Jyotisankar Ray
Gautam Sen
Biswajit Ghosh
Editors

Topics in Igneous Petrology

Jyotisankar Ray · Gautam Sen · Biswajit Ghosh
Editors

Topics in Igneous Petrology

A Tribute to Professor Mihir K. Bose

Springer

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ISBN 978-90-481-9599-2 e-ISBN 978-90-481-9600-5
DOI 10.1007/978-90-481-9600-5
Springer Dordrecht Heidelberg London New York

Cover Illustration: Pillow basalt from Chhitradurga green stone belt, South India. Photograph taken by Biswajit Ghosh

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

"Topics in Igneous Petrology: A Tribute to Professor Mihir K. Bose", as the title appropriately suggests, is a *Festschrift,* ably edited by Professors Jyotisankar Ray, Gautam Sen and Dr. Biswajit Ghosh. It includes 18 scientific papers by 53 authors from around the globe. This *Festschrift* is indeed a welcome tribute, a true "festival of writing", celebrating the life and works of the honoree, the admirable Professor Bose, by his students, colleagues and acquaintances. Unfortunately, Professor Bose passed away on October 1, 2009 before seeing these papers in print. The papers cover a broad range of topics and focus on igneous petrology that is bound to attract attentions of many igneous petrologist-geochemist, and certainly Professor Bose would have found himself drawn to many of these papers with utmost interest.

Professor Bose was born in Calcutta (now Kolkata), India on September 1, 1933 and attended the University of Calcutta for all his academic training, receiving B.Sc., and M.Sc. degrees in Geology. He joined the Department of Geology in Presidency College, Calcutta in 1956 as a Lecturer and taught there throughout his professional career. While teaching, he also enrolled in a doctoral program under the supervision of Professor S. Ray to do research on the alkalic igneous rocks of Koraput in Orissa for which he was awarded a D.Phil. degree in 1965, also from Calcutta University. In the same year he published a paper in the journal *Nature* on the differentiation of alkali basaltic magma, thus earning the attention of the international petrological community, including that of Professor T.F.W. Barth of the University of Oslo in Norway, who invited Dr. Bose to Oslo in 1967 as a post doctoral fellow.

Professor Bose carried out intensive petrological, mineralogical and structural research of a number of plutonic magmatic complexes along the Eastern Ghats Belt in India. Over the course of his distinguished career, starting with the 1965 paper in Nature, he was mostly known in India and abroad as a petrologist of alkalic igneous rocks, contributing many papers on the various nepheline syenite complexes along the Eastern Ghats and also those associated with the Deccan Volcanic Province. Nepheline syenite became widely known among the undergraduate students in Geology in Presidency College, and emerged as the *roche du jour* in geological circles. Professor Bose's fascination for alkalic magmatic rocks led him to investigate them within the vast tholeiitic lavas of the Deccan Traps. This inquiry resulted in a seminal paper in 1980 on alkaline magmatism in the Deccan volcanic province, published in the Journal of the Geological Society of India. He was also a pioneer in India in introducing geochemical modeling and numerical analysis in petrogenetic studies.

Throughout his professional career, Professor Bose received many awards for his innovative research in petrology and mineralogy, beginning with the Indian National Mineral Award in 1972 and the 1976 Bhatnagar Prize in the Earth Sciences in India. He was elected a Fellow of the Indian National Science Academy, and the Indian Academy of Sciences. He received the P.N. Bose Memorial Gold Medal of the Asiatic Society in 2006. Professor Bose was known and respected as a scientist in India and abroad. He was most happy doing science, and teaching and helping his students. On student appeal, later in his teaching career, he wrote a much needed text book on *Igneous Petrology* with relevant Indian context, published by the World Press, Calcutta in 1997. He was an excellent advisor and mentor to his students, and a generous, enthusiastic colleague and collaborator. He will be missed by those who knew him, but his legacy will prevail in his numerous publications and in the writings of the contributors to this *Festschrift.*

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Acknowledgements

We profusely thank all the contributors of this volume for making this special publication a grand success. We are grateful to all reviewers (see next page) who kindly devoted their valuable time to review the submitted papers at a reasonably short time.

