opportunity to study the nature of Proterozoic volcanism. The Dalma volcanic belt forms a median zone to a linear, arcuate basin of Proterozoic age (Fig. 1), and we have focussed upon the geochemistry of its rocks, in order to further understand its tectono-magmatic setting.

Geological Framework of the Dalma Volcanic Belt

The Dalma volcanic rocks form the median zone of a narrow, elongate Proterozoic basin (Fig. 1). The basin is filled with clastics, volcaniclastics and thin contemporaneous lava flows. The assemblage is situated around the northern flank of a granitic platform whose components are metasediments, ortho-amphibolites and tonalitic gneisses, the gneisses being dated by Rb-Sr and Pb$Pb methods at 3280 ± 130 Ma and 3378 ± 98 Ma levels respectively (MOORBATH & TAYLOR, 1988). The bulk of the platform is composed of Singhbhum granite representing a younger phase of granite magmatism dated at ca. 3200 Ma (SAHA & ROY, 1984; MOORBATH & TAYLOR, 1988). The northern boundary of the volcano-sedimentary basin is largely tectonic in nature, juxtaposing the basin fill against a gneiss-migmatite terrain (the Chotanagpur Plateau) (Fig. 1).

Dalma volcanism (1547 ± 20 Ma by K/Ar techniques: SARKAR et al., 1967) was contemporaneous with, or possibly outlasted, the basin filling (dated > 2000 ± 200 Ma, SARKAR & SAHA, 1977). Isotopic age dates are too meagre to present an accurate assessment of the duration of volcanic activity in the basin. The basalts, which are the final product of volcanism, locally overlie the metasediment. However, to the west of the present study area the ultrabasic lavas, the older member of the volcanic sequence, rest directly over the basement granite (BOSE, 1982). These relationships suggest a possible contemporaneity of volcanism and basin filling.

Regional studies subsequent to those of BALL (1881), established two phases of deformation in the basin, the later responsible for closure of the volcanic belt in the west (Fig. 2) and contemporaneous with a regional low to medium grade metamorphic event (DUNN & DEY, 1942). The basin to the north of granitic platform is characterised by a positive gravity anomaly (VERMA et al., 1984) similar to that observed over oceanic crust. Earlier a geophysical study on a section of the Dalma volcanic belt demonstrated its considerable structural depth (BHATTACHARYYA & BHATTACHARYYA, 1970). Taking into consideration the subsurface data, the apparent absence of any floor

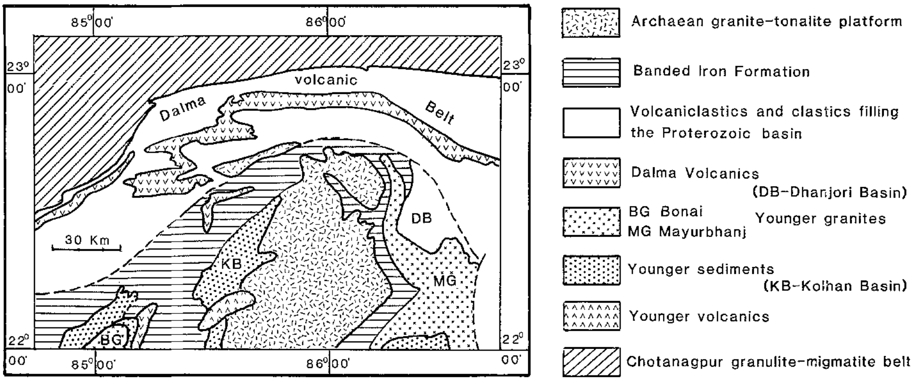

Fig. 1. Key map illustrating the geological setting of the Dalma Volcanic Belt.

for the Dalma volcanics and contemporaneous volcaniclastics interleaved with the sediments are suggestive of an oceanic floor for a larger part of the volcano-sedimentary basin with a possible mid-oceanic furrow along the median zone. The Dalma volcanic ridge very likely separated this basin into northern and southern sectors (Fig. 2), a reconstruction supported by palaeocurrent indicators and sedimentary facies models. Evidence of subaquous volcanism in the region is indicated by occasional pillow lavas (Gupta & Basu, 1979; Bose, 1982; Chakraborti & Bose, 1985).

A remarkable feature of the Dalma volcanic assemblage is its compositional bimodality, which is also coincident with lava stratigraphy (Fig. 3). The volcanic sequence is characterised by a lower unit of highly magnesian ultrabasics followed upwards by the mafic lavas. The two members are separated by a conspicuous horizon of feebly-reworked pyroclastic rocks (Chakraborti, 1980; Bose & Chakraborti, 1981). The younger basaltic flows, the dominant lithology of the volcanic pile, indicate occasional overlapping relationships with the flanking metasediments. Most of the volcanic pile has undergone pervasive low grade (dominantly greenschist to occasionally amphibolite grade) metamorphism, which has resulted in the replacement of much of the original igneous mineralogy.

Though this volcanic belt has been studied by a number of workers (Dunn & Dey 1942; Naha &

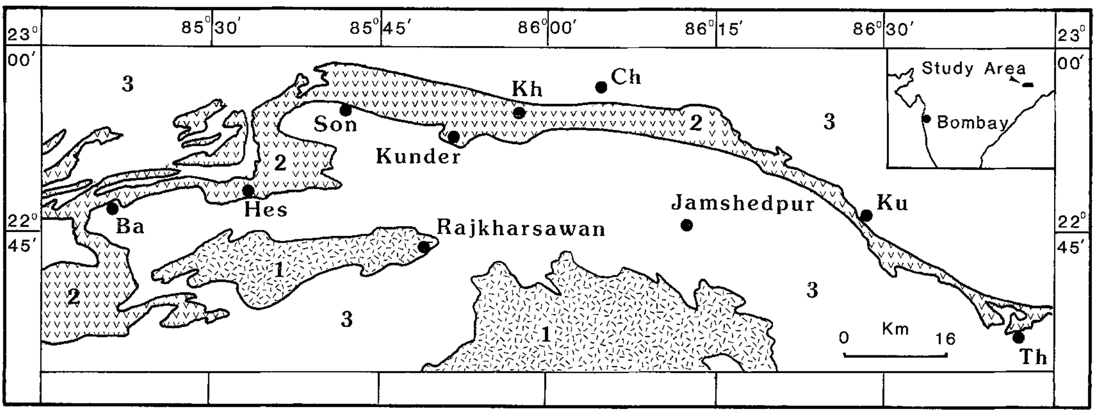

Fig. 2. Map of the Dalma Volcanic Belt, Singhbhum District, Bihar (after Dunn & Dey, 1942). Locations of the villages after which different study sectors are named, are as follows: Ba-Bano; Hes-Hessadih; Son-Sonapet Valley; Kunder-Kunderkuti; Kh–Khunti; Ch-Chandil; Ku-Kunchia; Th-Thakuranpahari. 1-Sialic platform; 2-Dalma Volcanic Belt; 3-Basin filled with volcaniclastic, clastic and volcanic debris.

