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Tectonic implications of new U–Pb zircon ages of the Ladakh batholith, Indus suture zone, northwest Himalaya, India

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ABSTRACT

We determined U–Pb ages on zircons from Ladakh granitoid samples of three previously undated plutons and deduced four distinct age groups between *c.* 67 and *c.* 45 Ma (66.6 ± 2.1, 57.6 ± 1.4, 53.4 ± 1.8, 52.50 ± 0.53 and 45.27 ± 0.56 Ma). This suggests that the Ladakh batholith grew by addition of at least four distinct subduction-related magma pulses at *c.* 67, 58, 53 and 45 Ma, thus indicating that the belt was continuously active throughout the Palaeocene and the Middle Eocene (Lutetian). The 45.27 ± 0.56 Ma pluton at Daah-Hanu is the last major calcalkaline arc magmatic pulse in the Ladakh batholith. Thereafter, the subduction-related major plutonism gradually waned. The earlier estimate for the youngest pluton within the Ladakh batholith is 49.8 ± 0.8 Ma for the Leh pluton (*J. Geol.*, 2000, 108, 303).

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Introduction

The Himalaya mountain chain is a classical example of continental collision tectonics (Molnar and Tapponnier, 1975; Gansser, 1977). It is an archive of the geodynamic response of the Indian and the Asian plates to collision since the Palaeogene (Patriat and Achache, 1984; Klootwijk *et al.*, 1992; Rowley, 1996). The collision is responsible for uplift of the Himalaya, Tibetan Plateau and rejuvenating the tectonic architecture of the Karakoram and the Kun Lun regions (Matte *et al.*, 1996; Searle *et al.*, 1999; Upadhyay, 2002 and references therein). The Trans-Himalayan plutons referred to as the Ladakh-Kohistan batholith in the west (Fig. 1) and Gangdese magmatic belt in the east occur as discontinuous bodies for a distance of about 3000 km (Harris *et al.*, 1988) from north Kohistan through Ladakh to Lhasa. The Trans-Himalayan magmatic arc is considered to have been formed due to subduction of Neo-Tethyan oceanic crust under the southern active margin of the Asian plate during Early Cretaceous-Lower Eocene times (Tahirkheli, 1979; Honegger *et al.*, 1982; Maluski *et al.*, 1982; Bard, 1983; Schärer *et al.*, 1984; Petterson and Windley, 1985; Debon *et al.*, 1986, 1987; Harris *et al.*, 1988; Khan *et al.*, 1989; Sharma, 1990; Ahmad *et al.*, 1998; Rolland *et al.*, 2000; Weinberg and Dunlap, 2000). In Ladakh, the Trans-Himalayan batholith lies immediately to the north of the Indus-Tsangpo Suture and forms a linear belt of tonalite–diorite–granodiorite–granite association (Sharma, 1990; Ahmad *et al.*, 1998). The plutons have predominantly mantle geochemical signatures and are, in many respects, compatible with I-type Cordilleran batholiths of Peru (Honegger *et al.*, 1982).

In this study, we determined U–Pb ages on zircons from Ladakh granitoid samples of three previously undated plutons. The results have been integrated with previous studies to provide a coherent picture of the regional geology and also to further constrain the youngest calcalkaline plutonism along north of the Indus Suture zone in Ladakh.

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Regional setting

The Trans-Himalayan batholith in Ladakh is located between two major tectonic suture zones, the Shyok Suture to the north and the Indus Suture to the south (Thakur and Misra, 1984; Upadhyay, 2002) (Fig. 1): the former represents a collisional boundary between the Karakoram block and the Kohistan-Ladakh island arc, and the latter represents the main boundary zone between the Indian and Asian plates (Gansser, 1977). The Indus Group, a pile of mainly continental sediments at least 2 km thick, drapes the boundary between the Ladakh batholith and the Indus Suture zone and records forearc and intermontane basin development (Garzanti and van Haver, 1988; Sinclair and Jaffey, 2001; Kirstein *et al.*, 2006). The batholith is bound to the north-east by the Karakoram fault, a major dextral strike-slip fault that bounds the southwestern margin of the Tibetan Plateau, and has been active since Miocene times (Searle *et al.*, 1992; Searle, 1996).

Several types of igneous bodies are reported from the Ladakh batholith ranging from gabbro to granite, with biotite- and hornblende-bearing granodiorite as the predominant rock type (Honegger *et al.*, 1982; Sharma, 1990; Weinberg, 1997). The Ladakh batholith is largely undeformed and has escaped intense brittle deformation to a very large extent. However, intense penetrative ductile shear fabrics have been observed within the NNW-trending dextral Thanglasgo Shear Zone and in a diffused deformation zone to the north of Leh (Weinberg and Dunlap, 2000) (Fig. 1).

