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Multiple sources of magmatism: granitoids from southeast Kohistan, NW Himalayas, Pakistan

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ABSTRACT: *The Kohistan island arc terrane in the northwestern Himalayas of N. Pakistan is sandwiched between the Indian and Karakoram plates. The base of the arc is occupied by a major stratiform ultramafic-gabbroic complex (the Sapat-Babusar complex), which overrides the crust of the Indian plate along the Indus suture (i.e., the Main Mantle Thrust; MMT). It was intruded into the base of a thick pile of metavolcanics (the Kamila belt), which comprise a tectonic collage of MORB-type tholeiitic basalts, island-arc tholeiites and calc-alkaline andesites. The Chilas complex, comprising ultramafic and gabbronorite rocks, is also intrusive into the Kamila belt, it is emplaced onto the top rather than the base of the Kamila belt. A sizeable proportion of granitoid rocks are present in the south-eastern part of Kohistan, which intruded the Kamila amphibolites. These are predominantly dioritic in composition, but include gabbros, granodiorites, granites and trondhjemites. The granitoids occur in two types: (1) large sheet-like lenticular masses, and (2) minor intrusives in the form of veins, sills or dykes. Three large sheets like bodies are mapped. All these bodies are composite, comprising gabbros, diorite/tonalite, granodiorite and granite. The minor intrusions of granitic and trondhjemitic composition are abundantly present in the form of veins, sills and dykes; and are characterized by variation in distribution. Strong shearing transformed the rocks into blastomylonite gneisses. The mineral assemblage consists of quartz, plagioclase, amphibole, epidote, chlorite, biotite, muscovite, sphene, magnetite and apatite. The granitoids show a wide variation in* SiO_2 *content. Spidergrams show three distinctive patterns; (i) flat patterns showing small enrichment in HFSE with lack of Nb anomaly, (ii) enrich in LILE sloping towards right with Nb anomaly and showing coherent trends with increasing LILE component from diorite through granodiorite to granite and (iii) the highly spiked patterns sloping towards right with more depletion in Nb, P, Zr, Ti and Y. The HFSE enriched granitoids are comparable with the host metavolcanics of MORB type Kamila amphibolite belt. This supports the petrogenetic link between this group of granitoids and the host Kamila amphibolites. The HFSE depleted granitoids include rock types gabbro, diorite, tonalite, granodiorite and granite, which show enrichments in LILE relative to HFSE, and coherent behavior. Majority of the rocks have typical subduction-related chemistry, with characteristics such as low* TiO_2 *and high* Al_2O_3 *contents, high LIL/HFS element ratios, variable inter-alkali ratios and distinct Nb depletion anomalies, all consistent with magma derivation from a metasomatized mantle wedge above a subduction zone. The trondhjemites, characterized by enriched HFSE, are in intimate association with Kamila amphibolite belt and the HFSE depleted trondhjemites with highly spiked patterns with very low incompatible trace element abundances are considered (1) to be unrelated with gabbro-*

diorite-tonalite-granodiorites-granite series, and (2) to have resulted from partial melting of Kamila amphibolites. The melt produced for these trondhjemites whether due to the process of subduction or due to the intrusion of 90-80 Ma Chilas Complex and crustal shortening accompanying the Jal shear zone of 80 Ma is not clear.

INTRODUCTION

The plutonic rocks of predominantly granitic composition with gabbros, diorites and tonalites occur in large proportions in the northern half of the Kohistan Island arc. These are described from different parts (Dir, Swat, Gilgit and Indus valleys) of the Kohistan terrane by a number of workers, e.g., Hyden (1916), Ivanac et al. (1956), Davies (1965), Chaudhry and Chaudhry. (1974), Jan and Mian (1971), Tahirkheli and Jan (1979), Butt et al. (1980), Jan and Khan (1983), Petterson and Windley (1985), and Ghazanfar et al., (1991). Jan and Hawie (1981) included these rocks in their Ladakh-Kohistan granitic belt, while Peterson and Windley (1985) and Coward et al., (1986) introduced the term Kohistan batholith for these plutonic rocks. The Kohistan batholith is commonly considered to be restricted to the northern half of the Kohistan terrane (see maps by Tahirkheli and Jan, 1979; Searle and Khan, 1996). The plutonic rocks of gabbro, diorite, tonalite, granodiorite and granite composition occur on a relatively limited scale in the southern parts of the Kohistan terrane as compare to the northern parts. The rocks are characteristically associated with the Kamila amphibolite belt, and are reported from Dir Valley (Butt et al., 1980), Swat (Jan & Mian, 1971) and Indus (Jan, 1970; Treloar et al., 1990; Khan, 1997; Vigneresse and Burg, 2003.).

The granitoids of different composition are intruding the Kamila amphibolite belt in the southern part of Kohistan Island arc (Khan, 1997). These are predominantly dioritic, but include gabbros, tonalite, granodiorites, granites and trondhjemites and are considered to be the equivalent of the Kohistan batholith in southern Kohistan. The granitoid sheets are described in terms of field relations, petrography and geochemistry in this paper and an attempt is made to evaluate their petrogenesis, comagmatic relationship and the link with the other granitic rocks of the area.

FIELD RELATIONS

Two modes of occurrence are characteristic in the field (1) large sheet-like lenticular masses, and (2) minor intrusions in the form of veins, sills or dykes. The sheet-like bodies are up to 5 km thick, and stretch east west for a distance over 40 km in the mapped area (Fig. 1). These are mainly comprised of gabbros, diorite/tonalite, granodiorite and granite. The minor intrusions, forming veins, sills and dykes are abundant in the studied part of Kohistan terrane, but are characterized by variance in distribution and composition. Minor intrusions are predominantly granitic or trondhjemitic in composition with aplitic as well as pegmatitic textures. The granitoids rocks of the SE Kohistan terrane are described in terms of observations in the Niat, Thak, Buto and Thor valleys from east to west in the following section.