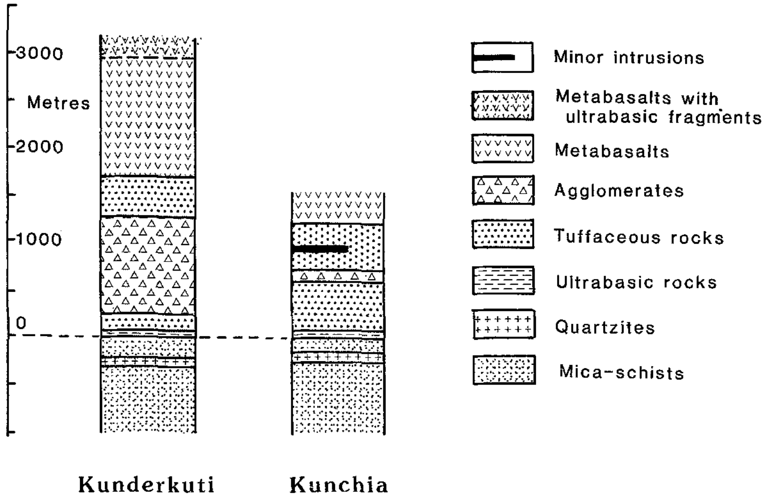

Fig. 3. Stratigraphic successions of the Dalma belt at Kunderkuti and Kunchia.

GHOSH, 1960; YELLUR, 1977; GUPTA et al., 1980; BHATTACHARYYA & DASGUPTA, 1982) no attempt has been made until recently to investigate the trace element chemistry of the lavas (CHAKRABORTI & BOSE, 1985). Our study presents data for both the ultrabasic and basic members of the Dalma volcanics. Within the extensive tract of the Dalma volcanics, several sectors were selected for study, on the basis of well-known and well-developed sections, and recognisable field relationships between the lithomembers. The different sectors are referred to in the text after the names of adjacent large villages (Fig. 2). Field studies were also carried out in other parts of the Dalma Hills range to confirm the regional distribution of lithomembers.

Petrography

The ultrabasic rocks characteristically comprise actinolite/tremolite with chlorite, carbonate and talc. They are usually fine-grained and schistose but contain rare relict vesicles as indicated by irregular tiny cavities and carbonate-chlorite filled deformed lenses. A general absence of lithic fragments suggests that they are lava effusions, although tuffaceous rocks are also occasionally present. Rare, small, corroded laths of plagioclase ($An_{43}Ab_{31}Or_6$) are present although these may be partly reconstituted. The majority of the samples are plagioclase-free which is consistent with the highly magnesian nature of these volcanics.

The Dalma basalts range from feebly schistose to undeformed types. The penetrative fabric is particularly well-developed where the volcanic belt narrows, e.g. in the Kunchia sector, although even here relict deformed vesicular textures may be seen. In addition, the occasional presence of pillowed surfaces in the basalts, as near Hesakocha village (Khunti sector) and Gunti and Kareranga Villages (Kunderkati sector), attest to the preservation of the primary igneous structures.

Mineralogically, corroded plagioclase laths are common in the less-deformed samples. In schistose varieties, the fabric is defined by oriented blades of actinolitic amphibole and chlorite. Xenoblastic feldspar grains are evenly distributed along with variable amounts of epidote, sphene, carbonate and rare quartz. Rarely, xenoblastic pyroxenes coexist with bladed hornblende. The mineral assemblages indicate PT conditions corresponding to the greenschist facies.

Analytical Techniques

35 samples were crushed in an agate swing mill, and formed into powder briquettes (for trace element analyses) and fusion beads (for major element analyses). Fusion beads were made by fluxing the rock with Johnson-Matthey lithium tetraborate/lithium carbonate Spectroflux 104. Ignition losses represent total ignition loss at 600°C on pre-dried (120°C) samples. Analyses were carried out using a Philips PW1400 automatic, wave-length dispersive X-ray fluorescence spectrometer at Bedford College (now Royal Holloway and Bedford New College), University of London. For further details of analytical techniques see SAUNDERS (1983).

The rare earth elements (REE) and Th, Hf and Ta were determined for seven samples using instrumental neutron activation techniques, also at Bedford College (see SAUNDERS 1983 for details).

Geochemistry

Ultrabasic Lavas

The MgO content of this group of rocks exceeds 20 wt % (Table 1), and Mg numbers (100 Mg/(Mg + Fe)) range from 81 to 87. Normative olivine content varies from 21 to 43 %, although in the chlorite-rich samples from the Hesadi sector (samples MH-64 and MH-64A), normative quartz is present. These two samples from the ultrabasic lavas from western part of the belt show high quantities of SiO_2 (up to 56.4 %), even at high levels of MgO (21 %), and Al_2O_3 is anomalously low. Superficially these two samples resemble boninitic lavas, although without textural evidence it is not possible to rule out the possibility that they are orthopyroxene-rich variants; they are, however, subordinate in volume to the other ultrabasic rocks.

The majority of the analysed ultrabasic lavas may be classified as picrites or even highly-magnesian basalts, because of their moderate normative anorthite contents. However, magnesian lavas are often classified on the basis of their MgO content in which case the Dalma lavas could be termed peridotitic, transitional to pyroxenitic (ARTH et al., 1977). Dalma ultrabasics from all of the sectors are characterised by very low content of alkalies, particularly of K_2O (0.02 to 0.08 %) although the extent to which this is due to post- magmatic loss of K_2O, is not clear.

The CaO/Al_2O_3 ratio of the analysed ultrabasic lavas ranges from 0.6 to 1.6 (excluding MH-64 and MH-64A), and in terms of the proportions of CaO-MgO-Al_2O_3, the samples plot close to the Geluk-type komatiites (Fig. 4). High CaO/Al_2O_3 ratios (> 1), once considered typical of the Barberton komatiites (VILJOEN & VILJOEN, 1969), are not the sole diagnostic feature of komatiitic lavas (ARTH et al., 1977; COX, 1978).

As with most ultrabasic magmas, those from the Dalma belt are characterised by very low abundances of Na, K and Rb. Most of the other incompatible elements, Zr, Y, Ti, P, Sr and Ba have low concentrations (i. e., much lower than in most basalts, even N-type mid-ocean ridge basalts (MORB)). Such low abundances are not unexpected and reflect the primitive nature of the melts and/or the effect of trace element dilution by cumulus olivine and pyroxene. Note that the abundances of Ni and Cr are high, consistent with the high abundances of MgO.

