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Geochemistry and geodynamic implications of magmatic rocks from the Trans-Himalayan arc

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Present study aims at understanding the genetic and tectonic relationship between the enclaves and enclosing granitoids, acidic volcanics and mafic dykes of the Ladakh plutonic complex. Similar rocks from Lhasa Block (Tibet) are also studied and compared. In terms of SiO_2 abundance, the enclaves vary in composition from basic to acidic but are predominantly andesitic-basalt. Mafic dykes intruding the Ladakh plutonic complex are of predominantly andesitic-basalt composition. Granitoids and acidic volcanics from Ladakh and Lhasa blocks are compositionally granodiorite, quartz monzonite and granite. They are predominantly meta-aluminous with slight peraluminous characters. The acidic volcanics, however, have $K_2O/Na_2O > 1$. All these rocks show calc-alkaline characteristics with high Al_2O_3 abundance, their rare earth elements (REE) and multi-element patterns depict enrichment of large ion lithophile elements (LILE)-light REE (LREE) and depletion of high field strength elements (HFSE) including Nb, P and Ti.

It is suggested that the enclaves in Ladakh plutonic complex probably represent the initial pulses of magmatism, in response to intra-oceanic northward subduction of Neo-Tethyan ocean beneath an immature arc. Subsequently huge pulses of granitoids were intruded as the arc matured, sutured with southern continental margin of Eurasian plate and the lithosphere thickened. The granitoids in turn were cut by mafic dykes and acidic volcanics probably representing the last significant episode of subduction related magmatism in this region. It is suggested that the youngest, highly siliceous acidic volcanics may represent melts generated by partial melting and/or dehydration of upper part of subducted north Indian continental lithosphere and southern Eurasian active margin wedge, subsequent to the closing of Neo-Tethyan ocean and collision of Indian and Eurasian plates.

INTRODUCTION

Granitoids of the Ladakh plutonic complex contain enclaves of varied compositions and textures. In the absence of adequate high quality data, little attempt has been made by earlier workers to understand the relationship between the enclaves and the host granitoids. Very little is also known about the acidic volcanics and basic dykes traversing through the pluton. This paper contributes a comprehensive set of data, describes classification and discusses the chemical characteristics of individual rock groups. It addresses some of the problems of host granitoids-enclaves relationships and their implications for the geodynamic evolution of the Trans-Himalayan arc.

The Trans-Himalayan Gangdise belt granitoids occur as discontinuous bodies for a distance of about 3000 km (Harris *et al.*, 1988) from north Kohistan and Karakoram (Pakistan), through Ladakh (India), Kailash (Nepal) to Lhasa (Tibet), exposed north of the Indus-Zangbo Suture (Fig. 1(a)). The Indus-Zangbo Suture marks the boundary between the Indian plate in south and the Eurasian plate in north. The Trans-Himalayan magmatic arc is considered to have formed due to subduction of Neo-Tethyan oceanic crust under the southern active margin of the Eurasian plate during early Cretaceous-Lower Eocene (Thakur, 1992). Granitoids of northern Kohistan and Karakoram have been studied in details by Petterson and Windley (1985) and Debon *et al.* (1987), those from western Ladakh by Honegger *et al.* (1982), Scharer *et al.* (1984) and Sharma

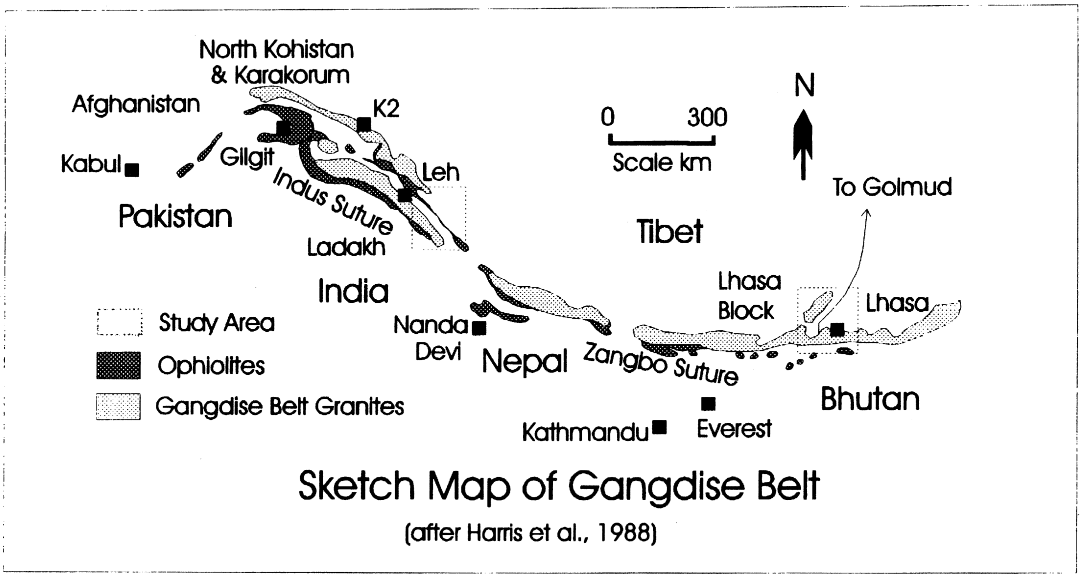
(1990). Nepal and Lhasa block granitoids have been studied by Debon *et al.* (1986) and Harris *et al.* (1988). Some geochronological data on the granitoids of western Ladakh indicate emplacement and crystallization of an early phase at 102 ± 2 Ma (Scharer *et al.*, 1984) and the most recent intrusions are estimated to have occurred 60 Ma ago (Honegger *et al.*, 1982). Based on geological and geochemical characteristics four phases of magmatism are identified in the Ladakh granitoids, better known as the Ladakh batholith (Sharma, 1990).

The occurrence of enclaves in granitoids is a common feature, they have variously been interpreted, as (a) partially digested fragments of the country or wall-rocks at emplacement or other levels, (b) early formed ferromagnesian minerals from the granitic melt itself forming cognate or autoliths (cumulate hypothesis), (c) refractory mineral residues (restite model), (d) globules of basic (hybrid) magma undercooled into the plutonic environment (magma mixing/mingling hypothesis) or (e) they are synplutonic formed at the waning stages of evolution of the granite pluton (Didier and Barbarin, 1991; Bateman, 1995). In the Ladakh batholith enclaves vary in size from few centimeters through meters to kilometer scales well within the pluton and finally occur as country rocks near the pluton margin particularly in eastern Ladakh, where the granitoids occur as minor apophyses and stocks. Based on shapes and field observations of an outcrop at Sobu (near Leh), some of the enclaves have been interpreted to represent magma mingling of dioritic and granitic compositions by Weinberg (1997). However, this does not explain the (a) large variation of grain size in different enclaves, (b) presence of foliation in a wide majority of the enclaves (implying that they were not melts but solidified rocks that had suffered post crystallization deformation) and (c) systematic decrease in size and abundance of the enclaves from margin towards the core of the pluton. It is possible that locally some of the enclaves may have formed due to magma mingling but it does not appear to be true for the whole pluton. No geochemical data is at present available on these enclaves, nor it is clear whether these enclaves represent (1) residual source material of the host granitoid, (2) entrained patches of the subducted Neo-Tethyan ocean, (3) portions of southern Tibet-Karakoram plate margin, (4) earlier phases of the arc magmatism itself, (5) represents magma mingling or (6) a combination of all or some of these possibilities.

Here we present a comprehensive set of major, trace and rare earth element data (Tables 1 to 3) on the Trans-Himalayan Gangdise belt granitoids, enclaves, acid volcanics and mafic dykes within the Ladakh plutonic complex from eastern Ladakh (India) and compare these with the granitoids and acid volcanics from the Lhasa Block of Tibet (marked as rectangles in Fig. 1(a)). The latter were collected during the 1994 Indian Silk Route Expedition by VCT.

Geological Setting

The Ladakh terrain is bounded in the south by the south-dipping Indus Suture Thrust separating it from the Zanskar zone and in the north by the north-dipping Karakoram Thrust separating it from the Karakoram zone (Fig. 1(b)). The Indus Suture Zone marks the boundary between the Indian and the Eurasian Plates (Gansser, 1977). It probably represents the remnants of Neo-Tethyan Ocean, when the latter closed via northward subduction under the Eurasian Plate. These ophiolitic rocks consist of chaotic blocks of schistose basic volcanics, agglomerates, amygdaloidal basalt, chlorite schist, deformed conglomerate schist, glaucophane schist, slates and large lenses of pelagic limestones dispersed in a turbiditic matrix (Thakur and Misra, 1984; Sinha and Upadhyay, 1990). The basaltic rocks show predominantly OIB-E-MORB and minor N-MORB trace-element characteristics (Honegger *et al.*, 1989, Ahmad *et al.*, 1996). Other major units of this zone include the sedimentary sequences of the Indus and Kargil Formations consisting of conglomerate, sandstones, siltstones and shale, subduction related mafic-intermediate-acidic magmatic rocks of the Ladakh plutonic complex and Dras island arc and associ-

