Geobarometric constraints on the depth of emplacement of granite from the Ladakh batholith, Northwest Himalaya, India

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The Ladakh batholith is exposed along the 600 km long and 20 to 80 km wide NW–SE trending Ladakh range north of the Indus–Tsangpo Suture Zone. It was emplaced within an unmetamorphosed thick pile of mafic and felsic volcanics, ultramafics and sediments of Upper Cretaceous–Eocene age (Dras Volcanics, Khardung Volcanics). The granites from the Ladakh batholith (60 Ma phase) within the Leh–Khardung La and Sakti–Chang La sections (samples collected between altitude of 3600 M and 5440 M above mean sea level) have been estimated for pressure and temperature of crystallization employing the hornblende geobarometer of Schmidt (1992) and hornblende–plagioclase geothermometer of Blundy and Holland (1990), with the results of pressure of 254 ± 67 MPa and temperature of $695 \pm 20^\circ\text{C}$. Therefore, these granites were solidified at a depth of 8.6 ± 2.3 km suggesting an unroofing of this thickness in this region.

Introduction

The palaeo–subduction zone between the Indian and Asian plates, where consumption of the Neo–Tethyan ocean and subsequent continental collision took place, is represented by the Indus–Tsangpo Suture Zone (ITSZ), consisting of ophiolitic melanges, high–pressure blueschist metamorphic rocks and tholeiitic volcanic rocks together with the deep–sea sediments and flysch deposits. A remarkable feature to the north of the ITSZ is the Trans–Himalayan Ladakh Batholith (Fig. 1a, b), a linear plutonic complex extending for nearly 600 km along the Himalayan orogenic belt, formed due to the subduction of the Neo–Tethyan ocean crust (Gansser, 1980).

Petrogenetic studies of Himalayan granitoids would contribute to the elucidation of the evolution of Himalaya in time and space. There are a number of granitoid belts in the Himalaya (Shams, 1983; Debon et al., 1985, 1986). The Ladakh batholith represents the largest and youngest one in the Himalayan orogenic belt. The batholith was emplaced during the Tertiary period and therefore is related to the Himalayan

orogeny.

Many works have been done on this batholith as regards petrography, geochemistry, radiometric dating and stable isotope studies (Rai, 1980; Honegger et al., 1982; Pande and Rai, 1982; Blattner et al., 1983; Reynolds et al., 1983; Sorkhabi et al., 1994). However, geobarometric and geothermometric studies on Ladakh batholith have not been attempted so far.

For the numerical estimation of the pressure, temperature, and accordingly of depth of crystallization of the Ladakh granites in the Leh–Khardung La and Sakti–Chang La sections (60 Ma phase) (Fig. 2), a hornblende geobarometer (Schmidt, 1992) and hornblende–plagioclase geothermometer (Blundy and Holland, 1990) have been employed. Estimation of population parameters of Ladakh granites (mean value of P, T and depth of crystallisation) have been done using student's *t*-statistic (Till, 1974; Swan and Sandilands, 1995).

Geological Setting and petrography of Ladakh batholith

The Ladakh batholith occurs in an elongated arc, convex northward, measuring about 600 km in length, 20–80 km in width, with 2.5–3.2 km of vertical exposure, north

Figure 1. (a): Geological structure of the Himalaya showing the position of the Trans-Himalayan LadaKh batholith (after Gansser 1980); HFT, Himalayan Frontal Thrust system; ITSZ, Indus-Tsangpo Suture Zone; KSF, Karakorum Strike-slip fault; MBT, Main Boundary Thrust system; MCT, Main Central Thrust system; NP, Nanga Parbat; SZ, Shyok Suture Zone. (b): Geological map of Ladakh (after Sharma and Choubey 1983; Thakur, 1987).

1- JL 28, JL 29 2- JM 128 3- JM 117, JM 118, JM 119, JM 121 4- JM 85
5- JM 90, JM 91, JM 92 6- JM 96.

Figure 2. Detailed geological map of the Ladakh batholith between Hundar and Chang La showing the sample locations (after Thakur et al., 1981).

of the Indus–Tsangpo Suture Zone (Sharma and Choubey, 1983). It is composed of multiple intrusions of variable compositions from norite and gabbro, through diorite and tonalite, to granodiorite and granite; many dykes also cut across these rocks (Rai and Pande, 1980; Honegger et al., 1982). From aerial photographs and geological mapping, their relative volumes have been estimated by Honegger et al. (1982) to be about 50% granodiorite, 20–30% intermediate granitoids, 10–20% mafic intrusives and about 10% biotite granite.