We profusely thank Petra D. van Steenbergen and Hermine Vloemans, of Springer for their ever-helping attitude and timely suggestions. We are grateful to Prof. Somdev Bhattacharji of Geology Department, Brooklyn College of the City University of New York, Brooklyn, New York, USA who provided his erudite guidance and thought-provoking ideas during the nucleation-time of this publication.

We are thankful to Sohini Ganguly, Mousumi Banerjee and Abhishek Saha (research-fellows of the Department of Geology, University of Calcutta) for their assistance during final editorial processing of the papers.

Last but not the least; we thank all our colleagues, friends, students and well wishers who helped us in any form or other and provided moral support (and encouragement) in connection with this publication.

Jyotisankar Ray
Gautam Sen
Biswajit Ghosh

The editors are grateful to the following reviewers who kindly provided erudite reviews of the papers submitted for this volume. Their help, support and co-operation are being acknowledged with profound thanks.

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Plume and Hotspots

Chapter 1
Upper Triassic Karmutsen Formation of Western Canada and Alaska: A Plume-Generated Oceanic Plateau Formed Along a Mid-Ocean Ridge Nucleated on a Late Paleozoic Active Margin

Jaroslav Dostal, J. Duncan Keppie, J. Brendan Murphy, and Nicholas W.D. Massey

Abstract The 1–6 km thick Upper Triassic Karmutsen basalts extend ca. 2,400 km along the Cordillera from British Columbia to Alaska and are characteristic of the Wrangellia terrane. The basalts were erupted in less than 3.5 million years following rapid >1 km uplift of an extinct Devono-Carboniferous island arc. Eliminating transcurrent dispersal reduces its original distribution to an elliptical area, ca. 1,200 × 700 km^2 in size. The convergent tectonic setting is inferred to be associated with amalgamation of Wrangellia out in the Pacific Ocean with its accretion to Laurentia occurring prior to Middle Jurassic. Geochemical data characterize the basalts as high- and low-Ti within-plate tholeiites derived from two components, an asthenospheric mantle plume at a depth ca. 80–100 km and partial melt of depleted lithospheric mantle enriched during the Paleozoic arc magmatism or of lower crust. Assuming that the ocean floor above the Paleozoic arc lay at a depth of ca. 4.5 km (i.e. 1 km above normal ocean floor) before passage over a plume, and accounting for extrusion of 6 km of basalt, the Karmutsen seamount experienced ca. 4 km of thermal uplift, was ca. 90 km wide and yielded a magma volume of ca. 15,600 km^3. Although the 90 km width is similar to that on Vancouver Island, the predicted

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J. Ray et al. (eds.), *Topics in Igneous Petrology*, DOI 10.1007/978-90-481-9600-5_1,

volume is only $^1/_{60}$th of the estimated volume. This discrepancy could be explained if the 2,400 km length of the volcanic belt represents a migrating volcanic chain but no diachronism has been detected. Even using the ca. 1,200 × 700 km^2 areal dimension prior to sinistral dispersal yields an unrealistic model plume size. This suggests that the Late Triassic magmatism formed as an oceanic plateau over a triple point or mid-oceanic ridge segment. However, the Karmutsen flood basalts are unusual as they formed over an extinct oceanic arc, which suggests that triple point or ridge may have nucleated on the extinct arc or trench. The modeling also shows that the bulk density of the lithosphere on which the oceanic plateau rests is never less than the asthenospheric density suggesting several possibilities for the plateau's preservation: (1) that the oceanic plateau jammed the trench causing the trench to jump oceanwards: this is consistent with the oceanic arc basement and the unimodal flood basalt magmatism; (2) that Wrangellia formed on the outer margin of Laurentia rather than in the middle of the Pacific Ocean: this is supported by correlation of the Devono-Carboniferous arc basement, but not with the absence of flood basalts on Laurentia; and (3) that the plateau and its arc basement may have been decapitated from the underlying mantle rather than subducted, however this latter possibility is inconsistent with the mild deformation and lack of a basal thrust.