Previous studies suggest that the magmatic rocks of the Ladakh batholith intruded between 102 ± 2 Ma (U–Pb ages near Kargil, west of Leh; Honegger *et al.*, 1982; Schärer *et al.*, 1984) and 60 ± 5 Ma (Rb-Sr whole-rock isochron age, Leh, Honegger *et al.*, 1982; Schärer *et al.*, 1984). Biotite from near Leh yielded a K-Ar age of 48.7 ± 1.6 Ma (Honegger *et al.*, 1982), suggesting significant cooling of the igneous rocks by that time. Based

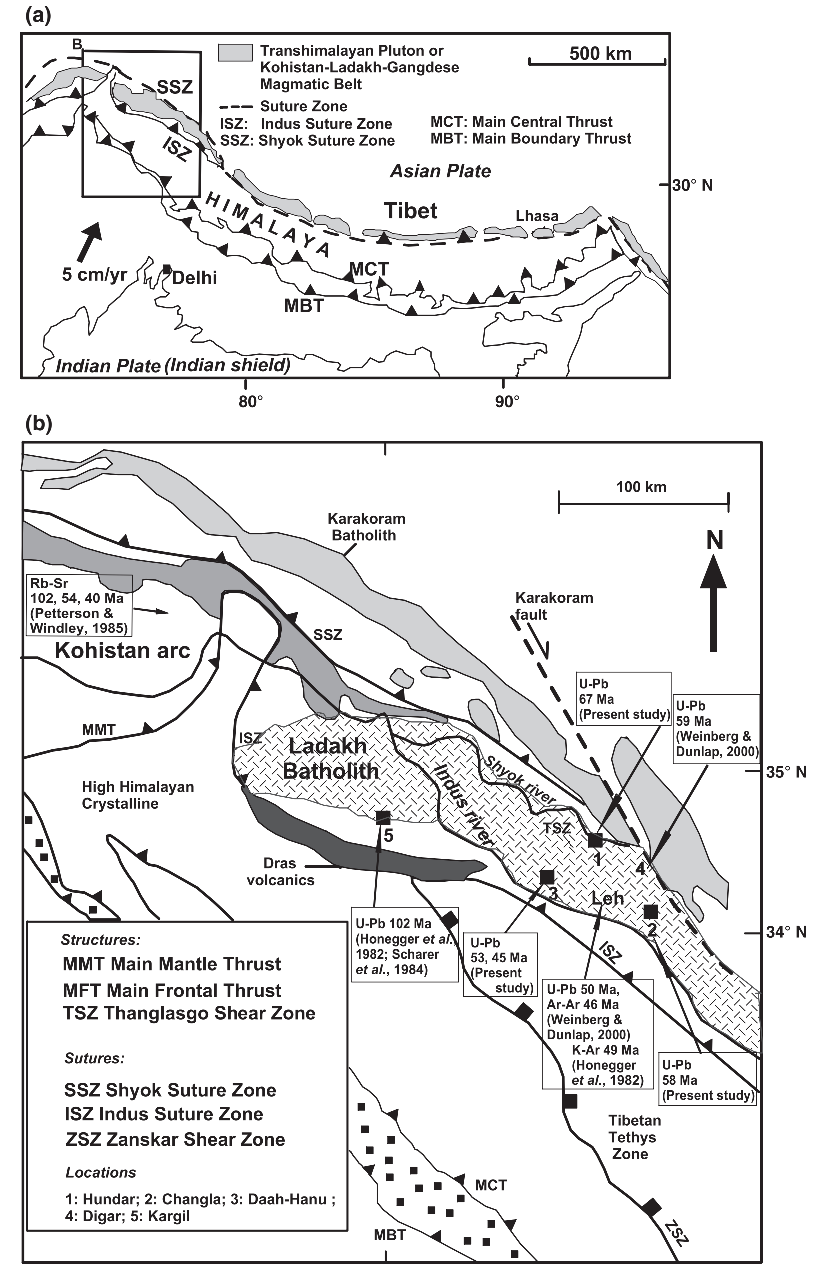

Fig. 1 (a) Generalized geological and structural map of the Himalayas showing location of Trans-Himalayan Plutonic Belt (modified after Kirstein *et al.*, 2006). SSZ, Shyok suture zone; ISZ, Indus suture zone; MCT, Main Central Thrust; MBT, Main Boundary Thrust. (b) Detail of western Himalaya showing sample locations (filled rectangles): 1 – Hundar; 2 – Chang La; 3 – Daah-Hanu; 4 – Digar; 5 – Kargil.

on U–Pb ages on zircons from three samples of the Ladakh batholith and K-Ar data from one subvolcanic dyke sample, Weinberg and Dunlap (2000) suggests that the magmatic activity near Leh in Ladakh occurred between 70 and 50 Ma, with the last major magmatic pulse crystallizing at *c*. 49.8 ± 0.8 Ma. This was followed by rapid and generalized cooling to lower greenschist facies temperatures within a few million years, and minor subvolcanic dyke intrusion took place at 45.7 ± 0.8 Ma (Weinberg and Dunlap, 2000). Zircon, apatite (U-Th)/He and fission-track dating record a rapid cooling event from 230 °C in the Leh-Khardung La region of Ladakh during the Miocene *c*. 22 Ma (Kirstein *et al.*, 2006).