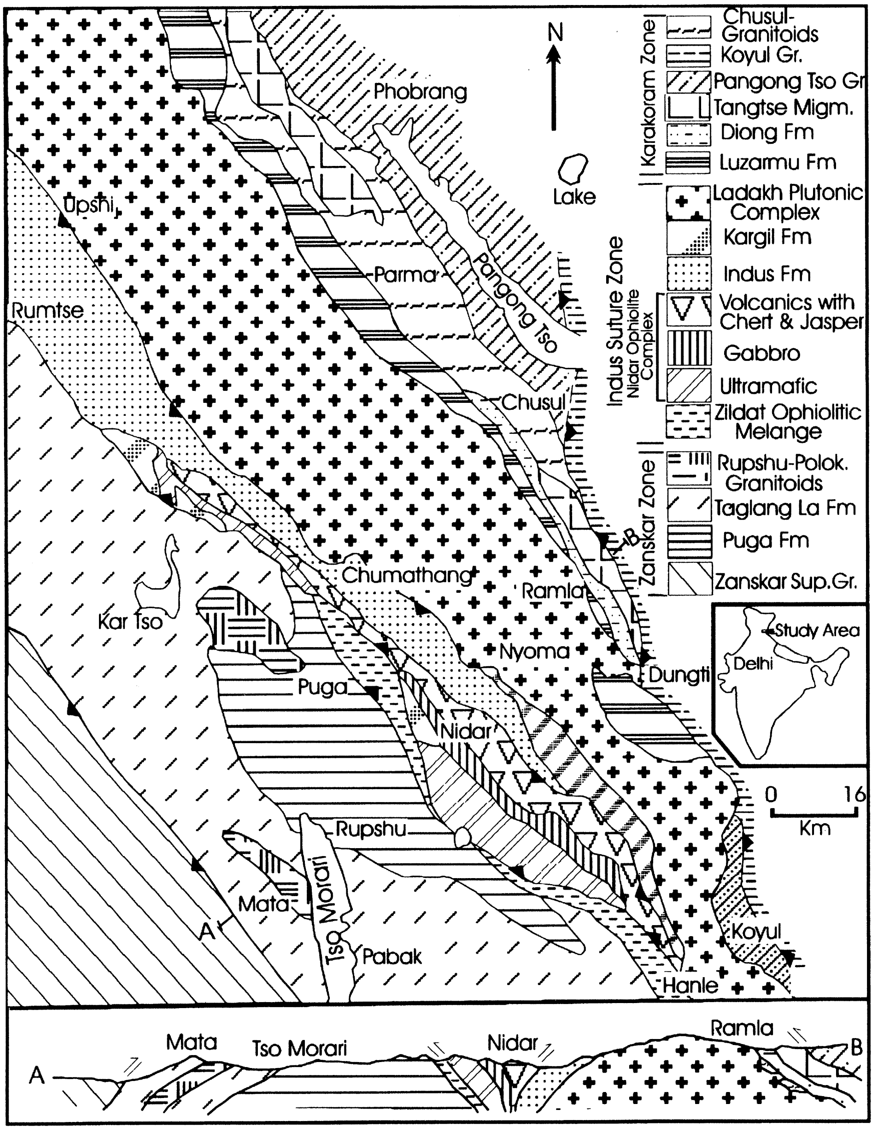


(a)

Fig. 1. (a) Sketch map of the distribution of Trans-Himalayan granitoids (after Harris et al., 1988). Dashed rectangles show the outlines of study areas in eastern Ladakh (Fig. 1(b)) and Lhasa terrain (Fig. 1(c)). (b) Geological map of eastern Ladakh and a cross section along the line A-B, showing contact relationships among the various lithological units of the study area (after Thakur and Misra, 1984). Inset map of India showing the outline of the study area. (c) Geological map of the Lhasa block, southern Tibet.

ated sedimentary sequences, south of the Ladakh plutonic complex. In the north the Gondwana Group rocks comprises orthoquartzite, calcareous sandstones, breccia and carbonaceous shales. The Shyok Group consists of chlorite schist, quartzite, limestone, basalts and andesites intruded by diorite and hornblendite in the lower part and the upper part consists of platy limestones, amphibolite, mica schist, serpentinite lenses, green and red sandstones, shales, conglomerates, pyroxenite, peridotite, gabbro, basalt and andesite. The Shyok Group has intrusive and at places tectonic contact with the Karakoram plutonic complex in the north (Fig. 1(b)). The Pangong Group consists of calcareous phyllites, mica schist, foliated metavolcanics and chlorite schist with bands of limestone and quartzite at lower grade and garnet-kyanite- and hornblende bearing schist, biotite gneiss, calc-silicates, marble and migmatites with aplites and pegmatite veins in medium grade rocks.

In Tibet the Lhasa terrain is bounded by Banggong Suture in the north and Indus-Zangbo Suture in the south (Fig. 1(c)). Although details of the geology is beyond the scope of this paper, occurrences of lithologies of widespread geological ages have been reported from the Lhasa block (Xu *et al.*, 1985; Debon *et al.*, 1986; Harris *et al.*, 1988; Thakur, 1990). The Gangdise belt granitoids represented by Yangbajin intrusion contain two plutonic facies, intruded into Carboniferous sandstone. The older biotite-hornblende-sphene granite-gneiss is intruded by a younger, more leucocratic biotite granite containing large xenolith of gneiss and injection migmatite (Harris *et al.*, 1988). However, our sampling is mostly restricted to leucocratic biotite granite type. The Eocene volcanics is exposed in the central west part of the map (Fig. 1(c)) overlying the granitoids and the Cretaceous lithologies. Eocene volcanics of the Lhasa block is considered equivalent to the Khardung acidic volcanics of Ladakh, which occurs as a linear volcanic unit overlying the Ladakh



(b)

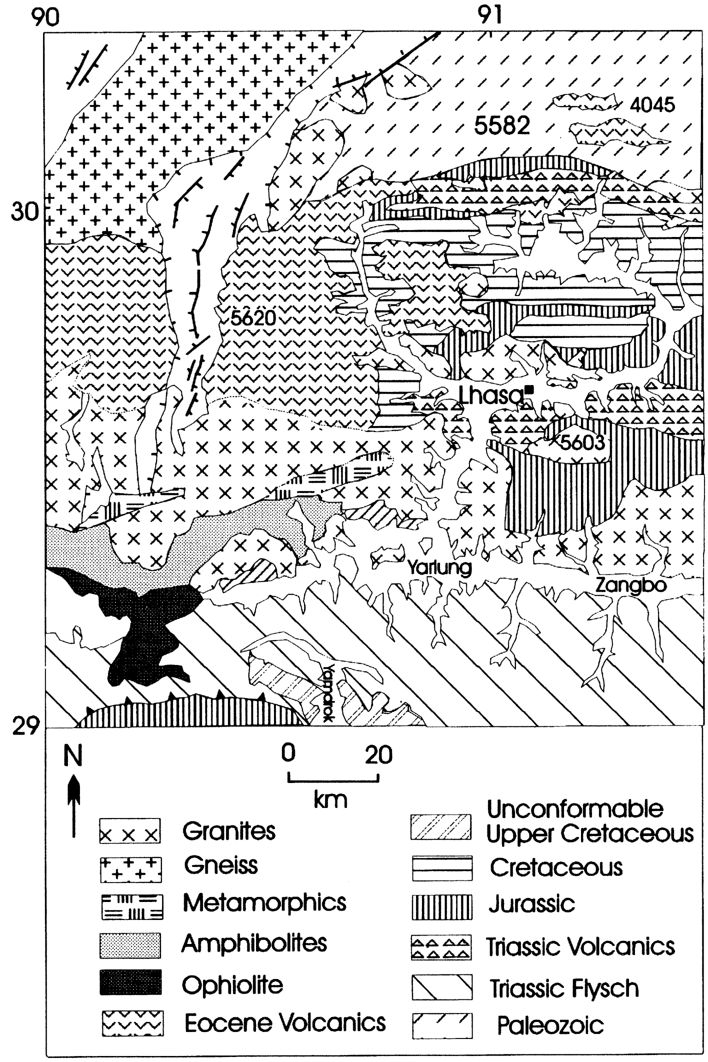
Fig. 1. (continued).

granitoids from Khardung (NW of Upshi) to Dungti in the SE (Fig. 1(b)). In this study the acidic volcanic samples of Ladakh were collected from Dungti. The Ladakh granitoids and enclave samples of were collected from the southern margin towards core of the pluton between Upshi and Dungti and the basic dykes were collected between Nyoma and Dungti (Fig. 1(b)).

Petrographic Characteristics

Ladakh enclaves

There are three major types of enclaves, namely (a) tonalitic, (b) dioritic/granodioritic and (c) metabasic. Tonalitic, dioritic and granodioritic enclaves are medium to coarse grained constituted dominantly of plagioclase and quartz with vary-



(c)

Fig. 1. (continued).

ing amounts of mafic (hornblende + biotite) phase. The mafic constituents varies between 10–20% of the bulk rock. Chloritization of mafic minerals is common. Some of the enclaves are partially corroded and show a gradational transition into granitic host. The An content of the plagioclase is higher compared to the host granitic rock. Relict pyroxenes are also quite common within hornblende phenocrysts. Alteration of hornblende to biotite is also seen, other accessory minerals include muscovite, zircon, opaques and apatite. The meta-basic enclaves are typically medium to fine-grained with development of schistosity. The absence of quartz and K-feldspars, distinguish it from the dioritic enclaves. The meta-basic enclaves characteristically show porphyritic textures with plagioclase and pyroxene phenocrysts. Clinopyroxene and minor orthopyroxene frequently alter partially or completely to hornblende. Clinopyroxene phenocrysts in few samples exhibit exsolution lamellae of orthopyroxene. One samples (LP-35M) exhibits gabbroic features, it is coarse-grained having typical ophitic texture. Exsolution of iron oxide from the mafic phase is observed giving rise to a spongy cellular appearance. Microscopic observations across the boundary between the felsic and fine-grained mafic enclaves, reveal that, in some of the enclaves, the granitic magma has invaded large hornblende grains along the fractures. The granitic magma near the contact are fine grained and gradually grades into a normal coarse-grained texture, with broken amphibole grains along the contact.

Ladakh mafic dykes

Dyke samples are medium to fine grained, with calcic-plagioclase, ortho- and clinopyroxene phenocrysts. The groundmass consists of plagioclase, pyroxene and abundant opaques and iron oxides. The mafic phases are partially or completely chloritized. Large clinopyroxene grains also show variably thick bands of orthopyroxene exsolved lamellae. Sample LP-13 shows a trachytic flow texture. Dyke sample KH-1, on the other hand, is coarser with plagioclase as the dominant phenocryst.

