

SHRIMP U–Pb ages and depth of emplacement of Ladakh Batholith, Eastern Ladakh, India

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Received 18 April 2005; received in revised form 19 April 2006; accepted 11 December 2006

Abstract

The Ladakh Batholith represents subduction-related Andean-type magmatism, intruding an island arc setting. The age and emplacement of the batholith was examined along the Kharu-Chang La section having a width of ~25 km. The SHRIMP-II U–Pb zircon age from a granodiorite near its northern boundary with the Shyok Suture Zone (SSZ) is 60.1 ± 0.9 Ma, whereas, a diorite from its southern boundary close to the Indus-Tsangpo Suture Zone (ITSZ) yields an age of 58.4 ± 1.0 Ma. Al-in-hornblende barometry indicates the depth of crystallization for the diorite to be 16 ± 1 km and granodiorite to be around 8 ± 1 km. The data indicate that diorite and granodiorite were emplaced with a depth difference of about 8 km, and are now juxtaposed at the present level of erosion, exposed with a 2 km elevation difference. This can be attributed to tectonic removal of material along the Kharu-Chang La Section. The depth of emplacement data also indicates northward tilting of the Ladakh Batholith after crystallization.

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Keywords: Andean-type magmatism; Himalaya; SHRIMP U–Pb dating; Depth of emplacement

1. Introduction

The Himalaya (Fig. 1) is a unique example of young continent-to-continent collision. It stretches continuously for about 2400 km from east to west between Namche Barwa ($29^{\circ} 37'N$; $95^{\circ} 15'E$; 7756 m) and Nanga Parbat ($33^{\circ} 15'N$, $74^{\circ} 36'E$; 8126 m). Its width varies from 230–300 km, with an average of about 270 km. The Neo-Tethyan oceanic crust attached to the Indian Continental crust subducted beneath the Eurasian Plate, with the Indian continental crust arriving at the Eurasian trench no later than 57 ± 1 Ma (Leech et al., 2005). It collided against the Eurasian Plate along the Indus-Tsangpo Suture Zone (ITSZ) and Shyok Suture Zone (SSZ) (Gansser, 1964; Dewey and Bird, 1970; Dewey and Burke, 1973; Le Fort, 1975, 1986; Thakur, 1993; Searle et al., 1988; Jain et al., 2002, 2003).

The closure of Neo-Tethys was followed by subduction of continental crust below the Eurasian Plate and reached a minimum depth of 90 km at 53.3 ± 0.7 Ma (de Sigoyer et al., 2000; Guillot et al., 2003; Sachan et al., 2004; Singh et al., 2003; Leech et al., 2005). The collision has caused intense crustal shortening and deformation along southerly migrating thrusts viz. the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT), as well as large-scale strike-slip faults in Tibet. These south-directed thrusts appear to sole into a common décollement, the Main Himalayan Thrust (MHT) (Zhao et al., 1993; Brown et al., 1996; Nelson et al., 1996; Jain et al., 2003).

The Trans-Himalaya is a mountain chain north of the suture zone separating the Indian and Eurasian Plates along the Indus-Tsangpo Suture Zone (ITSZ – Fig. 1). The Ladakh Batholith and the Kohistan Batholith constitute an important segment of the Trans-Himalaya that occurs as linear belts from Pakistan in the west (the

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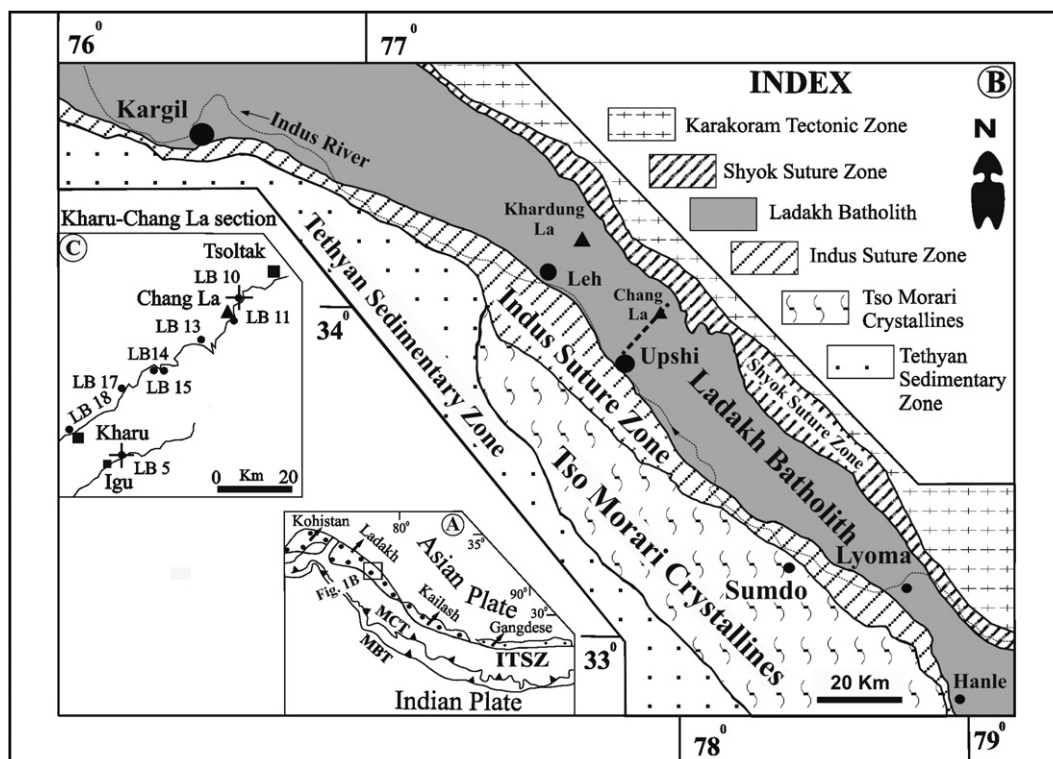


Fig. 1. (A) Simplified tectonic setting of the Trans-Himalayan calc-alkaline batholiths of Kohistan, Ladakh, Kailash and Gangdese within the framework of Indian Plate subduction beneath the Eurasian Plate along the Indus-Tsangpo Suture Zone. (B) Geological map of the Ladakh Batholith bounded by the Shyok Suture Zone in the north and Indus-Tsangpo Suture Zone in the south. UHP metamorphosed Indian Plate is shown as the Tso Morari Crystallines, which is covered by the Tethyan Sedimentary Zone. (C) Location of samples used for the Al-in-hornblende geobarometry, while 2 samples for SHRIMP II analysis are indicated with plus sign.