Present study

Samples for U–Pb dating were collected from three different localities across the Ladakh batholith, e.g. Daah-Hanu (also known as the Aryan villages, corresponding to the southern portion of the Ladakh batholith), Chang La (high pass situated E-SE of Leh and SE of the Khardung La along the Leh-Pangong Tso road section, corresponding to the central portion of the batholith) and Hundar (situated in the Nubra-Shyok valley and corresponding to the northernmost portion of the batholith) (Fig. 1). These localities were selected to provide representative coverage from south to north across the batholith.

Geochemistry of the dated samples

The geochemistry of the Ladakh batholith has been described in detail by a number of workers (e.g. Honegger *et al.*, 1982; Sharma, 1990; Ahmad *et al.*, 1998; Weinberg and Dunlap, 2000) and will not be discussed here in detail. However, the major and trace element analyses of five dated samples are shown in Table 1 and Fig. 2. The samples were analysed using X-ray fluorescence spectroscopy at Institute of Geosciences, University of Tuebingen, Germany. The samples show a wide compositional range with SiO_2 varying between 57.7 and 75.2 wt%. Based on their SiO_2 and total alkalis, these rocks are classified as subalkaline granites. In normative Ab-Or-An diagram (not shown) samples RG-13 and RG-14 (Daah-Hanu granitoid) plot in the field of tonalite, sample RG-16 (Chang La) is transitional between tonalite and granodiorite, sample RG-20 (Daah-Hanu) is transitional between trondhjemite and granodiorite, and sample RG-6 (Hunder) plots in the granite field. They are predominantly meta-aluminous. A/CNK values of sample RG-13, RG-14, RG-16 and RG-20 range between 0.83 and 0.94, indicating an I-type parentage except sample RG-6, which shows transition between I- and S-type granitoids with a higher A/CNK value of 1.10. This indicates

Table 1 Major oxides (in wt%) and trace element (in p.p.m.) analysis of dated samples of the Ladakh batholith.

Sample	RG-6	RG-13	RG-14	RG-16	RG-20
SiO_2	75.2	63.66	57.75	68.68	66.75
TiO_2	0.20	0.76	1.07	0.45	0.55
Al_2O_3	13.08	15.68	17.17	14.88	15.18
Fe_2O_3	1.89	6.19	7.98	3.76	3.84
MnO	0.073	0.108	0.148	0.093	0.073
MgO	0.42	2.54	3.13	1.28	1.59
CaO	1.29	5.38	6.86	3.56	3.88
Na_2O	3.82	3.98	3.86	4.27	4.41
K_2O	3.98	1.38	1.85	2.18	3.23
P_2O_5	0.057	0.176	0.322	0.125	0.269
CO_2	0.13	0.26	0.29	0.21	0.35
Ba	389.3	323.3	302	425.3	1378
Co	2	15.7	18.5	6.9	8.5
Cr	126.1	13.7	22.2	111.7	14.8
Rb	133	39.5	75.9	67.1	131.6
Sr	113.1	366.9	437.8	321.5	840.8
V	12.7	133	162.6	59.1	71.9
Y	18	25.7	33.1	18.5	13.8
Zn	8.8	62.6	101.6	36.9	45.9
Zr	119.2	174.3	181.6	141.9	227.6
Ce	37.8	48.2	60	27.1	136.6
Eu	0.3	0.9	1.4	1.1	2.3
La	59.7	57.1	62.6	50.4	105.1
Nb	0	0	0	0	0
Nd	21.4	19.9	34.8	19.9	51.7
Pb	13.7	7.6	15.2	3.4	62.8
Sm	2.2	0	5.5	4.4	7.9
Th	15.9	1.9	11.6	6.6	56.4
U	0	0	0	0	3.5
Yb	1.6	2.2	3	1.5	0.9
Sc	0	18.1	23.1	9.7	6
Cu	23.3	29.1	62.3	29.5	29.7
Ga	0	16.4	18.7	0	17.5
Hf	0.1	0	0	7.5	5
Pr	0	5.2	0	0	10.1
Gd	4	0	0	0	4.9
Tb	0.5	0.6	0.7	0.6	0.7
Sum (%)	100.2	100.2	100.6	99.63	100.4
A/CNK	1.10	0.88	0.83	0.94	0.85

0, not determined/below detection limit.

that the chemical variation of this granite (RG-6) may be controlled by assimilation and fractional crystallization processes. It is interesting to note that the Hundar granite is intruding into Early to Mid-Cretaceous volcano-sedimentary rocks of the Shyok Suture zone (Srimal *et al.*, 1987; Upadhyay *et al.*, 1999; Weinberg *et al.*, 2000). Therefore, it is quite likely that apart from crystal fractionation a metasedimentary source was also involved in magma genesis that led to formation of the Hundar granite.