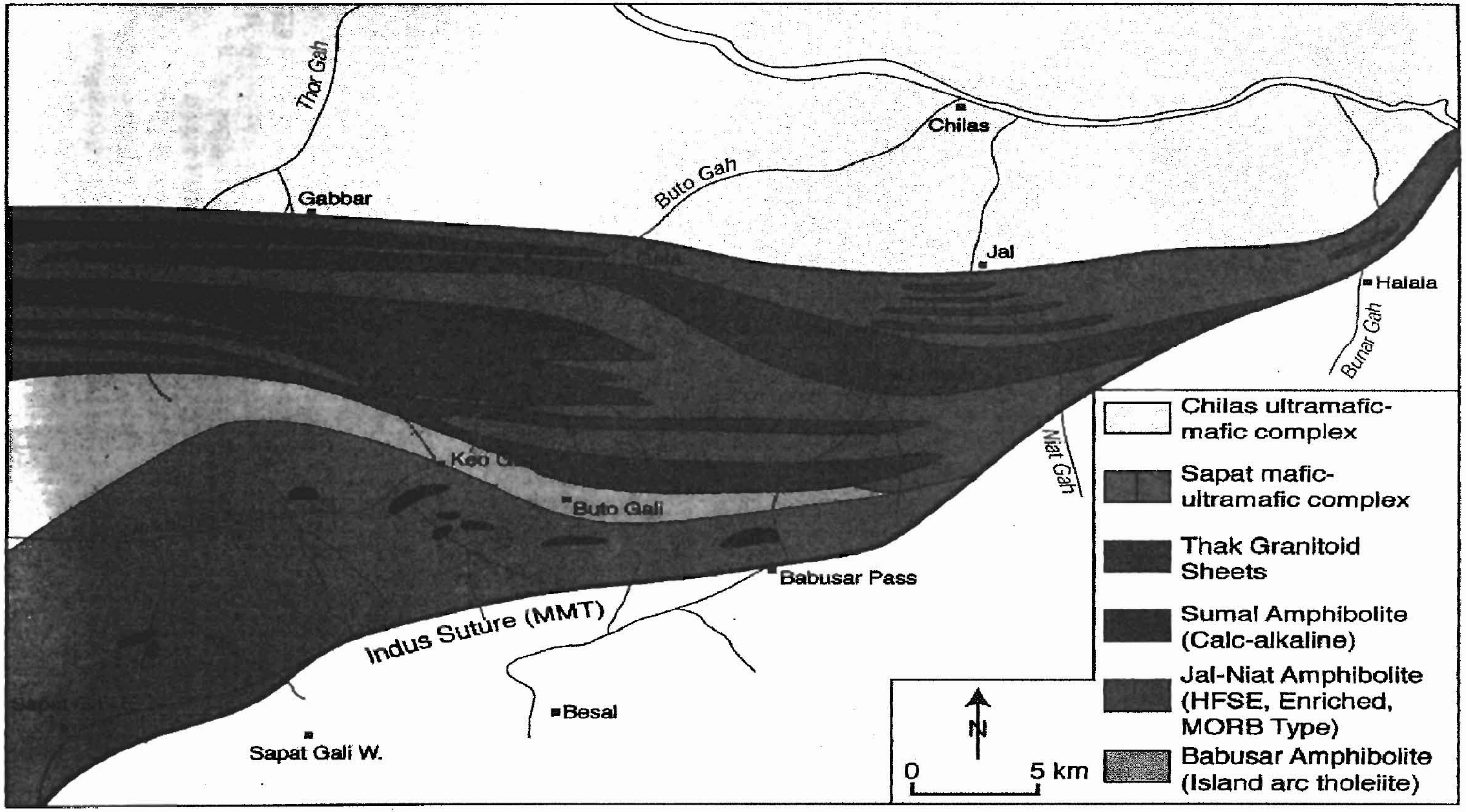


Fig. 1. Geology of southeastern part of Kohistan.

Niat Gah
A principal mass of granitic rocks occurs at Lumar-Niat confluence, in the Jal-Niat amphibolites unit. It is not a cohesive body, and comprises sheets of granites alternating with the amphibolites belonging to the host unit. The granite sheets are generally one to two meters thick, but some are several meters in thickness, while those of the host amphibolites are rarely thicker than a meter. The granites and amphibolites are strongly foliated, and commonly mylonitized. The pervasive deformation has obliterated the intrusive relations in the southern side of the sheet, but amphibolites occur as xenoliths in the granites. In northern side, strong shearing and folding mark the contact with Jal-Niat amphibolites. Even a minor brittle fault filled with gouge is observed at the contact.

To the north, several minor sheets, dykes and veins of the granitic rocks occur within the Jal-Niat amphibolite unit. Sheets comprising medium– to coarse-grained gabbroic diorites form a minor but important part of the amphibolite sequence. These are strongly sheared and appear to have undergone the same phase of deformation and metamorphism, which affected the host rocks. The granitic and trondhjemitic dykes and veins intersect the fabric in the amphibolites, and are commonly foliated, suggesting a syntectonic to rarely post-tectonic origin. There is a considerable variation in grain size, ranging from pegmatitic, through granitic to aplitic.

Thak Gah
Three sheet-like cohesive bodies of granitoids are encountered in the Thak Gah and a number of minor intrusions in the forms of veins and dykes within the Jal-Niat amphibolites unit. Locally, the rock is transformed into mylonites. Sheets of fine-medium grained amphibolite are locally found intercalated with the gneissose diorites. The fabric is defined by chlorite and tremolitic amphibole.

The principal 5 km thick granitoid body occurs in the Thak valley, between the Loshi and Khun; and extends for ~ 40 km. The constituent rocks are foliated but deformation is distinctly less intense than the two southern bodies. The deformation is more intense on the marginal parts; the northern 200 meters from the contact are strongly sheared and the shearing in the southern margin is pervasive up to a km from the contact, whereas the interior-most part of the body has escaped deformation. Compositionally, this body is relatively more mafic than the two southerly bodies; gabbroic diorite in the interior and diorites in the marginal parts are the principal constituents. The gabbroic and dioritic rocks of this body are characterized by the occurrence of xenoliths. These include fine-grained, amphibole-rich xenoliths resemble the metavolcanics of the Jal-Niat unit and the xenoliths of microdiorite

The minor intrusions in the form of dykes and veins are characterized by four compositional types; diorites, andesites, granites and trondhjemites. Strongly foliated gneissose diorites occur in intercalation with metavolcanics of the Jal-Niat unit. Granites occur as dykes, some as thick as 5 meter, intruding the host rocks and the trondhjemites are restricted to the northern parts of Jal-Niat amphibolite unit.