Kohistan Batholith) to Tibet in the east (Honegger et al., 1982). The batholith extends from Astor through Deosai-Skardu in Pakistan as the Kohistan Batholith (Auden, 1935; Wadia, 1937; Desio, 1977) to Leh–Upshi–Nyoma–Hanle in India as the Ladakh Batholith (Frank et al., 1977; Sharma, 1982; Thakur, 1993) and further southeast in southern Tibet as the Kailash Tonalite and the Gangdese pluton (Academica Sinica, 1980; Debon et al., 1981, 1986; Schärer et al., 1984). Further east, it has been called the Lohit Batholith in the Mishmi Hills of NE-India (Thakur and Jain, 1975; Sharma et al., 1991). The batholith is an Andean-type calc-alkaline plutonic complex with compositions varying from norite, gabbro to granite (Honegger et al., 1982). The batholith resulted from the northward subduction of Tethyan oceanic crust below an island arc, which was located along the southern margin of Eurasia (Schärer et al., 1984). A large sliver of a sedimentary sequence within the Ladakh Batholith led Raz and Honegger (1989) to suggest that it may have developed in a transitional environment between the Kohistan island arc in the west and the continental margin of Eurasia (Rolland et al., 2000; Dunlap and Wysoczanski, 2002). In the present work, the age of the Ladakh Batholith is studied by U–Pb SHRIMP analyses on zircon and the emplacement depths of exposed rocks are studied by Al-in-hornblende barometry along the Kharu-Chang La transverse section (Fig. 1C) in order to determine the depth of emplacement of calc-

alkaline magmatism in the subduction zone. The GPS data (with default datum of World Geodetic Reference System of 1984 – WGS84 for Gramin GPS) of samples are listed in Appendix A.

2. Geological setting

The Ladakh Batholith is part of the Trans-Himalayan complex and occurs as a WNW–ESE trending linear belt about 600 km long, 30–80 km wide and about 3 km in exposed thickness, and lies immediately north of the ITSZ (Fig. 1). The batholith continues from the Astor–Deosai–Skardu region (Auden, 1935; Wadia, 1937; Desio, 1977) eastward through Leh, Upshi and Nyoma to Hanle and further southeast into southern Tibet. The Ladakh Batholith has been referred to as the “Ladakh Intrusive” by Frank et al. (1977), “Ladakh–Deosai Batholith” (Brookfield and Reynolds, 1981) and “Ladakh Batholith” by Rai (1983). Honegger et al. (1982) and Schärer et al. (1984) carried out detailed geochemical and isotopic studies of various lithounits of the Indus-Tsangpo Suture Zone and the Trans-Himalayan Ladakh Batholith. Based on extensive field observations, Raz and Honegger (1989) described the tectonic and magmatic evolution of the Ladakh area. Sorkhabi et al. (1994) carried out fission track and Ar–Ar ages from the Trans-Himalayan Batholith and modelled its cooling history below 350 °C.

The Ladakh Batholith is partly covered by north-dipping fore-arc rocks and continental molassic sedimentary rocks derived from uplift and erosion of plutonic rocks (Garzanti and van Haver, 1988; Sinclair and Jaffey, 2001). The igneous complex consists of I-type lithologies, including gabbros, diorites, granodiorites and granites. The belt has an intrusive relationship with volcanic rocks of island arc assemblages, like the Dras volcanics (Sharma and Gupta, 1983; Choudhary, 1983). Sharma and Gupta (1983) also observed that the batholith reveals a zoned nature with more basic lithologies on its exterior close to the Indus Molasse and Indus Flysch, while more acidic varieties occur within its interior. They attributed this zoning to magmatic differentiation. The northern slope of this batholith is exposed in Shyok Valley and is in contact with the Khardung and Shyok Volcanics. In the south central part of the Shyok valley, between Diskit and Chandmarg, the batholith has intruded into sediments and ophiolitic mélange (Rai, 1983). Sharma (1982) and Sharma and Choubey (1983) recognized four phases of magmatic activity within the Ladakh Batholith. After a detailed survey of the batholith, Singh (1993) divided the Ladakh Granitoid Complex into five distinct units: diorite–tonalite, granodiorite–quartz–monzodiorite, biotite–hornblende granite, leucogranite and pink porphyritic granite. Although several types of igneous bodies have been reported, the predominant rock type is biotite- and hornblende-bearing granodiorite. Formation of the complex is thought to have occurred in several phases between 110 and 40 Ma with a dominant phase around 60 Ma (Honegger et al., 1982). Relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios (0.704 ± 0.001) and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (0.5126) support the derivation of these magmas from partial melting of subducting slab that was possibly contaminated by a small amount of crustal material (Allegre and Othman, 1980; Honegger et al., 1982). However, geochemical data of Kumar (2005) indicate an absence of continental crustal component in the eastern batholith. Numerous dolerite dykes cut almost orthogonal across the deformed batholith.

Part of the batholith is undeformed, but there is a diffuse deformation zone to the north of Leh and an intense penetrative ductile shear fabric in it has been observed within the NNW-trending dextral Thanglagso Shear Zone (Weinberg and Dunlap, 2000). Observations by Jain et al. (2003) on the deformation pattern along the Kharu-Chang La and Leh-Khardung La sections reveal intense development of mylonitized gneiss having 5–100 cm long ellipsoidal xenoliths of country rocks that trend $\text{N}90^\circ$ to $\text{N}120^\circ$ with steep dips towards the north. The presence of a NW-trending ductile shear zone having top-to-southwest overthrust sense of shearing, along with other brittle-ductile to brittle faults, have also been reported by Jain et al. (2003).

Weinberg and Dunlap (2000) obtained U–Pb SHRIMP ages of 58.1 ± 1.6 Ma from zircon cores and a younger 49.8 ± 0.8 Ma rim age from Leh, and interpreted these as the crystallization age of the source igneous rock and a

subsequent crystallization phase followed by rapid generalized cooling and dyke intrusion at 46 ± 1 Ma.

3. Petrography

The Ladakh Batholith in the Kharu-Chang La section includes medium to coarse grained diorite and granodiorite. All collected samples contain plagioclase, alkali feldspar, quartz, amphibole and biotite in variable proportions. The accessory minerals include muscovite, apatite, zircon and opaque phases with chlorite developed by alteration of hornblende and biotite. In many of the samples, opaque phases are abundant.

Plagioclase is generally coarser than K-feldspar and occurs as euhedral to subhedral grains having lamellar twinning. Sometimes, the twinning lamellae are partially erased due to deformation. Zoning is commonly observed in this feldspar. Inclusions of fine prismatic zircons are observed in some plagioclase grains. Plagioclase crystals show maximum extinction angles of $22\text{--}25^\circ$ indicating an andesine composition. Modally, andesine in diorite becomes more albitic to oligoclase in composition towards granodiorite. Myrmekites are developed at the margins of plagioclase as well as orthoclase and at contact with quartz. Quartz is anhedral and, sometimes, stretched and elongated. Most of the quartz looks strain-free, but undulose extinction is common. Quartz content increases towards the granodiorite. Quartz also occurs as inclusions in plagioclase and alkali feldspar. Both varieties of alkali feldspars are found. Orthoclase is dominant over microcline except in coarse-grained varieties. The alkali feldspar has inclusions of quartz, amphibole and biotite (Kumar, 2005).

Amphibole is mainly hornblende and occurs as euhedral to subhedral grains. Here, hornblende is used in the more generalized manner as used by Hawsthorne (1983) rather than the more specific definition of amphibole by the International Mineralogical Association Subcommittee (Leake, 1978; Leake et al., 1997). It is present in almost all samples. Crushed margins of amphiboles often show the development of altered chlorite. Biotite occurs in small amounts, both as brown and green biotite. The green variety indicates I-type composition. Bending of flakes of biotite indicate deformation. Biotite is less common than hornblende and opaques and constitutes $<5\%$ in more leucocratic varieties, but can reach $>25\%$ in diorite and quartz diorite.