The samples are poor in Rb (39.5–133 p.p.m.; the highly silicic variety has the highest Rb content) and have high Sr (113–841 p.p.m.). Rb in these samples shows positive trends with K_2O whereas Zr exhibits a negative correlation with SiO_2. Sr abundances show a systematic decrease with Eu/Eu*, indicating feldspar fractionation in Ladakh granitoids. Normalized rare earth elements (REE) and multi-element patterns (Fig. 2a) are enriched in terms of light REE and large ion lithophile elements (LILE) and depleted in high field strength elements (HFSE) (Ahmad *et al.*, 1998). These trace-element features are characteristics of subduction-related magmatism (Saunders *et al.*, 1980). The predominantly calcalkaline nature of these rocks also indicates their generation and evolution in subduction-related environments (e.g. Honegger *et al.*, 1982; Dietrich *et al.*, 1983; Sharma and Choubey, 1983; Petterson and Windley, 1985; George *et al.*, 1993; Ahmad *et al.*, 1998; Weinberg and Dunlap, 2000) (Fig. 2b). According to Rolland *et al.* (2002), the last stage (*c.* 55–50 Ma) granitic melts bear a strong continental crust affinity. This magmatic stage could thus correspond to partial melting of a continental crustal basement, or be due to melting of palaeo-arc siliceous sediments (Rolland, 2002). However, based on isotope systematics, Weinberg and Dunlap (2000), Weinberg and Dunlap (2001) suggest negligible continental influence and REE, trace element anomalies as determined by different workers are most likely the results from crystal fractionation. In summary, the geochemical data are consistent with the large compositional variations of the rocks and similar geochemical signatures were reported for other rocks of the Ladakh batholith and the Dras island arc (Honegger *et al.*, 1982; Radhakrishna *et al.*, 1984; Ahmad *et al.*, 1998; Weinberg and Dunlap, 2000).

Zircon U–Pb ages

Five samples, one each from Chang La (RG16) and Hundar (RG6) and three from Daah-Hanu region (RG13, RG14 and RG20), were processed to obtain U–Pb geochronological data on separated zircons using thermal ionization mass spectrometry (TIMS) technique at the geochronological laboratory of the University of Tübingen, Germany. The zircon morphologies are euhedral to subhedral, elongate, simply faceted and typical of igneous zircons.

Methodology

Rock samples (2–3 kg) were prepared for geochemical analyses by jaw crushing (< 1 cm), and disk mill grinding (< 1 mm). Zircon was obtained from the 200–125 and 125–63 μm mesh-size fractions by heavy mineral enrichment on a Wilfley table, subsequent magnetic separation on a Frantz isodynamic separator and final density separation using heavy liquids. Grains free of cracks and inclusions were individually handpicked using a binocular microscope. For U–Pb iso-

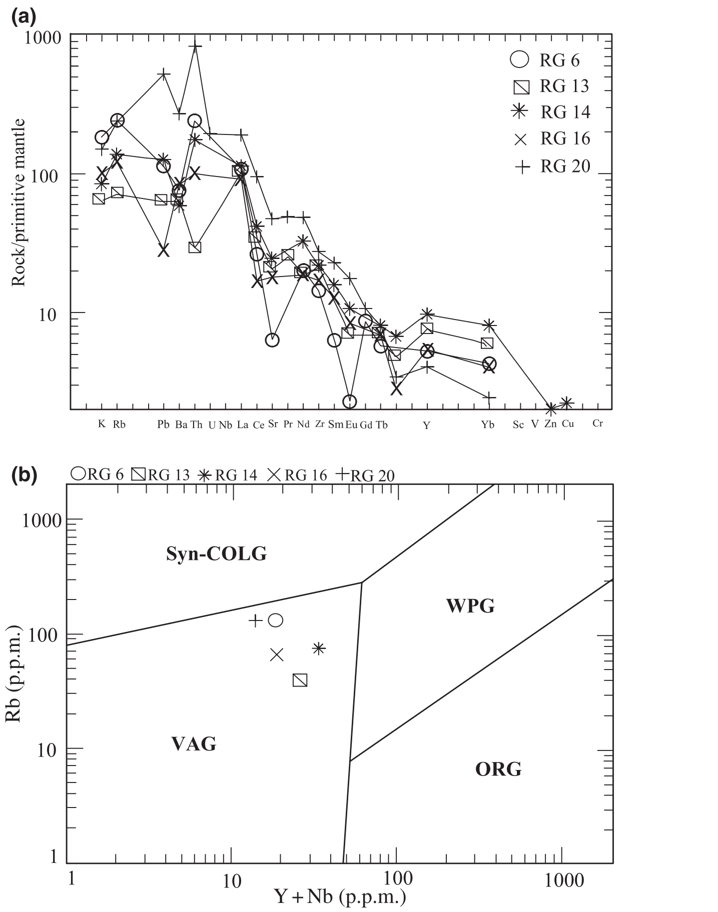

Fig. 2 (a) Primitive mantle normalized multi-element patterns for dated granitoids of the Ladakh batholith (normalizing values after Sun and McDonough, 1989); (b) Rb-Y + Nb tectonic discrimination diagram showing volcanic arc granite setting for the presently dated samples of the Ladakh batholith (plotted on the diagram of Pearce *et al.*, 1984). Open circle: sample-RG6 (Hundar); cross: sample-RG16 (Chang La); rectangle: sample-RG13 (Daah-Hanu); star: sample-RG14 (Daah-Hanu); plus: sample-RG20 (Daah-Hanu).

