Geol. Bull. Univ. Peshawar, Vol. 36, pp. 39-48, 2003

Trondhjemites in the southeastern part of the Kohistan island-arc terrane, Pakistan: A product of partial melting

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ABSTRACT:*The Kohsitan terrane in N. Pakistan is sandwiched between the Shyok suture in the north and Indus suture in the south. The SE base of the terrane is occupied by the stratiform Sapat mafic-ultramafic complex., which overrides the crust of the Indian plate along the Indus suture. The complex was intruded into the base of a thick pile of meta volcanics (now amphibolites) of different environments (the Kamila belt). The Kamila blet is intruded by various rocks including gabbros, diorites, tonalities, granodiorites, granites and trondhjemites. The trondhjemites occur as thin veins and dykes, mostly in the northern part of the Kamila amphibolite belt. Here, the belt is in contact with the Chilas Complex along the Jal shear zone. The tondhjemites contain feldspar, quartz and amphibole with minor epidote, muscovite, biotite, sphene, garnet and ore, and display parallel alignment of mineral grains in one major direction. They show very spiked pattern for mantel normalized incompatible trace elements and are depleted in all High Field Strength Elements (HFSE) particularly strongly in Ti, P and Nb relative to the other granitoids of the studied area. The trondhjemites are probably a product of partial melting of Kamila amphibolites, and a direct role of subduction is not observed.*

INTRODUCTION

In the NW Himalayas of N Pakistan, the Karakoram and Indian plate sialic rocks are separated by the rocks of the magmatic arc, commonly referred to as the Kohistan arc. The Kohistan arc terrane developed in response to subduction of Neo-Tethy ocean lithosphere during the Cretaceious (Serale et al., 1987). The arc covers 36,000 km^2 area in the western Himalaya, southern Karakoram and eastern Hindukush. Kohistan arc consists of a variety of volcanic and plutonic rocks and subordinate sedimentary rocks that have undergone varying degrees of deformation and metamorphism. The arc is divided into two sectors (Ladakh on the east and Kohistan on the wet) by the N-S trending Nanga-Parbat Harmosh massif. The terrane is bounded by two major sutures. It is juxtaposed against the Asian plate to the north along the Shyok suture or Main Karakoram Thrust (MKT) and against the Indian Plate to the south along the Indus suture or Main Mantle Thrust (MMT) (Tahirkheli & Jan, 1979; Coward et al., 1982; 1986; Bard, 1983).

The Kohistan terrane is known for its excellent exposures of a more or less complete island arc crust from the top sedimentary cover to those at the Moho (Tahirkheli et al., 1979; Jan, 1980; Bard et al., 1980; Coward et al., 1986; Miller & Cristenson 1994). It is occupied by several hundred kilometer long linear belts of amphibolites, gabbronorites, granitic rocks, volcanics and sedimentary rocks.