4. SHRIMP U–Pb dating

4.1. Sampling and analytical techniques

One unweathered sample of granodiorite from the Ladakh Batholith near Tsoltak village (LB 10/28) in the north, and one diorite near Igu village (LB 5/15) in the south (Fig. 1C), were subjected to standard mineral separation procedures using crushing, sieving, and heavy

liquid separation. All samples yielded a large number of zircons that were hand-picked to obtain grains for SHRIMP analysis. More than 250 zircon grains were randomly selected and mounted in epoxy resin with the CZ3 Sri Lankan zircon standard ($^{206}\text{Pb}/^{238}\text{U} = 0.0914$, corresponding to an age of 564 Ma; Pidgeon et al., 1994) on 25 mm diameter mounts. The polished mounts were exam-

ined utilizing backscattered electron (BSE) and cathodoluminescence (CL) imaging using a JEOL 6400 SEM at the Centre for Microscopy and Microanalysis (CMM) at the University of Western Australia. Sites for SHRIMP analysis were then selected on the basis of these images. Analyses were performed on the SHRIMP-II based at Curtin University following the techniques described by Smith et al. (1998) and also Singh (2003).

4.2. Results

Zircons hand-picked from LB 10/28 and LB 5/15 are transparent with a few inclusions. Crystals are euhedral and form elongated prisms. No distinct cores have been observed either in transmitted light or in cathodoluminescence (CL) imaging. The CL images grains show fine oscillatory growth and sector zoning (Fig. 2). For granodiorite (LB 10/28) from the main Ladakh Batholith on its northern face, 25 sites were analyzed on 23 grains. Of these, 22 near-concordant analyses of rim or grain gives a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 60.1 ± 0.9 Ma with a MSWD value of 1.93 (Table 1, Fig. 3a). The Th/U values are mostly >0.1 and typical of primary magmatic zircons (Williams and Claesson, 1987). For diorite (LB 5/15) near the lowermost exposure of the Ladakh Batholith in the south, 8 analyses on 8 zircons were performed. Seven out of 8 near-concordant analyses of zircon grains gives a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 58.4 ± 1.0 Ma with a MSWD value of 0.66 (Table 2, Fig. 3b). Both ages are indistinguishable from each other and the age obtained by Weinberg and Dunlap (2000) for Ladakh Batholith samples.

5. Depth of emplacement

The quantitative estimation of the pressure of crystallization of the Ladakh Batholith along the Kharu-Chang La Section is based on Al-in-hornblende barometry of Schmidt (1992). The estimation of pressure of crystallization corresponds to the Al^{T} content of magmatic hornblende (Wones, 1981), as has been calibrated experimentally under water-saturated conditions at 2.5–1.3 kbar and 700–655 °C (Hammerstrom and Zen, 1986). While all aspects of amphibole chemistry depend on the bulk composition of the system, the $\text{Mg}\#$ $\{\text{Mg}/(\text{Mg} + \text{Fe}^{2+})\}$ depends largely on the system composition and to a lesser extent on temperature. In contrast, the Al substitution $[\text{Al}]_{\text{C}} + [\text{Al}]_{\text{T}} = [\text{X}^{(2+)}]_{\text{C}} + [\text{Si}]_{\text{T}}$ increases with increasing pressure and also the amphibole becomes increasingly sodic and aluminous with increasing temperature. However, the substitution of ferric iron for aluminum in the C-sites also increases with increasing oxygen fugacity. Given these substitutions, it is possible that the Al-content of an amphibole could be used to indicate pressure, if the effects of the Na, ferric iron substitution on Al-content of amphibole can be accounted for. A quantitative application of this idea was presented by Hammerstrom and Zen (1986). They carried out an empirical study of total

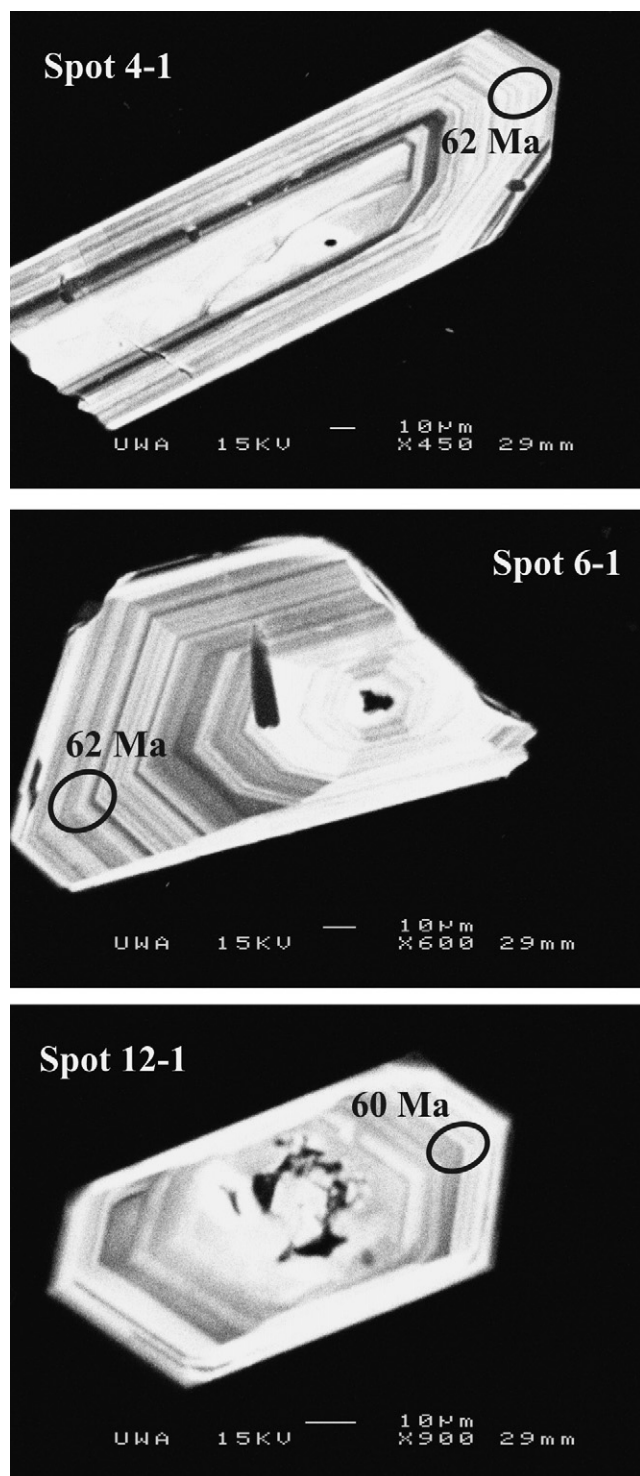


Fig. 2. Cathodoluminescence (CL) images of the Ladakh Batholith.

