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U–Pb zircon age for a granite intrusion within the Shyok suture zone, Saltoro Hills, northern Ladakh

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In the Saltoro Hills of northern Ladakh, Shyok volcanics of the Shyok suture zone are dissected by a ~5 m wide granite intrusion. Such granitic intrusions, in the Shyok volcanics are more pronounced to the west of Udmaru village and could be observed for several hundred metres. The Cretaceous Shyok volcanics consist of basalts and andesites. U–Pb age data from separated zircon suggests that the crystallization age of this calc-alkaline granitic body is 24.52 ± 0.40 Ma. Younger granitic intrusion or body has not been reported earlier from the Shyok suture zone of northern Ladakh, however, the younger intrusive bodies ranging between 25 and 17 Ma have been recorded from the Baltoro and Tangtse–Mugalib plutonic unit of the Karakoram block. Therefore, it is most likely that the young post-collisional intrusive phase of the Shyok suture zone and the Karakoram block are similar and may be part of a common major late-to-post-tectonic plutonic phase of the Karakoram batholith or they are related to the incipient synkinematic activity along the Karakoram fault.

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IN northern India, the Ladakh block lies between the Indian plate in the south and the Eurasian plate in the north[1]. To the west, this block is separated from the Kohistan complex[2] by the Nanga Parbat–Haramosh syntaxis and to the east it is separated from the Lhasa block by the Karakoram fault (Figure 1). Most workers interpreted the Ladakh block and the Kohistan complex, as one single accreted island arc terrane[3–7]. The Ladakh block is bounded by two suture zones – the Indus suture in the south and the Shyok suture to the north. These sutures mark the closing of different branches of the Tethys Ocean. The Indus suture records the final collision of India with Asia at 60–50 Ma (refs 3 and 8–10). The complex sequence of rocks that occur along the Indus suture is characterized by obducted remnants of the Neo–Tethyan oceanic crust[10]. The more northerly Shyok suture (Figure 1) separated Ladakh from the Asian continental rocks of the Karakoram mountains to the north and contains ophiolitic mélanges and thrust units derived from the southern Asian margin, which were juxtaposed when Kohistan/Ladakh collided with Asia during 102–85 Ma (refs 3 and 5). The Shyok suture zone is interpreted as a suture embodying the rocks of a marginal basin[11,12]. Recently, it has also been interpreted that the Kohistan arc is a fully oceanic arc[13,14], possibly formed near the equator in early Cretaceous time[15]. This interpretation implies that the Shyok suture zone records the destruction of a large oceanic basin.

In Saltoro Hills (Figure 1) the rocks of the Shyok suture zone trending northwest–southeast across the Nubra–Shyok valleys occur within intensely deformed tectonic slices between the Ladakh batholith to the southwest, and the Karakoram batholith to the northeast (Figure 1). Across a traverse through the Shyok–Nubra river valleys and the adjoining part of the Karakoram block, these tectonic slices comprise a variety of sedimentary, metamorphic and igneous rocks interpreted as an ancient accretionary complex[4,5,11,12,16]. From south to north, i.e. from the structural bottom to top, these tectonic units are: Saltoro/Hundri formation, Shyok volcanics, Saltoro molasse, ophiolitic mélange, Tirit granitoids and Karakoram batholith (Figure 1). The geological structure of the Shyok suture zone has recently been described and discussed elsewhere[4,7,16–20].

Adjoining to Shyok suture zone, to the north, lie the Karakoram mountains. In Karakoram, the granitoid batholith intrudes the Palaeozoic to early Mesozoic sedimentary sequences of southern edge of the Asian plate[3,7,21]. This belt comprises two major intrusive phases, i.e. older phase pre-dating the collision and younger phase post-dating the suturing of the Indian and Asian plates. This batholith is predominantly biotite granite with subordinate two-mica and hornblende–biotite granite. Age of the batholith ranges between 130 and 50 Ma along with younger phase of bodies ranging between 25 and 17 Ma (refs 22 and 23). The older phase in Karakoram batholith is of calc-alkaline composition and a distinct younger phase is a peraluminous leucogranite.