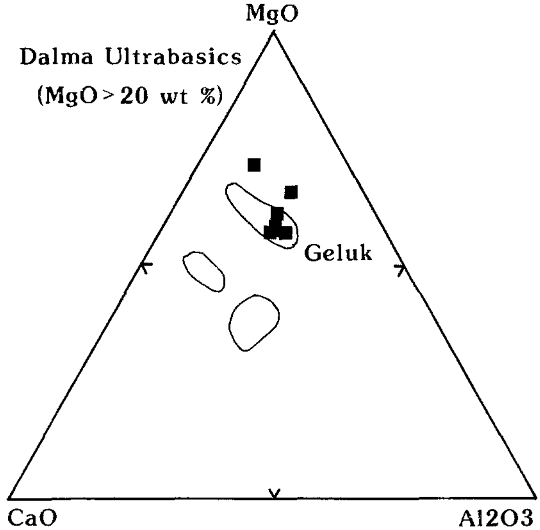

Fig. 4. Dalma ultrabasic effusives plotted on a CaO-MgO-A1203 diagram (after VILJOEN & VILJOEN, 1969).

Ti/Zr in the rocks ranges from 22.5 to 115, the higher values being similar to estimated Ti/Zr ratios in chondritic meteorites and modern-day MORB (Ca 110: NESBITT & SUN, 1976, 1980) (Fig. 5). TiO_2/P_2O_5 ratios are most constant, and again are similar to, or less than, the value seen in modern-day N-type MORB (~ 10) (NESBITT & SUN, 1980) (Fig. 6). Chondrite-normalised REE data show strong light-REE-depletion ($Ce_n/Yb_n = 0.6$) (Fig. 7). Al_2O_3/TiO_2 ratios range from 16 to 19, falling between the values measured in spinifex-textured peridotitic komatiites (STPK) (21) and the lower Proterozoic Cape Smith komatiites (15) (NESBITT & SUN, 1980).

Elements such as K, Rb, Sr and Ba may not have much petro-genetic significance in the present study, because of the likelihood of post-magmatic mobility.

Dalma Basalts

The majority of the Dalma basalts are moderately evolved, with Mg numbers between 41 and 64 (Table 2). The broad antipathetic correlation of MgO with TiO_2, and the positive correlation with Ni, reflect a primary character retained by the lavas. On the alkalis versus SiO_2 diagram, the basalts straddle the tholeiitic and high-alumina basalt fields of KUNO (1965), and on the Al_2O_3 versus alkalis plot, they are predominantly tholeiitic (Fig. 8). Furthermore, ne-normative basalts are rarely seen. It is therefore unlikely that the majority of the basalts could have been alkalic.

	MR-63	MR-68	MR-77	MR-103	MSB-3	MDK-6A	MH-64	MH-64A
SiO_2	45.80	41.70	39.50	45.80	45.20	45.20	53.40	56.40
TiO_2	0.46	0.48	0.26	0.46	0.45	0.52	0.27	0.06
Al_2O_3	7.90	8.20	4.10	8.30	8.70	8.70	2.10	bdl
Fe_2O_3	1.35	1.39	1.20	1.39	1.43	1.34	1.29	0.85
FeO	9.03	9.25	8.00	9.25	9.55	8.93	8.60	5.65
MnO	0.18	0.17	0.17	0.18	0.18	0.21	0.17	0.20
MgO	23.03	26.23	26.39	22.75	22.66	21.44	24.96	20.73
CaO	7.35	5.20	6.56	7.98	8.37	7.60	0.20	12.06
Na_2O	0.28	0.49	0.03	1.21	0.19	0.27	0.01	0.07
K_2O	0.03	0.05	0.03	0.08	0.04	0.04	0.04	0.02
P_2O_5	0.04	0.09	0.03	0.02	0.06	0.05	0.04	0.02
LOI	3.69	6.00	11.90	-	3.70	4.50	6.68	2.90
TOTAL	99.14	99.25	98.17	97.42	100.53	98.8	97.76	98.96
Mg Number	82.0	83.5	85.5	81.4	80.9	81.1	83.8	86.7

CIPW Norms

Qz	0.0	0.0	0.0	0.0	0.0	0.0	9.1	7.8
Or	0.2	0.3	0.2	0.5	0.2	0.2	0.2	0.0
Ab	0.4	4.2	0.3	10.5	1.6	2.3	0.1	0.0
An	20.3	20.2	11.1	17.3	22.6	22.7	0.7	0.0
Ne	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Di	12.9	4.2	17.3	18.5	14.6	12.1	0.0	47.8
Hy	34.1	18.7	17.2	12.3	26.9	34.4	78.8	39.8
Ol	23.4	43.3	39.4	37.8	27.2	20.7	0.0	0.0
Mt	2.0	2.1	1.8	2.1	2.1	2.0	1.9	1.0
Ilm	0.9	0.9	0.5	0.9	0.9	1.0	0.5	0.1
Ap	0.1	0.2	0.1	0.0	0.1	0.1	0.1	0.0

Trace elements in parts per million

Ni	1303	1502	1492	1072	1131	1181	2370	559
Cr	2493	2548	2954	2372	2552	2148	1536	135
V	226	193	112	211	234	203	95	29
Rb	1	1	1	1	1	2	2	2
Sr	9	30	35	30	38	10	3	8
Ba	1	1	1	1	1	26	26	11
Zr	31	25	31	25	36	49	15	16
Nb	3	1	2	1	4	4	3	2
La	-	bdl	-	-	-	-	-	-
Ce	-	1.9	-	-	-	-	-	-
Nd	-	1.5	-	-	-	-	-	-
Sm	-	0.85	-	-	-	-	-	-
Eu	-	0.36	-	-	-	-	-	-
Gd	-	1.28	-	-	-	-	-	-
Tb	-	0.20	-	-	-	-	-	-
Tm	-	-	-	-	-	-	-	-
Yb	-	0.80	-	-	-	-	-	-
Lu	-	0.13	-	-	-	-	-	-
Y	12	9	6	14	10	15	3	9
Th	-	bdl	-	-	-	-	-	-
Hf	-	bdl	-	-	-	-	-	-
Ta	-	bdl	-	-	-	-	-	-

Selected Ratios

CaO/Al_2O_3	0.93	0.63	1.60	0.96	0.96	0.87	0.10	-
Al_2O_3/TiO_2	17.2	17.1	15.8	18.0	19.3	16.7	7.8	-
Ti/V	12.2	14.9	13.9	13.1	11.5	15.4	17.0	12.4
TiO_2/P_2O_5	11.5	5.3	8.7	23.0	7.5	10.4	6.8	3.0
Ti/Zr	89.0	115.1	50.3	110.3	74.9	63.6	107.9	22.5
Zr/Y	2.6	2.8	5.2	1.8	3.6	3.3	5.0	1.8
Ce_n/Yb_n	-	-.60	-	-	-	-	-	-