Ladakh granitoid

The granitoids of Ladakh plutonic complex vary widely in modal mineralogy from quartz-diorite through granodiorite to granite. However, few samples with low K-feldspar/plagioclase ratio may well qualify as tonalite. The rocks are medium to coarse-grained with large crystals of feldspar (both alkali and plagioclase), quartz and varying amounts of micas (mainly biotite). K-feldspar is mainly orthoclase but microcline is observed in coarse-grained varieties. Plagioclase phenocrysts are mostly oligoclase and albite. K-feldspar and plagioclase grains frequently shows fracturing due to brittle deformation. Feldspar phenocrysts are frequently zoned with inclusions and some are altered to sericite and muscovite. Graphic intergrowth of K-feldspar and quartz, vermicular relationship showing myrmekite textures and exsolution perthite are also common. Quartz grains occur both as phenocrysts and groundmass along with alkali feldspar and plagioclase. The mafic minerals dominantly consist of biotite, hornblende and opaques. The mafic minerals constitute <5% in more leucogranitic varieties to as high as >25% in quartz dioritic rocks. The proportion of mafic minerals in granodioritic and tonalitic types are intermediate. The tonalitic rocks commonly contain abundant amphibole whereas granodiorites are more enriched in biotite. The two varieties are distinguished by their relative proportions of K-feldspar and plagioclase. Secondary chloritization of mafic phases is quite frequent. Occasional bending of mica flakes are observed indicating post-crystallization deformation. Varying amounts of acicular apatite, euhedral to subhedral zircon and euhedral sphene are also observed as accessory phases. Relict pyroxenes attached to hornblende is also seen in some of the samples (e.g., LP 20 tonalite).

Ladakh acid volcanics

Acidic volcanic rocks are classified as rhyolites and rhyolitic breccia. Most of the rhyolitic sample include andesitic and/or rhyolitic rock fragments along with rounded ovoids of K-feldspar (sanidine) and quartz phenocrysts. These rock fragments and phenocrysts are set in a glassy groundmass showing flow banding. Phenocrysts of plagioclase are also quite common. Amygdules are partially filled with secondary quartz, chlorite and calcite. Quartz-filled vesicles are quite common. The sanidine phenocrysts shows simple fanning. Some of the rock fragments contain elongated glass fragments or shards that are preferentially oriented along the flow banding as commonly observed in ignimbrites. Andesitic volcanic rocks are fine-grained with phenocrysts of plagioclase (sodic) and pyroxene. The groundmass consists of plagioclase and pyroxene. There are abundant opaques in the groundmass and few occur as phenocryst. The groundmass contain interstitial glass, occasionally chloritized. Plagioclase phenocrysts are partly altered. Plagioclase laths show preferred orientation giving trachytic flow texture. The granitoids and acidic volcanics of the Lhasa terrain are similar in most of their textural and mineralogical characteristics to those of Ladakh.

Table 1. Representative major oxide (in wt%) and trace element (in ppm) analysis of Ladakh enclaves and dykes

Sample No.	Ladakh enclaves											Ladakh dykes				
	LP1M	LP2CFM	LP3AM	LP4AMF	LP5CM	LP10M	LP35M	LP36M	LP2BM	LP9M	LP19M	KH1M	KH2M	LP13M	LP14M	LP16M
SiO_2	58.1	52.1	50.6	67.7	69.0	55.9	49.2	54.4	57.7	58.0	56.9	62.4	53.5	52.7	55.3	53.6
TiO_2	1.05	1.41	1.03	0.69	0.62	1.27	0.29	0.91	0.87	0.93	1.00	1.28	0.99	1.12	1.01	1.00
Al_2O_3	15.8	15.2	16.0	14.6	15.3	16.5	17.0	13.3	16.9	18.4	16.0	15.6	16.2	15.5	16.0	16.1
Fe_2O_3	6.7	10.0	11.5	4.4	3.5	9.6	7.4	10.4	6.4	6.8	8.3	6.4	9.0	9.8	9.1	9.6
MnO	0.13	0.14	0.37	0.06	0.07	0.17	0.15	0.19	0.11	0.12	0.13	0.12	0.14	0.20	0.17	0.16
MgO	4.5	7.3	6.2	1.5	1.3	5.5	14.9	9.0	3.3	3.8	6.1	1.8	7.6	8.3	7.7	7.7
CaO	5.9	9.4	9.9	3.3	2.7	7.6	11.8	8.4	5.7	6.4	7.8	3.7	8.4	10.3	7.6	8.9
Na_2O	4.6	2.6	3.6	3.2	3.4	3.1	0.9	2.2	5.0	4.1	3.1	4.0	3.2	2.9	1.8	3.1
K_2O	2.0	1.3	0.7	4.2	4.2	1.8	0.3	1.8	1.9	2.4	1.9	3.4	1.3	0.8	2.3	1.2
P_2O_5	0.49	0.60	0.16	0.18	0.16	0.29	0.06	0.20	0.44	0.31	0.23	0.45	0.21	0.26	0.19	0.20
LOI	1.13	1.89	0.54	0.86	0.97	1.04	2.03	1.52	0.70	1.59	0.98	0.98	1.23	1.42	1.11	2.26
Ni	28	8	15	16	23	12	74	119	4	13	30	2	62	37	54	63
Cr	74	114	129	41	56	95	176	314	26	290	138	10	182	215	154	216
Cu	23	118		18	18	37	11	42	40	37	9	12	53		61	55
Zn	120	85	198	52	51	91	63	84	84	81	98	84	97	149	130	102
Ga	23	19	21	16	18	20	15	15	22	21	20	19	19	19	20	21
Pb	12	7	9	18	23	16	5	7	10	12	41	12	14	14	15	16
Th	5	3	2	9	24	5	2	3	5	10	7	9	4	3	4	3
U	1	2	0	4	6	2	1	2	0	2	3	2	2	1	3	2
Rb	72	40	7	208	215	62	8	47	55	114	93	116	54	22	97	51
Sr	722	610	319	234	210	452	522	293	746	506	329	332	458	588	357	438
Ba	589	290	574	554	457	379	166	151	755	459	108	576	112	151	193	109
Zr	163	74	80	311	305	155	37	85	244	252	159	364	112	115	105	103
Y	18	23	24	30	29	32	9	24	21	26	35	29	25	22	31	24
Nb	7	4	4	15	16	9	1	4	8	10	9	18	4	6	5	4
La	34.50	22.90					6.20	14.70					16.90	18.90	11.95	
Ce	81.00	54.80					10.10	27.10					32.10	38.90	27.81	
Nd	35.10	30.10					6.00	15.00					18.10	21.50	15.51	
Sm	6.30	6.80					1.71	3.82					4.23	5.19	3.93	
Eu	1.62	1.77					0.561	1.13					1.29	1.43	1.22	
Gd	4.10	5.10					1.38	3.82					3.90	4.25	3.44	
Dy	2.42	3.93					1.31	3.54					3.55	4.25	2.86	
Er	0.94	1.61					0.86	2.04					2.00	2.15	1.81	
Yb	0.77	1.52					0.85	1.98					1.92	1.87	1.69	
Lu	0.157	0.205					0.133	0.342					0.292	0.307	0.212	

Table 2. Representative major oxide (in wt%) and trace element (in ppm) analysis of Ladakh granites and acidic volcanics

Sample No.	Ladakh granites												Ladakh acidic volcanics				
	LP2BF	LP5AF	LP15FM	LP17FM	LP28F	LP29F	LP30F	LP33AF	LP33AMF	LP37F	LP26AF	LP32F	LP22M	LP23M	LP24M	LP25M	LP26M
SiO_2	61.5	63.6	63.8	61.4	70.7	72.7	74.0	79.5	67.3	71.7	61.5	68.3	60.0	60.7	72.4	71.1	72.6
TiO_2	0.56	0.53	0.71	0.87	0.26	0.14	0.20	0.08	0.47	0.26	0.57	0.45	0.99	0.95	0.25	0.34	0.25
Al_2O_3	18.4	18.3	15.8	16.0	16.1	16.6	15.5	13.6	16.5	15.3	17.7	16.2	16.5	16.1	14.9	15.0	14.6
Fe_2O_3	4.0	3.8	5.3	6.2	2.0	1.1	1.3	1.0	3.0	2.1	4.6	2.6	6.7	6.4	2.5	3.1	2.5
MnO	0.08	0.09	0.08	0.09	0.04	0.03	0.02	0.02	0.07	0.03	0.09	0.04	0.13	0.12	0.05	0.03	0.03
MgO	2.0	1.8	2.7	3.4	0.7	0.3	0.3	0.1	1.2	0.7	1.9	0.9	2.9	2.6	0.4	0.6	0.4
CaO	4.3	4.6	4.5	5.0	2.2	1.1	1.2	1.1	2.5	2.9	4.4	2.2	3.8	4.1	1.6	1.3	1.6
Na_2O	5.3	4.3	3.0	3.1	3.7	4.2	3.7	2.7	4.7	4.1	4.7	4.5	4.4	4.3	3.7	3.9	3.5
K_2O	1.7	2.8	3.3	3.1	4.7	4.9	4.7	5.2	2.9	1.6	1.4	4.0	2.9	2.7	4.9	4.8	4.9
P_2O_5	0.18	0.18	0.14	0.18	0.10	0.12	0.09	0.02	0.19	0.09	0.21	0.26	0.34	0.33	0.05	0.60	0.05
LOI	0.75	1.13	1.06	0.94	0.69	1.16	0.94	0.64	0.67	0.81	1.74	0.96	2.98	2.19	1.68	1.80	1.80
Ni	5	12	24	24	8	11	10	5	15	6	3	16	6	5	13	19	13
Cr	16	21	55	64	4	9	9	1	43	24	16	33	23	15	30	27	19
Cu	19	10	29	34	10	4	5	7	17	7	23	9	30	27	11	16	9
Zn	56	77	68	74	40	52	49	22	67	25	62	57	95	89	45	53	50
Ga	21	18	16	18	18	25	22	12	20	15	19	22	20	20	15	16	15
Pb	10	22	18	16	75	49	53	32	28	8	14	67	11	11	21	27	25
Th	6	12	9	7	69	26	39	24	22	3	4	57	4	5	23	23	24
U	1	4	3	1	11	6	11	5	3	1	1	7			6	5	7
Rb	52	187	119	146	306	360	313	183	173	39	77	204	114	93	221	217	220
Sr	671	379	285	276	348	140	195	251	328	372	447	510	359	356	98	113	105
Ba	505	376	350	370	622	358	547	1111	729	278	244	1123	576	558	480	469	471
Zr	282	192	153	207	131	69	112	87	169	134	258	209	225	226	176	172	176
Y	19	30	21	23	27	27	26	22	23	14	20	25	25	25	32	30	33
Nb	6	12	8	9	10	10	9	3	7	5	6	13	9	10	11	11	12
La			27.50		26.20	20.11	26.50		38.90	14.20	17.40	85.10	28.40		36.80		36.20
Ce			57.70		51.30	33.85	61.80		89.30	21.20	33.20	184.00	65.80		84.10		79.80
Nd			25.40		17.10	16.53	19.90		31.40	7.40	16.34	51.00	30.50		31.10		32.23
Sm			5.59		3.61	3.61	3.91		6.52	1.57	3.44	8.40	7.60		6.90		7.32
Eu			1.240		0.610	0.460	0.581		1.000	0.552	1.380	1.450	1.680		0.890		0.903
Gd			4.40		2.30	2.09	2.43		4.04	0.97	2.95	4.40	6.21		5.40		5.45
Dy			4.26		1.90	1.44	1.38		2.98	0.79	2.89	2.42	6.30		5.40		5.30
Er			2.60		0.62	0.62	0.54		1.25	0.58	1.74	0.98	3.39		3.10		3.89
Yb			2.25		0.73	0.45	0.29		0.88	0.59	1.76	0.59	2.95		3.38		3.82
Lu			0.323		0.123	0.087	0.082		0.130	0.144	0.259	0.087	0.384		0.495		0.531