The granites are calc-alkaline and belong to I-type (Chappell and White, 1974). Major part of the batholith is biotite and/or hornblende rich granodiorite. In Leh–Khardung La and Sakti–Chang La sections hornblende–biotite granites and granodiorites are the predominant rock types.

The northern face of this batholith is exposed in the Nubra Valley and there it is juxtaposed with the Khardung and Shyok volcanics. Intrusive relationship is well documented at many places. In the south central part of the Nubra Valley, between Diskit and Chandmarg, the batholith intrudes into the sediments and ophiolitic melange (Rai, 1983). Near the intrusive contact with the volcanic rocks, an intrusive breccia has developed, suggesting a forceful intrusion and brittle nature of the volcanic rocks (Rai, 1980).

The Ladakh batholith was emplaced into an unmetamorphosed thick pile of mafic and felsic volcanic rocks, ultramafic and sedimentary rocks of Upper Cretaceous–Eocene age (Dras Volcanics, Khardung Volcanics). Radiometric dating on the Ladakh batholith yields late Cretaceous to Eocene ages. The late Cretaceous–Eocene Ladakh batholith is interpreted to represent an Andean-type coastal batholith formed by accumulation of granitic magma as a result of northward subduction of Mesozoic oceanic crust beneath Tibet. Relatively low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.707) and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (0.5126) support the derivation of granitic magma from partial melting of subducted mantle material contaminated by a small amount of crustal material (Allegre and Othman, 1980; Honegger et al., 1982).

Sorkhabi et al. (1994) interpreted a thermotectonic history of the Trans–Himalayan Ladakh Batholith in the Kargil area in view of new and old radiometric data. They reported fission-track (FT) ages of 20 ± 2 Ma on apatite, recording cooling through temperatures of 100°C and indicating an unroofing of 4 km of Ladakh range since the Early Miocene. Zircon FT ages and also mica K–Ar cooling ages from the Ladakh batholith cluster around 40–50 Ma, probably indicating an Eocene phase of uplift and erosion that affected the bulk of the

batholith after the continental collision of India with the Ladakh arc at 55 Ma. Components of the granitoids in Upper Eocene–Lower Oligocene sediments of the Indus Molasse in Ladakh supports this. Three phases of I-type plutonism in Ladakh are suggested by available radiometric data: 102 Ma (mid-Cretaceous), 60 Ma (Palaeocene), and 40 Ma (Late Eocene); the last phase being represented by the localised sheet injections (Sorkhabi et al., 1994).

The phase-II granite (60 Ma phase) is coarse to medium-grained and porphyritic to equigranular in nature. Quartz, plagioclase and K-feldspar are the dominant mineral component of the granite along with minor hornblende and biotite. Sphene, apatite and zircon are the common accessories. Quartz (40–25%) grains are subhedral to anhedral. Plagioclase (40–30%) is oligoclase (in the rims, X_{An} varies from 0.22 to 0.36), grains are euhedral to subhedral and show well developed polysynthetic twinning. Some of the plagioclases show zoning. Most of the plagioclase grains are very fresh, but some grains are sericitized and are altered to micas. K-feldspar (20–5%) is microcline and microcline–microperthite. The grains are subhedral to anhedral and show well developed cross-hatched twinning. Untwinned K-feldspar which is microperthitic is also present. Hornblende (5–4%) and biotite (4–3%) are dominant mafic constituents. Hornblende grains are euhedral to subhedral and show pleochroism from green to greenish brown. Sphene is associated with hornblende grains. Biotite grains are euhedral and show pleochroism from dark brown to light brown and yellowish brown. Chlorite and opaque minerals are present in oxidized portions of biotite grains.

Aluminum in Hornblende as a Geobarometer

Mineral chemical and experimental studies show that the composition of amphibole varies with bulk composition, pressure (P), temperature (T), and oxygen fugacity (f_{O_2}) of the system. Wones (1981) suggested the chemical variability in amphiboles and also other mafic silicates to be potential indicators of intensive variables in granitic magmas. Raase (1974), Laird and Albee (1981), Spear (1981), Helz (1982) and Wones and Gilbert (1982) elucidated the factors controlling the hornblende composition.