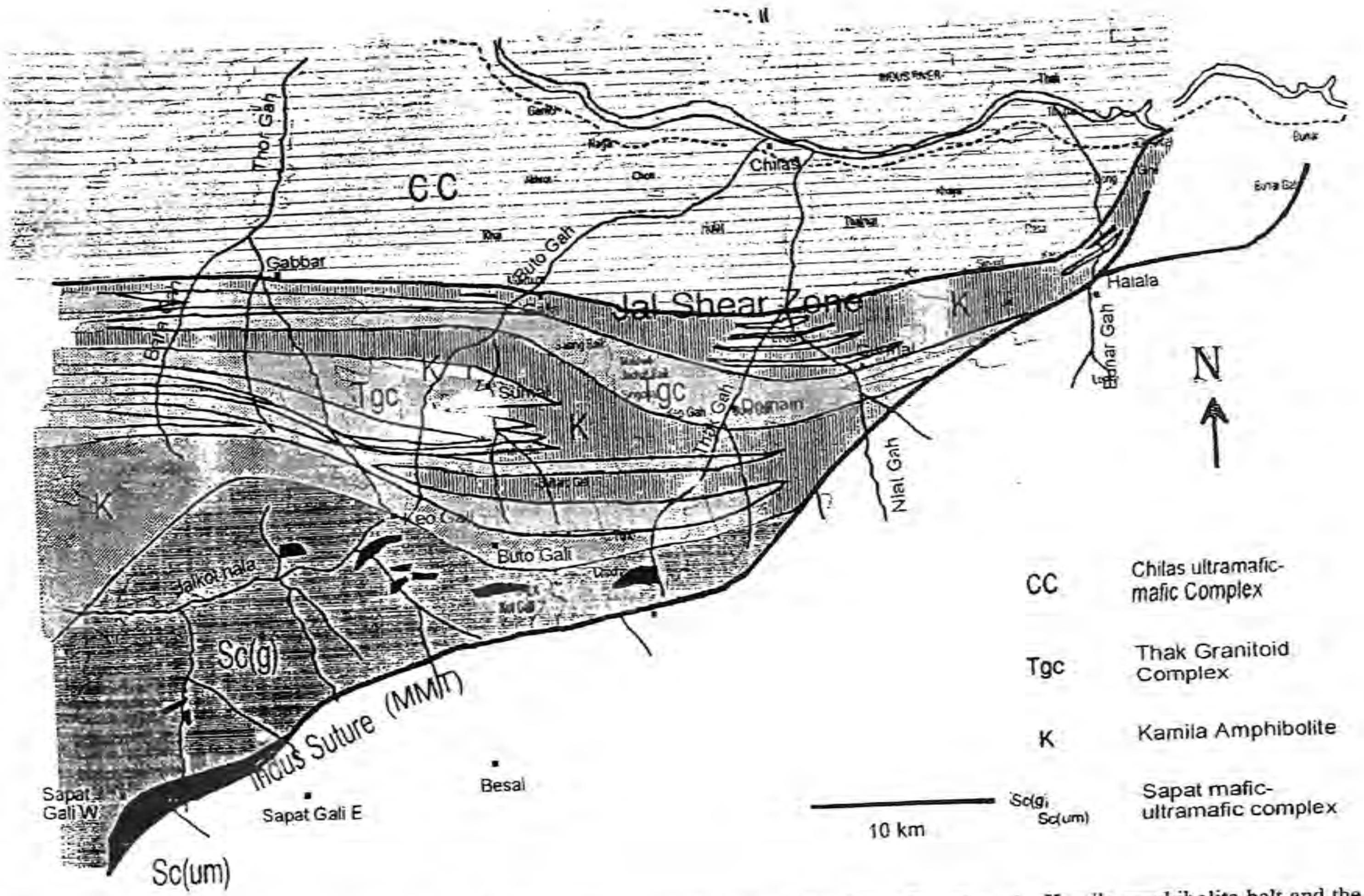

Fig. 1. Geological map of SE Kohistan, showing lithological subdivisions of the Sapat Complex, the Kamila amphibolite belt and the Thak granitoid complex.

Several factors, including a high relief, lack of roads, and a tribal political status of the area, restricted the past geological work in Kohistan to only major river valleys (e.g., Indus, Swat and Dir). The present work has been carried out in the remotely located southern part of the terrane. This work adds several new dimensions to the geological understanding of the Kohistan magmatic arc.

LOCAL GEOLOGY

The southeastern part of the Kohistan terrane lies between the MMT at its southern and eastern side and the Jal Shear zone, at the southern contact of the Chilas complex, at its northern side. The studied area includes various valleys of Bara gah, Buto gah, Thak gah, Niat gah and Buner gah. The peripheral parts towards north of the mapped area are accessible by the Karakoram Highway (KKH) along the Indus river and towards south by the Jeepable road between Kaghan and Babusar. The interior of the area can be accessed by trekking across ~ 4200 m high passes connecting northern tributaries of the Indus with those to the south of these passes (e.g., Jalkot Nala and Kunar river).