Table 3. Representative major oxide (in wt%) and trace element (in ppm) analysis of Yangbajin granites and Lhasa acidic volcanics

Sample No.	Yangbajin granites										Lhasa acidic volcanics					
	YB01	YB03	YB04	YB06	YB08	YB11	YB14	YB15	YB17	YB19	EV10/15B	EV15A	EV15D	EV15E	EV6/10D	EV6/10F
SiO_2	73.0	67.1	66.5	65.8	68.3	66.3	71.2	68.1	67.0	67.9	72.0	72.1	75.0	68.6	72.7	78.9
TiO_2	0.42	0.45	0.39	0.36	0.34	0.42	0.44	0.42	0.34	0.36	0.21	0.22	0.18	0.36	0.21	0.07
Al_2O_3	15.2	16.1	16.6	16.8	16.4	16.7	16.0	16.3	16.5	16.3	16.0	15.6	14.3	16.1	15.6	14.7
Fe_2O_3	2.9	3.2	2.8	2.5	2.4	3.0	2.9	3.1	2.4	2.6	1.4	1.7	1.2	2.7	1.4	1.0
MnO	0.09	0.10	0.09	0.08	0.07	0.09	0.09	0.09	0.08	0.09	0.03	0.05	0.05	0.08	0.05	0.02
MgO	1.1	1.3	1.1	0.9	0.9	1.2	1.1	1.1	1.0	1.0	0.5	0.4	0.2	0.5	0.5	0.1
CaO	2.3	2.5	2.4	2.6	2.2	2.7	2.4	2.6	2.4	2.3	0.5	0.8	1.3	1.3	1.0	0.2
Na_2O	3.6	3.3	3.3	3.2	3.5	3.6	3.9	3.7	3.4	3.3	3.1	3.0	3.4	4.3	2.8	2.3
K_2O	4.6	4.2	4.5	5.4	5.3	4.1	4.8	4.2	4.7	4.3	3.9	4.0	3.5	3.5	3.7	4.1
P_2O_5	0.14	0.14	0.12	0.12	0.11	0.14	0.14	0.13	0.11	0.11	0.05	0.05	0.04	0.07	0.03	0.02
Ni	7	7	5	3	4	7	5	7	4	7	2	5	1	5	5	6
Cu	11	13	10	5	8	20	13	21	14	8	1	3	3	10		
Zn	64	53	56	38	53	67	60	66	59	46	43	42	73	66	35	33
Ga	12	12	13	10	11	14	13	14	13	12	14	13	12	15	12	15
Pb	24	24	23	20	21	25	24	25	22	22	24	23	24	31	22	29
Th	2	3	2	3	1	3	3	4	1	3	12	10	8	7	11	21
U			1		1	1	1	1	1	1	4	3	3	2	4	6
Rb	133	148	150	169	145	127	148	140	144	149	169	148	110	124	167	200
Sr	317	326	335	335	336	364	330	326	346	326	178	185	202	236	178	67
Zr	204	221	189	162	159	210	197	200	179	174	116	123	93	286	103	104
Y	20	21	20	17	20	22	22	24	20	18	17	17	16	28	20	30
Nb	5	7	5	1	2	6	6	8	3	5	10	8	6	10	8	16
La	55.00			41.20				54.40			16.70	18.90		32.10	26.50	
Ce	102.00			77.35				105.40			40.70	48.90		66.50	54.60	
Nd	38.00			27.78				37.00			11.00	12.50		29.10	19.74	
Sm	7.66			5.55				7.30			2.10	2.69		6.42	3.94	
Eu	1.36			1.09				1.22			0.346	0.504		1.45	0.63	
Gd	5.29			3.74				5.24			1.65	1.95		5.25	2.66	
Dy	4.66			3.29				4.50			1.39	1.90		5.28	2.44	
Er	2.62			1.68				2.46			1.20	1.36		3.20	1.40	
Yb	2.45			2.00				2.80			1.32	1.80		3.54	1.72	
Lu	0.320			0.285				0.350			0.213	0.295		0.507	0.279	

GEOCHEMISTRY

Major elements were analysed using standard XRF technique as described by Bhat and Ahmad (1990). Trace elements including REEs were analysed by monochromator of ICP-AES (Jobin Yvon, Model: JY 70 Plus) at the Wadia Institute of Himalayan Geology, Dehradun. Instrumental parameters are given in Rathi *et al.* (1991). 100 ml of 1% rock solutions were prepared by the method given in Walsh *et al.* (1981). 75 ml of this solution were processed for REEs and 25 ml were used for estimating other trace elements. REEs were separated by ion chromatography technique of Walsh *et al.* (1981). All REEs except for Ce, Sm and Gd were determined using multi-element salt standard. Concentrations of Ce, Sm and Gd were measured using the separated REE fraction of a rock standard of matching matrix. The accuracy and precision are described in Ahmad *et al.* (1996). The chemical data are shown in Tables 1, 2 and 3.

Elemental mobility

A series of binary plots, showing inter-element relationships, use SiO_2, MgO, K_2O and Zr for the enclaves and mafic dykes (Fig. 2) and SiO_2, Fe_2O_3, Rb and Sr for the granitoids and acidic volcanics (Fig. 3), as measures of fractionation against other elements. These plots are quite informative in terms of assessment of the mobility of various elements under low-grade metamorphism and alteration that these rocks have undergone. Zr is considered nearly immobile during low grade of metamorphism and/or alteration (Winchester and Floyd, 1977). It is essentially incompatible in basaltic system (Tarney *et al.*, 1979) and in a recent study it is shown that Zr behaves incompatibly in magmatic systems up to ≈68 wt% SiO_2. This is because of the fact that fractionation of zircon can be suppressed due to higher temperature and volatile contents of the melt (Bradshaw, 1992). Plot of Zr against SiO_2 (Fig. 2) shows a strong positive correlation for rocks with SiO_2 contents of ≈50 to ≈62 wt%. An inflection is observed in the trend at >68 wt% SiO_2, where the trend becomes negative, probably indicating commencement of zircon fractional crystallization (Bradshaw, 1992). Similarly negative trends are observed for the more siliceous granitoid and acidic volcanics (Fig. 3). Considering the low grade of metamorphism and alteration that these rocks have undergone, Zr should be immobile and therefore, the observed trends of SiO_2 against Zr (Figs. 2 and 3) probably indicate that (a) SiO_2 abundance are not perturbed by post-crystallization processes and (b) that SiO_2-Zr trends may be primary magmatic trends. Similarly, the observed inter-element trends for various major and trace elements (Figs. 2 and 3) may imply that the bulk chemistry of these rocks is not significantly disturbed by post-crystallization processes. However, limited scatter of the data for some elements could be due to secondary processes.

Magma type

The enclaves exhibit a wide compositional range from basic to acid (SiO_2 - 49.24 to 70.60 wt%: Table 1), however, majority of these are basaltic-andesite and andesite in terms of SiO_2 and are sub-alkaline in terms of total alkalis (Fig. 4(a)). Dykes within the Ladakh plutonic complex exhibit predominantly basaltic-andesite and andesite composition but with restricted SiO_2 range and are sub-alkaline in terms of the total alkalis. A similar compositional range with a sub-alkaline nature is exhibited by these rocks in terms of relatively less mobile incompatible trace-element ratios of Nb/Y vs. Zr/TiO_2 (Fig. 4(b): Winchester and Floyd, 1977). These samples are calc-alkaline in terms of the AFM diagram and the same characteristics is exhibited in term of FeOt/MgO vs. FeOt (Table 1).