Hammarstrom and Zen (1983, 1985, 1986) showed an empirical correlation between the pressure of crystallization of calc-alkaline plutons and the total Al content of their constituent hornblende. Hammarstrom and Zen (1986) proposed the following calibration:

Table 1. Representative microprobe analyses of hornblendes from Ladakh granites

Sample No.	JL29 Rim n=14	JL29 Core n=6	JM119 Rim n=8	JM119 Core n=4	JM85 Rim n=8	JM85 Core n=4	JM91 Rim n=8	JM91 Core n=4
No. of points analysed								
SiO ₂	45.10	46.24	46.88	47.09	47.29	48.09	47.50	48.07
TiO ₂	1.34	1.36	1.14	1.16	0.87	1.01	0.96	1.21
Al ₂ O ₃	8.22	7.72	6.82	6.50	7.16	6.55	6.23	6.05
Cr ₂ O ₃	0.12	0.04	0.08	0.04	0.03	0.01	0.13	0.04
FeO	16.75	16.32	15.80	15.26	14.56	13.77	14.99	14.46
MnO	0.55	0.54	0.80	0.78	0.45	0.53	1.06	1.13
MgO	10.83	11.45	12.61	12.65	13.04	13.80	12.56	12.88
CaO	11.65	11.84	11.60	11.62	11.75	11.68	11.69	11.58
Na ₂ O	1.23	1.18	1.07	1.05	0.96	0.96	1.04	1.15
K ₂ O	0.96	0.92	0.65	0.61	0.30	0.28	0.58	0.56
Total	96.75	97.61	97.44	96.75	96.40	96.67	96.73	97.12
Cations 13eCNK								
Si	6.778	6.864	6.885	6.960	6.955	7.016	7.032	7.071
Al ^{iv}	1.222	1.136	1.115	1.040	1.046	0.985	0.968	0.930
T site	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{vi}	0.233	0.215	0.066	0.094	0.196	0.142	0.119	0.120
Ti ⁴⁺	0.151	0.152	0.126	0.129	0.096	0.111	0.107	0.134
Fe ³⁺	0.374	0.331	0.700	0.581	0.615	0.635	0.502	0.454
Cr ³⁺	0.014	0.005	0.010	0.005	0.004	0.001	0.015	0.005
Mg	2.427	2.535	2.761	2.788	2.859	3.002	2.772	2.824
Fe ²⁺	1.731	1.694	1.240	1.307	1.176	1.045	1.354	1.324
Mn	0.070	0.068	0.100	0.098	0.056	0.065	0.133	0.142
M1,M2,M3 sites	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Ca	1.876	1.883	1.825	1.841	1.851	1.826	1.854	1.825
Na	0.124	0.117	0.176	0.160	0.149	0.174	0.147	0.176
M4 site	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.235	0.224	0.129	0.142	0.125	0.098	0.153	0.153
K	0.184	0.174	0.121	0.115	0.055	0.052	0.109	0.105
A site	0.420	0.398	0.250	0.257	0.180	0.150	0.261	0.258
Cations	15.420	15.398	15.250	15.257	15.180	15.150	15.261	15.258
Mg#	0.5838	0.5998	0.6901	0.6810	0.7087	0.7418	0.6719	0.6810
Mg#*	0.5356	0.5558	0.5873	0.5964	0.6150	0.6412	0.5990	0.6137
Fe ratio	0.1777	0.1625	0.3612	0.3065	0.3431	0.3777	0.2706	0.2558

$$\text{Mg\#} = \text{Mg}/(\text{Mg} + \text{Fe}^{2+})$$

$$\text{Mg\#}^* = \text{Mg}/(\text{Mg} + \text{Fe}^{2+} + \text{Fe}^{3+})$$

$$\text{Fe ratio} = \text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$$

$$P(\pm 300 \text{ MPa}) = -3.92 + 5.03 \text{ Al}^{\text{T}}, r^2 = 0.80$$

This calibration can be applied to the tonalitic rocks of the following mineral assemblage: plagioclase, hornblende, biotite, K-feldspar, quartz, titanite, magnetite or ilmenite±epidote.