1.1 Introduction

The mantle plume concept is generally regarded as a narrow fixed upwelling, solid-state current originating at the core–mantle or upper–lower mantle boundary that leaves a volcanic chain showing an age progression as the lithospheric plate moves relative to the plume (e.g., Hawaii-Emperor volcanic island chain: Wilson 1973). Although the very existence of mantle plumes has recently been questioned because, among other things they were not detected by seismic data and could not be thermally modeled (e.g., Anderson 2005; and references therein), more recent studies have overcome these difficulties. Thus, an alternate finite-frequency tomographic method for analyzing seismic data has detected roughly circular plumes, 200–800 km in diameter, rising from near the core–mantle boundary and from ca. 670 km depth (Montelli et al. 2004). Also, Farnetani and Samuel (2005) show that thermo-chemical plume models are viable, however, they cannot be applied to ancient plumes and so other criteria are necessary for their identification. In this paper, we examine one of the largest "fossil" plumes in the world, the Triassic Karmutsen Formation (Wrangellia terrane, British Columbia to Alaska), and show that the combination of characteristics, such as the high rate of magma generation, geochemical and thermal modeling, are most compatible with a plume origin. We here present new geochemical data to supplement that already available (Barker et al. 1989; Lassiter et al. 1995; Nixon et al. 2008). Furthermore, the Karmutsen flood basalts are unusual because they rest on an arc basement rather than upon the ocean or continental crust.

1.2 Geological Setting

Upper Triassic flood basalts are characteristic of the Wrangellia terrane (Fig. 1.1) and consist of a sequence bracketed by fossil ages that is ca. 3.5 km thick, subaerial and ca. 231–225 Ma in Alaska, ca. 1 km thick, submarine-subaerial and ca. 236–225 Ma in the Yukon, to ca. 6.3 km thick, mainly submarine and ca. 228–224 Ma on Vancouver Island (Greene et al. 2004, 2005, 2009; Nixon et al. 2008). Wrangellia comprises several large blocks, with those on Vancouver Island and in the Wrangell Mountains being the largest (Fig. 1.1). Barker et al. (1989) and Panuska (1990)