SiO_2 in the Ladakh granitoids varies between 57 and 79.48 wt% and between 59.95 and 72.62 wt% in the Ladakh acidic volcanic samples (Fig. 4(a) and Table 2). Felsic samples from Lhasa block of Tibet are known as Yangbajin granites and Eocene acidic volcanics. The Yangbajin granites show SiO_2 range of 65.84 to 72.97 wt%, and the Eocene acidic volcanics exhibit a silica range of 68.22–78.88 wt%. Based on their SiO_2 and total

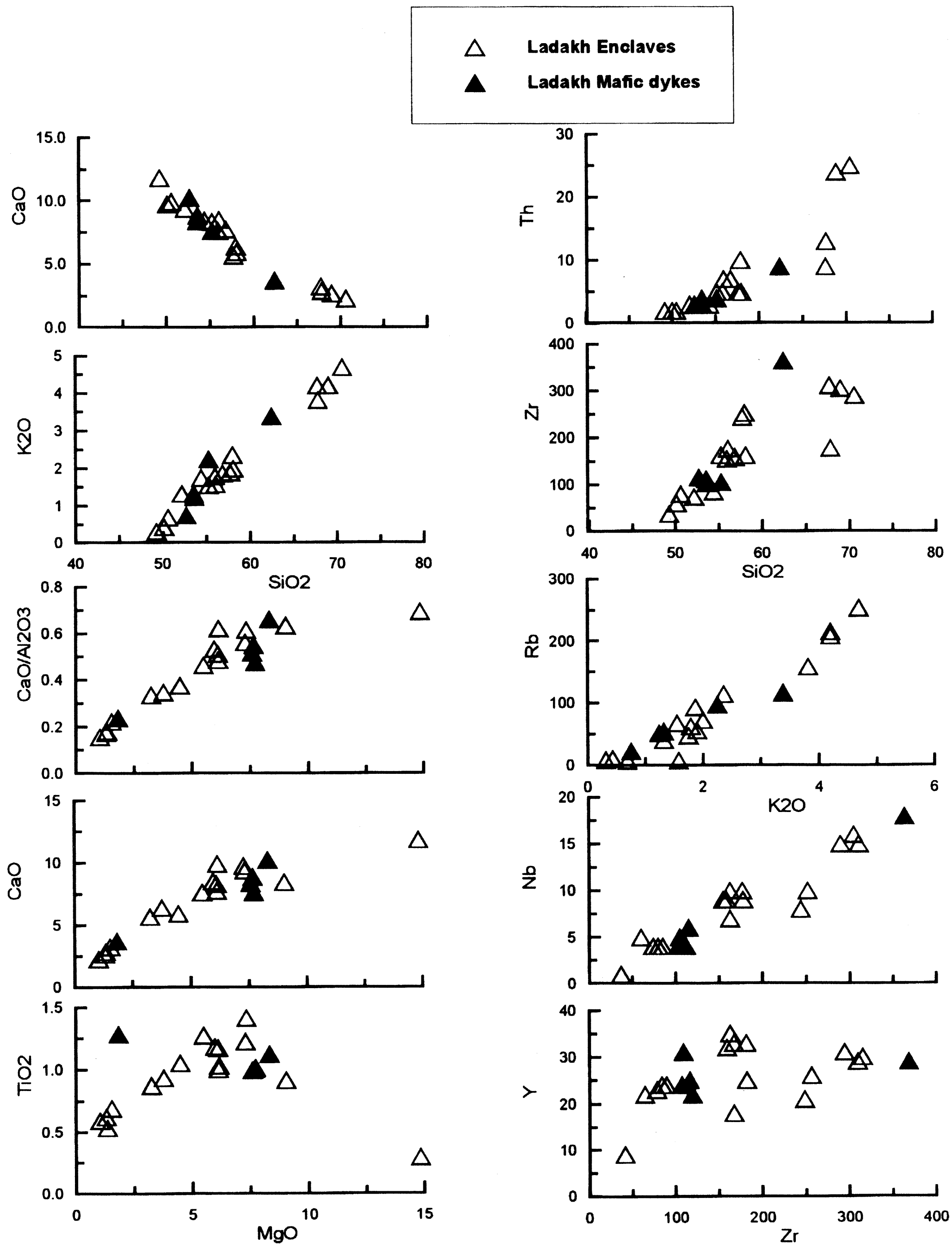


Fig. 2. Binary plots of major and trace elements for the Ladakh enclaves and mafic dykes.

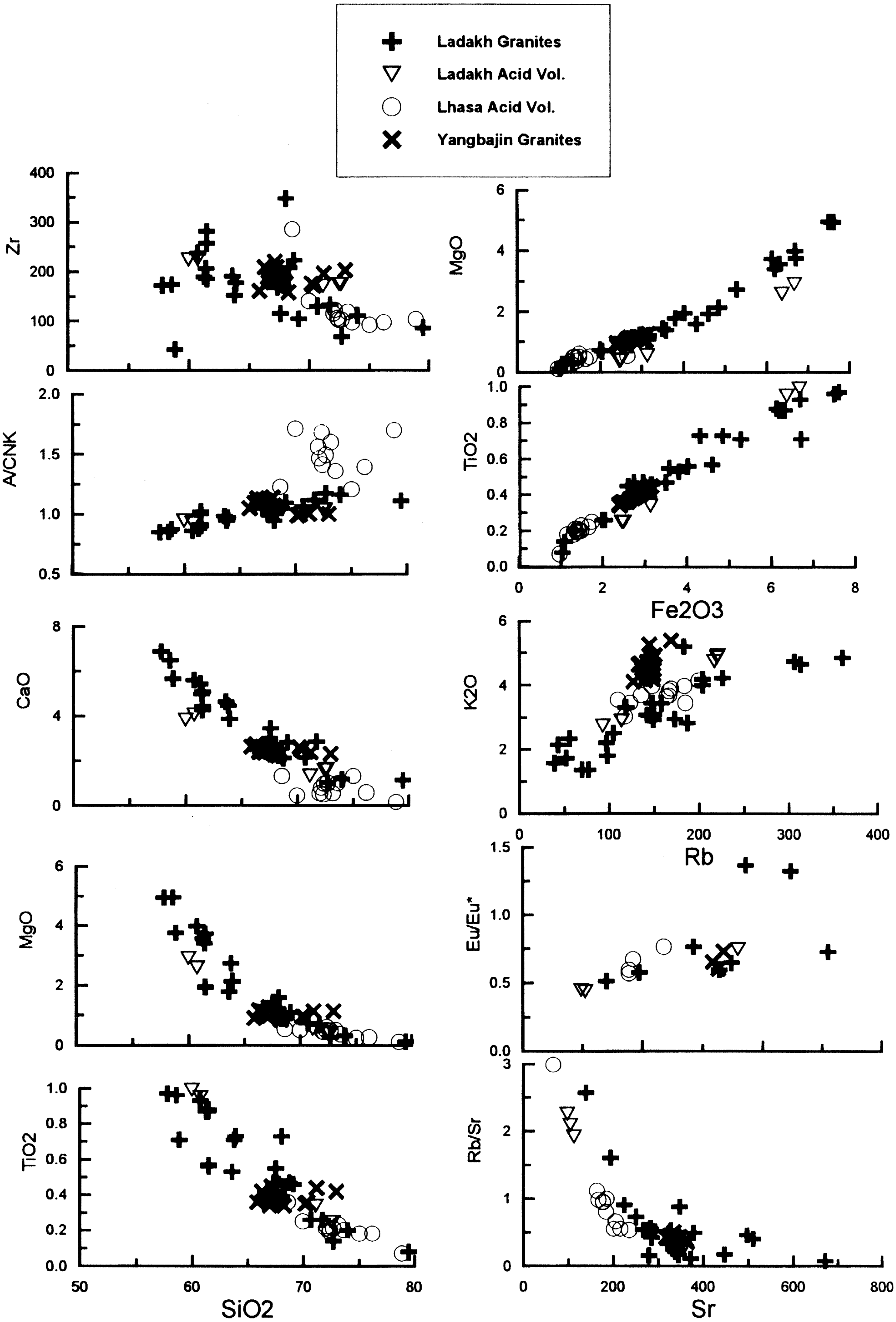


Fig. 3. Binary plots of major and trace elements for the granites and acidic volcanics from Ladakh and Tibet.