Table 1
SHRIMP-II analytical data of zircons from the Ladakh Batholith (LB 10/28)

Spot	U (ppm)	Th/U	% f206	207/206	±	208/206	±	206/238	±	207/235	±	% conc	Age 206/238	±
1-1	355	0.575	<0.1	0.0361	0.0097	0.1609	0.0219	0.0092	0.0002	0.046	0.012	0	59	1
1-2	141	1.214	<0.1	0.0570	0.0052	0.4028	0.0151	0.0093	0.0002	0.073	0.007	12	60	1
2-1	369	0.577	<0.1	0.0602	0.0042	0.1951	0.0095	0.0086	0.0002	0.071	0.005	9	55	1
3-1	507	0.299	<0.1	0.0488	0.0123	0.0890	0.0274	0.0095	0.0002	0.064	0.016	44	61	1
4-1	360	0.659	<0.1	0.0418	0.0029	0.2223	0.0069	0.0097	0.0002	0.056	0.004	0	62	1
5-1	483	0.338	<0.1	0.0412	0.0086	0.1075	0.0193	0.0094	0.0002	0.053	0.011	0	60	1
6-1	895	0.330	<0.1	0.0482	0.0019	0.1042	0.0029	0.0097	0.0001	0.065	0.003	57	62	1
7-1	236	0.527	<0.1	0.0516	0.0043	0.1800	0.0083	0.0092	0.0002	0.065	0.006	22	59	1
8-1	451	1.176	<0.1	0.0418	0.0095	0.3540	0.0226	0.0093	0.0002	0.053	0.012	0	60	1
10-1	563	0.358	<0.1	0.0434	0.0070	0.0932	0.0156	0.0094	0.0002	0.057	0.009	0	61	1
11-1	158	0.506	<0.1	0.2225	0.0498	7.8163	1.4163	0.0118	0.0007	0.363	0.086	3	76	4
12-1	530	0.817	<0.1	1.0093	0.0170	18.5168	0.2030	0.0094	0.0002	1.306	0.034	1	60	1
13-1	325	0.288	<0.1	0.6481	0.0171	22.5782	0.2847	0.0149	0.0003	1.333	0.050	2	95	2
14-1	711	0.297	<0.1	0.0476	0.0051	0.1016	0.0112	0.0094	0.0002	0.061	0.007	72	60	1
15-1	372	0.549	<0.1	0.0483	0.0030	0.1771	0.0060	0.0095	0.0002	0.063	0.004	54	61	1
16-1	181	0.383	<0.1	0.0352	0.0205	0.0997	0.0466	0.0093	0.0003	0.045	0.026	0	60	2
17-1	489	0.357	<0.1	0.0411	0.0080	0.1010	0.0179	0.0097	0.0002	0.055	0.011	0	62	1
18-1	382	0.661	<0.1	0.0462	0.0095	0.2221	0.0218	0.0089	0.0002	0.057	0.012	212	57	1
19-1	350	0.710	<0.1	0.0428	0.0103	0.2146	0.0236	0.0091	0.0002	0.054	0.013	0	58	1
20-1	2430	0.654	<0.1	0.0457	0.0012	0.2084	0.0027	0.0098	0.0001	0.062	0.002	0	63	1
21-1	172	1.056	<0.1	0.0546	0.0186	0.3481	0.0435	0.0092	0.0003	0.069	0.024	15	59	2
22-1	144	0.785	<0.1	0.0411	0.0297	0.2399	0.0686	0.0092	0.0003	0.052	0.038	0	59	2
23-1	188	0.782	<0.1	0.0464	0.0205	0.2511	0.0472	0.0090	0.0003	0.057	0.026	191	58	2
24-1	389	0.354	<0.1	0.0521	0.0113	0.1333	0.0252	0.0092	0.0002	0.066	0.015	20	59	1
24-2	506	0.420	<0.1	0.0438	0.0075	0.1230	0.0177	0.0092	0.0002	0.056	0.010	0	59	1
25-1	231	1.009	<0.1	0.0502	0.0120	0.3230	0.0282	0.0091	0.0002	0.063	0.015	28	58	1

Aluminum content (on a cations per 23 oxygen basis) of amphiboles in granitic intrusives for which emplacement pressures could be determined by application of conventional metamorphic geobarometry to the thermal contact aureoles. They generated the following equation for the crystallization pressure of an amphibole in terms of the number of Al-cations in its structure:

$$P(\text{kbar}) = 5.03\text{Al}_T - 3.92$$

They were aware that the total Al-content of an amphibole depended on temperature and oxygen fugacity as well as on pressure, and they attributed some of the scatter in their data set to these effects. Nonetheless, they concluded that for granitic plutons with the mineral assemblage plagioclase (An_{20-40}) + K-feldspar + quartz + hornblende + biotite + titanite + magnetite (or ilmenite), the pressure effect was the dominant control on the total Al-content of amphibole. Their results led to several experimental studies which improved the calibration of the Al-in-hornblende geobarometer (cf., Johnson and Rutherford, 1989; Thomas and Ernst, 1990; Schmidt, 1992) resulting in the calibration equation used here:

$$P(\text{kbar}) = 4.76\text{Al}_T - 3.01$$

5.1. Analytical procedure

Fine polishing was done with diamond paste, and 40 hornblende mineral spot analyses on 8 samples along the Kharu-Chang La Section (Fig. 1C) were performed on a

JEOL-JXA-8600 M Electron Probe Micro-Analyzer (EPMA) at the Institute Instrumentation Center at the Indian Institute of Technology Roorkee, Roorkee. A probe current of 20 nA at 15 Kev with a beam size of 2 μm was employed and the data was obtained after using ZAF correction of Philibert (1963). Standardization of the unknown used synthetic and natural standards before and after analysis.

5.2. Results

The EPMA data for hornblende are shown in Table 3 while Table 4 presents the estimation of pressure along with the rock type, altitude of the sample and calculated depths. Primary magmatic hornblende was used. The hornblende appeared to be formed late on textural grounds and with composition representing late-stage alteration {having Leake (1971)'s limit of $\text{Si} \leq 7.5$ with $\text{Ca} \geq 1.6$ for 'igneous' hornblende} were not used for pressure calculation. All hornblendes reported show textural evidence of coexistence with quartz, and analyses of rim compositions of unaltered hornblende provide the best estimate of pressure for late stages of crystallization. The chemical composition of hornblende appears to be similar in both granodiorite and diorite with typical mineral assemblages of quartz, plagioclase, K-feldspar, biotite, hornblende and opaque minerals. Hornblende from rocks crystallized at low pressure have higher $\text{Mg}/(\text{Mg} + \text{Fe})$ ratios than those for high-pressure rocks along with some overlap in $\text{Mg}/(\text{Mg} + \text{Fe})$ between low and high-pressure samples (Fig. 4a). The data