Buto Gah
Several sheet-like granitoid bodies are the direct continuation of the granitoid bodies exposed in the upper reaches of the Thak Gah, i.e., Babusar Rest House and Shai. The granitoids at and around the Katai-Buto confluence have a limited eastern extension and comprise medium– to coarse-grained and strongly foliated gabbroic-diorites. There are veins and up to one meter thick dykes of

trondhjemitic composition intruding the diorites and Jal-Niat amphibolite unit which are equally deformed. A thick body of medium to coarse-grained granitic composition is exposed at the mouth of the Chakkar confluence in Jal-Niat amphibolite unit. This body is about 3 km thick and is a western continuation of the granitoid body exposed between Loshi and Khun in the Thak Gah. The body is typically composite, comprising gabbro-diorite in its southern parts and coarse-grained pegmatitic trondhjemites in its northern parts. The trondhjemites are clearly younger than the gabbro-diorite as suggested by the cross-cutting field relations between the two in the southern part of the body near the Chakkar confluence.

Thor Gah

Two major bodies of granitoid composition occur in the Thor Gah, to the north and to the south of the village Makheli. These bodies comprise gabbroic diorites or diorites with intruding dykes of andesite and granite composition. As in the Niat Gah, the minor intrusions in the form of veins and dykes comprise trondhjemites, and are restricted to the northern parts of the Jal-Niat amphibolite unit.

On the basis of the field observations, some important points concerning the granitoids are as under: (1) Compositionally, tonalite/diorite forms the principal component of the granitoids in SE Kohistan, relatively more mafic rocks (e.g., gabbros) also form a significant proportion of these bodies. Trondhjemites, granites, andesite and dacite occur as dykes and veins, of these, the trondhjemites are the most abundant than granites, while andesite and dacite are uncommon. (2) Almost all the granitic intrusive complex is younger than the host Jal-Niat amphibolites. Amongst the various constituent lithologies the order of intrusion appears to be as follow: (i) High Ti-diorite gneisses intercalated with Jal-Niat unit. These diorites have composition very close to the host metavolcanics and share the same phase of metamorphism and deformation, suggesting an early stage of intrusion. (ii) Gabbros, diorites and tonalites. (iii) Trondhjemites, granites and andesite/dacite dykes and veins. (3) Trondhjemites have a preferred distribution in SE Kohistan, restricted to the northern parts of the amphibolite belt. In Niat and Thak valleys, they are restricted to the northern parts of Jal-Niat amphibolite unit, whereas to the west, in the Butto and Thor, they, in addition, intrude the diorite, which is exposed in the middle of Jal-Niat amphibolite unit. The only exception is the upper reaches of Buto Gah (Katai-Buto Confluence), where trondhjemites have been noticed in the south-central parts of the amphibolite belt. (4) All the granitoid rocks in SE Kohistan are ductily deformed. The deformation is particularly strong in the most southern bodies (e.g., Babusar), where the rock is transformed into blastomylonite gneisses. Smoky gabbros and gabbroic diorites to the south of Khun Bridge (Thak Gah) are the least deformed rocks in SE Kohistan. These rocks escaped deformation due to their location in the interior of the 5 km thick body, rather than being post tectonic. Even the trondhjemites, which are showing the crosscutting fabric in the amphibolites, are syntectonic in origin. The presence of foliation in the granitoid rocks of SE Kohistan enables their correlation with stage-I Kohistan batholith of Petterson and Windley (1985).

PETROGRAPHY

Petrographically the granitoids of the study area can be divided in to (1) southern group, (2) the northern group and (3) the minor intrusions in the form of veins and dykes scattered throughout the area.

The southern group

The rocks of this group are mainly composed of plagioclase and quartz with subordinate amount of amphibole, epidote and chlorite. Sphene, magnetite and ilmenite occur as accessories. The rocks are foliated and exhibit shearing at places. The foliation is defined by plagioclase, quartz, amphibole and chlorite, which are mutually parallel in the fabric direction. Quartz ribbons, eye shape feldspar/clinozoisite aggregates, amphibole and chlorite mark the gneissic texture. Banding is defined by segregation of quartz and feldspar in bands alternating with bands rich in epidote+amphibole±chlorite. Plagioclase mainly occurs as short, stumpy, euhedral/subhedral crystals and shows a range in anorthite (An_{30-46}) content, in some cases, it is labradorite but andesine (An_{36-42}) is the most common. All plagioclase grains are invariably saussuritized but in some rocks they are completely cloudy. Irregular and patchy zoning is well observed in some samples. Green amphibole, mainly tremolite-actinolite; is an important constituent, but hornblende is encountered in the relatively basic varieties. Hornblende contains inclusions of epidote and quartz and shows complete or partial alteration to chlorite. Chlorite is characteristically light green and non-pleochroic. Epidote is fine to medium-grained and forms anhedral to euhedral six sided crystals with two distinct compositional groups, one shows bright and the other shows grey interference colours. Bright colored epidote occurs mostly in the mafic parts whereas the grey epidote is present in felsic parts of the rock. A complex zoning with a peculiar twinning is noticed in euhedral epidote grains. Sphene, magnetite and ilmenite are present as accessory minerals. Sphene is present mainly along the borders of mafic minerals (amphibole, chlorite and epidote) with quartz.