Hollister et al. (1987) have analysed the hornblende composition of the calc-alkaline plutonic rocks of the Coast Mountain B.C., in which depth of emplacement has been constrained by the metamorphic aureole condition, they revised the barometer and gave the following

empirical calibration:

$$P(\pm 100 \text{ MPa}) = -4.76 + 5.64 \text{ Al}^{\text{T}}, r^2 = 0.97.$$

On the other hand, Schmidt (1992) experimentally calibrated the hornblende geobarometer at pressures of 0.2–1.3 GPa, giving the following equation:

$$P(\pm 60 \text{ MPa}) = -3.01 + 4.76 \text{ Al}^{\text{T}}, r^2 = 0.99$$

Hornblende–Plagioclase Geothermometer

Blundy and Holland (1990) proposed an amphibole–

Table 2. Representative microprobe analyses of plagioclases from Ladakh granites

Sample No.	JL29 Rim n=12	JL29 Core n=6	JM119 Rim n=7	JM119 Core n=4	JM85 Rim n=7	JM85 Core n=4	JM91 Rim n=8	JM91 Core n=4
No. of points analysed								
SiO ₂	61.61	61.48	60.44	57.43	60.33	57.65	62.66	62.49
TiO ₂	0.01	0.00	0.01	0.01	0.02	0.02	0.01	0.02
Al ₂ O ₃	24.18	24.22	25.05	27.36	25.14	26.81	23.81	23.34
FeO	0.09	0.09	0.16	0.14	0.17	0.05	0.16	0.11
MgO	0.02	0.05	0.00	0.01	0.01	0.00	0.01	0.01
CaO	6.38	6.57	6.49	9.14	7.27	9.42	5.47	5.30
Na ₂ O	7.95	7.85	8.94	6.98	7.33	6.18	8.88	8.80
K ₂ O	0.15	0.17	0.18	0.18	0.12	0.10	0.24	0.22
BaO	0.01	0.01	0.03	0.00	NA	NA	0.03	0.01
Total	100.39	100.46	101.28	101.24	100.37	100.22	101.25	100.28
Cations per 8 oxygens								
Si	2.727	2.722	2.671	2.552	2.678	2.578	2.752	2.766
Al	1.262	1.264	1.305	1.433	1.315	1.413	1.232	1.218
Na	0.682	0.674	0.766	0.602	0.631	0.536	0.756	0.755
Ca	0.302	0.312	0.307	0.435	0.346	0.452	0.258	0.252
K	0.008	0.010	0.010	0.010	0.007	0.006	0.014	0.013
Ba	0.000	0.000	0.001	0.000	NA	NA	0.001	0.000
Ti ⁴⁺	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.001
Fe ²⁺	0.003	0.004	0.006	0.006	0.006	0.002	0.006	0.004
Mg	0.002	0.004	0.000	0.001	0.001	0.000	0.001	0.001
Sum cations	4.988	4.988	5.065	5.038	4.984	4.986	5.018	5.008
X _{Ab}	0.6867	0.6773	0.7073	0.5749	0.6415	0.5394	0.7362	0.7409
X _{An}	0.3049	0.3130	0.2835	0.4156	0.3514	0.4551	0.2507	0.2469
X _{Or}	0.0085	0.0097	0.0092	0.0096	0.0072	0.0056	0.0132	0.0123

plagioclase thermometer based on the Al^{IV} content of amphibole coexisting with plagioclase in silica saturated rocks. Their calibrations are as follows:

$$T = \frac{0.677P - 48.98 + Y}{-0.0429 - 0.008314 \ln K}$$

$$\text{where } K = \left(\frac{\text{Si} - 4}{8 - \text{Si}} \right) X_{\text{Ab}}^{\text{plag}}$$

P: in kbar; T in K

Si: number of atoms per formula unit in amphiboles

Y=0 for $X_{\text{Ab}} > 0.5$

Y = $-8.06 + 25.5(1 - X_{\text{Ab}})^2$ for $X_{\text{Ab}} < 0.5$.

This formulation has been utilized to estimate the temperature of crystallization of the Ladakh granites.