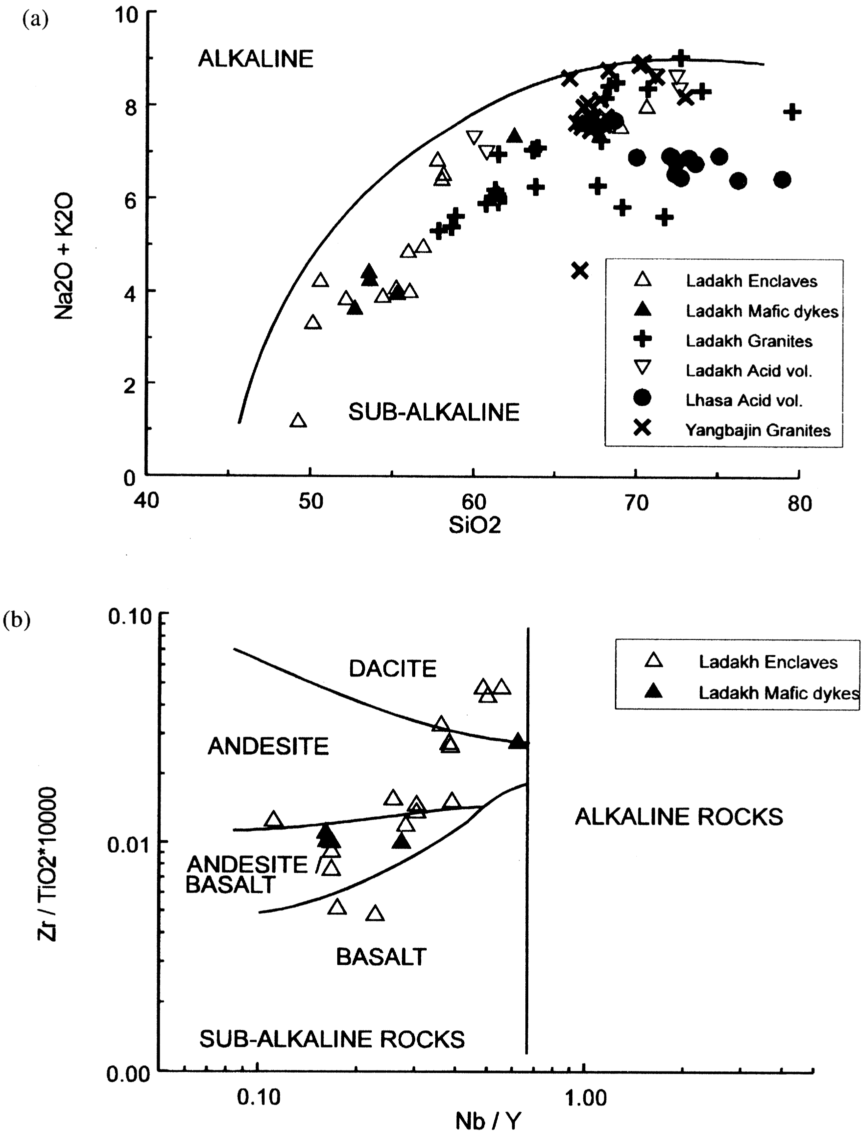


*Fig. 4. (a) Binary plots of Na_2O+K_2O vs SiO_2 (Miyashiro, 1978) for the enclaves, mafic dykes, granites and acidic volcanics from Ladakh and Tibet. Note their predominantly sub-alkaline nature. (b) Binary plots of Nb/Y vs. Zr/TiO_2*10000 (Winchester and Floyd, 1977) for the Ladakh enclaves and mafic dykes. Note the sub-alkaline nature and large compositional variation from basalt through to dacite for the enclave samples.*

alkalis majority of these rocks are classified as sub-alkaline granites (Fig. 4(a)). In normative Ab-Or-An diagram (not shown here) majority of the Ladakh granitoids plot in the field of granodiorite, a few plot in the field of tonalite. They are predominantly meta-aluminous (A/CNK ranges from 0.80 to 1.18). For more evolved samples with >70 wt% SiO_2, the peraluminousity increases with A/CNK value >>1. In normative Ab-Or-An diagram, the Ladakh acidic volcanics are largely granite but two silica poor samples plot in the field of granodiorite. The Yangbajin granite plot it the field of quartz-monzonite (s.s) although a few are transitional between quartz-monzonite and granite. The acid volcanics of Lhasa block are highly siliceous and rhyolitic in nature.

Major and Trace Element Variation

Ladakh enclaves and mafic dykes

In the binary plots positive relationships are observed for TiO_2, CaO and CaO/Al_2O_3 against MgO. CaO shows a strong negative and K_2O a strong positive correlation with SiO_2 for the enclave samples (Fig. 2). In terms of trace elements Zr, Th (Fig. 2), Rb, Pb, Y, Nb and LREE show strong positive and Sr, Cr and Ni show negative correlations against SiO_2. Ni and Cr show positive relationship against MgO. Positive correlations are also observed for Rb, Nb and Y against Zr (Fig. 2). The inter-element relationships for the mafic dykes remain same as those for the enclave samples except that the dykes show restricted variation for most of the elements and its trends are enveloped by the enclave samples (Fig. 2). Similarly many other inter-element relationships can be described, they all confirm to the inference that our samples have preserved their primary chemical characteristics. These relationships are useful to constrain the generation and evolution of these rocks. The negative relationship of MgO, Fe_2O_3, MnO, TiO_2, CaO, Al_2O_3 against SiO_2 (all plots not shown in Fig. 2) and positive trends of TiO_2, CaO and CaO/Al_2O_3 vs. MgO (Fig. 2) may indicate fractionation of the gabbroic assemblage, however, the absence of a negative Eu and Sr anomalies in the normalized REE and multi-element patterns (Figs. 5(a) and 5(b)) probably indicate that plagioclase was not an important fractionating phase. Strong negative relationships of Fe_2O_3 and TiO_2 with SiO_2 may indicate fractional crystallization of Fe-Ti oxides. The MgO-TiO_2 relationship shows an increase in TiO_2 with decreasing MgO for the samples with >7 wt% MgO and below this level TiO_2 decreases with decreasing MgO. Such relationships are also observed, but with lesser clarity, for the plots CaO and CaO/Al_2O_3 against MgO (Fig. 2). These relationships may indicate that olivine was the first phase to fractionate followed by titanomagnetite and/or pyroxene. One of the enclave sample (LP35M) plots separately in most of the binary plots due to its very high MgO (14.85 wt%), CaO (11.83 wt%) and very low TiO_2 (0.29 wt%) with respect to other enclaves. Moreover, it is distinct in terms of its petrographic and mineralogical features. These observations open the possibility that (a) all the enclaves may not be co-genetic and/or (b) some of the enclaves like LP35M could represent local segregation of early formed ferromagnesian phases of the host granite itself and therefore they may be cognate or autoliths, as suggested earlier by Honegger *et al.* (1982) for some of the enclaves from western Ladakh. However, our field observations and laboratory investigations indicate that most of the xenoliths are entrained patches of pre-existing rocks.

To understand the source characteristics, ratios of highly incompatible elements, preferably the least mobile ones with small ionic radius and high charge (Tatsumi *et al.*, 1986) e.g., HFSE are very useful. Ratios of these elements do not change significantly from moderate degrees of fractional crystallization (Saunders *et al.*, 1988) but are sensitive to varying degrees of partial melting and to source inhomogeneties (Ahmad and Tarney, 1991). As the degrees of partial melting for subalkaline basaltic rocks are expected to be high (≈10–15%: Bender *et al.*, 1984) ratios of these highly incompatible trace elements are expected to reflect the source characteristics (Saunders *et al.*, 1988). Therefore, the ratios such as Th/La, Th/Nb, Zr/Nb, Ce/Nd etc. may mimic the source characteristics. These ratios for the enclaves and mafic dykes (Table 1) are higher than those of the primitive mantle ratios (Sun and McDonough, 1989) probably indicating their derivation from enriched mantle sources. Normalized REE and multielement patterns for the enclaves and mafic dykes are shown in Fig. 5. In order to avoid crowding and overlapping of patterns, particularly for the enclave samples, only representative patterns are shown to cover the observed wide compositional range (Table 1, Figs. 2 and 4). The REE patterns for all the enclave and mafic dyke samples are enriched with respect to chondrite. Nearly eight-fold enrichment for the LREE (from ~20× to ~150× chondrite) for the enclave samples is difficult to explain by simple fractional crystalli-

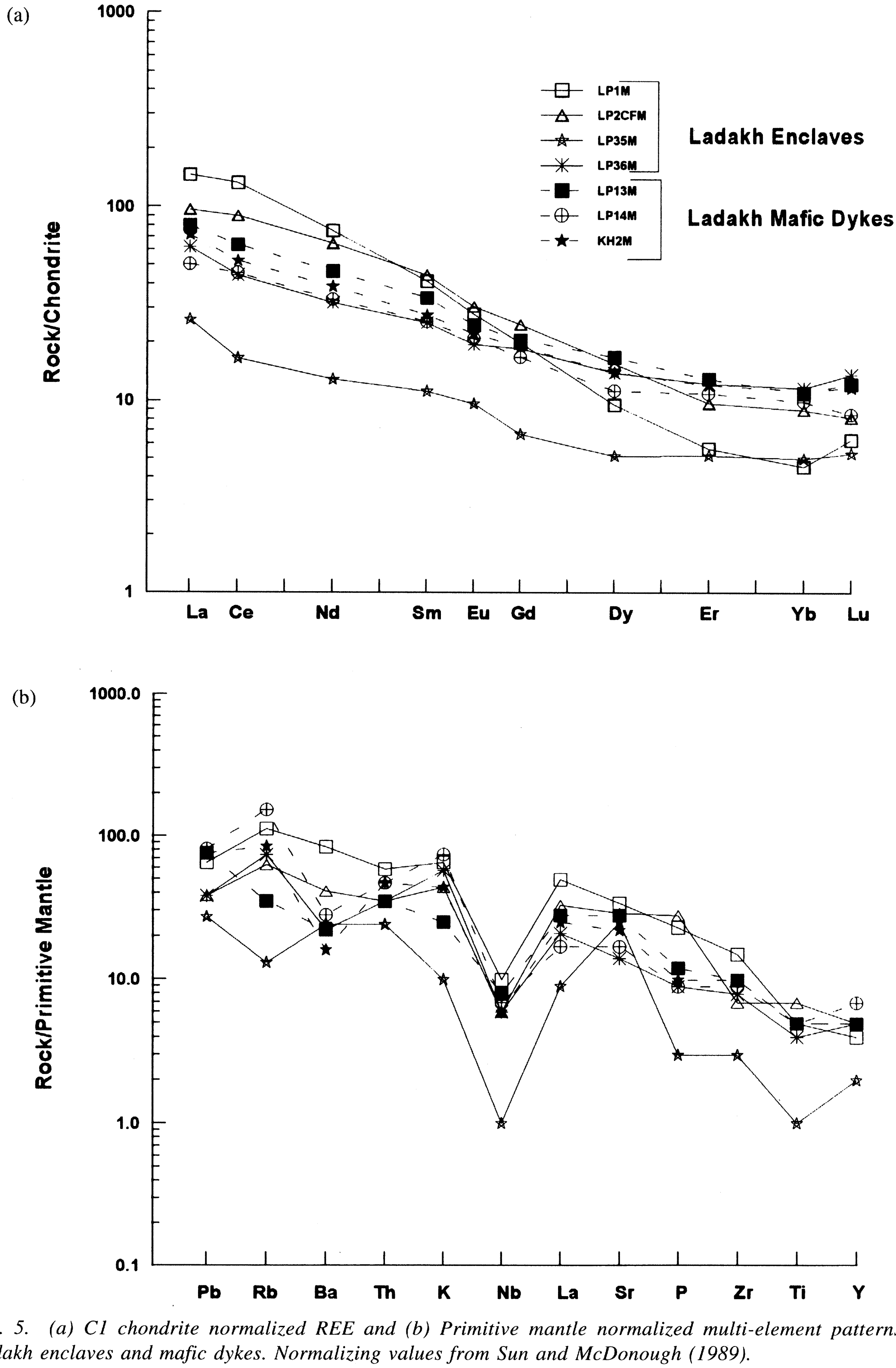


Fig. 5. (a) C1 chondrite normalized REE and (b) Primitive mantle normalized multi-element patterns of the Ladakh enclaves and mafic dykes. Normalizing values from Sun and McDonough (1989).