Note: Samples MR-63, MR-68 and MR-77 from the Kunchia Sector; MSB-3 from the Chandil Sector; MDK-6A from the Kunderkuti Sector; and MH-64 and MH-64A from the Hessadih Sector. Fe_2O_3, FeO, Mg number (100 Mg/(Mg+Fe)) and CIPW norms calculated using an assumed Fe_2O_3/FeO ratio of 0.15. LOI = Total Loss On Ignition at 600°C after pre-drying at 120°C for 24 hours. Ce_n/Yb_n = chondrite-normalised Ce/Yb ratio. All analyses by X-ray fluorescence except the lanthanides which were determined by instrumental neutron activation analysis. bdl = below detection limit

Table 1. Representative analyses of ultrabasic rocks from the Dalma volcanic Belt.

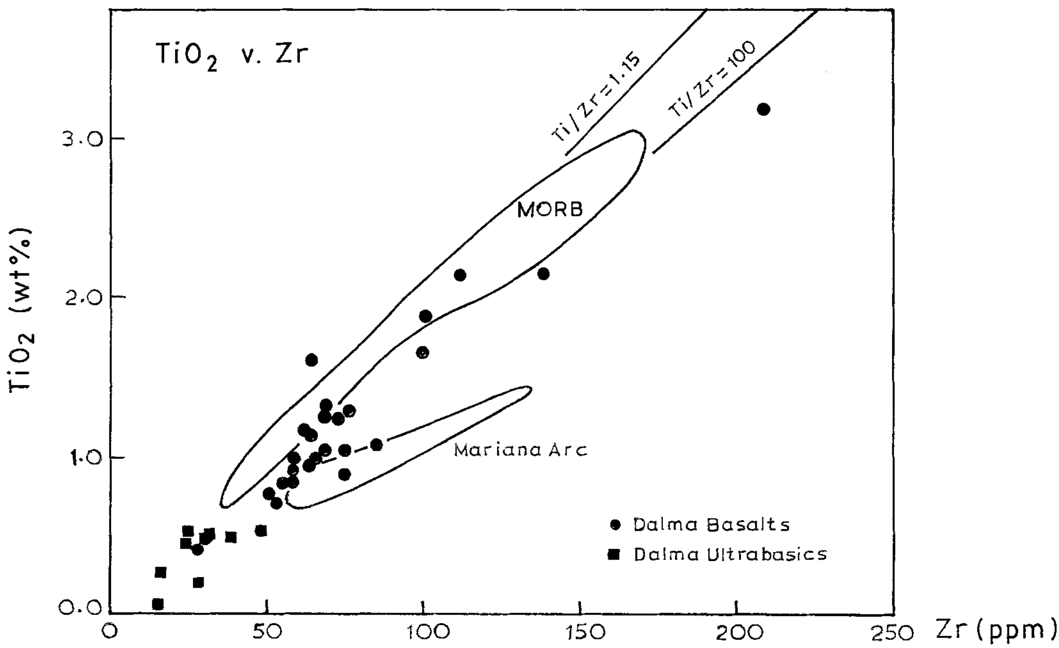

Fig. 5. TiO_2 versus Zr for Dalma lavas. Note the broad consanguineity of the basic and ultrabasic lavas (Ti/Zr~ 110). »MORB« represents the field for N-type MORB (i. e. light-REE-depleted, low Nb seafloor basalts from the Pacific basin (SAUNDERS, 1983; unpublished data). Field for Mariana Islands basalts and basaltic andesites from data in HOLE et al. (1984). On this diagram, back-arc basalts (e.g. Mariana Trough, East Scotia Sea, etc.) straddle the MORB and island arc fields (see SAUNDERS et al., 1980).

	MS-56	MS-95	MR-274	MR-37	MR-70	MDC-49	MG-7	MG-159	MDK-14	MDK-45	MDK-49	MDS-71
SiO_2	49.90	49.90	49.70	47.90	43.10	47.90	48.40	50.60	50.30	49.30	52.30	50.30
TiO_2	1.14	1.42	1.30	1.87	3.19	0.83	0.86	1.05	0.94	1.27	2.12	0.95
Al_2O_3	14.60	13.80	14.10	13.10	13.20	14.30	18.90	14.40	13.50	15.20	11.30	13.40
Fe_2O_3	1.60	1.53	1.67	2.11	2.31	1.36	1.25	1.52	1.46	1.78	2.05	1.46
FeO	10.63	10.21	11.10	14.04	15.43	9.10	8.30	10.13	9.75	11.88	13.67	9.75
MnO	0.19	0.19	0.21	0.24	0.29	0.19	0.17	0.20	0.19	0.22	0.28	0.19
MgO	7.83	6.22	8.74	5.50	6.06	8.94	7.45	7.35	7.41	8.49	5.62	8.04
CaO	11.80	6.13	5.81	8.95	10.27	9.61	9.65	11.94	10.41	8.81	9.15	10.92
Na_2O	2.43	3.07	3.72	2.98	4.65	2.92	3.19	2.03	2.88	2.98	1.88	2.43
K_2O	0.07	0.08	0.11	0.23	0.23	0.10	0.09	0.14	0.21	0.22	0.38	0.18
P_2O_5	0.09	0.12	0.17	0.13	0.40	0.07	0.07	0.09	0.08	0.09	0.16	0.08
LOI	0.00	5.80	2.99	-	-	-	-	-	1.23	-	-	1.05
TOTAL	100.28	98.47	99.62	97.05	99.13	95.32	98.33	99.45	98.36	100.24	98.91	98.75
Mg Number	56.7	52.0	58.4	41.1	41.2	63.7	61.5	56.4	57.5	56.0	42.3	59.5
CIPW Norms												
Qz	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	8.2	0.0
Or	0.4	0.5	0.7	1.4	1.4	0.6	0.5	0.8	1.3	1.3	2.3	1.1
Ab	20.5	26.4	31.6	26.0	14.5	25.9	27.4	17.3	24.8	25.2	16.1	20.8
An	28.6	24.0	21.5	22.4	14.5	26.9	37.6	29.8	23.6	27.5	21.6	25.3
Ne	0.0	0.0	0.0	0.0	13.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Di	24.1	5.0	5.2	19.0	28.7	18.4	8.6	24.1	23.4	12.8	19.5	23.8
Hy	15.1	28.9	22.0	17.1	0.0	9.7	6.2	22.6	17.6	13.4	24.9	22.2
Ol	6.6	0.0	10.7	7.0	16.8	14.5	15.8	0.0	3.9	14.6	0.0	1.5
Mt	2.4	2.3	2.5	3.3	3.5	2.1	1.9	2.3	2.2	2.7	3.1	2.2
Ilm	2.2	2.7	2.5	3.7	6.1	1.7	1.7	2.0	1.8	2.4	4.1	1.8
Ap	0.2	0.3	0.4	0.3	1.0	0.2	0.2	0.2	0.2	0.2	0.4	0.2
Trace elements in parts per million												
Ni	115	146	93	69	75	185	158	119	112	158	55	124
Cr	223	194	76	37	38	411	367	176	281	218	19	265
V	242	324	424	486	490	235	223	316	311	385	603	333
Rb	2	4	1	2	4	0	1	4	2	5	18	5
Sr	56	83	26	169	71	104	83	105	91	71	35	84
Ba	28	59	21	66	106	51	82	59	61	47	55	57
Zr	64	134	76	100	207	56	58	69	59	67	137	65
Nb	2	9	5	6	13	5	5	3	4	5	6	5
La	-	13.9	-	1.6	-	4.9	-	-	1.9	3.0	3.8	-