The northern group

The rocks are undeformed or less deformed as compare to the southern varieties of granitoids, and more or less equigranular with coarse to medium-grained textures. The principal constituents are plagioclase, hornblende, quartz, and chlorite, whereas biotite, muscovite, magnetite, sphene and apatite are the accessory minerals. Epidote and chlorite occur as secondary minerals. Plagioclase is generally andesine in composition, rarely ranging into labradorite in the case of gabbros. It occurs as euhedral to subhedral and medium to coarse-grained crystals and generally exhibit alteration to kaolin, sericite, epidote and calcite. Large crystals of plagioclase show myrmekitic intergrowth with quartz. Hornblende varies widely in proportion in the rocks of this group and occurs generally as subhedral prismatic crystals. Epidote, both zoisite and clinozoisite, occur as discrete grains as well as granular aggregates and is the alteration product of plagioclase and hornblende. Chlorite, the alteration product of hornblende and biotite, is frequently associated with epidotization and is mainly developed in the hybrid zones. It is light-green, pleochroic and sometimes shows blue anomalous interference colors. Biotite and chlorite occur in patches in association with altered hornblende. Subhedral to anhedral biotite occurs in all facies of this intrusive group. Its amount increases in quartz-diorites and it becomes a ubiquitous minor to accessory mineral in tonalites. Some biotite grains contain ilmenite inclusions. Quartz occurs either in little pools of granules or as an interstitial mineral. It is invariably anhedral and often shows wavy extinction. It also occurs as fine-grained inclusions in hornblende and in biotite at some places. Sphene, calcite, apatite, magnetite, and hematite are the accessory minerals.

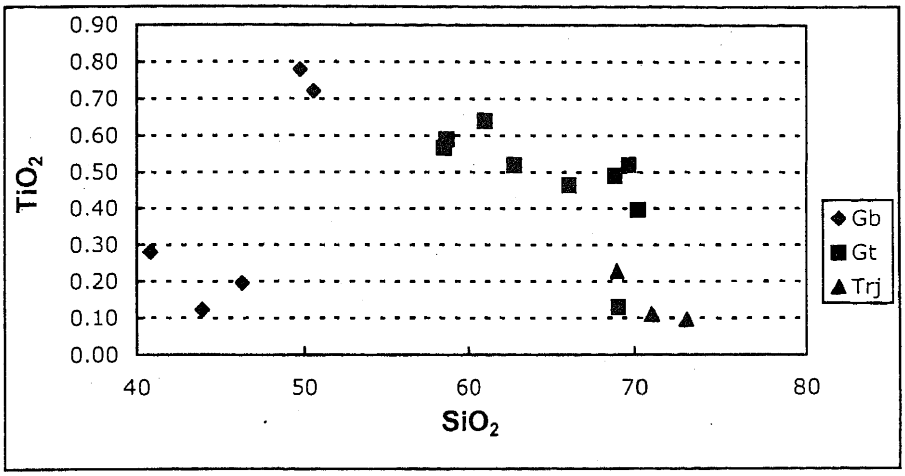
TABLE 1. GEOCHEMICAL DATA OF THE STUDIED ROCKS

S.No.	A-195	A-212	A-236	A252	A-172	A-247	A-144	A-146	A255	A-60	A-65	A-71
SiO2	43.9	46.3	40.8	49.8	50.6	66.0	70.2	69.6	68.9	58.5	69.0	73.0
TiO2	0.12	0.19	0.28	0.78	0.72	0.46	0.40	0.52	0.23	0.57	0.13	0.10
Al2O3	18.2	20.8	23.1	17.2	15.4	15.2	14.2	15.0	16.4	17.6	15.8	14.7
Fe2O3*	9.99	4.71	8.40	11.32	11.78	4.87	3.56	2.54	2.63	6.76	2.22	0.85
MnO	0.191	0.078	0.142	0.204	0.210	0.112	0.056	0.023	0.093	0.142	0.068	0.019
MgO	8.56	8.63	7.48	4.77	5.73	2.03	0.85	0.96	0.69	2.87	0.83	0.40
CaO	14.39	14.71	14.09	9.64	10.01	4.44	3.00	4.08	4.57	6.99	3.84	3.83
Na2O	0.44	1.47	0.91	2.34	2.01	3.72	3.92	5.09	4.14	3.22	3.68	4.60
K2O	0.02	0.30	0.12	0.06	0.06	0.57	2.15	0.25	0.34	0.32	1.85	0.48
P2O5	0.03	0.04	0.04	0.12	0.07	0.18	0.13	0.14	0.10	0.19	0.10	0.06
CO2	0.05	0.02	0.02	0.04	0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.03
H2O	4.17	1.84	4.30	3.90	3.27	2.31	1.55	1.49	1.83	2.94	1.89	1.49
Total	100.00	99.10	99.69	100.13	99.88	99.92	100.00	99.72	100.00	100.16	99.48	99.61

Trace elements

S.No	A-195	A-212	A-236	A-252	A-172	A-247	A-144	A-146	A-255	A-60	A-65	A-71
Li	1	5	4	5	4	8	5	4	11	6	4	2
Ni	47	5	40	15	11	6	10	12	9	4	9	5
Cu	52	5	9	40	29	3	13	5	32	41	10	4
Cr	24	531	8	23	43	7	3	4	3	3	10	9
Zn	55	34	42	78	75	100	35	10	43	41	14	10
Ga	15	14	16	15	17	25	22	28	22	20	22	23
Mo	0	0	0	0	0	0	0	0	0	0	0	0
Cd	0	0	0	0	0	0	0	0	0	0	0	0
Sn	0	0	0	0	0	0	1	2	1	0	0	0
Sb	0	0	0	1	0	1	0	0	0	0	0	0
Rb	0	6	3	1	1	17	39	5	91	10	47	7
Ba	7	14	11	17	3	204	271	60	132	79	1106	109
Th	0	0	0	0	0	10	6	6	2	4	8	0
U	0	0	0	0	0	1	1	1	0	0	2	0
K	0	2496	988	511	468	4761	17881	2036	2848	2624	15348	4006
Nb	0	1	0	1	1	4	4	7	7	3	6	1
Cs	0	1	0	0	0	2	1	0	3	0	0	0
Pb	0	3	1	1	1	5	2	2	18	5	4	4
Sr	44	475	315	184	138	397	149	195	85	305	304	346
P	145	165	167	540	311	787	551	628	436	823	457	276
Sc	49	32	29	50	55	10	16	18	8	20	11	9
V	139	87	142	291	373	72	28	47	15	74	28	7
Zr	14	16	9	11	24	90	147	163	91	102	48	150
Ti	731	1167	1681	4667	4319	2785	2379	3114	1370	3398	781	577
Y	3	4	2	4	21	9	25	34	6	18	5	5

which slope towards right but show stronger depletion in incompatible trace elements than all other studied rocks. Moreover the pattern is highly spiked. The REE patterns are distinct with Eu positive anomaly. The overall concentration of REE is very low as compare to the main group of granitoids and gabbros. For these reasons they are considered to represent a discrete petrogenetic group.