tope analyses, zircons were air-abraded (Krogh, 1982) for about 25 h. The minerals was washed in 6 N HNO_3 and 6 N HCl for half-an-hour at room temperature and rinsed with ultra-clean H_2O. A mixed $^{205}Pb/^{235}U$ spike was added to the samples before dissolution. After dissolution in 22 N HF at 210 °C for 1 week in a Parr bomb, the solutions were subsequently evaporated, re-dissolved in 6 N HCl, and finally in 0.8 N HBr and passed through mini-columns with a 40-μL bed of AG1-X8 (100–200 mesh) anion exchange resin in a HBr and HCl medium to purify U and Pb. Pb and U were collected together from the columns, loaded on outgassed Re-filaments together with 0.1 N H_3PO_4 and Si-gel, and run on a Finnigan Mat 262 mass spectrometer in static mode on single filament configuration. Blanks were < 10 pg for Pb and U. Fractionation factors for U and Pb correspond to 0.1% per atomic mass unit. Initial common Pb remaining after correction for tracer and blank was corrected following the model of Stacey and Kramers (1975). U–Pb data were calculated and plotted with software from Ludwig (1988, 2003).

Results

The results of the high-quality zircon U–Pb dating with weighted average age are given in Table 2 and Fig. 3. The $^{238}U/^{206}Pb$ and $^{235}U/^{207}Pb$ ages are largely concordant. The $^{238}U/^{206}Pb$ age has a higher precision, because of the much higher signal/intensities of the ^{238}U and ^{206}Pb masses during measurements, and, in the following, we refer to the $^{238}U/^{206}Pb$ ages.

The granite at Hundar, which corresponds to the northernmost limit of the batholith, givesan age of 66.6 ± 2.1 Ma. Near Chang La, which corresponds to the central sector of the batholith, the granitoid is dated at 57.6 ± 1.4 Ma. However, the granitoids near Daah-Hanu, which corresponds to the southern part of the batholith, yields ages of 53.4 ± 1.8, 52.50 ± 0.53 and 45.27 ± 0.56 Ma. These new age data clearly indicate that, between Hundar and Daah-Hanu, the Ladakh batholith grew by the addition of at least four distinct subduction-related magma pulses at *c.* 67, 58, 52 and 45 Ma, thus indicating that the belt was continuously active from at least *c.* 67 Ma to *c.* 45 Ma.

Discussion

So far, U–Pb geochronological information on the Ladakh batholith is very limited and the few known data were obtained from Kargil and around Leh (Honegger *et al.*, 1982; Schärer *et al.*, 1984; Weinberg and Dunlap, 2000). Zircons from Kargil yield a U–Pb age of 102 ± 2 Ma (Honegger *et al.*, 1982; Schärer *et al.*, 1984) and those from the Leh pluton (including the Shey body) yield a U–Pb age of 49.8 ± 0.8 Ma with older components present there, however, the Gyamsa body yields a U–Pb zircon age of 61.5 ± 2 Ma and a body at Digar yields an age of 58.4 ± 1 Ma (Honegger *et al.*, 1982; Schärer *et al.*, 1984; Weinberg and Dunlap, 2000). In addition, crystallization ages of the Ladakh plutons broadly coincide with Rb-Sr ages (whole-rock isochrons) from the Kohistan arc [e.g. 102 ± 12, 54 ± 4, 40 ± 6 Ma, and two post-collisional leucogranite (aplite-pegmatite) sheets are dated at 34 ± 14 and 29 ± 8 Ma; Petterson and Windley, 1985; George *et al.*, 1993]. Interestingly, our new age data are in good agreement with the age range (*c.* 70 Ma to *c.* 50 Ma) suggested for the growth of Ladakh batholith by Honegger *et al.* (1982), Schärer *et al.* (1984) and Weinberg and Dunlap (2000).

Table 2 U–Pb analytical data for zircon, Ladakh batholith.