Apart from other tectonostratigraphic units, the Shyok volcanics are the most widespread lithology in the Nubra–Shyok valley. It is estimated that the volcanics are up to 4 km thick, consisting of a heterogeneous sequence of basalts and andesites with ignimbrites[19,24]. Outcrops of Shyok volcanics also occur below the Saltoro/Hundri Formation near Shukur and Udmaru (Figure 1). Southeast of Diskit, the Saltoro Formation is tectonically overlain along a steeply dipping thrust by chlorite schists, basic volcanics and cherts of the Shyok volcanics. West of the Karakoram fault, the Shyok volcanics are tectonically sandwiched between the Saltoro molasses and the ophiolitic mélange (Figure 1). East of the Karakoram fault, they occur between the villages of Panamik and Tirit. Geochemically, the Shyok volcanics are basalts and andesites with calc-alkaline signatures[4,19]. On the basis of the occurrence of middle Cretaceous (Aptian–Albian) orbitolina-bearing limestone, the age of the Shyok volcanics is suggested to be middle Cretaceous or older[12].

Along the Shyok suture zone, a granite intrusion (body) is observed to dissect across the Cretaceous Shyok volcanics (Figures 1–3). Although the rocks of the Shyok suture zone have earlier been reported to be dissected by several basic and acidic volcanic dykes[4], this is the first report of occurrence of a young plutonic intrusive phase along the Shyok suture zone. This new finding provides important clues regarding magmatic processes in the region. Knowledge of their precise age and field relations has considerable bearing on interpretation of the tectonic evolution of the Shyok suture and correlation with equivalent young magmatism in northern and eastern Karakoram.

During field excursion in and around the village of Udmaru (Figure 1), in the Nubra–Shyok river valleys, a ~5 m wide, coarse-grained granitic intrusion, trending WNW–ESE, is encountered which cuts across the Shyok volcanics (Figure 2). Such granitic intrusions in the

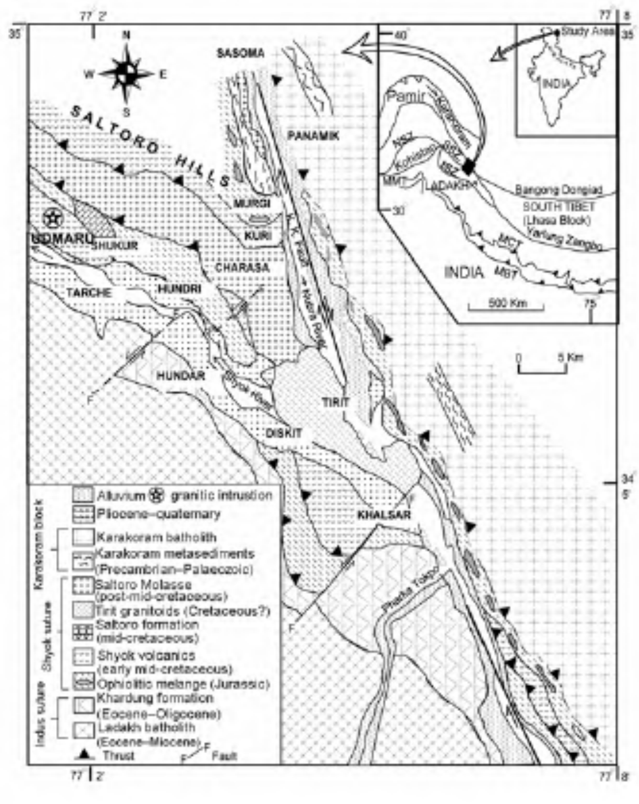

Figure 1. Geological map of the Shyok suture zone in Nubra–Shyok valley, Saltoro Hills, northern Ladakh, India (modified after Upadhyay *et al.*[4]) showing the location of granite intrusion. K.K. Fault, Karakoram Fault; NSZ, Northern Suture Zone; SSZ, Shyok Suture Zone; MMT, Main Mantle Thrust; MCT, Main Central Thrust; MBT, Main Boundary Thrust.