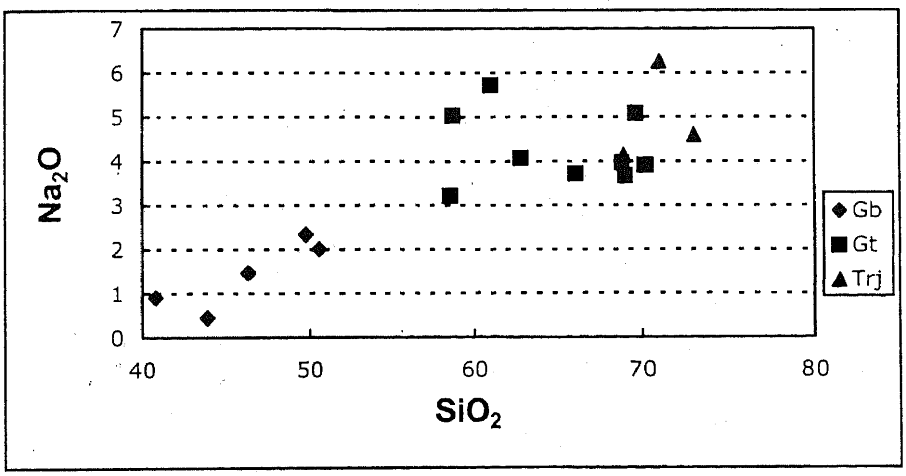
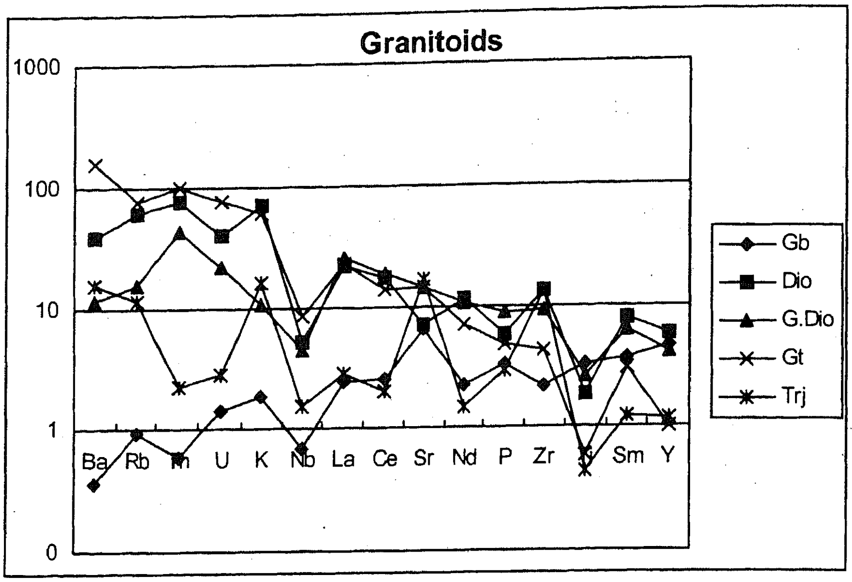


Fig. 2. Variation diagrams distinguishe the three suites of granitoids.

Gb = Gabbro; Gt = Granitoid; Trj = Tronndhjemite



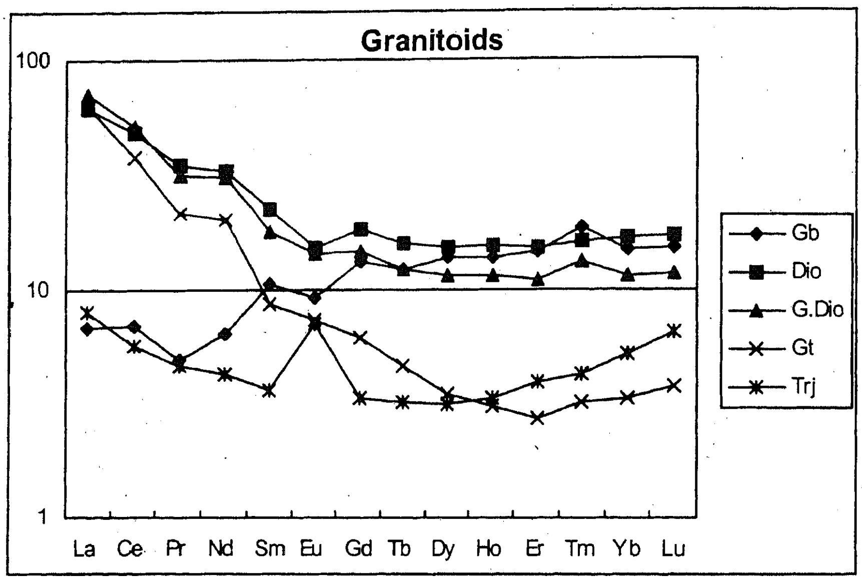


Fig. 3. Variations in trace-element abudances of granitoids, nomalized against Primordial Mantle (Sun & Mc Donough, 1989) and Chondrite (Evenson, 1978).

Gb = Gabbro; Dio = Diorite; G.Dio = Granodiorite; Gt = Granatoid; Trj = Trondhjemite

older Rb depleted crustal source, and the source region was close to the base of the crust.