Location	Sample/ fraction*a	Weight (mg) †	^{206}Pb‡/ ^{204}Pb	Pb (p.p.m.)†	U (p.p.m.)†	Atomic ratios§			Apparent ages (Ma)			Weighted average age (Ma)¶		Absolute errors	
						$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{238}U/^{206}Pb$	$^{235}U/^{207}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$
Chang La	RG16-1	0.017	237	3.7	313.2	0.008971	0.058184	0.047038	57.6	57.4	51.1	57.6 ± 1.4	57.89 ± 0.91	±0.00012	±0.00395
	RG16-2	0.038	380	2.3	221.9	0.008989	0.059389	0.047917	57.7	58.6	95.1			±0.00008	±0.00233
	RG16-3	0.012	89	6.6	379.6	0.009187	0.061463	0.048522	58.9	60.6	124.8			±0.00009	±0.00313
	RG16-4	0.025	448	3.3	308.6	0.009103	0.059065	0.047057	58.4	58.3	52.1			±0.00007	±0.00177
	RG16-5	0.028	628	3.7	367.6	0.008770	0.057666	0.047689	56.3	56.9	83.8			±0.00006	±0.00138
Daah-Hanu	RG13-1	0.038	68	43.4	24.8	0.008932	0.062323	0.050607	57.3	61.4	222.9	52.50 ± 0.53	50.1 ± 2.2	±0.00039	±0.01420
	RG13-2	0.059	111	1.2	98.0	0.007615	0.049528	0.047173	48.9	49.1	57.9			±0.00012	±0.00390
	RG13-3	0.061	81	1.3	79.5	0.008139	0.048863	0.043541	52.3	48.4	−136.6			±0.00013	±0.00370
	RG13-4	0.045	118	1.5	111.6	0.008278	0.052599	0.046085	53.1	52.1	2.0			±0.00016	±0.00427
	RG13-5	0.059	111	1.5	104.2	0.008150	0.050801	0.045207	52.3	50.3	−44.5			±0.00014	±0.00355
	RG14-1	0.024	46	1.6	63.8	0.008050	0.049827	0.044889	51.7	49.4	−61.7	53.4 ± 1.8	52.2 ± 2.2	±0.00026	±0.01176
	RG14-2	0.016	106	3.8	261.8	0.008559	0.054663	0.046322	54.9	54.0	14.4			±0.00016	±0.00413
	RG14-3	0.027	71	2.4	139.0	0.008081	0.047392	0.042533	51.9	47.0	−194.9			±0.00016	±0.00458
	RG14-4	0.024	107	1.9	152.1	0.008022	0.051981	0.046994	51.5	51.5	48.9			±0.00037	±0.00894
	RG14-5	0.038	197	2.8	196.5	0.008431	0.055132	0.047427	54.1	54.5	70.6			±0.00013	±0.00375
	RG20-1	0.024	591	8.0	992.7	0.007099	0.045624	0.046610	45.6	45.3	29.3	45.27 ± 0.56	45.54 ± 0.49	±0.00005	±0.00099
	RG20-2	0.034	380	10.2	1181.5	0.007264	0.047514	0.047441	46.7	47.1	71.5			±0.00004	±0.00048
	RG20-3	0.035	804	6.9	899.2	0.007074	0.046099	0.047263	45.4	45.8	62.5			±0.00004	±0.00077
	RG20-4	0.016	508	10.8	1346.2	0.006968	0.045042	0.046888	44.8	44.7	43.5			±0.00006	±0.00129
	RG20-5	0.033	154	5.8	552.8	0.007023	0.046545	0.048070	45.1	46.2	102.7			±0.00005	±0.00135
Hundar	RG6-2	0.012	183	9.7	706.3	0.010483	0.067137	0.046449	67.2	65.9	21.0	66.6 ± 2.1	67.3 ± 3.1	±0.00038	±0.00705
	RG6-3	0.008	78	8.3	393.0	0.010285	0.069335	0.048896	65.9	68.0	142.8			±0.00017	±0.00587
	RG6-4	0.016	226	7.7	543.7	0.010507	0.068599	0.047353	67.4	67.4	67.0			±0.00019	±0.00442

*All zircon fractions consisting of one to five single grains; a = air-abraded fraction (Krogh, 1982).
†Weight and concentration error better than 20%.
‡Measured ratio corrected for mass discrimination and isotope tracer contribution.
§Corrected for blank Pb, U, and initial common Pb based on Stacey and Kramers (1975) model.
¶Weighted average ages are calculated with Isoplot-Program (Ludwig, 2003).