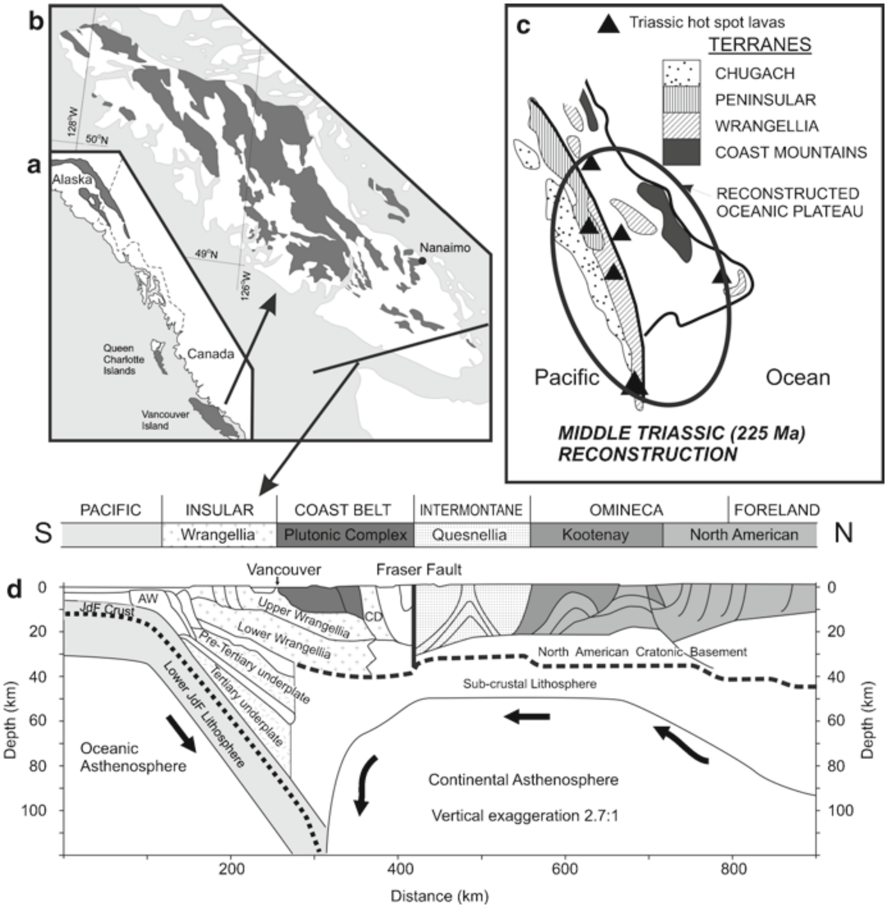

Fig. 1.1 (**a**) Distribution of the Late Triassic tholeiites in the northern Cordillera; (**b**) Geological map of Karmutsen Formation on Vancouver Island (Modified after Nixon et al. 2008); (**c**) Late Triassic plume magmatism after removal of sinistral displacements (Modified after Keppie and Dostal 2001); (**d**) Cross-section across southern British Columbia showing Wrangellia which is capped by the Late Triassic Karmutsen Formation (After Monger and Price 2002). *JdF* Juan de Fuca oceanic plate, *AW* accretion wedge, *CD* Cadwallader terrane

estimated the volume of flood basalts to be 64,000 – >1,000,000 km^3, respectively, and paleomagnetic data suggest that they were erupted in the Pacific Ocean at a latitude of 10–17° (Irving and Wynne 1991 and references therein). A Middle Jurassic conglomerate (ca. 180 Ma) in Wrangellia contains pebbles probably derived from the neighbouring Chilliwack terrane, which has Middle–Upper Triassic rocks that have been correlated with the peri-Laurentian Stikine arc (Monger and Struik 2006). These observations indicate that Wrangellia was accreted to the Laurentian margin by the Middle Jurassic, and was subsequently dispersed sinistrally along the orogen (Jones et al. 1977; Monger et al. 1982, 1994). Resurgence of arc volcanism in Wrangellia is recorded in the Early-Middle Jurassic Bonanza arc (DeBari et al. 1999).

The flood basalts of the Karmutsen Formation on Vancouver Island (Fig. 1.2) are mainly submarine, 6.1–6.6 km thick tholeiites and consist of ca. 2,900 m of basal submarine pillow lavas overlain by ca. 600–1,100 m of pillow breccia and aquagene tuff, followed upwards by ca. 2,600 m of massive basalt flows (occasionally pillowed) interbedded with shallow water and subaerial sedimentary rocks (Carlisle and Suzuki 1974; Greene et al. 2004, 2005, 2006, 2009; Nixon et al. 2008). Locally, sills, plugs and dikes accompany the volcanic rocks; however, a sheeted dike complex has not been observed. Fossils constrain the age of the basalts between middle Ladinian (Middle Triassic: ca. 230 Ma) and Carnian-Norian (Upper Triassic: ca. 224 Ma)

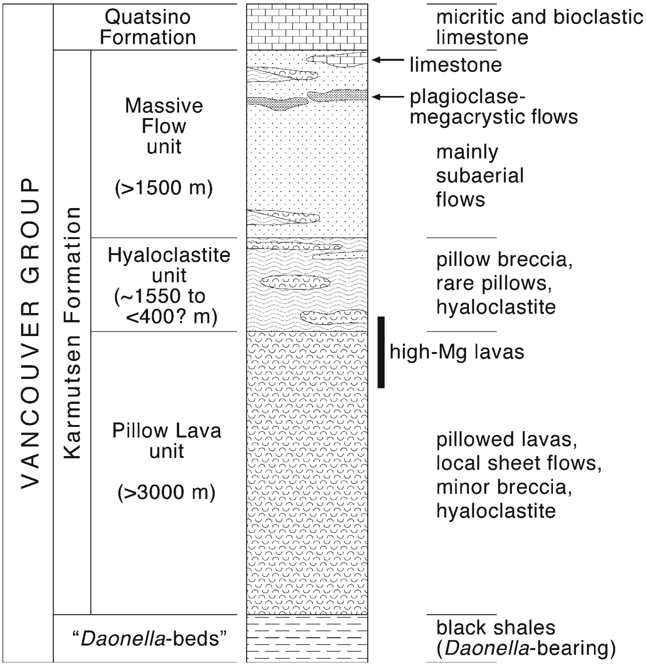

Fig. 1.2 Triassic stratigraphy on Vancouver Island (Modified after Massey 1995a–c; Nixon et al. 2008)

(Carlisle and Suzuki 1974), and suggest that they were erupted rapidly in ca. 2.5–3.5 million years. According to Nixon et al. (2008) the cessation of volcanism was followed by gradual submergence culminating in the deposition of a Late Triassic platform carbonate, known as the Quatsino Formation. Upper Triassic sedimentary rocks interbedded with and overlying the uppermost part of the Karmutsen Formation show a gradually increasing depth of deposition estimated to be no deeper than 60 m (Carlisle and Suzuki 1974; Richards et al. 1991).