George et al. (1993) discussed the two varieties of KG, the Confluence granite (CG) and Parri granite (PG). The Confluence granites are broadly similar to relatively large, evolved plutons like Shirote granitoids, which intruded the Kohistan Batholith between 40 and 54 Ma (Petterson & Windley, 1985); and was probably generated by the fractionation of a magma derived from a variable-metasomatized mantle source. The other possibility, as suggested by Petterson and Windley (1991), the Confluence granites may have generated by partial melting of juvenile, possibly crystalline, arc crust. The presence of high Ba would imply that temperature in the source region were sufficiently high to exhaust biotite, so,. considering the reasoning of Zen and Hammarstrom (1983), the presence of magmatic epidote would suggest that pressures in the source region were also moderately high. The high Rb/Sr ratios of the Parri granites suggest either extreme fractionation or small degree of partial melting of a mica rich source (Harris & Inger, 1992). George et al. (1993) suggested that the Parri granites were derived at shallower, cooler crustal level, such that mica was retained in the protolith, thus limiting Ba abundance in the melt. The metasediments exposed in the Gilgit valley would be a potential source; their epidote amphibolite grade precludes partial melting of this rock at the present exposure level.

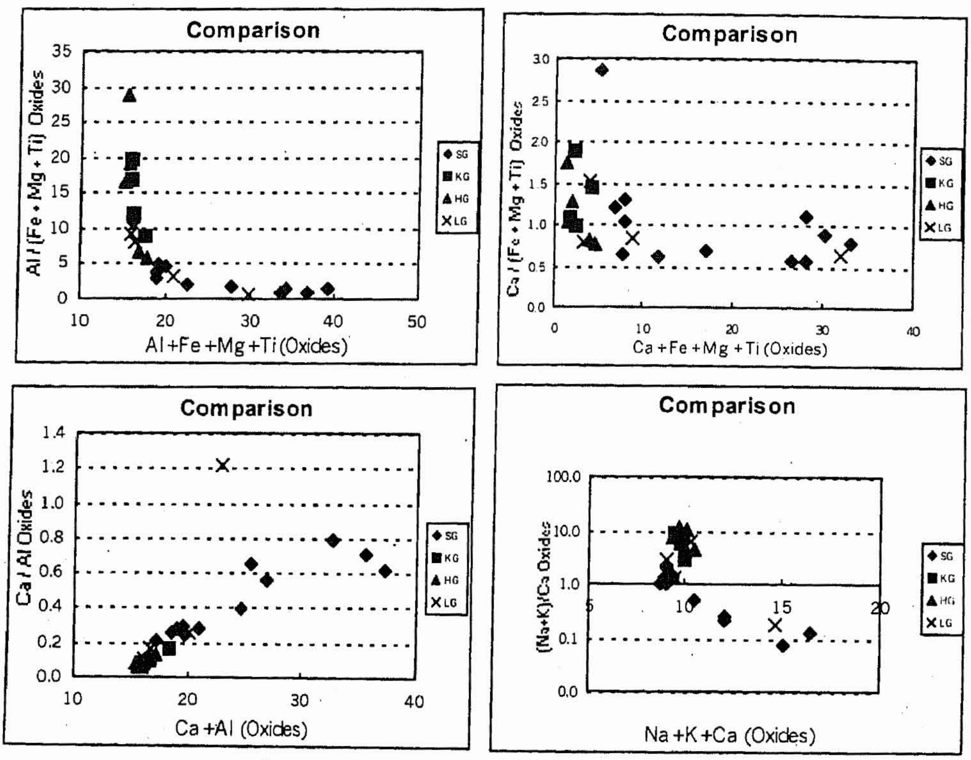


Fig. 4. Variation diagrams compare the studies granitoids with other three suites of granitoids from adjoining areas.

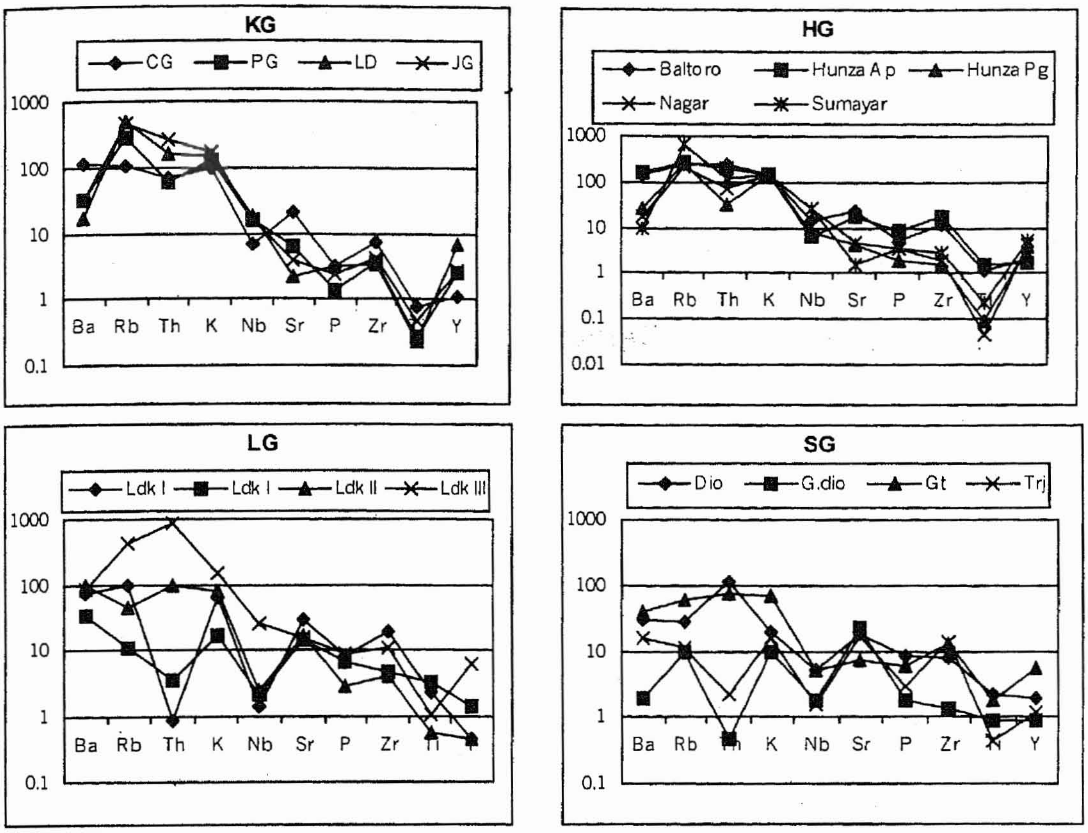


Fig. 5. Multi-element variation diagrams comparing the studied granitoids with other three suites of granitoids from adjoining areas.