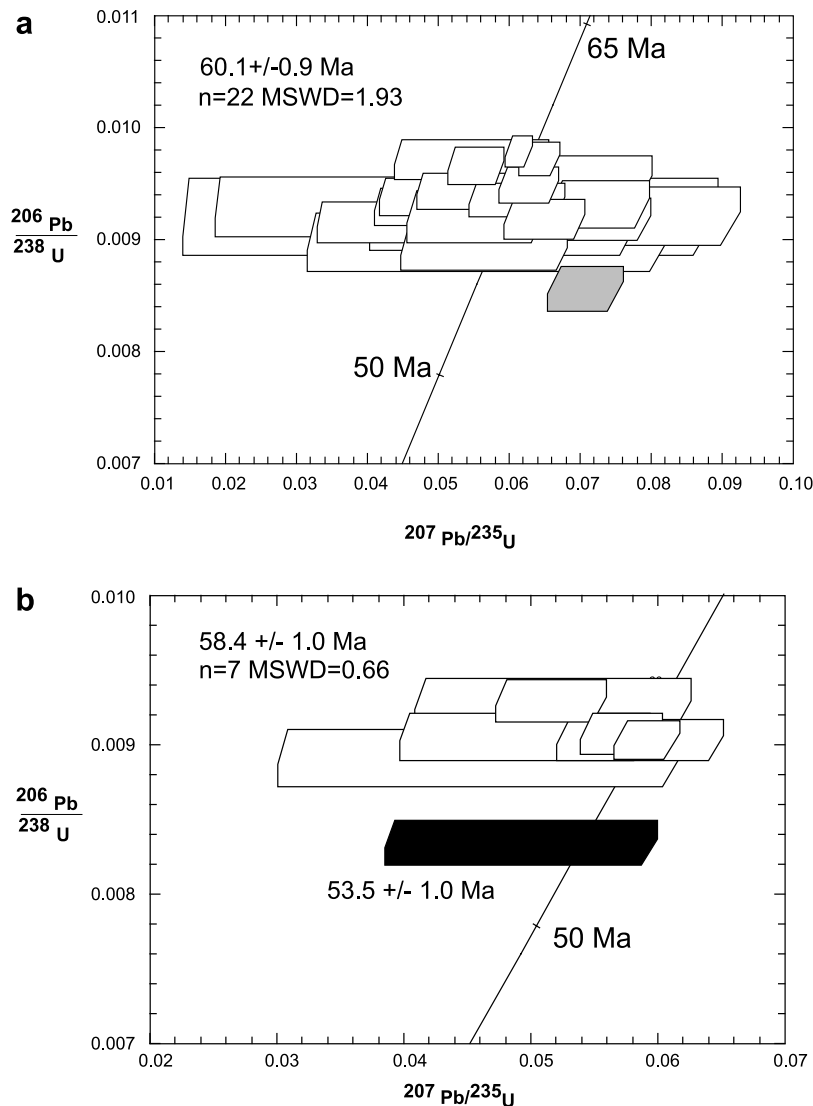


Fig. 3. U–Pb Concordia diagram of (a) granodiorite (LB 10/28) and (b) diorite (LB 5/15) from the Ladakh Batholith.

Table 2
SHRIMP-II analytical data of zircons from the Diorite near Igu (LB 5/15)

Spot	U (ppm)	Th/U	f ₂₀₆	207/206	±	208/206	±	206/238	±	207/235	±	% conc	Age 206/238	±
1-1	542	1.801	<0.1	0.0428	0.0092	0.5723	0.0239	0.0083	0.0002	0.049	0.011	0	54	1
2-1	469	0.859	<0.1	0.0397	0.0078	0.2566	0.0182	0.0091	0.0002	0.050	0.010	0	58	1
3-1	765	1.870	<0.1	0.0471	0.0051	0.6026	0.0140	0.0090	0.0001	0.059	0.007	101	58	1
4-1	319	0.793	<0.1	0.0375	0.0128	0.2438	0.0297	0.0089	0.0002	0.046	0.016	0	57	1
5-1	1054	1.939	<0.1	0.0475	0.0018	0.6134	0.0075	0.0090	0.0001	0.059	0.003	76	58	1
6-1	584	1.161	<0.1	0.0457	0.0024	0.3712	0.0073	0.0091	0.0001	0.057	0.003	0	58	1
7-1	592	0.835	<0.1	0.0405	0.0084	0.2626	0.0196	0.0093	0.0002	0.052	0.011	0	59	1
8-1	1123	1.167	<0.1	0.0403	0.0033	0.3629	0.0084	0.0093	0.0001	0.052	0.004	0	60	1

point's fall mainly in the Edenite field on the Mg/(Mg + Fe) vs Al^{iv} plot (Fig. 4a). The Al^{iv} vs Al^{T} plot shows a positive correlation with the regression line defined by the equation $\text{Al}^{\text{iv}} = 0.133 + 0.82 \text{Al}^{\text{T}}$ and r^2 value of 0.96 that has also been observed by Hammerstrom and Zen (1986). The data points fall mainly between line $\text{Al}^{\text{iv}} = 0$ and $\text{Al}^{\text{iv}} < 0.6\text{Al}^{\text{iv}} + 0.25$ (Fig. 4b).

6. Discussion

On the basis of zircon U–Pb geochronology, Weinberg and Dunlap (2000) concluded that the Ladakh Batholith around Leh represent magma pulses emplaced between 70 and 50 Ma. It appears that remelting of earlier plutons produced younger ones in the evolution of this batholith.

Table 3
EPMA analysis of hornblende with data based on 23 oxygen and pressure calculated based on the formula of Schmidt (1992)

Sample No.	LB 5/14		LB 10/28			
	1st point	2nd point	1st point	2nd point	3rd point	4th point
SiO ₂	44.452	43.018	42.126	42.531	43.544	43.179
Al ₂ O ₃	8.179	8.389	6.505	6.655	6.423	6.234
FeO	18.427	19.255	13.036	13.534	13.008	13.401
MgO	11.083	10.243	13.167	12.679	14.218	13.473
MnO	0.666	0.557	0.564	0.388	0.484	0.489
CaO	10.927	10.701	11.473	11.389	11.226	11.517
K ₂ O	0.811	0.550	0.494	0.410	0.460	0.438
Na ₂ O	1.167	1.264	0.720	1.027	1.065	0.739
TiO ₂	0.547	0.479	1.574	1.598	1.535	1.420
Cr ₂ O ₃	–	–	–	–	0.011	–
Total	96.285	94.456	89.660	90.206	91.974	90.890
Cations (23 Oxygen)			Cations (23 Oxygen)			
Si	6.8122	6.7548	6.8024	6.8295	6.8315	6.870
Al	1.4775	1.5526	1.2381	1.2597	1.1877	1.1692
Fe	2.3617	2.5286	1.7605	1.8176	1.7068	1.7832
Mg	2.5318	2.3977	3.1693	3.0335	3.3251	3.1956
Mn	0.0864	0.0741	0.0772	0.0528	0.0643	0.0659
Ca	1.7943	1.8005	1.9851	1.9596	1.8871	1.9634
K	0.1587	0.1102	0.1017	0.0840	0.0921	0.0888
Na	0.3467	0.3849	0.2256	0.3199	0.3241	0.2279
Ti	0.0662	0.0565	0.1911	0.1930	0.1811	0.1699
Cr	–	–	–	–	0.0013	–
Total	15.6355	15.6599	15.5510	15.5496	15.6011	15.5339
Pressure (kbar)	4.02	4.38	2.88	2.98	2.64	2.55
Al ^{iv}	1.1878	1.2452	1.1976	1.1705	1.1685	1.13
Mg/Fe + Mg	0.517	0.487	0.643	0.625	0.661	0.642
LB11/29						
	1st point	2nd point	3rd point	4th point	5th point	
SiO ₂	43.894	45.021	45.029	44.918	42.873	
Al ₂ O ₃	5.737	5.444	5.876	5.893	5.958	
FeO	15.376	14.81	12.672	16.0761	15.239	
MgO	12.446	12.6	13.79	12.427	11.993	
MnO	0.777	0.696	0.546	0.772	0.663	
CaO	11.635	11.814	10.835	11.711	11.559	
K ₂ O	0.333	0.299	0.566	0.43	0.476	
Na ₂ O	0.628	0.673	0.869	0.687	0.645	
TiO ₂	1.005	0.625	0.976	0.789	1.187	
Cr ₂ O ₃	0.024	0.035	0.067	–	0.021	
Total	91.855	92.010	91.225	93.703	90.615	
Cations (23 Oxygen)						
Si	6.9706	7.097	7.073	7.0016	6.9154	
Al	1.074	1.0115	1.088	1.0827	1.1328	
Fe	2.0421	1.9525	1.6647	2.0957	2.0557	
Mg	2.9463	2.961	3.229	2.8875	2.8838	
Mn	0.1046	0.0929	0.0726	0.102	0.0906	
Ca	1.9798	1.9955	1.8236	1.956	1.9979	
K	0.0674	0.0589	0.1134	0.0855	0.0979	
Na	0.1933	0.2058	0.2646	0.2077	0.2019	
Ti	0.12	0.074	0.1153	0.0925	0.144	
Cr	0.0031	0.0043	0.0083	–	0.0027	
Total	15.5012	15.4534	15.4525	15.5111	15.5227	
Pressure (kbar)	2.10	1.80	2.16	2.14	2.38	
Al ^{iv}	1.0294	0.903	0.927	0.9984	1.0846	
Mg/Fe + Mg	0.591	0.603	0.659	0.579	0.584	