Beneath the flood basalts, Middle Triassic rocks consist of <100 m thick, basinal argillite, siltstone and bivalve-bearing limestone (Richards et al. 1991). In Alaska and southwestern Yukon, the basaltic rocks that are underlain by mid- to Upper Permian argillite and radiolarian chert, which indicates deposition below the calcium carbonate compensation depth, i.e. >1 km below the surface of the sea (Richards et al. 1991; Greene et al. 2004). In turn, these rocks rest upon Lower Permian shallow water limestone, sandstone and shale that overlie 2–3 km thick late Pennsylvanian to earliest Permian arc (Skolai Group) volcanic and plutonic rocks consisting of mafic and felsic flows and tuffs (Berg et al. 1972). On Vancouver Island, Mississippian to Permian sedimentary rocks (Buttle Lake Group) unconformably overlie 2,500 m of Devonian-Lower Mississippian arc-related intermediate to felsic volcanic rocks and chert that rest upon mafic volcanic rocks (Sicker Group; Richards et al. 1991; Greene et al. 2005; Nixon et al. 2008) dated at 370–355 Ma (Parrish and McNicoll 1992; Brandon et al. 1986; Sluggett and Mortensen 2003).

Lassiter et al. (1995), Greene et al. (2009) and Nixon et al. (2008) published geochemical data for the Karmutsen Formation in Vancouver Island and Alaska-Yukon. Based on the geochemical parameters, particularly isotopic data, Lassiter et al. (1995) concluded that the Karmutsen flood basalts originated in a mantle plume. In order to augment the geochemical database and provide additional data for thermal modeling, we sampled another section of the Karmutsen Formation on Vancouver Island (Fig. 1.1).

1.3 Petrography

The Karmutsen volcanic rocks in southern Vancouver Island are dark grey feldspar-phyric basalt. They form pillowed flows, pillowed basalt breccias and hyaloclastite breccias that are interbedded with massive flows and sills. Massive flows predominate in the upper part of the formation whereas mainly pillowed flows are found in lower parts. Pillows are usually 1–2 m in size, rounded to irregular in shape and loosely packed with intra-pillow hyaloclastite. The petrography of the Karmutsen volcanic rocks is relatively uniform throughout the sequence (Barker et al. 1989). The basaltic rocks are typically plagioclase- and clinopyroxene-phyric with less than 10% phenocrysts. Plagioclase (labradorite to bytownite) is frequently ragged or forms glomerophenocrysts enclosed in a fine-grained groundmass. Olivine phenocrysts are rare and are typically pseudomorphed by serpentine.

However, pyroxene and plagioclase are mostly fresh. The groundmass contains plagioclase, pigeonite, clinopyroxene, chlorite and Fe–Ti oxides. Many flows are amygdaloidal. Amygdules are usually filled by chlorite, calcite or epidote or rare pumpellyite or prehnite.

The volcanic rocks are associated with mafic subvolcanic sills, dikes and plugs (Massey 1995a). These mafic intrusions are coeval and probably fed the Karmutsen volcanic pile (Massey 1995b). The thickness of the dikes and sills ranges from <1 to 200 m. They consist of fine to coarse-grained, equigranular to plagioclase-phyric gabbro with mineralogy comparable to the Karmutsen lavas. Mafic phenocrysts are generally absent. Locally, the gabbros show compositional layering and/or cumulate textures.

1.4 Analytical Notes

Representative samples were selected from a suite collected by Massey (1995a–c) during the mapping of southern Vancouver Island in the scale of 1:50,000. Major and some trace (Rb, Sr, Ba, Ga, Zr, Nb, Y, Cr, Ni, Sc, V, Cu and Zn) elements were analyzed by X-ray fluorescence. Twenty-three samples were also analyzed by an inductively coupled plasma mass spectrometry for the rare-earth elements (REE), Hf, Ta and Th (Table 1.1). The precision and accuracy are discussed in Dostal et al. (1986, 1994). In general, they are less than 5% for major elements and 2–10% for trace elements.