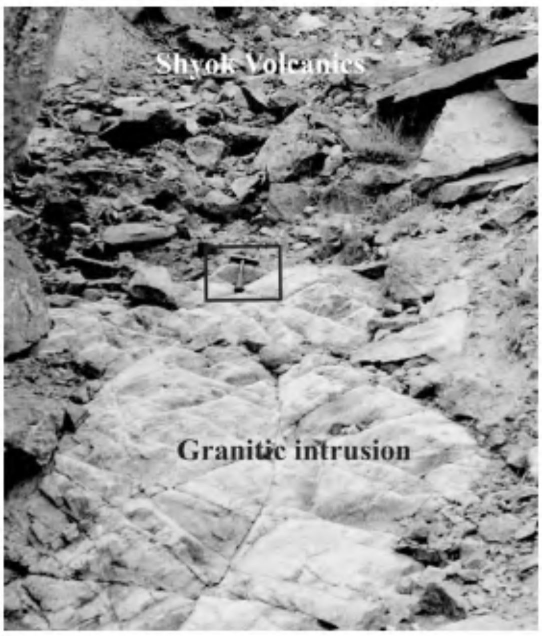

Figure 2. Field outcrop of WNW–ESE trending granite intrusion which is cutting across the Shyok volcanics, northeast of the village of Udmaru, Saltoro Hills, Nubra–Shyok river valley. Scale – geological hammer inside square.

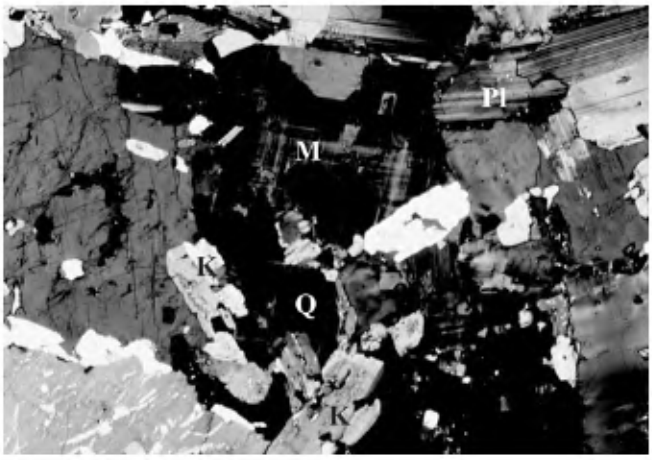

Figure 3. Thin-section photograph of granite 10X. Q, quartz; M, microcline; K, K-feldspar; Pl, plagioclase.

Shyok volcanics are more pronounced to the west of Udmaru village and could be observed for several hundred metres. The village of Udmaru is located about 40 km north of Hundar or ~20 km southwest of the Karakoram fault in lower Shyok river valley.

Six granite samples were collected. Three were processed to obtain petro-geochemical data and one sample was processed for U–Pb zircon geochronological data using X-ray fluorescence (XRF) and thermal ionization mass spectrometry (TIMS) techniques at the Institute of Geosciences, University of Tübingen, Germany. The implications of these new geochronological data are discussed in this communication. Petrographically, the granite consists of quartz, K-feldspar, microcline, plagioclase, biotite and hornblende (Figure 3) with accessory green coloured zircon, apatite, monazite and opaque minerals. The investigated granite sample assayed (in wt%) 71 SiO_2, 14.7 Al_2O_3, 1.6 CaO, 5.0 Na_2O, 4.0 K_2O, 0.76 MgO, 1.99 Fe_2O_3 and 0.26 TiO_2 and 1203.3 ppm Sr, 2134.9 ppm Ba and 213.4 ppm Rb.