Table 3 (continued)

	LB13/31					
	1st point	2nd point	3rd point	4th point	5th point	6th point
SiO ₂	44.654	39.531	41.189	39.707	41.702	41.250
Al ₂ O ₃	6.276	6.077	6.980	6.909	5.977	6.228
FeO	15.831	13.928	15.849	15.689	15.120	15.471
MgO	11.410	11.986	11.932	11.746	12.668	12.014
MnO	0.866	0.799	0.811	0.810	0.807	0.728
CaO	10.820	11.861	11.661	11.704	11.740	11.722
K ₂ O	0.340	0.444	0.482	0.468	0.468	0.388
Na ₂ O	0.841	0.767	0.893	0.901	0.837	0.750
TiO ₂	0.531	1.479	1.106	0.668	1.011	0.750
Cr ₂ O ₃	–	0.007	–	0.007	–	–
Total	91.568	86.878	90.901	88.609	90.330	89.423
Cations (23 Oxygen)						
Si	7.0924	6.6870	6.6819	6.6336	6.7834	6.7853
Al	1.1749	1.2117	1.3346	1.3604	1.1460	1.2076
Fe	2.1028	1.9704	2.1503	2.1921	2.0569	2.1283
Mg	2.7014	3.0224	2.8855	2.9253	3.0718	2.9460
Mn	0.1165	0.1144	0.1114	0.1146	0.1112	0.1014
Ca	1.8414	2.1498	2.0270	2.0951	2.0462	2.0660
K	0.0689	0.0957	0.0997	0.0997	0.0970	0.0814
Na	0.2590	0.2516	0.2807	0.2919	0.2640	0.2393
Ti	0.0634	0.1881	0.1350	0.0839	0.1237	0.1078
Cr	–	0.0009	–	0.0009	–	–
Total	15.4207	15.6922	15.7060	15.7975	15.7003	15.6634
Pressure (kbar)	2.60	2.76	3.34	3.47	2.45	2.74
Al ^{iv}	0.9076	1.313	1.3181	1.3664	1.2166	1.2147
Mg/Fe + Mg	0.562	0.605	0.573	0.572	0.599	0.581
	LB13/31		LB14/32			
	7th point	8th point	1st point	2nd point	3rd point	4th point
SiO ₂	41.007	40.768	40.811	41.760	41.380	44.028
Al ₂ O ₃	6.175	6.283	6.639	6.093	7.307	5.746
FeO	15.110	15.547	16.185	15.083	16.331	13.559
MgO	12.485	12.418	10.933	11.644	11.934	12.924
MnO	0.842	0.812	0.713	0.763	0.651	0.682
CaO	11.719	11.783	11.757	11.723	11.740	11.923
K ₂ O	0.396	0.344	0.546	0.337	0.528	0.319
Na ₂ O	0.722	0.791	0.801	0.635	0.847	0.574
TiO ₂	0.722	0.791	1.255	1.080	1.087	0.589
Cr ₂ O ₃	–	0.007	–	0.031	–	–
Total	89.443	89.373	89.640	89.149	91.805	90.343
Cations (23 Oxygen)			Cations (23 Oxygen)			
Si	6.7422	6.7265	6.7332	6.8624	6.6531	7.0411
Al	1.1967	1.2218	1.2911	1.1802	1.3848	1.0832
Fe	2.0778	2.1453	2.2332	2.0728	2.1959	1.8135
Mg	3.0601	3.0544	2.6888	2.8523	2.8604	3.0811
Mn	0.1173	0.1135	0.0996	0.1062	0.0887	0.0928
Ca	2.0646	2.0832	2.0788	2.0641	2.0226	2.0431
K	0.0831	0.0724	0.1149	0.0708	0.1084	0.0651
Na	0.2301	0.2531	0.2563	0.2023	0.2640	0.1779
Ti	0.1220	0.0768	0.1558	0.1335	0.1314	0.0708
Cr	–	0.0009	–	0.004	–	–
Total	15.6940	15.7841	15.6511	15.5486	15.7098	15.4680
Pressure (kbar)	2.69	2.81	3.14	2.61	3.58	2.18
Al ^{iv}	1.2578	1.2735	1.2668	1.1376	1.3469	0.9589
Mg/Fe + Mg	0.596	0.587	0.546	0.579	0.566	0.629

(continued on next page)

Table 3 (continued)

	LB15/33					
	1st point	2nd point	3rd point	4th point	5th point	6th point
SiO ₂	41.214	38.967	39.254	37.607	39.266	40.849
Al ₂ O ₃	7.280	7.526	7.374	7.480	7.273	6.280
FeO	15.785	16.332	15.588	14.919	15.940	14.652
MgO	12.604	12.011	11.780	11.115	11.656	12.901
MnO	0.748	0.665	0.622	0.619	0.614	0.743
CaO	11.722	11.697	11.884	11.290	11.930	11.649
K ₂ O	0.436	0.549	0.532	0.541	0.564	0.292
Na ₂ O	1.121	0.967	0.770	0.461	0.556	0.996
TiO ₂	1.252	1.174	0.795	0.862	1.097	1.484
Cr ₂ O ₃	–	–	0.021	0.062	0.066	–
Total	92.161	89.901	88.621	84.958	88.962	89.846
Cations (23 Oxygen)						
Si	6.5951	6.4492	6.5561	6.5393	6.5430	6.6889
Al	1.3732	1.4682	1.4517	1.5332	1.4285	1.2093
Fe	2.1125	2.2606	2.1774	2.1696	2.2214	2.0020
Mg	3.0065	2.9632	2.9328	2.8812	2.8954	3.1420
Mn	0.1014	0.0932	0.0881	0.0912	0.866	0.1029
Ca	2.0100	2.0743	2.1268	2.1036	2.1302	2.0393
K	0.0890	0.1160	0.1134	0.1201	0.1200	0.0608
Na	0.3477	0.3104	0.2494	0.1553	0.1797	0.3154
Ti	0.1506	0.1461	0.0999	0.1128	0.1375	0.1823
Cr	–	0.0018	0.0027	0.0086	0.0086	–
Total	15.7860	15.8829	15.7982	15.7147	15.7508	15.7276
Pressure (kbar)	3.52	3.97	3.90	4.28	3.78	2.74
Al ^{iv}	1.4049	1.5508	1.4439	1.4607	1.457	1.311
Mg/Fe + Mg	0.587	0.567	0.574	0.570	0.566	0.611
	LB15/33			LB17/35		
	7th point	8th point	9th point	1st point	2nd point	3rd point
SiO ₂	40.909	38.614	38.748	49.094	48.310	48.216
Al ₂ O ₃	6.290	8.493	6.579	6.189	6.677	6.165
FeO	14.863	15.119	12.782	14.104	13.960	16.680
MgO	13.072	11.968	12.463	15.151	14.465	15.239
MnO	0.634	0.560	–	0.319	0.284	0.406
CaO	11.838	11.514	10.791	10.474	10.189	10.059
K ₂ O	0.425	0.435	0.436	0.202	0.260	0.150
Na ₂ O	0.433	0.584	0.927	1.096	1.086	0.914
TiO ₂	0.254	1.056	1.237	0.663	0.670	0.576
Cr ₂ O ₃	0.010	0.052	–	0.011	–	0.042
Total	89.727	88.396	84.484	97.303	95.899	95.454
Cations (23 Oxygen)				Cations (23 Oxygen)		
Si	6.4341	6.8194	6.8949	7.1827	7.1664	7.1771
Al	1.2123	1.6679	1.3367	1.0672	1.0193	1.1674
Fe	2.0325	2.1069	1.8426	1.7258	1.7319	1.7030
Mg	3.1862	2.9728	3.2022	3.3044	3.1987	3.3814
Mn	0.0877	0.0791	0.0761	0.0396	0.0357	0.0512
Ca	2.0739	2.0557	1.9930	1.6420	1.6195	1.6043
K	0.0886	0.0925	0.0960	0.0377	0.0491	0.0284
Na	0.1372	0.1886	0.3098	0.3109	0.3123	0.2639
Ti	0.1542	0.1323	0.1603	0.0729	0.0748	0.0645
Cr	0.0018	0.0068	–	0.0012	–	0.0050
Total	15.6630	15.7368	15.6955	15.3845	15.3558	15.3612
Pressure (kbar)	2.76	4.92	3.35	2.07	2.55	2.14
Al ^{iv}	1.5659	1.1806	1.105	0.8173	0.8336	0.8229
Mg/Fe + Mg	0.611	0.585	0.635	0.657	0.649	0.665