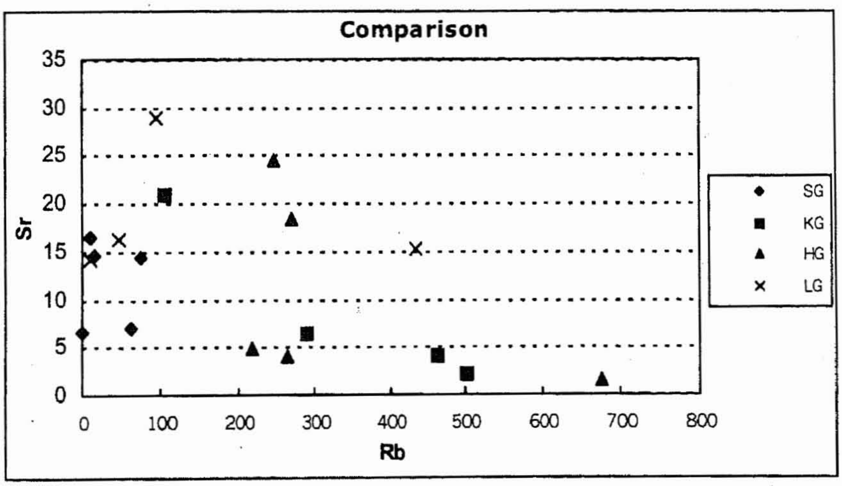


Fig. 6. Rb versus Sr plot distinguishes the studies granitoids with other three suites of granitoids from adjoining areas.

George et al. (1993) determined the isotopic ($^{87}Sr/^{86}Sr$) composition in the range 0.704-0.710 for CG and 0.705-0.778 for PG. The deformed granites from the both suites show enrichment in radiogenic Sr compared with their undeformed counterparts outside the shear zones. These fine heterogeneities may reflect processes occurring prior to crystallization, such as wall-rock contamination or subsolidus fluid interaction. The initial Sr isotopic ratios of the undeformed granites are low compared with Miocene leucogranites from the Central Himalaya, derived from metapelites (Deniel et al., 1987; Inger & Harris, 1993), indicating less radiogenic source regions for the Confluence and Parri granites.

PETROGENESIS

The discussion above, based on field observation, petrography and on major, trace and rare earth elements, three main groups of the granitoids in the southern part of Kohistan are proposed; the comparable granitoids with the host Jal-Niat amphibolites, main group (diorite, tonalite, granodiorite and granite) and the trondhjemites (Fig. 3). The rocks of the three groups are the result of several processes occurring at different levels in the mantle and crust.

Comparable granitoids

The group consists of mainly gabbros with tonalite, diorite and trondhjemites as thin sheets (commonly only a few centimeters thick) intercalated with amphibolites of the Jal-Niat. They are pervasively foliated with abundant amphibole and are enriched in HFSE, particularly Y, Ti, Zr, and P. Nb is variable but displays a positive spike rather than a negative one as is the case in HFSE depleted group (see later). Sr is multi times higher, while Rb approaches the primordial mantle values and K is little bit higher than it. Several of the compositional attributes of this group from the granitoids are comparable with the host metavolcanics of Jal-Niat, particularly the relative enrichment of the HFSE over LILE (Fig. 7a). The Jal-Niat metavolcanics / amphibolite has features like MORB (Khan, 1997) and the occurrences of gabbros, tonalites and trondhjemites as their plutonic equivalents or differentiates is not unusual. The REE patterns of the Jal-Niat metavolcanics / amphibolites show a close similarity in terms of comparable slopes inclined towards the left and have the same concentration of HREE with flat patterns (Fig. 7b). This further supports the petrogenetic link between this group of granitoids and the Jal-Niat metavolcanics / amphibolites.

Main granitoids

This group includes diorite, tonalite, granodiorite and granite, which show coherent behavior and trends. Much of the granitoids sheets belong to this group, their distinguishing feature is a slight to high enrichment of LILE (mainly Rb, Th and K) over HFSE (Y, Sm, Ti, Zr, P and Nb), resulting in trace element patterns sloping towards right (Fig. 8a). Majority of the rocks of this group have typical subduction-related chemistry, with characteristics such as low TiO_2 and high Al_2O_3 contents (Chappell & White, 1974), high LIL/HFS element ratios (Tarney & Saunders, 1979; Saunders et al., 1980; Pearce et al., 1984), variable inter-alkali ratios and distinct Nb depletion anomalies (Saunders et al., 1980; Saunders et al., 1988), all consistent with magma derivation from a metasomatized mantle wedge above a subduction zone. These magmas are characterized by enrichments in LILE. The LREE are enriched relative to HREE with Eu negative anomaly. The diorite/ tonalite and granodiorite are showing flat patterns in HREE whereas granites are depleted in overall REE. The depletion of