The project area composed of a variety of low-grade metamorphosed mafic-ultramafic rocks, plutonic rocks and a succession of volcanic rocks. The rocks are divisible into three main groups. The southern part of the area comprises mainly mafic-ultramafic plutonic rocks of the Sapat Complex (Jan et al., 1993). The area between the Sapat Complex and the Babusar Pass comprises amphibolites of metavolcanic origin included in the Kamila Amphibolite Belt of Tahirkheli and Jan (1979). This belt in the studied area is intruded by diorite, granodiorite, granite, trondhjemite and granitic pegmatite of the Thak Granitoid Complex (Fig. 1) The contacts between the different units run almost parallel to one another in east-west direction. All units are terminated in the eastern part by the Main Mantle Thrust. The foliation of the units shows an approximately constant east- west strike with gentle to moderate northerly dips.

The plutonic igneous rocks intruding the Kamila amphibolite belt are predominantly dioritic in composition, but include gabbros, granodiorites, granites and trondhjemites. The trondhjemites occur as thin veins and dykes in the northern part of the Kamila amphibolite belt. Here, the belt is in contact with the Chilas Complex along a strongly sheared zone known as Jal shear zone. Locally they are so abundant that they have imparted a banded appearance to the amphibolites. In Niat and Thak valleys, they are restricted to the northern parts of the Kamila amphibolite belt, whereas to the west, in the Buto and Thor valleys, they also intrude the diorite body. The only exception is the upper reaches of Buto Gah, where trondhjemites have been noticed in the south-central parts of the amphibolite belt (Fig. 1).

PETROGRAPHY

The trondhjemites are medium to coarse-grained and show alternating bands of felsic minerals and amphibole. Feldspar, amphibole and quartz are the mineral along with minor epidote, muscovite, biotite, sphene, garnet and ore. All mineral grains are aligned in one major direction defining foliation or general fabric. Quartz and amphibole grains show elongation and rotation. Overall the rocks are fresh, however, minor alterations such as epidotization and sericitization are also noticed in the trondhjemites.

Plagioclase is the most abundant phase in these rocks and as a whole comprises from 30 to 70 volume percent of the rocks. Two types of plagioclase crystals are recognized. One type consists of coarse and subhedral to euhedral grains with anorthite content ranging from 26 to 42 percent. Inclusions of epidote, sericite, and at places biotit are present in cores. The other type of crystals is fine to medium-grained and are closely associated with perthite and myrmekite. They are unzoned having an average composition of An_{26} and show many inclusions of sericite. Epidote, biotite and muscovite are present along the margins of all the plagioclase grains irrespective of their crystal size.

Hornblende is the dominant mineral in the amphibole group and prismatic in forms. Most of the grains are subhedral to euhedral, medium-grained, and dark green in color. It is commonly found in association with biotite and epidote. In some rocks, euhedral sphene occurs as inclusions in the hornblende. Quartz makes up approximately 25 volume percent of the trondhjemitic rocks and varies from 0.2 to 3 mm in diameter. It is generally anhedral in shape and exhibits a highly undulose extinction. Epidote, sphene and magnetite represent the accessory phases in these rocks. Sphene is brownish and occurs as discrete euhedral crystals but is also common as inclusions in biotite and hornblende.

GEOCHEMISTRY

Major and trace element data of ten representative samples are presented in Table 1. The variation in the chemical compositions of the studied rocks is very clear in this Table. However, a closer scrutiny of the data, coupled with the close spatial and possibly temporal field relations of the rocks, reveals that the chemical contrasts are systematic. Eight of the ten analyses contain high SiO_2 (>70%), Al_2O_3 (13.3-16.8%), CaO (1-4.5%), and Na_2O (4.3-6.6%). The concentrations of TiO_2, K_2O and MgO are low except A-62, which contains abnormally high amounts of TiO_2 (1.2%) and MgO (2.2%).