Table 3 (continued)

	LB18/36				
	1st point	2nd point	3rd point	4th point	5th point
SiO ₂	48.708	44.019	44.767	45.674	45.519
Al ₂ O ₃	7.204	7.328	7.240	6.830	6.727
FeO	17.368	18.077	17.856	17.470	17.801
MgO	11.225	11.164	11.413	11.821	11.618
MnO	0.480	0.455	0.505	0.473	0.461
CaO	10.528	10.706	10.772	10.763	10.981
K ₂ O	1.194	1.122	1.123	1.207	1.049
Na ₂ O	1.119	1.025	1.257	1.256	1.049
TiO ₂	0.981	1.040	0.957	1.005	0.878
Cr ₂ O ₃	—	—	—	—	—
Total	98.807	94.937	95.909	94.499	96.008
Cations (23 Oxygen)					
Si	7.1620	6.8461	6.8801	6.9529	6.9690
Al	1.2485	1.3434	1.3116	1.2256	1.2139
Fe	2.1358	2.3512	2.6148	2.6824	2.6515
Mg	2.4604	2.5882	2.6148	2.6824	2.6515
Mn	0.0598	0.0600	0.0658	0.0610	0.0598
Ca	1.6587	1.7842	1.7739	1.7555	1.8014
K	0.2241	0.2226	0.2201	0.2345	0.2049
Na	0.3191	.03091	0.3476	0.3706	0.2849
Ti	0.1085	0.1217	0.1127	0.1150	0.1010
Cr	—	—	—	—	—
Total	15.3768	15.6264	15.6488	15.6218	15.5701
Pressure (kbar)	2.93	3.39	3.23	2.82	2.77
Al ^{IV}	0.838	1.1539	1.1199	1.0471	1.031
Mg/Fe + Mg	0.535	0.524	0.500	0.500	0.500

Table 4

Pressure and depth calculated using Al in hornblende from the Ladakh Batholith

Samples (altitude)	Pressure calculated (kbar)										Average pressure (kbar) (rock type)	Depth (km)
LB5/14 (3354 m)	4.02	4.38									4.2 ± 0.25 (diorite)	15.85 ± 0.9
LB10/28 (5301 m)	2.88	2.98	2.64	2.55							2.76 ± 0.20 (granodiorite)	10.42 ± 0.9
LB11/29 (5060 m)	2.10	1.80	2.16	2.14	2.38						2.11 ± 0.21 (granodiorite)	7.96 ± 0.9
LB13/31 (4742 m)	2.60	2.76	3.34	3.47	2.45	2.74	2.69	2.81			2.86 ± 0.36 (granodiorite)	10.79 ± 1.3
LB14/32 (4409 m)	3.14	2.61	3.58	2.18							2.88 ± 0.61 (granodiorite)	10.87 ± 2.3
LB15/33 (4241 m)	3.52	3.97	3.90	4.28	3.78	2.74	2.76	4.92	3.35		3.69 ± 0.70 (granodiorite)	13.93 ± 2.6
LB17/35 (3902 m)	2.07	2.55	2.14								2.25 ± 0.26 (diorite)	8.49 ± 0.9
LB18/36 (3732 m)	2.93	3.39	3.23	2.82	2.77						3.04 ± 0.27 (Diorite)	11.47 ± 0.9

Our zircon data indicate ages around 60 Ma for the emplacement of the Ladakh batholith along the Kharu-Chang La Section. This age is in conjunction with the widespread plutonism around the Leh area. The batholith subsequently was affected by minor intrusives and dolerite dykes. The absence of older, inherited cores in zircon, along with published data from Weinberg and Dunlap (2000) and Kumar (2005) clearly indicate the near absence of a continental crustal component in the formation of the Ladakh Batholith around and east of Leh.

Ambihobles are frequently used for geothermobarometry in calc-alkaline rocks of mafic, intermediate and felsic

compositions (Stein and Dielt, 2001). The main pre-requisite for Al-in-hornblende geobarometric studies are the mineral assemblages quartz, plagioclase, hornblende, K-feldspar, biotite, titanite and magnetite (Hammerstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Vyhnaal and McSween, 1990; Schmidt, 1992; Anderson and Smith, 1995; Stein and Dielt, 2001). This method has been widely used for batholiths of granodioritic and dioritic compositions (Vyhnaal et al., 1991; Leake and Said, 1994; Ague and Brandon, 1992, 1996; Ague, 1997; Tulloch and Challis, 2000; Stein and Dielt, 2001; McCausland et al., 2002; Zhang et al., 2006). The suitable mineral assemblages in both diorite and granodiorite of the