Distinguishing Trondhjemites

The gabbro-diorite-tonalite-granodiorite series shows mutually comparable geochemical characteristics, the trondhjemites have compositional attributes, which suggest a different petrogenesis. Figure 9 is used to compare tonalite, granodiorite, granite and trondhjemite. The trace element patterns of all the four rocks have lot of similarities as well as differences. The granodiorite and granite has a pattern, which matches closely with the diorite / tonalite in terms of HFSE, but are distinctly enriched in Rb, Th, U and K. The granodiorite is slightly depleted in HFSE (Y, Sm, Ti, Zr, P, and Nd) relative to the diorite / tonalite. It may be noted that the distribution coefficients of trace elements are different in granitic systems compared to basaltic systems. For instance, HFSE, which are incompatible in basaltic systems become compatible in granitic systems due to crystallization of various phases. The only true incompatible trace elements (other than the REEs), in the granitic system, are Rb and K (Pearce et al., 1984). If it is so, the enrichment of Rb and K in granite relative to the tonalite may be attributed to fractional crystallization from a common magma. The trace element pattern of the trondhjemites, in comparison, is very different from those of the diorite/tonalite and granodiorite (Fig. 9a). It is depleted in all HFSE, particularly in Ti, P, Nd, Ce, La and Nb relative to the diorite/ tonalite and granodiorite. The concentrations of K, Rb and Sr are comparable with those in the tonalite, but not enriched, negating relationship between the two through the process of fractional crystallization. The REE patterns reflect the same trend like trace elements except the positive Eu anomaly for the trondhjemites. Overall REE are depleted in trondhjemites relative to diorite/ tonalite and granodiorite; whereas the granites are more depleted in Er, Tm, Yb and Lu than trondhjemites but the patterns are different (Fig. 9b). Thus whereas the tonalites and granodiorites (and granites) are probably comagmatic mutually as well as so with gabbros and diorites, being fractional crystallization products of a common parental melt; and the trondhjemites are different from gabbro-diorite-granodiorite-granite series.

Trondhjemites

Trondhjemites are found in a variety of geologic environments. The principal occurrences are in the Archean grey gneiss terranes and greenstone belts and at Proterozoic-Paleozoic continental margins. The Mesozoic-Cenozoic trondhjemites occur in two major associations: 1) ophiolites, 2) subduction-related settings at the continental margins and island arcs. In majority of cases, the trondhjemites from the ophiolites are "plagiogranites" and represent a product of fractional crystallization from a MORB, controlled by crystallization of minerals like olivine, pyroxenes, etc. The trondhjemites characterized by low Al_2O_3 and K_2O, and high TiO_2, Fe_2O_3 and Na_2O on comparison with subduction-related complexes. The subduction-related trondhjemites are further distinguishable on the basis of their petrogenesis; one type is a product of fractional crystallization from a mantle derived arc-tholeiite magma, while the other is a product of partial melting from the arc basement. The two types are easily distinguishable on the basis of REE, the type-I trondhjemites are enriched in middle and heavy REEs compared to the type-II, which are typically depleted in these elements due to occurrence of amphibole and garnet as the residual phases in the arc basement.

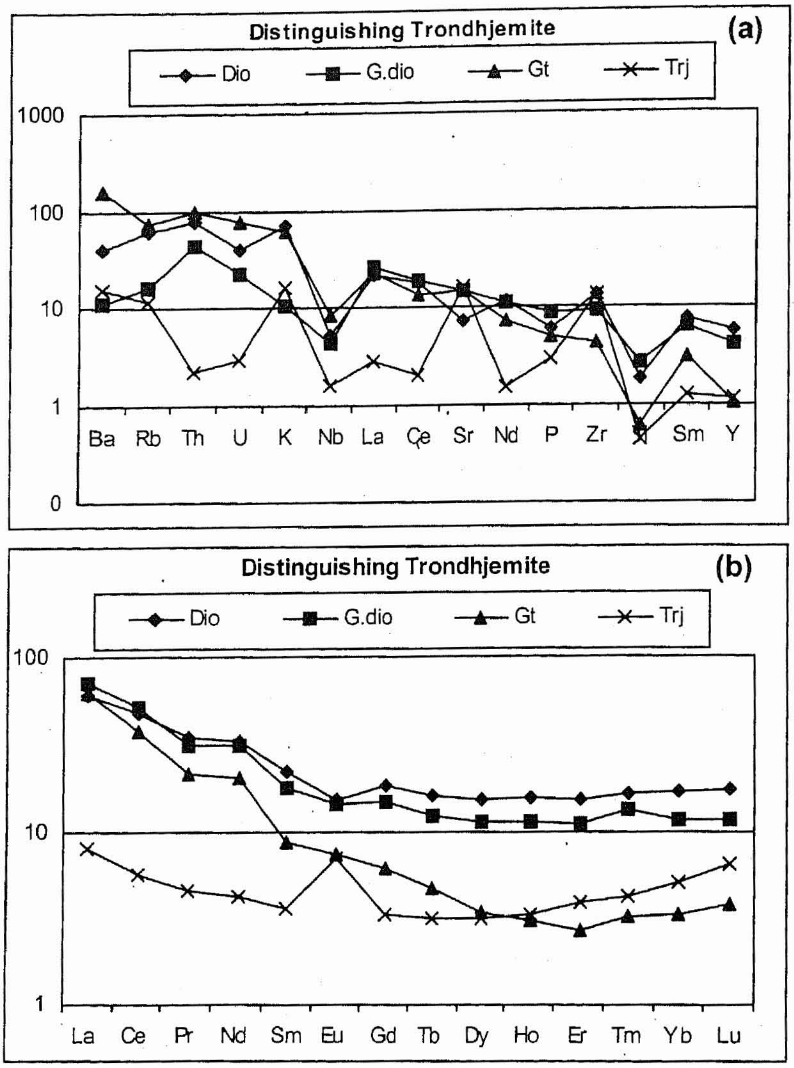


Fig. 9. Multi-element variation diagrams distinguishing the trondhjemites from the other studied granitoids. Same nomalizing values are used as in Fig. 3.

In the present study in the southeastern part of the Kohistan terrane, a variety of trondhjemites are encountered. The trondhjemites characterized by enriched HFSE with an origin in an ocean-floor setting occur in intimate association with Jal-Niat amphibolites. The other trondhjemites are distinguished from the HFSE enriched trondhjemites of ocean-floor type by their highly spiked patterns with distinct slopes towards the right. These trondhjemites could have formed by two processes; either as differentiates of the gabbro-diorite-tonalite-granodiorite-granite series present in the investigated area, or by partial melting of the Jal-Niat amphibolites. Almost all the trondhjemites in this group have incompatible trace element abundances lower than the

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