zation of a single parental melt. It has been shown by Ahmad and Rajamani (1991) that nearly 66% fractional crystallization is required to achieve 3-fold (~6× to 18× chondrite) enrichment of Ce in a basaltic melt, which is not supported by other data. The observed 8-fold variation in the case of Ladakh enclaves, therefore, has to be explained by some and/or a combination of other petrogenetic processes. $(La/Yb)_N$ ratios for the enclave samples vary between 5.23 and 32.14, such a large variation can be explained by large variation in the degrees of partial melting (Smedley, 1988) and/or variable depth of melting, implying the absence or varying abundances of garnet in the source (Hanson, 1980) and/or the source was heterogeneous in terms of enrichment and/or a combination of some of the above controlling factors (Ahmad and Tarney, 1994). Multi-element patterns for the enclaves show enriched characteristics with respect to the primitive mantle (Sun and McDonough, 1989), however, it also shows depletion of HFSE including Nb, P and Ti. Such trace-element characteristics are commonly observed in subduction-related magmatism (Saunders *et al.*, 1980; Holm, 1985), but are also common in Phanerozoic continental flood basalts and Proterozoic dyke swarms (Tarney, 1992). However, the latter two also have distinctive negative Sr anomaly in their multi-element patterns, which is generally positive in the case of subduction-related magmatism (Holm, 1985). That these enclaves were generated in a subduction-related environment is evidenced by their high Al_2O_3 abundance, predominantly calc-alkaline characteristics and rock association (Brookfield and Andrew-Speed, 1984). The REE and multi-element patterns for the mafic dykes (Fig. 5) are similar to those of the enclaves, the only difference being that the dyke patterns are parallel to each other with almost constant inter-element ratios. These probably indicate similarity of P-T and other petrogenetic factors including source characteristics for the generation of all the studied dykes. Trace-element characteristics overwhelmingly indicate their generation in a subduction-related environment.

Granitoids and acidic volcanics of Ladakh and Lhasa

Series of binary plots for felsic rocks of Ladakh and Lhasa areas exhibit well-defined linear trends for TiO_2, MgO, CaO, and A/CNK against SiO_2 (Fig. 3). Although Yangbajin granite and acid volcanics of the Lhasa block exhibit linear relationships, clustering of Yangbajin granite samples is observed between 65 and 70 wt% SiO_2. Ladakh granitoids exhibit a positive correlation between K_2O and SiO_2 probably indicating concentration of K_2O in K-feldspar and biotite. Considering Fe_2O_3 as the differentiation index, its extremely good correlations with TiO_2, MgO (Fig. 3) and CaO probably indicate fractionation of biotite and plagioclase. A/CNK values of Ladakh granite ranges between 0.80–1.112, indicate an I-type parentage for most of the samples, whereas some samples show transition between I- and S-type granitoids. The more mafic rocks have lower A/CNK value, but highly siliceous rocks have high A/CNK values probably indicating that the chemical variation of these granites may be controlled by fractional crystallization processes. Both Ladakh and Yangbajin granites exhibit $Na_2O > K_2O$, whereas Ladakh acid volcanics and the acid volcanics of Lhasa block has $Na_2O < K_2O$.

Important trace elements like Zr, Sr, Rb and trace elements ratios such as Rb/Sr and Eu/Eu* are plotted in the binary diagram (Fig. 3). Rb in these samples exhibits positive trends with K_2O. Negative trends are observed between Sr-SiO_2 and Sr-Rb for the samples from both the areas. Overall Zr exhibits a negative correlation with SiO_2. CaO and Sr exhibit a positive correlation. Strong negative and positive relationships are observed between Rb/Sr and Eu/Eu* against Sr respectively (Fig. 3), probably indicating K-felspar-plagioclase fractionation. The Ladakh granitoids are poor in Rb (ranges between 39–360 ppm; the highly silicic variety has the highest Rb content) and have high Sr (140–671 ppm), these characteristics are also exhibited by Yangbajin granites. In case of Ladakh acidic volcanics the highly evolved samples (SiO_2 > 70 wt%) show high Rb and low Sr contents. Whereas the Rb/Sr ratio does not

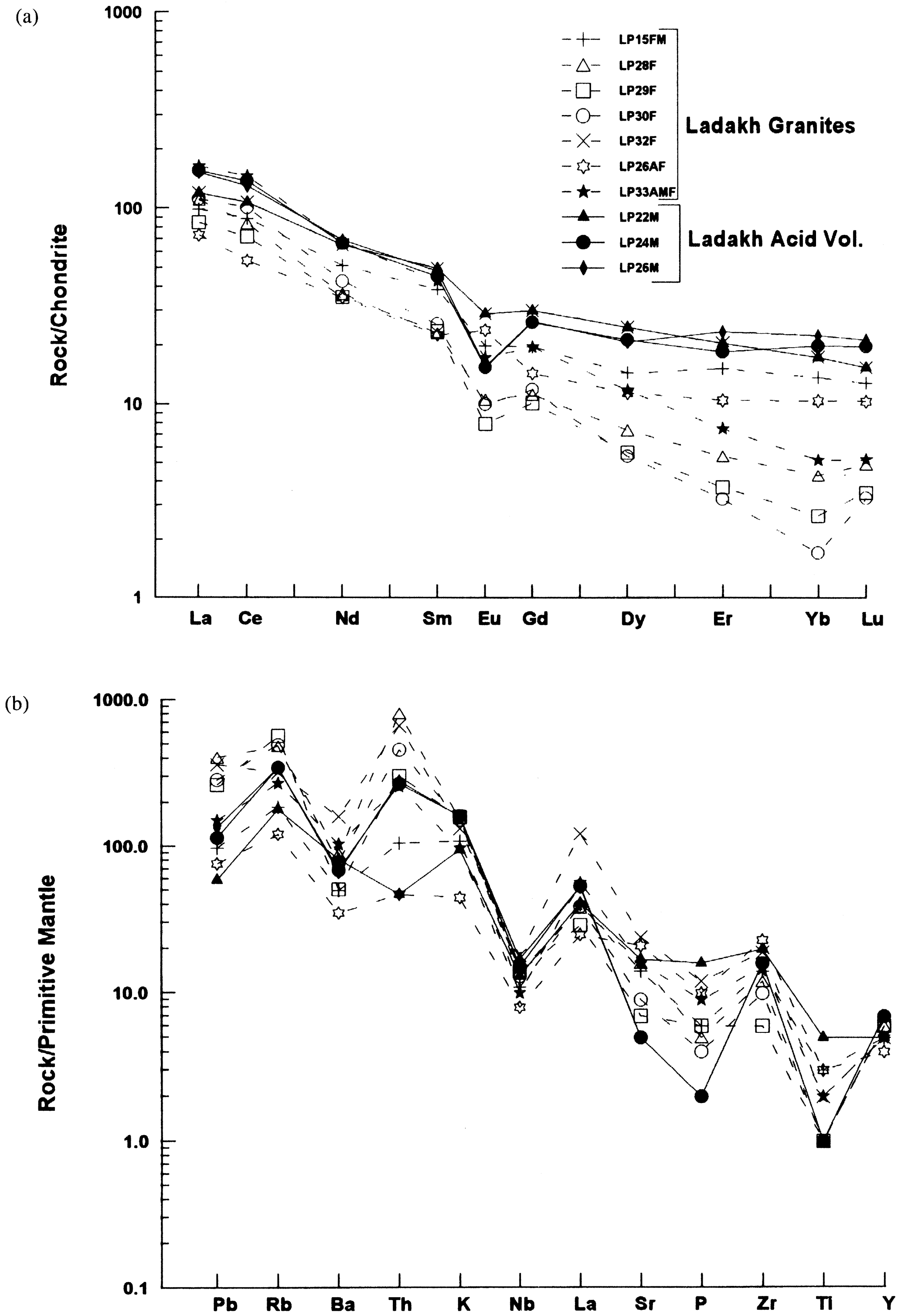


Fig. 6. (a) C1 chondrite normalized REE and (b) Primitive mantle normalized multi-element patterns of the Ladakh granites and acidic volcanics. Normalizing values as in Fig. 5.