Mineral Chemistry

The mineral analyses were performed with a JEOL JXA-8600M super microprobe at the University Science Instrumentation Center, University of Roorkee, Roorkee, India. A probe current of 20 nA at an accelerating voltage of 15 KeV and a beam size of 2 microns were

used. Standardization was conducted against natural standards using ZAF corrections after Philibert (1963). **Hornblende** — Representative microprobe analyses of the hornblendes from Ladakh granites are shown in Table 1. Cations are first calculated on the basis of 23 oxygens and then recalculated to account for ferric iron by using Droop's (1987) equation. Cations are normalized to total 13 cations excluding Ca, Na and K. Cation site distributions have been made after Leake et al. (1997) and Mogessie et al. (1990). In the M4 site Ca varies from 1.751 to 1.893 and Na from 0.107 to 0.249. Na in the A site varies from 0.048 to 0.315. Si in the tetrahedral site (T site) varies from 6.666 to 7.242. $[\text{Mg}/(\text{Mg} + \text{Fe}^{2+})]$ varies from 0.5745 to 0.7673. Following the amphibole classification scheme of Mogessie et al. (1990), in all the analysed amphiboles $(\text{Ca} + \text{Na})_{\text{M4}} \geq 1.34$, $\text{Na}_{\text{M4}} < 0.67$, $\text{Ti} < 0.5$, $(\text{Na} + \text{K})_{\text{A}} < 0.5$, $6.50 \leq \text{Si} < 7.25$ and $[\text{Mg}/(\text{Mg} + \text{Fe}^{2+})] \geq 0.50$, therefore all of them belong to the calcic amphiboles and are assigned to Magnesian-Hornblende.

In the rim of hornblende, M4 site Ca varies from 1.781 to 1.893 and Na from 0.107 to 0.219. Na in the A site varies from 0.068 to 0.315. Si in the tetrahedral site

Table 3. Estimated depth of crystallization of Ladakh granites

Sample No.	Al (Total)	Pressure(MPa) using Schmidt (1992) calibration	Depth (h) in Kms.
JL28	1.4638	395.8	13.449
JL29	1.4548	391.4	13.299
JM117	1.1090	226.9	7.710
JM118	1.1595	250.9	8.525
JM119	1.1805	260.9	8.865
JM121	1.1347	239.1	8.124
JM128	1.1780	259.7	8.824
JM85	1.2410	289.7	9.844
JM90	1.0137	181.5	6.167
JM91	1.0870	216.4	7.353
JM92	0.9807	165.8	5.634
JM96	0.9977	173.9	5.909
Sample Mean ($\bar{X}$)	1.1667	254.3	8.642
Standard Deviation (s)	0.1580	75.2	2.554
Population Mean (μ) using student t-statistic	1.1667 $\pm$ 0.1416	254.3 $\pm$ 67.4	8.64 $\pm$ 2.29

(T site) varies from 6.666 to 7.242. $[Mg/(Mg + Fe^{2+})]$ varies from 0.5745 to 0.7549.

Al^I (total aluminum) varies from 0.981 to 1.464. Al^{IV} (Aluminum in 4 fold T site) varies from 0.747 to 1.334.

Plagioclases — Table 2 gives the representative microprobe analyses of plagioclases coexisting with the above hornblendes. In the rim of plagioclases X_{An} varies from 0.22 to 0.36. Majority of plagioclase rim composition are oligoclase. Cores of plagioclases are higher in X_{An} than rims. Core composition varies from oligoclase to andesine ($X_{An}=0.19$ to 0.49).

Geothermobarometry and depth estimates

The estimated pressure of crystallization of Ladakh granites range from 166 MPa to 396 MPa and mean pressure of crystallization as 254 ± 67 MPa (at 99% confidence interval) which has been estimated statistically by using student's t-statistic (Till, 1974; Swan and Sandilands, 1995) (Table 3). Temperature of crystallization range from 660 to 723°C giving a mean value of $695 \pm 20^\circ\text{C}$. However, it may be noted that calculated pressures for some samples (e.g. sample no. JL28, JL29 and JM92) are outside the estimated population mean of 254 ± 67 MPa (at 99% confidence interval) for the Ladakh granites, this is partly due to the statistical theory for estimation of population mean and partly because dispersion in measured pressure values will be due to the fact that granite crystallized over a range of P and T.

Assuming the density of Ocean crust to be 3×10^3 kg/m³, we can estimate the depth of the solidification of granitic magma.

$P = 254 \pm 67$ MPa, gives the depth of 8.6 ± 2.3 km (Table 3), implying these granites from the Ladakh batholith to have been solidified at this depth. These geobarometric results indicate 8.6 ± 2.3 km of unroofing in this region.