Alkali ratio is an important parameter in the nomenclature of granitic rocks; felsic rocks with sodic affinity (Na_2O/K_2O) > 2 are classified as tonalite or trondhjemite. On Na_2O-K_2O and Na_2O-K_2O-CaO diagrams, these rocks classify as tonalite. On the normative Ab-Or-An diagram, which discriminates between tonalite and trondhjemite, the studied rocks are restricted to the field of trondhjemite (Fig. 2). The analyses of the trondhjemites are plotted on the AFM diagram, together with the analyses of other granitoids from the area for comparison (Fig. 3). The trondhjemites, together with the rest of the rocks, display a well-defined calc-alkaline trend, but they have a distinctly higher (Na_2O+K_2O) / (MgO+FeO) content than the rest of the rocks including granites and granodiorites.

Incompatible trace elements normalized against primitive mantle concentrations, are presented on spidergram in Figure 4. All display very similar pattrns: highly spiked due to positive Rb, K, Sr, Zr and Y anomalies, and negative Nb, P and Ti anomalies; and sloping right (from RB towards Y). The granodiorite and granite series shows mutually comparable geochemical characteristics; and the trondhjemites have compositional attributes, which suggest a different petrogenesis. A comparison between representative granodiorite, granite and trondhjemite of the area for mantle normalized incompatible trace elements is shown in Figure 5. The trace element patterns of all the three rocks have lots of similarities as well as differences. The granodiorite has a pattern which matches closely with the granite in terms of HFSE, but is distinctly enriched in RB and K. In essence the granodiorite is even slightly depleted in HFSE (Y, Ti, P, and Sr) relative to the granite. It may be noted that the distribution coefficients of trace elements are different in granite system compared to basaltic systems. For instance, HFSE, which are incompatible in basaltic systems become compatible in granitic systems. 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 granodiorite relative to the granite may be attributed to fractional crystallization from a common magma.

TABLE 1. MAJOR AND TRACE ELEMENT ANALYSES OF TRONDHJEMITES OF SE KOHISTAN

	A-62	BS25	A-146	A-103	A-104	A-99	A-108	A-129	A-123	A-127
SiO_2	63.86	67.25	70.82	70.99	73.02	73.21	73.54	74.68	75.28	75.37
TiO_2	1.21	0.60	0.51	0.11	0.11	0.08	0.35	0.06	0.02	0.04
Al_2O_3	14.05	13.37	15.15	16.88	15.70	15.67	13.70	15.21	14.66	15.22
FE_2O_3	9.09	8.43	2.79	1.43	1.34	1.18	3.59	0.64	0.56	0.99
MgO	2.24	0.53	0.97	0.48	0.55	0.43	0.68	0.21	0.17	0.34
CaO	4.16	4.45	4.06	3.17	3.23	2.53	2.65	2.77	1.03	1.47
Na_2O	5.11	5.17	5.35	6.25	5.79	6.56	4.31	5.80	5.34	4.78
K_2O	0.01	0.02	0.25	0.68	0.24	0.31	1.10	0.61	2.92	1.67
P_2O_5	0.29	0.16	0.11	0.01	0.02	0.03	0.08	0.01	0.02	0.03
Total	100.02	99.98	100.01	100.00	100.00	100.00	100.00	99.99	100.00	99.91
Ti	7254	3597	3058	659	659	480	2098	360	120	240
K	83	166	2075	5645	1992	2573	9132	5064	24241	13864
P	1266	698	480	44	87	131	349	44	87	131
Nb	ND	21	7	1.20	2	2	4	1	15	6
Zr	ND	707	151	44	56	23	98	104	54	9
Y	ND	204	29	14	4	7	12	3	29	23
Sr	ND	182	204	236	336	265	172	260	25	167
Rb	ND	ND	4	22	26	11	27	24	71	55
Th	ND	2.20	6	2	2	4	4	2	2	2
Pb	ND	1.10	2	3	4	5	4	5	12	8
Ga	ND	27	15	14	13	12	14	12	17	17
Zn	ND	14	26	34	44	30	46	25	22	43
Cu	ND	140	2	5	18	12	2	2	2	2
Co	ND	ND	30	32	30	37	24	35	36	36
Ni	ND	6.00	2	2	2	2	2	2	2	2
Ti^*	15	8	6	1	1	1	4	1	-	1
Al^*	276	262	297	331	308	307	269	298	288	299
Fe^*	114	106	35	18	17	15	45	8	7	12
Mg^*	56	13	24	12	14	11	17	5	4	8
Ca^*	74	79	72	57	58	45	47	49	18	26
Na^*	165	167	173	202	187	212	139	187	172	154
Sr/Y	ND	0.89	7.03	16.86	84.00	37.86	14.33	86.67	0.86	7.26
K/Rb	ND	ND	518.75	256.59	76.62	233.91	338.22	211.00	341.42	252.07
Rb/Sr	ND	ND	0.02	0.09	0.08	0.04	0.16	0.09	2.84	0.33
Na_2O/K_2O	511	259.50	21.40	9.19	24.13	21.16	3.92	9.51	1.83	2.86
Fe_2O_3/MGO	4.06	15.91	2.88	2.98	2.44	2.74	5.28	3.05	3.29	2.91
Mg/(Mg+Fe)	0.20	0.06	0.26	0.25	0.29	0.27	0.16	0.25	0.23	0.26