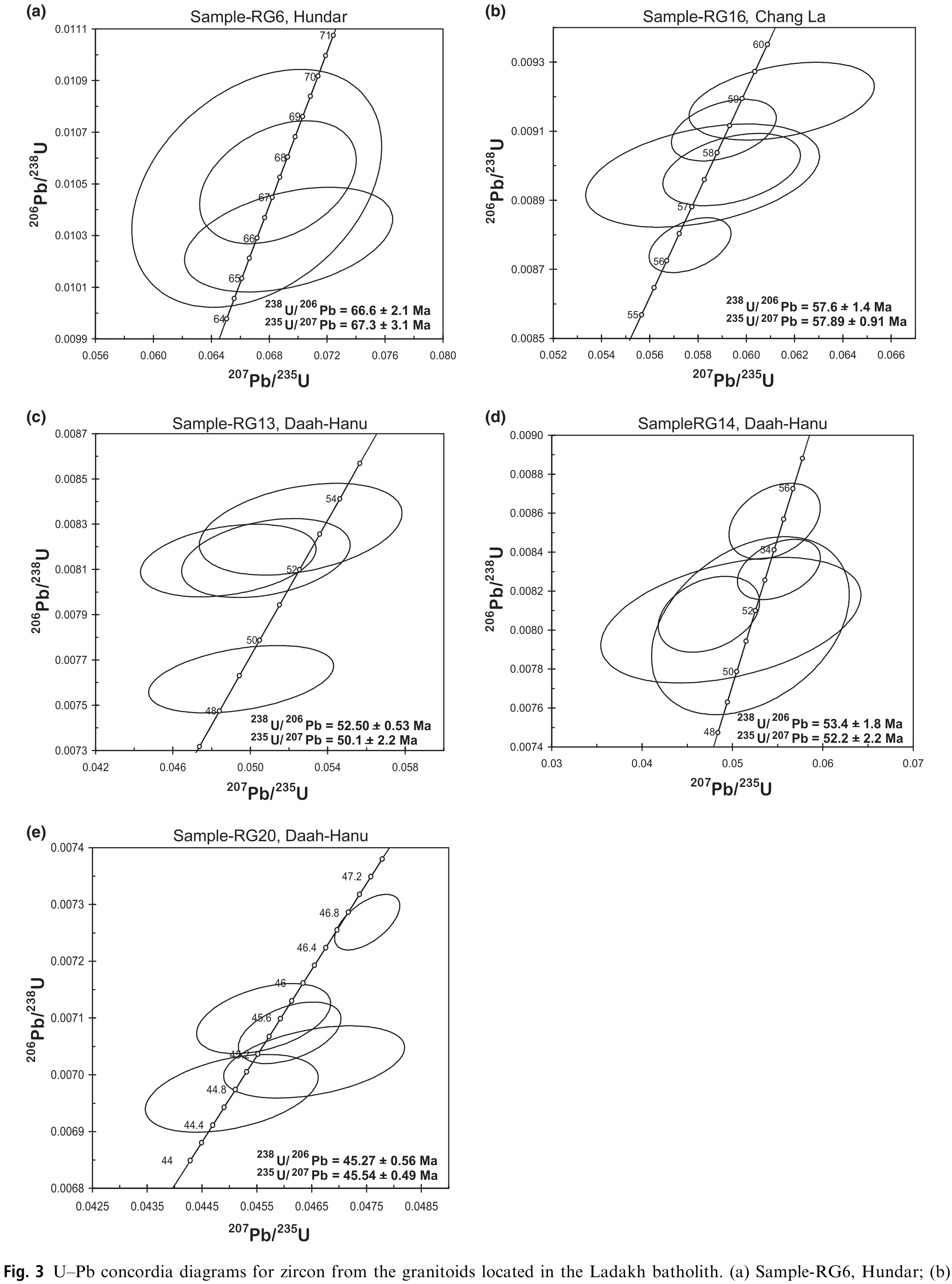

Fig. 3 U–Pb concordia diagrams for zircon from the granitoids located in the Ladakh batholith. (a) Sample-RG6, Hundar; (b) sample-RG16, Chang La; (c) sample-RG13, Daah-Hanu; (d) sample-RG14, Daah-Hanu; (e) sample-RG20, Daah-Hanu.

The age of collision between the Indian and the Asian plates remains poorly constrained and range from the Late Cretaceous (> 65 Ma) to latest Eocene (< 40 Ma) and Eocene/Oligocene boundary (*c.* 34 Ma) with little consensus in between (Patriat and Achache, 1984; Garzanti *et al.*, 1987; Bossart and Ottiger, 1989; Jaeger *et al.*, 1989; Klootwijk *et al.*, 1992; Beck *et al.*, 1995; Pivnik and Wells, 1996; Rowley, 1996; Aitchison *et al.*, 2007). It is also believed that there was an eastward younging (Schärer *et al.*, 1984; Harrison *et al.*, 1992) of the initiation of collision from 65 Ma in the west (NW Pakistan) to perhaps as young as about 41 Ma in the east (Lhasa in Tibet). Magnetic studies have evidenced an abrupt decrease in convergence rate, from 18–19.5 to 4.5 cm yr^{-1}, at *c.* 50–55 Ma (Klootwijk *et al.*, 1992) and 50 Ma (Patriat and Achache, 1984). The drop in convergence rate coincides with a reduction in the spreading rate of SW and central Mid-Indian Ocean ridge from 56.1 to 50.3 Ma (Klootwijk *et al.*, 1992; Molnar and Tapponnier, 1975). These age estimates are interpreted to date the initiation of continent–continent collision between Indian and the Asian plates. Based on structural evidence, Beck *et al.* (1995) place collision as old as the Cretaceous/Tertiary boundary in northwest Pakistan. Tectono-sedimentary and biostratigraphic data from the Zanskar-Hazara region of NW Himalaya suggest that collision started sometimes during the Ypresian, *c.* 52–50 Ma and extends into Lutetian (Garzanti *et al.*, 1987; Garzanti and van Haver, 1988; Rowley, 1996). The sedimentary record in Ladakh shows that the age of collision is post-Early Eocene possibly younger than 49 Ma (Garzanti and van Haver, 1988). Biostratigraphic data of Malla Johar, SE of Ladakh, suggest that the start of collision in this region occurred within the post-Ypresian or Middle Eocene (49–41.3 Ma) (Rowley, 1996). The collision started initially in the NW and propagated to the SE (e.g. Klootwijk *et al.*, 1992). This diachronous collision may be due to the initial shape of the Indian continent, colliding with NW–SE Asian margin (Rolland, 2002). In a first stage, NW Indian continental crust was subducted to a minium depth of 60 km, as indicated by eclogitic metamorphism documented in the Tso Morari area at ~55 (Guillot *et al.*, 1997; De Sigoyer *et al.*, 2000). Subsequently, in the Palaeocene, the Kohistan-Ladakh sequences were obducted (in two stages) onto the Indian margin (Garzanti *et al.*, 1987; Reuber *et al.*, 1987). In the meantime, and until 50 Ma, granitic magmatism still occurred in Ladakh (Weinberg and Dunlap, 2000).