Conclusions

Estimation of pressure and temperature of crystallization of Ladakh granites carried out by using the hornblende geobarometer of Schmidt (1992) and hornblende-plagioclase geothermometer of Blundy and Holland (1990) along with population mean estimated by using student's t-statistic at 99% confidence interval (level of significance $\alpha=0.01$) reveals that:

1. Pressure and temperature of crystallization was 254 ± 67 MPa and $695 \pm 20^\circ\text{C}$.
2. The granites from the Ladakh batholith solidified at a depth of 8.6 ± 2.3 km.
3. The Ladakh batholith has been unroofed of 8.6 ± 2.3 km in this region.

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References

- Allegre, C.J. and Othman, D.B. (1980) Nd-Sr isotopic relationship in granitoid rocks and continental crust development: a chemical approach to orogenesis. *Nature*, 286, 335–342.
- Blattner, P., Dietrich, V. and Gansser, A. (1983) Contrasting ^{18}O enrichment and origins of High Himalayan and Transhimalayan intrusives. *Earth and Planetary Science Letters*, 65, 276–286.
- Blundy, J.D. and Holland, T.J.B. (1990) Calcic amphibole equilibria and a new amphibole-plagioclase geothermometer. *Contributions to Mineralogy and Petrology*, 104, 208–224.
- Chappell, B.W. and White, A.J.R. (1974) Two contrasting granite types. *Pacific Geology*, 8, 173–174.
- Debon, F., Le Fort, P., Sheppard, S.M.F. and Sonet, J. (1986) The four plutonic belts of the Transhimalaya-Himalaya: a chemical-mineralogical, isotopic, and chronological synthesis along a Tibet-Nepal section. *Journal of Petrology*, 27, 219–250.
- Debon, F., Zimmermann, J.L., Liu, G.H., Jin, C.W. and Xu, R.H. (1985) Time relationships between magmatism, tectonics and metamorphism in three plutonic belts in southern Tibet: New K-Ar data. *Geologische Rundschau*, 74, 229–236.
- Droop, G.T.R. (1987) A general equation for estimating Fe^{3+} concentrations in ferromagnesian silicates and oxides from microprobe analyses, using stoichiometric criteria. *Mineralogical Magazine*, 51, 431–435.
- Gansser, A. (1980) The significance of the Himalayan suture zone. *Tectonophysics*, 62, 37–52.
- Hammarstrom, J.M. and Zen, E-An. (1983) Possible use of Al content in hornblende as a geobarometer for plutonic rocks. *Geological Society of America, Abstracts with Program*, 15, 590.
- Hammarstrom, J.M. and Zen, E-An. (1985) An empirical equation for igneous calcic amphibole geobarometry. *Geological Society of America, Abstracts with Program*, 17, 602.
- Hammarstrom, J.M. and Zen, E-An. (1986) Aluminum in hornblende: An empirical igneous geobarometer. *American Mineralogist*, 71, 1297–1313.
- Helz, R.T. (1982) Phase relations and compositions of amphiboles produced in studies of the melting behaviour of rocks. In *Amphiboles: Petrology and Experimental Phase relations* (Veblen, D.R. and Ribbe, P. H. Eds.). pp. 390, *Reviews in Mineralogy*, 9B, 279–346, Mineralogical Society of America, Washington, D.C.
- Hollister, L.S., Grissom, G.C., Peters, E.K., Stowell, H.H. and Sisson, V.B. (1987) Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc-alkaline plutons. *American Mineralogist*, 72, 231–239.
- Honegger, K., Dietrich, V., Frank, W., Gansser, A., Thoni, M. and Trommsdorff, V. (1982) Magmatism and metamorphism in the Ladakh Himalayas (the Indus-Tsangpo suture zone). *Earth and Planetary Science Letters*, 60, 253–292.
- Laird, J. and Albee, A.L. (1981) Pressure, temperature, and time indicators in mafic schist: Their application to reconstructing the polymetamorphic history of Vermont. *American Journal of Science*, 281, 127–175.
- Leake, B.E., Woolley, A.R., Arps, C.E.S. and 19 others (1997) Nomenclature of amphiboles: Report of the Subcommittee on amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names. *American Mineralogist*, 82, 1019–1037.
- Mogessie, A., Tessadri, R. and Veltman, C.B. (1990) EMP-AMPH-A Hypercard program to determine the name of an amphibole from Electron Microprobe analysis according to the International Mineralogical Association Scheme. *Computers and Geosciences*, 16, 309–330.
- Pande, I.C. and Rai, H. (1982) Origin and emplacement of tonalite along the Indus Suture Zone, Kargil area, Ladakh District, India. In *Recent Researches in Geology* (Gupta, V.J. et al. Eds.). pp. 581, Hindustan Publishing Corporation, Delhi (India), 8, 98–125.
- Philibert, J. (1963) X-ray optics and X-ray microanalysis. pp. 329, Academic Press, New York.
- Raase, P. (1974) Al and Ti contents of hornblende, indicators of pressure and temperature of regional metamorphism. *Contributions to Mineralogy and Petrology*, 45, 231–236.
- Rai, H. (1980) Origin and emplacement of Ladakh batholith: present day knowledge. *Himalayan Geology*, 10, 78–93.
- Rai, H. (1983) Geology of the Nubra Valley and its significance on the evolution of the Ladakh Himalaya. In *Geology of Indus Suture Zone of Ladakh* (Thakur, V.C. and Sharma, K.K. Eds.). pp. 204, Wadia Institute of Himalayan Geology, Dehra Dun, 79–97.
- Rai, H. and Pande, I.C. (1980) Geology of the Kargil Igneous Complex, Ladakh, Jammu and Kashmir, India. In *Recent Researches in Geology*, (Gupta, V.J. et al. Eds.). pp. 324, Hindustan Publishing Corporation, Delhi (India), 5, 219–228.
- Reynolds, P.H., Brookfield, M.E. and McNutt, R.H. (1983) The age and nature of Mesozoic-Tertiary magmatism across the Indus Suture Zone in Kashmir and Ladakh (N.W. India and Pakistan). *Geologische Rundschau*, 72, 981–1004.
- Schmidt, M.W. (1992) Amphibole composition in tonalite as a function of pressure: an experimental calibration of the Al-in hornblende barometer. *Contributions to Mineralogy and Petrology*, 110, 304–310.
- Shams, F.A. (1983) (Ed.) *Granites of Himalayas, Karakorum and Hindukush*. pp. 425 Institute of Geology, Punjab University, Lahore, Pakistan.
- Sharma, K.K. and Choubey, V.M. (1983) Petrology, Geochemistry and Geochronology of the southern margin of the Ladakh batholith between Upshi and Chumathang. In *Geology of Indus Suture Zone of Ladakh* (Thakur, V.C. and Sharma, K.K. Eds.). pp. 204, Wadia Institute of Himalayan Geology, Dehra Dun (India), 41–60.
- Sorkhabi, R.B., Jain, A.K., Nishimura, S., Itaya, T., Lal, N., Manickavasagam, R.M. and Tagami, T. (1994) New age constraints on the cooling and unroofing history of the