Ce	-	28.6	-	6.5	-	11.1	-	-	5.6	8.7	11.8	-
Nd	-	17.9	-	5.8	-	7.0	-	-	4.5	5.9	9.9	-
Sm	-	4.66	-	3.42	-	2.32	-	-	2.11	2.32	4.36	-
Eu	-	1.38	-	1.3	-	0.86	-	-	0.87	0.94	1.35	-
Gd	-	-	-	4.8	-	2.8	-	-	3.1	3.6	-	-
Tb	-	0.78	-	0.88	-	0.50	-	-	0.56	0.64	1.27	-
Tm	-	0.28	-	2.95	-	0.29	-	-	0.32	0.33	0.74	-
Yb	-	2.23	-	0.51	-	1.80	-	-	2.20	2.24	4.83	-
Lu	-	0.36	-	-	-	0.30	-	-	0.35	0.36	0.77	-
Y	27	27	31	35	61	22	21	27	23	25	51	26
Th	-	4.44	-	1.15	-	1.35	-	-	0.96	1.15	2.94	-
Hf	-	3.25	-	3.05	-	1.59	-	-	1.69	2.18	4.34	-
Ta	-	0.45	-	0.12	-	0.15	-	-	0.10	0.12	0.27	-

Selected Ratios

Ti/V	28.2	26.3	18.4	23.1	39.0	21.2	23.1	19.9	18.1	19.8	21.1	17.1
TiO_2/P_2O_5	12.7	11.8	7.6	14.4	8.0	11.9	12.3	11.7	11.7	14.1	13.3	11.9
Ti/Zr	106.8	63.5	102.5	112.1	92.4	88.9	88.9	91.2	95.5	113.6	92.8	87.6
Zr/Y	2.4	5.0	2.5	2.9	3.4	2.5	2.8	2.6	2.6	2.7	2.7	2.5
Ce_n/Yb_n	-	3.3	-	3.2	-	1.6	-	-	0.6	1.0	0.6	-
Zr/Hf	-	41.2	-	32.8	-	35.2	-	-	34.9	30.7	31.6	-
La/Ta	-	30.9	-	13.3	-	32.7	-	-	19.0	25.0	14.1	-
Th/Ta	-	9.9	-	9.6	-	9.0	-	-	9.6	9.6	10.9	-

Note: Samples MS-56, MS-95 and MS-274 from the Thakuranpahari Sector; MR-37 and MR-70 from the Kunchia Sector; MDC-49, MG-7, MG-159 from the Chandil Sector; MDK-14, MDK-45, MDK-49 from the Kunderkuti Sector; and MDS-71 from the Sonapet Valley.

Fe_2O_3, FeO, Mg number (100 Mg/(Mg+Fe)) and CIPW norms calculated using an assumed Fe_2O_3/FeO ratio of 0.15.

LOI = Total Loss On Ignition at 600°C after pre-drying at 120°C for 24 hours.

Ce_n/Yb_n = chondrite-normalised Ce/Yb ratio. All analyses by X-ray fluorescence except the lanthanides, Th, Hf and Ta which were determined by instrumental neutron activation analysis.

Table 2. Representative analyses of basalts from the Dalma volcanic Belt.

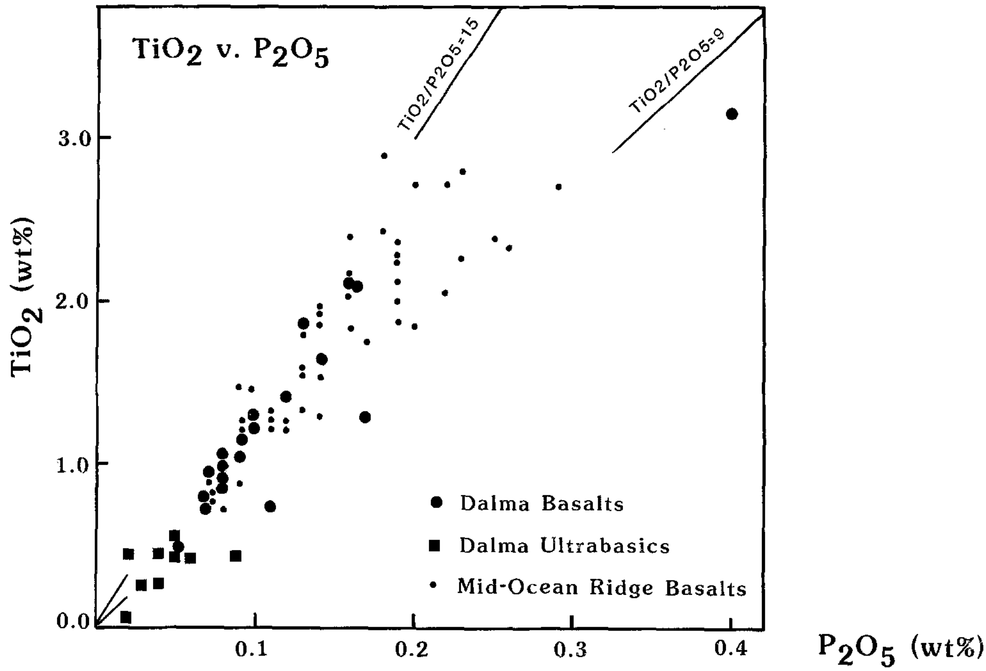

Fig. 6. TiO_2 versus P_2O_5, for Dalma lavas. The TiO_2/P_2O_5 ratio for the Dalma samples (~ 12) is indistinguishable from Phanerozoic MORB (9–15) (data sources in Fig. 5), and similar to the values reported for Archaean STPK (11-NESBITT & SUN, 1980).