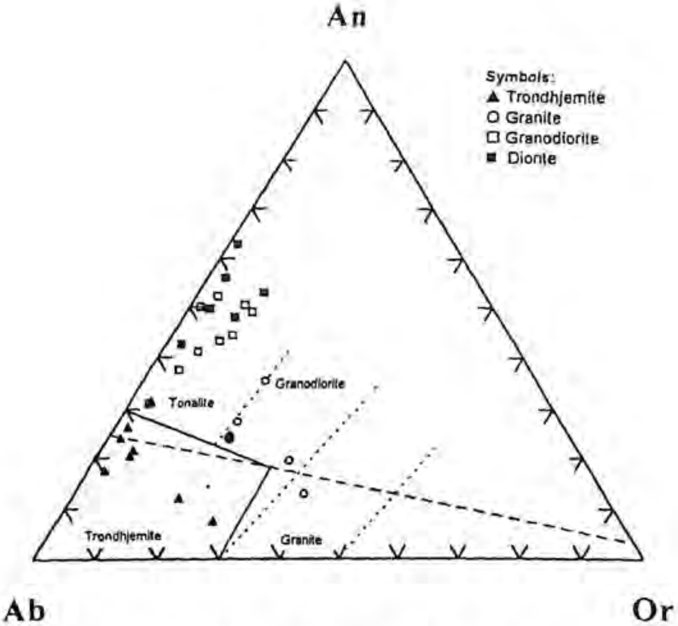

Fig. 2. Normative Ab-An-Or ternary plot distinguishes the trondhjemites from the other silicic rocks (> 10% modal quartz) of the studied area. Note that rocks classified petrographically as granodiorite plot in tonalite field, whereas granites plot in granodiorite field. Dashed lines of the O' Connor (1965) and solid lines after Barker (1979).