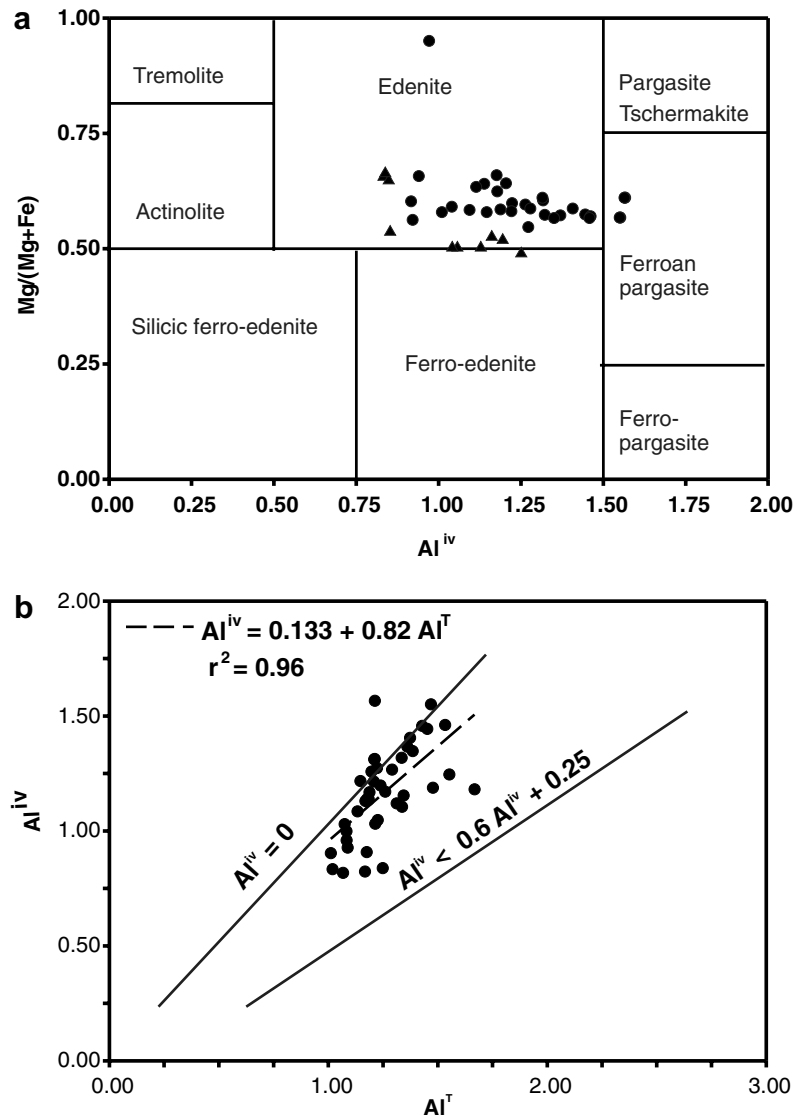


Fig. 4. (a) Modified version of the IMA recommended plot of amphiboles (fields after Hammertrom and Zen, 1986). Triangles denote the diorite samples and circles indicate granodiorite. (b) Plot of Al^T vs Al^{iv} in hornblende.

Ladakh batholith justify using Al-in-hornblende geobarometry in the present work.

Amphiboles from diorites at the lowest elevation of 3354 m near Igu village (LB5/14) give an average pressure of 4.2 ± 0.25 kbar, which is the highest pressure calculated for our samples (Fig. 5). This is equivalent to the depth of 15.85 ± 0.9 km [$P = \rho gh$, where ρ is rock density of 2.7 g/cm^3 of overlying column of mass and $g = 9.81 \text{ m/g}^2$ is considered for depth calculation]. Furthermore, the diorite samples along the main Kharu-Chang La section (LB17/35, LB18/36) from the lower levels of the exposed batholith yield values of 2.25 ± 0.26 and 3.04 ± 0.27 kbar (Fig. 5) that average to be around 2.65 ± 0.27 kbar, which is equivalent to 10.00 ± 0.9 km depth.

Amphiboles from granodiorite (LB10/28, LB11/29) obtained from altitudes of 5301 and 5060 m, respectively, indicate pressures of 2.76 ± 0.20 and 2.11 ± 0.21 kbar

(Fig. 5, is equivalent to 10.42 ± 0.9 and 7.96 ± 0.9 km depth). Granodiorite amphibole samples (LB13/31, LB14/32 and LB15/33) from the middle level of the exposed batholith have values of 2.86 ± 0.36 , 2.88 ± 0.61 and 3.69 ± 0.70 kbar (Fig. 5), averaging 3.14 kbar that is equivalent to 11.85 ± 2.6 km depth. The data from granodiorite amphiboles are in closer agreement to dioritic amphiboles.

The pressure data from hornblende indicate that the southern edge of the batholith had more overlying rocks removed compared to the northern edge. This data clearly indicate a northward tilting of the area and this is further supported from field observations indicating a northerly dip in the molassic sedimentary rocks overlying the Ladakh Batholith along Upshi-Leh road. Similar observations have also been recorded from Gangadese to the east (Yin et al., 1994).

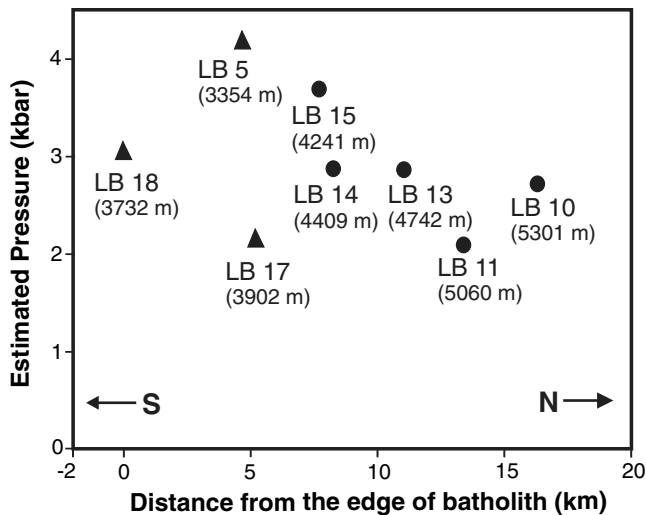


Fig. 5. Distance vs pressure plot of Ladakh Batholith along the Kharu-Chang La section. Triangles denote the diorite samples and circles indicate granodiorite.

7. Conclusion

Based on SHRIMP-II U–Pb zircon dating and Al-in-Hornblende pressure data, it appears that the Ladakh Batholith in the studied Kharu-Chang La section crystallized at around 60 Ma, at a depth between 16 and 8 km over a vertical section of around 2 km. Diorite near the southern boundary with the Indus-Tsangpo Suture Zone (ITSZ) was deepest (16 km), whereas granodiorite near the northern boundary with the Shyok Suture Zone (SSZ) was shallowest (8 km). The depth difference of emplacement of ~8 km exposed within the ~2 km elevation difference can be attributed to denudation by tectonic removal of material along the Kharu-Chang La Section. Tilting of the batholith can be attributed to underthrusting of the Indian Plate beneath the Eurasian Plate following continent–continent collision.

Acknowledgments

Fieldwork was funded by the Department of Science and Technology (DST) of India under its HIMPROBE program. We are grateful to Kailash Chandra and T.K. Ghosh for use of the EPMA facilities at the Institute Instrumentation Centre, IIT Roorkee. Ion-Probe zircon analyses were carried out on SHRIMP-II operated by a consortium consisting of Curtin University of Technology, the Geological Survey of Western Australia, and the University of Western Australia, with the support of the Australian Research Council. R.K. thank Council for Scientific and Industrial Research, New Delhi for financial support in the form of SRF. Comments by an anonymous reviewer and Roberto Weinberg drastically improved the manuscript.

Appendix A

Sample No.	Latitude	Longitude
LB 5/14	33° 53.461'N	77° 46.871'E
LB18/36	33° 54.006'N	77° 42.453'E
LB17/35	33° 57.345'N	77° 46.891'E
LB15/33	33° 58.017'N	77° 48.967'E
LB14/32	33° 58.034'N	77° 49.124'E
LB13/31	33° 59.889'N	77° 52.045'E
LB11/29	34° 01.006'N	77° 54.865'E
LB10/28	34° 04.532'N	77° 56.673'E

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