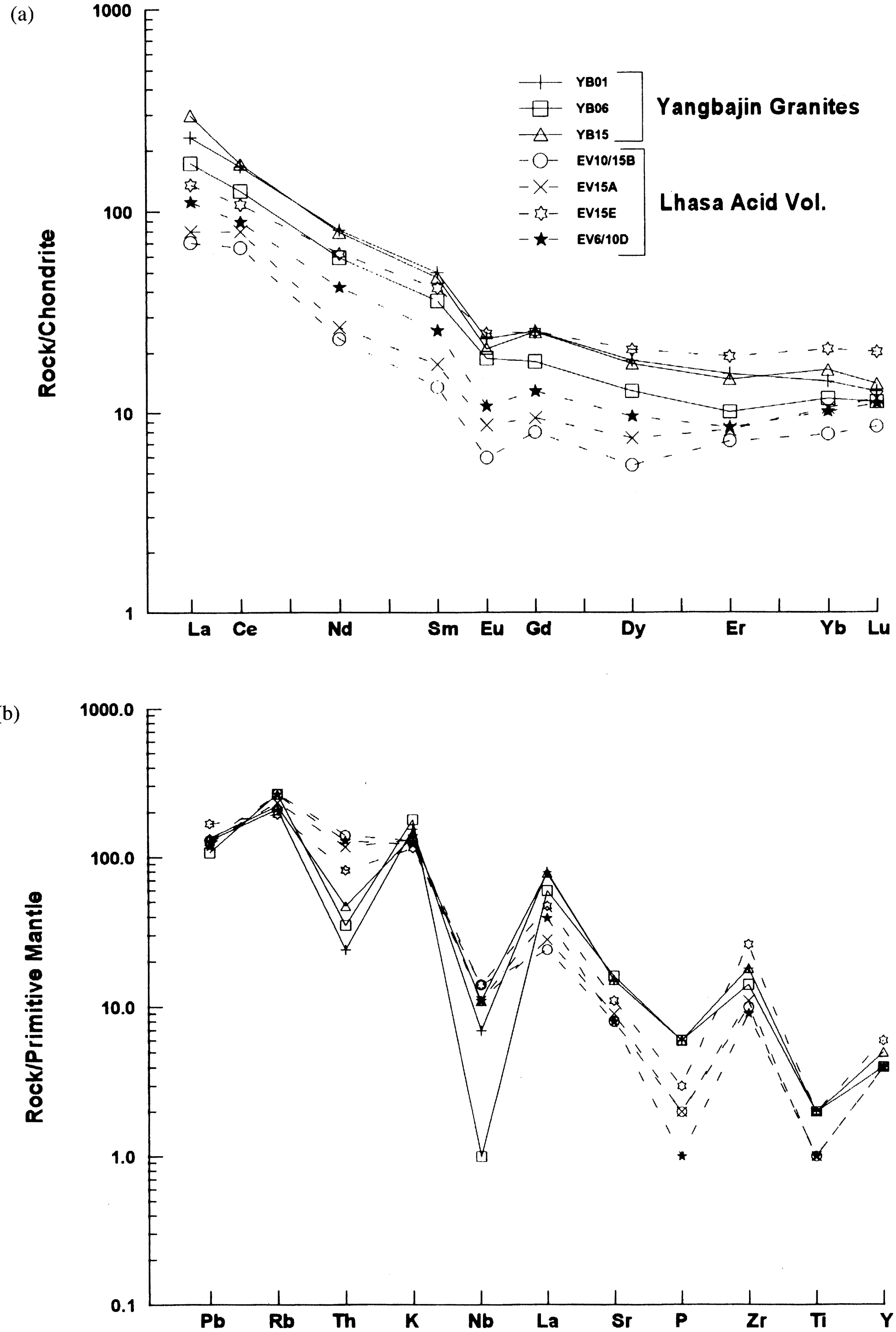


Fig. 7. (a) C1 chondrite normalized REE and (b) Primitive mantle normalized multi-element patterns of the Yangbajin granites and Lhasa acidic volcanics. Normalizing values as in Fig. 5.

change much with the fractionation in the Ladakh granite (0.08 -< 1), only two samples exhibit as high as 1.61 and 2.57. Ladakh acidic volcanics exhibit a wide range of Rb/Sr ratio (0.26–2.26) from less evolved to more evolved samples (Fig. 3). In case of Yangbajin granite Rb content is lower relative to Sr, which indicates a close similarity between Ladakh and Yangbajin granite. Sr abundances show a systematic decrease with Eu/Eu*, probably indicating plagioclase dominated fractionation in the Ladakh granites. This phenomena is also well matched with the Yangbajin granites of Lhasa block. Ladakh acid volcanics and acid volcanics of Lhasa also exhibit similar characteristics (Fig. 3).

Chondrite-normalized REE patterns for the Ladakh granites exhibit enrichment of LREE with variable but predominantly negative Eu anomalies, the Eu/Eu* varies between 0.51–1.37. The more fractionated sample with the lowest iron content exhibits the highest $(La/Yb)_N$ ratio. Ladakh acid volcanics exhibit enriched LREE with variable negative Eu anomalies, the Eu/Eu* varies between 0.44 and 0.75. These rocks are moderately fractionated with higher HREE contents than the Ladakh granitoids (Fig. 6(a)). Complimentary, multi-element patterns show enrichment of LILE, with distinct negative Pb, Ba, Nb, P and Ti anomalies for both the Ladakh granitoids and acidic volcanics (Fig. 6(b)).

The REE patterns of Yangbajin granite are quite smooth with enriched LREE and moderately negative Eu anomaly (Fig. 7(a)). The Eu/Eu* varies between 0.60 to 0.73. Lhasa acid volcanics also exhibit smooth enriched LREE patterns with variable Eu anomalies. The samples with the lowest SiO_2 and the highest total iron contents show the highest ΣREE contents and it also shows high Eu/Eu* ratio (0.76). This sample is also enriched in CaO and Sr. The REE patterns of the Lhasa acid volcanics compare well with those of the Ladakh acidic volcanics (Figs. 6(a) and 7(a)). Multi-element patterns of these rocks display similarly enriched LILE and systematic depletion of Pb, Ba, Nb, P and Ti (Fig. 7(b)) as observed for Ladakh and for most subduction-related volcanic and plutonic rocks (Wood *et al.*, 1979. Briqueu *et al.*, 1984). Nb depletion is typical of the calc-alkaline magmatism from a subduction-zone environment. The preceding geochemical discussion on the granitoids and acid volcanics of Ladakh and Lhasa block suggests that the Ladakh and Yangbajin granites have close affinities, although Ladakh samples exhibit a much wider range of elemental variation.

GEODYNAMIC IMPLICATIONS

Normalized REE and multi-element patterns for magmatic rocks of Ladakh and Lhasa show enriched characteristics in terms of LREE-LILE and depletion of HFSE (Figs. 5–7). These trace-element features are characteristics of subduction-related magmatism (Saunders *et al.*, 1980; Holm, 1985), but such signatures are also seen in most of the continental flood basalts and dyke swarms (Tarney, 1992). However, the predominantly calc-alkaline nature of these rocks (Honegger *et al.*, 1982; Dietrich *et al.*, 1983), overwhelmingly indicates their generation and evolution in subduction-related environments. This interpretation is also supported by valuable information on the sedimentary rocks associated with these arc magmatic rocks. The sediments of Nidam Formation comprise a thick flyschoid sequence of olive-green and purple shale, siltstone, greywacke, sandstone, quartzite and carbonates. This unit was termed Nidam flysch and interpreted to have been deposited in response to the uplift and erosion of Dras island arc (Brookfield and Andrew-Speed, 1984) or they could well represent subduction-accretion regime.

The sequence of events envisaged for the Ladakh terrain starts with the northward-directed intra-oceanic subduction of the Neo-Tethyan oceanic lithosphere during the Late Jurassic and Cretaceous period (Searle *et al.*, 1987), giving rise to the Dras island arc. Magmatism was dominated by calc-alkaline basalt and andesite (Honegger *et al.*, 1982; Dietrich *et al.*, 1983) and it became more siliceous as the arc matured. The early basaltic rocks of the Dras island arc was dated to be

157 ± 12 Ma and at 140 ± 15 Ma for equivalent magmatic rocks at Spongtang nappe. The early phase of granitoid magmatism of the Ladakh plutonic complex dated at 102 ± 2 Ma by Honegger *et al.* (1982) and Scharer *et al.* (1984), was probably emplaced in an Andean type, Trans-Himalayan margin (Thakur, 1992), coincidentally being contemporary to the Andes. Laterally the Dras island arc and its equivalents must have developed as a chain of magmatic arcs both east and west of the present position of Dras island arc in western Ladakh. Its equivalent in Pakistan is represented by the southern portion of the Kohistan arc. It is inferred that the arcs equivalent to Dras were also present in eastern Ladakh but were probably invaded by younger (102 ± 2 and 60 Ma: Honegger *et al.*, 1982 and Scharer *et al.*, 1984) subduction related granitoids of the Ladakh plutonic complex. The remnants of these inferred arcs are probably represented by the enclaves of various sizes and compositions, being described in quite details in the present study. It is suggested that in eastern Ladakh these inferred magmatic arcs were also initially well developed and probably varied in composition, from initial basaltic-andesitic to more siliceous younger rocks, as seen in the Dras (Honegger *et al.*, 1982. Dietrich *et al.*, 1983; Sharma, 1990) and its equivalent in Kohistan arc (Khan *et al.*, 1989; Treloar *et al.*, 1996). These inferences about the eastern Ladakh arc are based on the major and trace element data on the enclaves within the Ladakh plutonic complex (Table 1; Figs. 2–6). Based on REE and trace element ratios of the enclaves it is suggested that (a) all the enclaves cannot be related to one parental melt and (b) that they appear to have complex petrogentic histories. These observations are consistent with large variations in chemical characteristics and similar signatures in terms of published trace element data for the rocks of Dras island arc (Honegger *et al.*, 1982; Radhakrishna *et al.*, 1984). The youngest phase of subduction-related magmatism in this area is represented by the Early Tertiary acidic volcanic (Khardung volcanic and Dras Phase-II volcanics: Reuber, 1989) and minor basic dykes being reported in this study. The Neo-Tethyan ocean probably closed around 50 Ma (Searle *et al.*, 1987) and the youngest phase of granitoid of the Kohistan arc is about 40 ± 6 Ma (Petterson and Windley, 1985). However, the subduction of the north Indian continental lithosphere continued and we suggested here that the highly siliceous acidic volcanics of Ladakh and Lhasa may have been generated due to the partial melting and/or dehydration of a part of the subducted Indian lithosphere below and the active margin wedge above. These melts probably interacted with the deeper portions of Trans-Himalayan Gangdise belt magmatic arc and southern margin of the Eurasian plate during its ascent. It is possible that the time gap between the end phase of granite plutonism and the younger acidic volcanism was probably required to accumulate enough heat and fluids and to acquire the favorable P-T conditions to induce partial melting of the upper part of the subducted Indian continental lithosphere and/or the lower part of the active margin wedge.

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