- Trans-Himalayan Ladakh Batholith (Kargil area), N.W. India. Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences Section), 103, 83–97.
- Spear, F.S. (1981) An experimental study of hornblende stability and compositional variability in amphibolite. American Journal of Science., 281, 697–734.
- Swan, A.R.H. and Sandilands, M. (1995) Introduction to Geological data analysis. pp. 446, Blackwell Science, London.
- Thakur, V.C. (1987) Plate tectonic interpretation of the western Himalaya. Tectonophysics, 134, 91–102.
- Thakur, V.C., Virdi, N.S., Rai, H. and Gupta, K.R. (1981) A note on the geology of Nubra–Shoyk area of Ladakh, Kashmir, Himalaya. Journal of the Geological Society of India, 22, 46–50.
- Till, R. (1974) Statistical methods for the Earth Scientist. An Introduction. pp. 154. Macmillan, London.
- Wones, D.R. (1981) Mafic silicates as indicators of intensive variables in granitic magmas. Mining Geology, 31, 191–212.
- Wones, D.R. and Gilbert, M.C. (1982) Amphiboles in the igneous environment. In Amphiboles: Petrology and Experimental Phase relations (Veblen, D.R. and Ribbe, P.H. Eds.). pp. 390, Reviews in Mineralogy, 9B, 355–390, Mineralogical Society of America, Washington, D.C.

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