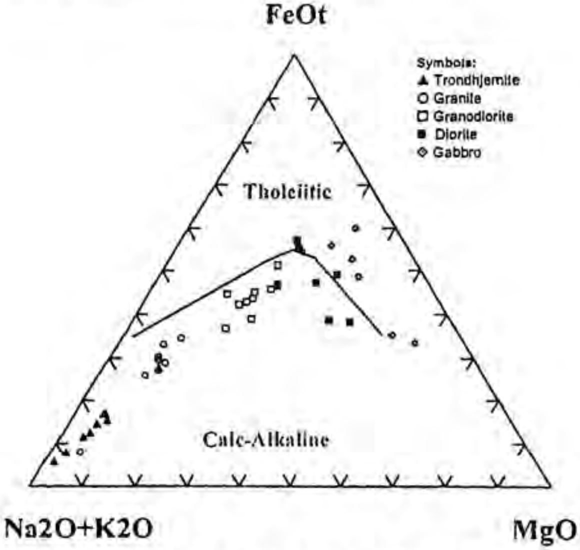

Fig. 3. AFM diagram for various rocks of the area define a calc-alkaline trend. Note: The trondhjemites have distinctly higher alkali/(Mg+Fe) ratio than the rest of the rocks, including granites and granodiorites. Analyses are listed in Khan, M. A. (1997) Ph.D. thesis. Boundary between tholeiite and calc-alkaline after Irvine and Barager (1971).

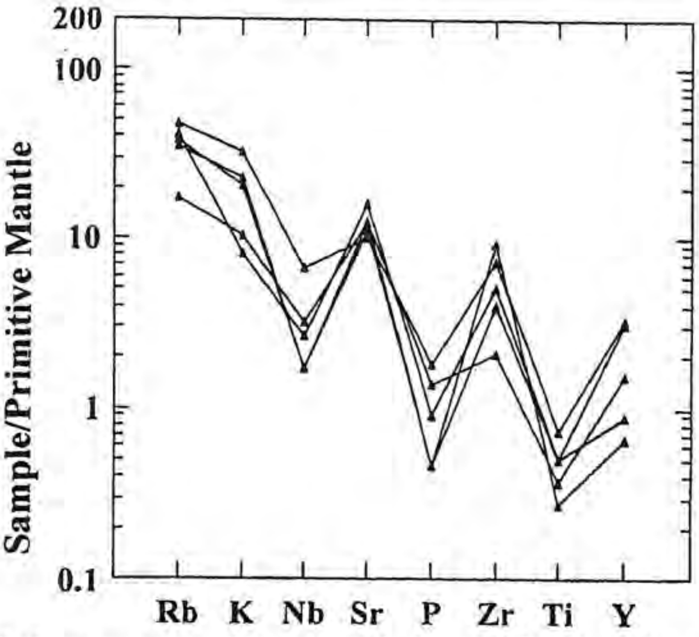

Fig. 4. Very spiked patterns of trondhjemites are sloping towards right with strong depletion in incompatible \trace elements. Normalizing values of Primordial Mantle: Rb 0.635, K 250, Nb 0.713, Sr 21.1, P 95, Zr 11.2, Ti 1300 and Y 4.55 are after Sun and McDonough (1989).

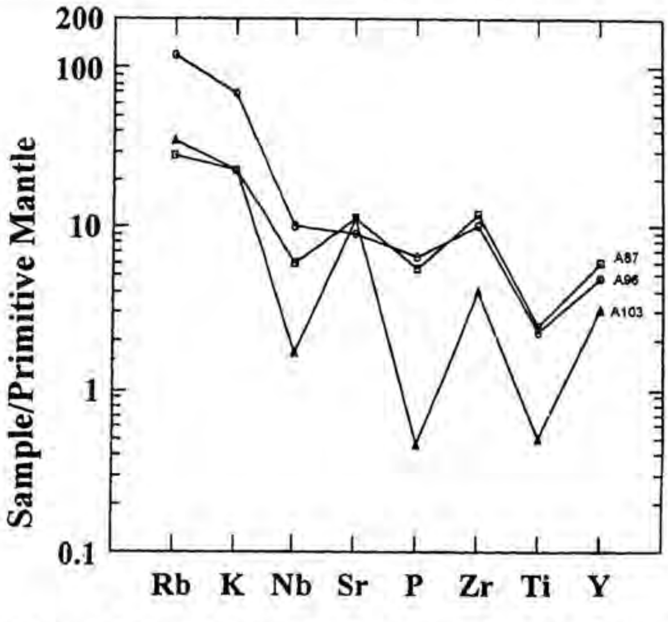

Fig. 5. A comparision of the mantle normalized incompatible trace elements between granite (A96), granodiorite (A87) and typical trondhjemite (A103) of the area. Note the highly spiked pattern of the trondhjemite as compared to the other two.