The total iron contents of many of the basalts are high, often in excess of 12 wt%. Indeed, some samples contain more than 14.0 wt% Fe_2O_3, and can be classified as ferrobasalts, with one sample, MR-70 from the Kunchia sector, containing 19.5 wt% Fe_2O_3.

There is a reasonable positive correlation between Fe and the more immobile elements Ti, P, Zr, Nb, Ta, Th and Hf (see Figs. 5, 6, 9 and 10) although K, Rb, Sr and Ba show no strong correlation when plotted against Fe, Mg or any other index of fractionation. Such behaviour may suggest that these latter elements have probably been partly mobilised since emplacement of the lavas.

Most of the basalt samples are light-REE-depleted (Fig. 7) with Ce_n/Yb_n ranging from 0.55 to 0.99. However, two samples, MDC-49 and MS-95, are light-REE-enriched, with Ce_n/Yb_n values of 1.56 and 4.2 respectively. Note that with increasing REE abundances, the more evolved basalts (MDK-49 and MS-95) develop small negative Eu anomalies, consistent with plagioclase extraction.

Included in the biaxial plots (Figs. 5, 6, 9 and 10) are data for representative modern basalts. Table 3 is a summary of salient trace element ratios in Dalma basalts, ultrabasics, Phanerozoic basalts, chondrites and Archaean basalts. On the Zr-Y plot (Figure 9), already mentioned, the bulk of the basalt and ultrabasic data cluster around a Zr/Y ratio of 2.6, slightly higher than N-type MORB (2) and similar but lower than to chondritic ratios (2.8). Zr/Y ratios may be used as indicators of REE distribution, reflecting the values of Ce/Yb ratio (SUN et al., 1979). The lower-than-chondritic Zr/Y ratio implies that the majority of the samples have flat to light-REE-depleted patterns. Note that the Zr/Y ratios for the basalts and ultrabasic rocks are (apart from the few light-REE-enriched samples), indistinguishable, implying consanguinity of magma types.

On the TiO_2 versus Zr diagram (Fig. 5), most samples plot about a line of Ti/Zr ratio 100, similar to chondritic meteorites and N-type MORB (~ 100). There is a greater scatter on the P_2O_5 versus TiO_2 diagram (Fig. 6), perhaps due to the slightly greater mobility of P_2O_5, although the samples define a TiO_2/P_2O_5 ratio of approximately 12.5. This value is again similar to that measured in MORB and Archaean spinefex-textured peridotitic komatiites, but is much higher than estimated chondritic values (0.1 : NESBITT & SUN, 1980), presumably because sub-

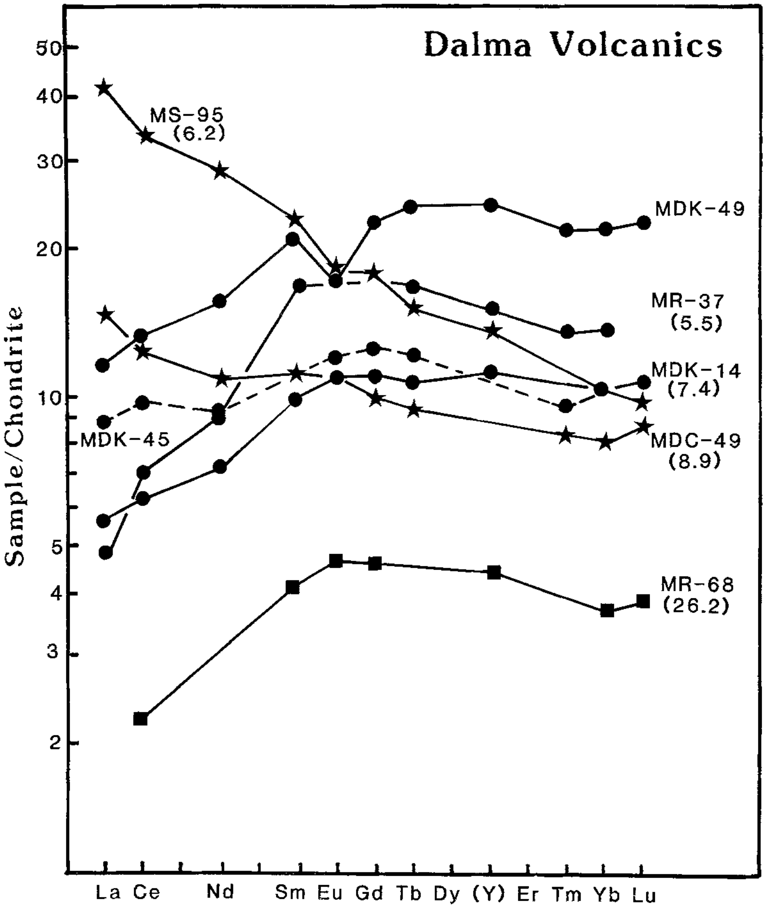

Fig. 7. Chondrite-normalised REE data. Values in parentheses refer to MgO contents in weight percent.

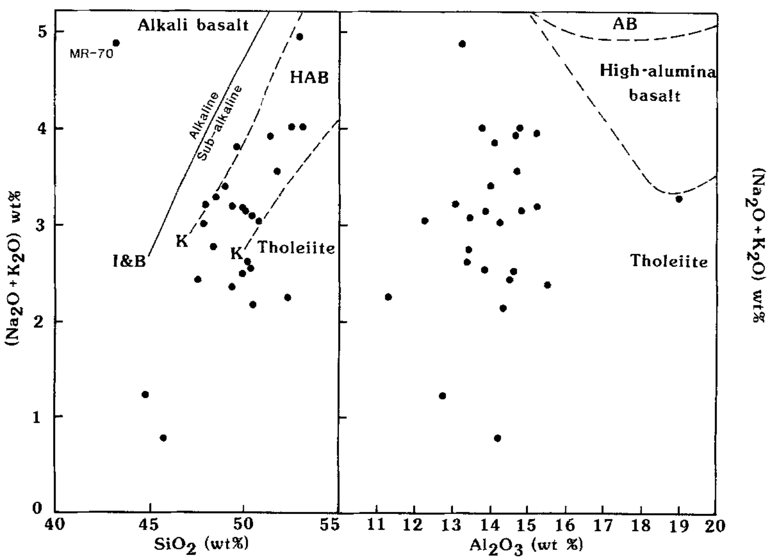

Fig. 8. Total alkalis versus SiO_2 and Al_2O_3 for the Dalma basalts. Fields for alkali basalt (AB), high-alumina basalt (HAB) and tholeiite from KUNO (K) (1965). Alkaline/sub-alkaline boundary from IRVINE & BARAGAR (I & B) (1971).