1.5 Alteration

The Karmutsen volcanic and associated subvolcanic rocks were affected to varying degrees by secondary processes including zeolite facies metamorphism, which modified the chemical composition of these rocks (Massey 1995a–c). For example, several samples yielded elevated LOI values and display secondary mobility of alkali metals indicated by the wide range of K and Rb contents (Table 1.1). The concentrations of most major elements, high-field-strength elements (HFSE, i.e. Ti, Nb, Ta, Zr, Hf), REE and transition elements are thought to reflect the primary magmatic distribution. When these elements including Y and Th are plotted against Zr, which is considered to be a good indicator of the fractionation and is apparently immobile under most metamorphic conditions (e.g., Winchester and Floyd 1977; Dostal et al. 1980), they display distinct correlations (Fig. 1.3). Similarly, these elements display coherent primitive mantle- and chondrite-normalized patterns (e.g., Figs. 1.4 and 1.6). Remobilization during metamorphism is unlikely to produce such a consistent result. The consistency of these trends and their similarities to those of modern volcanic rocks suggest that the distribution patterns of these elements were not significantly modified.

Table 1.1 Chemical analyses of rocks of the Karmutsen Formation

	High-Ti basalt							High-Ti gabbro				Low-Ti basalt		Low-Ti gabbro		
Sample	69	101	46	15	28	6	24	79	84	47	89	70	88	29	32	61
SiO_2 (wt%)	48.11	50.41	48.49	49.57	49.52	49.03	50.25	46.73	48.22	48.85	48.84	47.26	52.22	49.06	48.19	49.52
TiO_2	1.56	1.68	1.70	1.51	1.62	1.44	2.46	0.99	1.33	1.63	1.76	0.90	1.14	1.92	1.71	1.81
Al_2O_3	13.52	13.55	14.77	14.48	14.32	15.68	12.13	15.00	15.62	17.57	16.48	16.81	16.37	14.53	13.95	14.96
Fe_2O_3	3.67	2.93	2.63	0.00	5.90	4.06	9.45	1.06	1.04	1.90	1.55	3.07	3.24	11.29	10.68	3.81
FeO	7.83	8.41	9.05	11.82	6.27	6.62	4.25	7.90	9.08	8.13	9.00	6.93	6.56	2.12	2.62	8.54
MnO	0.16	0.25	0.20	0.20	0.21	0.18	0.24	0.16	0.18	0.16	0.18	0.18	0.20	0.26	0.22	0.19
MgO	8.75	5.97	6.06	7.25	6.08	6.46	5.99	9.10	6.96	5.03	5.31	4.91	3.69	7.03	6.87	6.72
CaO	8.35	11.70	11.39	12.28	12.23	11.35	10.97	12.51	9.68	11.31	11.64	8.72	6.11	6.20	8.58	3.19
Na_2O	3.11	2.37	2.35	2.10	1.80	2.59	2.03	1.41	2.40	2.12	2.02	2.75	4.61	2.82	3.03	4.24
K_2O	0.53	0.28	0.39	0.18	0.16	0.44	0.27	0.28	0.56	0.51	0.32	2.20	1.12	1.15	1.00	1.62
P_2O_5	0.11	0.14	0.13	0.11	0.12	0.11	0.20	0.07	0.12	0.14	0.15	0.26	0.31	0.24	0.19	0.30
CO_2	0.24	0.27	0.10	0.21	2.44	0.00	0.00	0.10	0.26	0.14	0.21	0.82	0.24	0.00	0.00	0.45
LOI	3.11	0.90	1.61	0.58	0.81	1.07	1.06	1.53	2.14	1.88	1.54	3.95	2.77	2.74	2.45	3.21
Total	99.05	98.86	98.87	100.29	101.48	99.03	99.30	96.84	97.59	99.37	99.00	98.76	98.58	99.36	99.49	98.56
Cr (ppm)	375	247	92	352	153	296	56	595	172	84	128	53	41	38	71	43
Ni	179	96	74	110	69	96	61	198	110	80	81	12	6	9	25	13
Sc	35	36	42.9	43.4	39	29	34	0	0	32.4	35.6	28	25	30	38	0
V	319	357	360	351	332	340	417	274	304	282	331	300	287	383	394	352
Cu	97	178	170	177	164	142	258	59	122	165	160	53	57	22	47	22
Rb	12	7	8	0	0	7	6	9	19	11	8	42	16	13	11	24
Ba	116	85	89	39	97	167	140	80	141	291	805	1055	412	577	425	580
Sr	582	294	268	210	218	244	235	236	387	323	256	981	486	341	320	352
Ga	21	23	19	20	20	18	21	18	17	26	22	21	19	23	21	21
Ta	0.45	0.63	0.61	0.56	0.50	0.50	0.89	0.32	0.46	0.55	0.56	0.22	0.25	0.42	0.37	0.60