To obtain U–Pb age data, zircons were separated from one granite sample. The zircons are morphologically euhedral to subhedral, elongate and simply faceted implying their igneous origin. All zircon grains were individually handpicked and abraded[25] for about 25 h prior to U–Pb isotope analyses. Rock sample (2–3 kg) was prepared for geochemical analyses by jaw crushing (<1 cm) and disk mill grinding (<1 mm). Zircon was obtained from the 200–125 μm and 63–125 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. Whenever possible, grains free of cracks and inclusions were used for analysis. For U–Pb isotope analyses zircons were air-abraded[25]. The minerals were 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 one week in a Parr bomb, the solutions were subsequently evaporated, redissolved in 0.8 N HBr and passed through minicolumns 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 less than 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 Stacey and Kramers[26] model. U–Pb data were calculated and plotted with software from Ludwig[27,28].

Table 1 lists the U–Pb data of zircon and Figure 4 shows their concordia plot with best fit intercept at 24.52 ± 0.40 Ma, suggesting that the granite intrusion near Udmaru formed at 24.52 ± 0.40 Ma. This is the first record of the presence of youngest post-collisonal intrusive phase along the entire stretch of the Shyok suture zone exposed in northern Ladakh and northern Kohistan. The only known geochronological age data so far from the Shyok suture is for Tirit granitoids, i.e. 73.6–68 Ma (refs 16 and 29). It was postulated that the Shyok suture (northern suture in northern Kohistan, Pakistan) resulted from collision between the Kohistan island arc and the Asian margin between 100 and 75 Ma (refs 29 and 30). The major plutonic activity occurred at 75–65 Ma along the Shyok suture zone, earlier in Kohistan (~75 Ma; ref. 2), and later in northern Ladakh (Tirit granite, 73.6–68 Ma; refs 16 and 29). However, the arc plutonism along the Indus suture zone have yielded 103–45 Ma age for Ladakh batholith[31–34] and 102 ± 12 to 49 ± 11 Ma for Kohistan batholith[2,34,35].

In contrast to Ladakh, a young (26 ± 1 Ma) post-collisional granitic phase intruded the Kohistan batholith and surroundings[35]. These are biotite–muscovite leucogranite sheets (Parri granites) and show strong mantle geochemical signatures[35]. Such young granites have not yet been recorded from the Ladakh batholith. Interestingly, the younger intrusive phase ranging between 25 and 17 Ma has also been recorded from the Baltoro plutonic unit (northern Karakoram, Pakistan) and 22 and 14 Ma in Tangtse–Mugalib leucogranite (Pangong range of eastern Karakoram) respectively[36–39]. In Karakoram batholith region, the Baltoro plutonic unit consists of peraluminous monzogranites and leucogranites and the Tangtse–Mugalib leucogranite is two-mica bearing along with garnet. Geochemistry and U–Pb ages of the leucogranites at Tangtse and Mugalib show that they are equivalent to the younger granites in the Baltoro batholith[36–39]. Searle *et al.*[37] opined that no Baltoro–Tangtse-type granites occur southwest of the Karakoram fault in Ladakh. However, the newly recorded Udmaru granite intrusion

Table 1. U–Pb analytical data for zircon, granite intrusion of the Shyok suture zone, northern Ladakh

						Atomic ratios[4]			Apparent ages (Ma)			Weighted average age[5] (Ma)		Absolute errors	
Location	Sample/ fraction[1a]	Weight[2] (mg)	$^{206}Pb^{3}/^{204}Pb$	Pb[2] (ppm)	U[2] (ppm)	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{238}U/^{206}Pb$	$^{235}U/^{207}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$
Udmaru	RV12-1	0.017	483	15.9	3847.3	0.003814	0.024777	0.047114	24.5	24.9	55.0	24.52 ± 0.40	24.73 ± 0.31	± 0.00003	± 0.00032
(Shyok suture)	RV12-2	0.010	6088	500.2	5.4%	0.003842	0.024637	0.046508	24.7	24.7	24.0			± 0.00003	± 0.00019
	RV12-3	0.013	313	13.0	3102.3	0.003698	0.023712	0.046508	23.8	23.8	24.0			± 0.00005	± 0.00100
	RV12-4	0.019	181	16.0	3070.8	0.003805	0.024500	0.046696	24.5	24.6	33.7			± 0.00002	± 0.00035

[1]All zircon fractions consisting of 1–5 single grains; *a* = air-abraded fraction[25].
[2]Weight and concentration error better than 20%.
[3]Measured ratio corrected for mass discrimination and isotope tracer contribution.
[4]Corrected for blank Pb, U, and initial common Pb based on Stacey and Kramers[26] model.
[5]Weighted average ages are calculated with Isoplot program[28].