	Dalma Basalt	Dalma U'basic	STPK	Cape Smith	Chon-drite	MORB	IAT
Ti/Zr	110	89	100	110	110	110	70
TiO_2/P_2O_5	11.7	11.5	22	13	0.1	9–15	–
CaO/Al_2O_3	0.77	0.93	1	1	0.82	0.8	–
Zr/Y	2.6	2.6	2.5	2.6	2.8	2	3.2
Ti/V	18.1	12.2	14	19	10	22	16
Th/Ta	9.6	–	–	–	2.1	1.25	14
La/Ta	19	–	–	–	16	18	111
Zr/Hf	34.9	–	–	–	34.2	39	41

Note: Wherever possible, representative, rather than average values of least fractionated samples were chosen. Data sources: Dalma Basalt, sample MDK-14 (Table 2); Dalma Ultrabasic, sample MR-63 (Table 1); STPK: spinifex textured komatiitic peridotite, non-Barberton type (Nesbitt & Sun, 1980); Cape Smith: Lower Proterozoic komatiite province (Nesbitt et al., 1979; Nesbitt & Sun, 1980); Chondrite: Nesbitt & Sun (1980); Sun (1980); Thompson et al. (1984); MORB: N-type mid-ocean ridge basalt, compiled from Sun et al. (1979), Sun (1980), Saunders (1985). IAT: Island-arc tholeiite from the Mariana Islands (sample AGI from Hole et al., 1984), TiO_2/P_2O_5 and CaO/Al_2O_3 ratios not quoted because sample has undergone fractionation (Ni = 7 ppm, MgO = 2.8%).

Table 3. Trace Element Ratios in Terrestrial Magmas

stantial amount of P have entered the Earth's core.

La/Ta ratios range from 14 to over 30, values which among modern basalts correspond to those seen in N-type MORB (Bougault et al., 1978; Tarney et al., 1980) and island arc basalts (Hole et al., 1984). Zr/Hf ratios are very constant, and at 36 approximate chondritic ratios (30–40: Ehman & Rebagay, 1970; 34: Thompson et al., 1984) (see Table 3).

Th-Ta interrelation in the rocks is also remarkable. They reveal a good correlation, giving a Th/Ta ratio of 10.3 (Fig. 10). Th is considered to be less mobile than other LIL elements such as K, Rb, Sr, Ba or U, a feature which gives Th importance in attempting to understand the petrogenesis of ancient magmatic rocks (see for example Wood et al., 1979). A good correlation between Th and Ta in the Dalma basalts

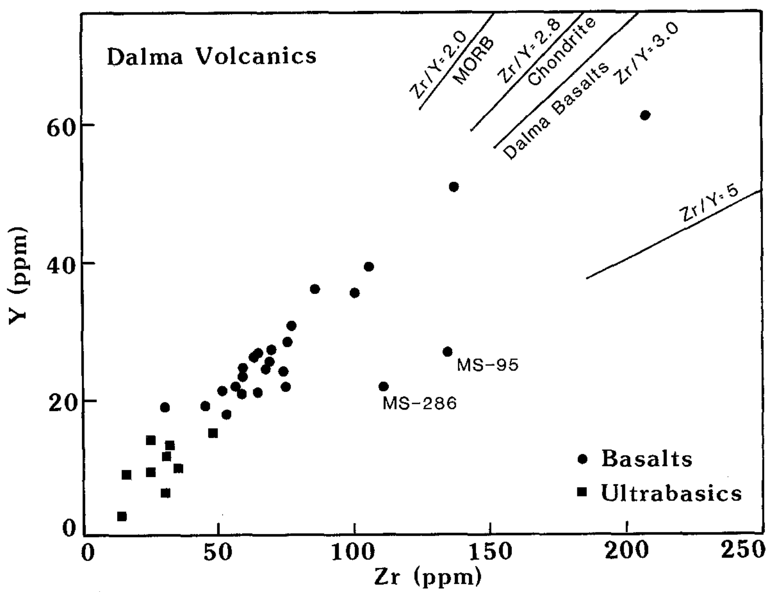

Fig. 9. Zr versus Y for the Dalma lavas. Data sources: MORB (see Fig. 5); Chondrite : Sun (1980) (although Thompson et al. 1983 use a chondritic Zr/Y ratio of 3.42, and Nesbitt & Sun (1980) use a ratio of 2.5).

suggests that Th is immobile here. Furthermore, a high Th/Ta ratio (Fig. 10) leads to the suggestion that the source of the basalts had a high Th/Ta ratio (a supra-subduction zone environment?) or that the magmas inherited a high Th/Ta ratio during their ascent through the continental crust and/or basin filling derived from platform wash.

Discussion

On the basis of present investigations several features of the Dalma volcanics are worthy of discussion.

i) The broad chemical similarity between the Dalma ultrabasics and Archaean equivalents (e.g. STPK: spinifex-textured peridotitic komatiite) in terms of CaO/Al_2O_3, Ti/Zr, Ti/V, Al_2O_3/TiO_2 and Zr/Y ratios (Table 3), suggests a similar origin for these rock types, thus bringing Proterozoic volcanicity closer to Archaean effusive process in terms of magma genesis and eruptive environment. The occurrence of Mg-rich, ultrabasic lavas in a Proterozoic volcanic setting is reminiscent of Archaean komatiitic terrain.

ii) The broad chemical consanguinity of the Dalma ultrabasics and basalts, at least in terms of the immobile elements, which implies derivation of the original melts from similar sources. In detail, however, trace element ratios show some variation: for example in Ce/Yb and Zr/Y, along with some samples exhibiting light-REE-enrichment, possibly through limited fractionation.

iii) The MORB-like trace element ratios in many of the basalts, although the Th/Ta ratios are much higher than in Phanerozoic MORB. This indicates a suprasubduction zone setting for the Dalma suite, as discussed below.