(continued)

Table 1.1 (continued)

	High-Ti basalt							High-Ti gabbro				Low-Ti basalt		Low-Ti gabbro		
Sample	69	101	46	15	28	6	24	79	84	47	89	70	88	29	32	61
Nb	8.00	9.00	9.00	10.00	8.00	10.00	13.00	0.00	7.00	10.00	10.00	5.00	5.00	8.00	7.00	8.00
Hf	2.46	2.98	2.92	2.51	2.80	2.47	4.23	1.60	2.28	2.84	2.72	1.92	2.99	3.37	2.65	3.87
Zr	94	108	102	88	101	89	151	58	86	101	103	73	108	125	100	149
Y	21	23	22	21	21	19	30	15	18	21	22	21	28	29	25	34
Th	0.48	0.71	0.73	0.60	0.67	0.59	1.16	0.41	0.54	0.71	0.75	0.98	2.04	1.99	1.35	2.22
La	5.63	7.84	7.69	7.51	6.62	6.24	11.17	4.13	5.95	7.47	8.44	9.87	14.37	13.44	11.72	16.54
Ce	14.76	20.08	19.59	17.47	16.74	15.80	27.30	10.60	15.09	19.08	20.90	23.19	32.64	30.66	26.68	37.16
Pr	2.23	2.86	2.77	2.48	2.42	2.25	3.92	1.55	2.19	2.80	3.03	3.21	4.41	4.08	3.57	4.98
Nd	11.21	13.70	13.23	11.73	11.61	10.58	18.65	7.73	10.36	12.98	14.14	14.70	19.59	18.65	16.14	22.47
Sm	3.42	3.85	3.67	3.40	3.36	3.02	5.36	2.39	3.01	3.78	3.97	3.63	4.87	4.82	4.19	5.69
Eu	1.18	1.35	1.37	1.21	1.25	1.11	1.83	0.85	1.01	1.37	1.49	1.07	1.47	1.66	1.44	1.84
Gd	3.93	4.36	4.52	3.95	4.12	3.61	6.15	2.74	3.58	4.47	4.77	3.66	5.27	5.57	4.84	6.32
Tb	0.60	0.69	0.67	0.60	0.61	0.55	0.88	0.44	0.53	0.66	0.73	0.56	0.76	0.84	0.71	1.01
Dy	4.30	4.78	4.58	4.29	4.13	3.75	6.04	3.01	3.79	4.57	4.79	4.11	5.29	5.72	4.92	6.98
Ho	0.80	0.90	0.91	0.88	0.82	0.74	1.17	0.57	0.71	0.82	0.89	0.77	1.04	1.12	0.94	1.32
Er	2.22	2.58	2.63	2.50	2.28	2.05	3.16	1.58	2.00	2.30	2.43	2.25	3.17	3.19	2.67	3.82
Tm	0.32	0.35	0.34	0.31	0.32	0.29	0.45	0.22	0.28	0.32	0.33	0.35	0.45	0.47	0.38	0.56
Yb	1.98	2.34	2.27	2.12	2.01	1.86	2.74	1.39	1.75	1.98	1.99	2.23	2.87	2.89	2.38	3.59
Lu	0.31	0.34	0.33	0.32	0.32	0.29	0.41	0.21	0.27	0.30	0.29	0.35	0.45	0.47	0.36	0.54