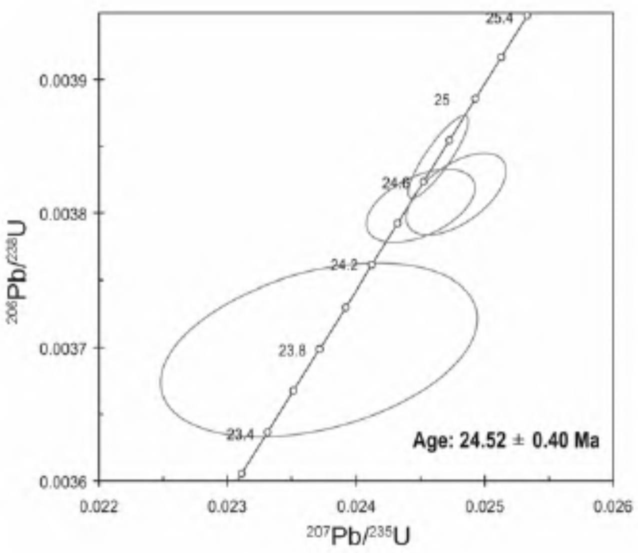

Figure 4. U–Pb concordia diagram for zircon from the granite intrusion located near the village of Udmaru in the Shyok suture zone, northern Ladakh, India.

(24.52 ± 0.40 Ma), which also has similar chemical composition to those recorded from the Baltoro region, is situated ~20 km southwest of the Karakoram fault. This suggests that the Baltoro–Tangtse–Mugalib type granites do exist to the southwest of the Karakoram fault in the Nubra–Shyok valley of northern Ladakh, and this granite is not far off from the Karakoram batholith. Therefore, it is likely that the young post-collisional intrusive phase of Udmaru and the Baltoro–Tangtse granites are similar and may be part of a common major late- to post-tectonic plutonic phase of the Karakoram batholith. Alternately, they may be related to the incipient synkinematic activity of the Karakoram fault that took place sometime between 25 and 15 Ma (refs 38–40) and this would have contributed towards the origin of a young intrusive phase in the region. Interestingly, the young granitic intrusion in the Shyok suture zone is also contemporaneous with the 26 Ma Parri granite (Kohistan) and also with the 24–17 Ma high Himalayan leucogranites (e.g. Shisha Pangma[41]) which may be related to the collision-related compressional and extensional tectonics[42–44].

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Evidences for seawater–rock hydrothermal interaction in the serpentinites from Northern Central Indian Ridge

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Serpentinites and serpentinized harzburgites were collected from a ridge-transform intersection at 6°39′S–68°19′E from the Northern Central Indian Ridge. The degree of serpentinization is extensive and varies from 90 to 100%. Olivine and orthopyroxene are largely pseudomorphed to lizardite-chrysotile 'mesh' and 'bastite' respectively. Numerous serpentine vein network associated with clusters of magnetite are also present. On the basis of mineralogical paragenesis, mineral chemistry and bulk rock analyses, we infer that the present serpentinites might have formed due to the interaction of harzburgites and seawater at a low temperature. Additionally, positive Eu anomaly, higher La/Sm and low Nb/La ratios suggest substantial hydrothermal input during the onset of serpentinization.

Keywords: Hydrothermal alteration, mid-oceanic ridge, Northern Central Indian Ridge, serpentinites, seawater–rock interaction.

THE Northern Central Indian Ridge (NCIR; half spreading rate of 18–22 mm/year), one of the least explored

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