The highly magnesian character of komatiitic lavas suggests that they represent high degrees of mantle melting (40 to 60% see NESBITT & SUN, 1980) produced in a high geothermal gradient. A consequence of the high degrees of melting, and resulting phase

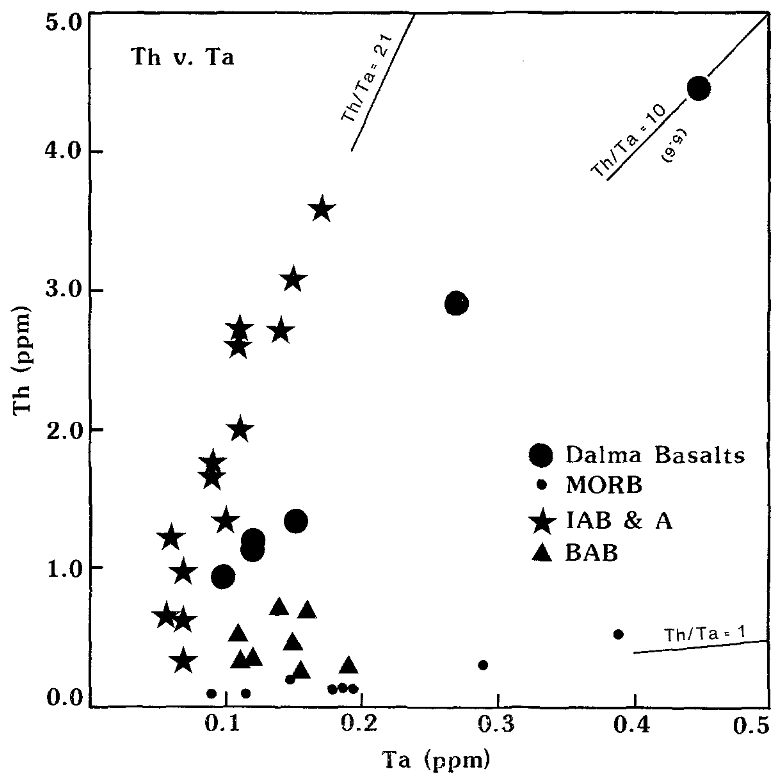

Fig. 10. Th versus Ta for Dalma and other igneous rocks. IAB & A – island arc basalts and andesites from the Mariana Islands (WOOD et al. 1981; HOLE et al. 1984); BAB – back-arc basalts from Mariana Trough (BOUGAULT et al., 1981); MORB – N-type mid-ocean ridge basalts from the central Atlantic (BOUGAULT et al., 1978), Nazca Plate (ADS, unpublished); Pacific Plate (ADS, unpublished).

exhaustion, is that the measured incompatible element ratios in the lavas will closely reflect those of the source. Furthermore, incompatible element abundances will be low, as is the case in STPK and indeed in the Dalma ultrabasics.

Measured incompatible element ratios in the Dalma ultrabasics overlap those reported for Archaean STPK and Proterozoic Cape Smith komatiites (Table 3) and, whilst these ratios are not unique to these rock types, they do lend support to the suggestion that the Dalma samples represent ultrabasic liquids. Simple addition of cumulus olivine to a liquid of the composition of a Dalma basalt, for example, would not reproduce the measured high CaO/Al_2O_3 ratio in the ultrabasic rocks; rather, both olivine and clinopyroxene need to be added to the system. The ultrabasic eruption was separated from the majority of the volcanism by a time gap, (represented by partly reworking pyroclastics), excluding any chance of addition of cumulus crystals to form the ultrabasic suite from the basaltic magmas.

The basalts have more clearly-defined major and trace element characteristics. Within the constraints imposed by post-magmatic alteration, most of the samples are tholeiitic, and several are ferrobasalts. As demonstrated above, many of the basalts show the chemical characteristics of N-type MORB (SUN et al., 1979), viz. light-REE-depletion, and sub-chondritic Zr/Y and Ta/La ratios. These data imply that the Dalma basalts were derived from a mantle source depleted in the more incompatible elements, and possibly similar to the source of present-day MORB – at least in terms of these elements. The very low abundances of K, Rb, Ba and Sr concur with this suggestion, although as noted earlier, strong emphasis cannot be placed on the abundances of these elements.

On the basis of critical chemical parameters therefore, the Dalma basalts appear to represent the Proterozoic equivalent of Phanerozoic N-type MORB. However, in details some minor deviations occur. Firstly, some samples (e.g. MS-85) do not possess a MORB-like chemistry, being LREE-enriched. This feldspar-rich sample with low MgO (6.22%) from eastern most Thakuran Pahari sector, apparently represents a fractionated product. In terms of partial melting, retention of garnet in the source is able to increase the Ce/Yb ratio of the melt via heavy-REE-depletion. However, the light-REE-enriched character could have been inherited by assimilation of country rock with only limited fractionation.

A further deviation from Phanerozoic MORB compositions is the high Th/Ta ratios (~ 10) observed in the analysed Dalma basalts. Phanerozoic MORB have low Th/Ta ratios – usually less than one (WOOD et al., 1979; TARNEY et al., 1980; SAUNDERS, 1983).

Modern basalts with high Th/Ta ratios are typically found in island arcs associated with subduction zones (see Table 3). Indeed WOOD et al. (1979) erected a discrimination diagram based on the elements Th, Ta and Hf. It is thought that the high Th/Ta ratios result from decoupling of the two elements. Firstly, during subduction, Th being flushed from the subducting slab and incorporated in the overlying mantle wedge (see e.g. HAWKESWORTH et al., 1979; SAUNDERS et al., 1980; HOLE et al., 1984). Ta, however, which may be sequestered in rutile, remains in the subducted slab, thus very little Ta is transferred to the suprasubduction zone. Thus suprasubduction zone magmatism (back-arc basins or island arc environment) may bear imprint of such element behaviour.

Many aspects of arc volcanism, particularly voluminous andesitic and rhyolitic volcanism, are absent from the Dalma volcanic belt (NAHA & GHOSH, 1986). Furthermore, other characteristics of island arc basalt compositions (high-alumina, low Ni, high Sr and high La/Ta ratios) are absent or poorly developed. An alternative explanation is that the Dalma basalts originated in a setting analogous to a back-arc basin. Back-arc basalts frequently exhibit compositions transitional between MORB and island arc basalts, retaining the major element chemistry of MORB, but showing variable degrees of enrichment of K, Rb, Ba and Th (see SAUNDERS & TARNEY, 1979; WOOD et al., 1980). Furthermore, TARNEY et al. (1976) have proposed a general model whereby greenstone belts originate in a marginal basin setting, so such a suggestion for the Dalma belt is not unexpected. The absence of a sheeted dyke complex suggests that the lavas were erupted in a basin which had not developed sufficiently to fully split the basinal floor. Possibly, the lavas rose through attenuated sialic crust via fissure systems or miniature rift, perhaps in a setting analogous to the Proto-Gulf of California (KARIG & JENSKY, 1972) or Bransfield Strait in the Antarctic (WEAVER et al., 1979).

Significantly the occurrence of ultrabasics towards the base of volcanic sequence is considered characteristic of Archaean greenstone belts (O'NIONS & PANKHURST, 1978). The occurrence of the bimodal basic-ultrabasic assemblages in the Dalma Belt suggests that this character may develop in Proterozoic too. Without textural evidence it is not possible to classify the Dalma ultrabasics as STPK although in terms of major and trace element geochemistry there is little to distinguish the two rock types. The study confirms that the processes operating during the formation of peridotitic lavas in the Archaean were extant, albeit on a more localised scale, during Proterozoic times.

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