The end of calcalkaline magmatism in the Ladakh batholith also provides an indirect way of dating collision (Weinberg and Dunlap, 2000). Prior to this study, the youngest U–Pb crystallization age was measured from the Leh pluton (49.8 ± 0.8 Ma). Weinberg and Dunlap (2000) argued as a result that the main episode of batholith growth ended at that time and that this effectively marks the timing of continental collision. Furthermore, the batholithic emplacement was followed by rapid cooling at the presently exposed levels to below 350 °C (indicated by K-Ar dating of biotite), and shortly thereafter intrusion of minor subvolcanic dyke at 45.7 ± 0.8 Ma (Weinberg and Dunlap, 2000).

Our U–Pb zircon data from five samples of previously undated plutons of the Ladakh batholith yield individual ages between *c.* 67 Ma and *c.* 45 Ma (Table 2), all dating growth of the Ladakh batholith. This age range suggests that the calcalkaline arc magmatism was continuously active throughout the Palaeocene and the Middle Eocene (Lutetian), with a southward younging of magmatism, which may at least be localized in some sections across the Ladakh batholith, i.e. Hundar (66.6 ± 2.1 Ma) – Chang La (57.6 ± 1.4 Ma) – Daah-Hanu (53.4 ± 1.8, 52.50 ± 0.53 and 45.27 ± 0.56 Ma). The youngest 45.27 ± 0.56 Ma magmatism at Daah-Hanu indicates that subduction-related magmatism in Ladakh did not halt entirely after continental collision which possibly started *c.* 52–50 Ma ago (Patriat and Achache, 1984; Rowley, 1996). Our new data also imply that the Ladakh batholith around Hundar, Chang La and Daah-Hanu grew by the addition of several magma pulses crystallized between *c.* 66.6 ± 2.1 and 45.27 ± 0.56 Ma. It becomes also evident that it is not the Leh pluton but the 45.27 ± 0.56 Ma pluton at Daah-Hanu which most probably represents the last major magma pulse in the Ladakh batholith. Its emplacement was followed by rapid cooling and subsequent dyke intrusions. The 45.7 ± 0.8 Ma Phyang subvolcanic dyke intrusion of Weinberg and Dunlap (2000) and the 45.27 ± 0.56 Ma old Daah-Hanu pluton are contemporaneous. It is quite likely that the magmas were generated over a longer time above the subduction zone and penetrated the upper plate; therefore, magmatism persisted for some time after collision. It is also conceivable that magmatism slowed down between 52 and 45 Ma and successively waned and terminated around 45 Ma (Lutetian) in Ladakh. It is important to mention here the interpretation of Petterson and Windley (1985) that the second stage I-type plutons of the Kohistan-Ladakh batholith were intruded in the period 60–40 Ma. If the onset of collision between India and the margin of Asia was at 50 Ma, and of India with the Kohistan-Ladakh island arc as early as 54 Ma, there was a time-lapse of at least 10 Ma before the intrusion of the last major calcalkaline plutons in the Trans-Himalayan batholith, such a time-lapse may be a common feature in collisional orogenic belts (Petterson and Windley, 1985). Similarly, Harrison *et al.* (2000) proposed that a continuous process produced calcalkaline Gangdese magmatism through the Tertiary, caused by an input of heat from the asthenosphere.

Interestingly, the zircon and apatite fission track work suggest that the batholith near Kargil had cooled to below 230 °C in the Late Eocene (Sorkhabi *et al.*, 1994) but that in the region of the Khardung La it cooled to below 230 °C in the Miocene (Kirstein *et al.*, 2006), suggesting an eastward progression in cooling history. The 41 Ma crystallization age of a granodiorite along the eastward continuation of the Trans-Himalayan batholith near Lhasa in Tibet (Schärer *et al.*, 1984; Harrison *et al.*, 1992) testifies to a possible eastward younging of the collision on plate scale. By 41 Ma, India was fully colliding with Asia on 2000 km length (Rowley, 1996), the collision propagating from NW to SE. Between 57 and 41 Ma, the direction of India–Asia convergence had rotated from NNE–SSW to N–S (e.g. Guillot *et al.*, 1999; Rolland, 2002 and references therein).

Conclusion

Our U–Pb zircon age data of the Ladakh batholith established that the growth of the calcalkaline arc magmatism was continuously active between *c.* 67 Ma and *c.* 45 Ma. The Ladakh batholith around Hundar, Chang La and Daah-Hanu grew by the addition of several magma pulses crystallized between 66.6 ± 2.1 and 45.27 ± 0.56 Ma. Unlike Leh pluton (Weinberg and Dunlap, 2000), the 45.27 ± 0.56 Ma Daah-Hanu pluton is most likely the last major magma pulse in the Ladakh batholith. Its emplacement was followed by rapid cooling and subsequent dyke intrusions. In Ladakh, the magmas were generated over a longer time above the subduction zone and penetrated the upper plate; therefore, the subduction-related magmatism persisted for sometime and gradually waned after continent–continent collision between Indian and the Asian plates.

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