The trace element pattern of the trondhjemite, in comparison, is very different from those of the granite and granodiorite. It is depleted in all HFSE, particularly strongly in Ti, P and NB relative to the granite and the granodiorite (Fig. 5). The concentrations of K, Rb and Sr are comparable with those in the granite but not enriched, negating relationship between the two through the process of fractional crystallization. Thus whereas the granites and granodiorites are probably co-magmatic mutually as well as with gabbros and diorites, being fractional crystallization products of a common parental melt, the trondhjemites may be a product of partial melting from a source which was different from that of the gabbro-diorite-granodiorite-granite series.

DISCUSSION

Trondhjemites are found in a variety of geologic environments. The principal occurrences are in the Archean gray gneiss terranes and greenstone belts and at Proterozoic-continental margins. The Mesozoic-Cenozoic trondhjemites occur in two major associations: 1) ophiolites, and 2) subduction-related settings at the continental margins and island arcs (Barker, 1979; Gill, 1981; Drummond & Defant, 1990). 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 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 (Arth et al., 1978; Singer et al., 1992), while the other is a product of partial melting from the arc basement (Arth et al., 1978; Drummond & Defant, 1990; Beared & Lofgren, 1991; Rapp et al., 1991: Wolf & Wyllie, 1994). 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.

In the presently investigated part of the Kohistan terane, the trondhjemites have highly spiked patterns with distinct slopes towards the right. These trondhjemites could have formed by two processes; either as differentiates of the gabbro-diorite-granodiorite-granite series present in the investigated area or by partial melting of the Kamila amphibolites. All the studied trondhjemits have incompatible trace element abundance's lower than the gabbros, diorties, granodiorites and granites, negating the possibility of the trondhjemites as a fractional crystallization product. Partial melting of a basaltic source material is considered to be the most viable mechanism for the generation of high-Al trondhjemites similar to those of the area studied by Drummond and Defant (1990). Basalts converted to amphibolites and eclogites when involved in subduction-zone setting are partially fused to generate trondhjemites (De Vore, 1983a, b; Windley, 1984; Martin, 1986; Martin, 1986; 1987). The geochemical modeling and experimental studies (Drummund & Defant, 1990) favor a hot oceanic crust (20-30 Ma old) subducting and melting to produce trondhjemites. The high-Al trondhjemites of the present study are probably a product of partial melting but a direct role of subduction is not observed.

CONCLUSIONS

Field evidence suggests that the studies trondhjemites 1) occur as thin veins and dykes intimately associated with Kamila amphibolites, 2) they are concentrated in the northern part of the amphibolites, i.e. close to the Chilas Complex, and 3) they are syn- to post-kinematic. The amphibolite-facies metamorphism and deformation in the Kamila belt is considered related with the Kamila / Jal shear zone of 80 Ma (Treloar et al., 1990), suggesting a similar age for the trondhjemites. If so, the Kamila amphibolites did not melt in a subduction setting but in an intra-arc shear zone. The Chilas Complex of 90-80 Ma might have played an equally important role in the genesis of the trondhjemites as a heat source. In summary, the trondhjemites of the studied area are considered 1) to be unrelated with gabbro-diorite-tonalite-granodiorites-granite series, and 2) to have resulted from partial melting of Kamila amphibolite due to intrusion of the Chilas Complex and crustal shortening accompanying the Jal shear zone. The exact petrogenesis of the trondhjemite, however, cannot be properly evaluated without data of rare-earth elements.

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