Age of the Karakoram fault activation:  
\(^{40}\)Ar–\(^{39}\)Ar geochronological study of Shyok suture zone in northern Ladakh, India

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Shyok volcanics, from the Shyok suture zone in northern Ladakh, ranging from basalts to andesites are analysed for \(^{40}\)Ar–\(^{39}\)Ar isotopic systematics by step heating experiment. All samples, collected along the Nubra river, in the vicinity of Karakoram fault zone, yielded disturbed age spectra, reflecting subsequent tectono-thermal events. However, consistency in the pattern of the age spectra, particularly at the low temperature steps, indicate a strong tectono-thermal event between ~10 to ~20 Ma ago. Mica-segregate from a sheared granite of Karakoram fault zone near village Murgi has yielded an excellent plateau age of 13.9 ± 0.1 Ma. This age of Karakoram fault activation explains the consistent but disturbed age spectra of Shyok volcanics within the vicinity of the fault zone. The Karakoram fault activation in Shyok suture zone is therefore synchronous with the extensional tectonic regime within the Tibetan plateau.

NORTH of the Ladakh batholith is characterized by the linear volcanic belts, and ophiolitic mélangé, which separate it from the Karakoram batholith in the north (Figure 1). The ophiolitic mélangé and associated flyschoidal and molassic sediments are believed to be representing the line of a subduction named as the Shyok Suture\(^1\)–\(^4\) (Figure 1). The Shyok suture zone in northern Ladakh is a highly tectonized zone as evidenced by highly deformed volcano-sedimentary rocks and ophiolitic mélange in the Nubra-Shyok valley\(^5\). Lithologically there are six major units of the Shyok Suture, which are more or less found to be in the form of tectonic slices between Ladakh batholith and Karakoram batholith. Ophiolitic Mélange, which marks the suture, mainly consists of serpentinitized ultramafics, and meta-sediments. Shyok volcanics, which are supposed to be similar to Chalt volcanics of Kohistan sector\(^5\)–\(^8\) are a very heterogeneous sequence comprising of basalts to andesites. At most of the places the volcanics are greenish gray, fine-grained and massive in nature. They are tectonically sandwiched between the underlying Saltoro Molasse and are characterized by red and green shales, siltstones, conglomerate and breccias – and the Ophiolitic mélange in the west of Karakoram fault. In the East of Karakoram fault Shyok volcanics are exposed from Panamik to Tirit villages intercalated with the metasediments. Explosive volcanism also has been reported from the Shyok–Nubra valley, represented by Khardung Volcanics that overlie Ladakh batholith\(^9\). A thick succession of rhyolite, ignimbrite, dacite, agglomerate and volcanic breccia is exposed near the village Khardung.

Several models have been proposed to explain the evolution of the island-arc terrain and formation of the Shyok Suture within the India–Asia collision zone\(^15\)–\(^12\). However, the debate on the age of the suture and whether it is older or younger than the Indus suture, as well as the mode of subduction/suturing has not yet been settled. Brookfield and Reynolds\(^15\), and Reynolds \textit{et al.}\(^5\) suggested that the Shyok suture did not close until Miocene and the Indus suture closed earlier in the Late Cretaceous. Coward and Butler\(^1\), Petterson and Windley\(^10\), Treloar \textit{et al.}\(^11\), Searle \textit{et al.}\(^12\) and Upadhyay \textit{et al.}\(^7\) favoured an early closure of the Shyok suture in Cretaceous. Rai\(^13\) argued against any subduction along the Shyok suture.

The present \(^{40}\)Ar–\(^{39}\)Ar study of the Shyok volcanics from the vicinity of Karakoram fault zone indicates that Karakoram fault has played a crucial role in the evolution of Shyok suture zone to the present-day tectonic setting.

Regional strike slip faults in Himalaya–Tibet orogenic system are vital in understanding the uplift, deformation and overall accommodation of ~2500 km of crust into it\(^14\)–\(^15\). Karakoram fault at the western margin of the Tibetan plateau (Figure 1) has been traced for more than thousand kilometers starting from north-west Tibet and cutting across the suture in north-west Himalaya to the south Kailas thrust system\(^15\)–\(^16\). The Karakoram fault system has been visualized in different ways by different workers, e.g. as the major boundary in the west along which the Tibetan block has been extruding towards the east\(^14\), as a major strike slip fault which facilitated the indentation of Pamirs in the north\(^17\). It is also thought to have played a crucial role in the internal deformation of the Himalayan arc\(^18\)–\(^19\). Timing of its activation is crucial in understanding its implication and its role in the overall evolution of India–Asia collision zone. Various indirect geological methods have been used to know the timing of this fault. Since it cuts across the 18 Ma leucogranites in the Karakoram batholith, it is supposed to be younger than 18 Ma\(^7\). Yin \textit{et al.}\(^20\) and Murphy \textit{et al.}\(^16\) proposed that it did not get activated until 13 Ma in the southern end where it offsets the 13 Ma-old Kailas Thrust system. Yin \textit{et al.} further noticed that it has varying timings and amount of net slip along the strike, which they attributed to the southward propagation of faulting. Here we present a direct estimate of age of Karakoram fault activation in northern Ladakh\(^15\).
The samples of the Shyok volcanics are collected mainly along the Nubra river, comprising the major geochemical varieties of this suite. Nubra river essentially occupies the trace of the northwest-southeast trending Karakoram fault. Various lithological units are disposed in highly deformed tectonic slices. At least three distinct episodes of deformations are identified in this region with earliest thrusting being pre-Eocene and youngest being related to strike-slip movement along the dextral Karakoram fault\textsuperscript{21}. We have identified a highly deformed and mylonitized zone near the village of Murgi (Figure 1), where Ophiolitic Mélange comprising of serpentinized ultramafics and metasediments are exposed in tectonic contact with porphyritic Karakoram granitoids. The shearing and mylonitization of granitoids of Karakoram batholith decreases rapidly on the either side of this zone. A sample of segregated mica (LK 47) is collected from this zone near the village of Murgi. Trend of foliation is found to be parallel to Karakoram fault along the Nubra river\textsuperscript{21}.

A total number of five samples from Shyok volcanics covering around 15 km along the Nubra river from Panamik to Sumur village and one fault zone sample from near the village Murgi (Figure 1) were analysed by \textsuperscript{40}Ar-\textsuperscript{39}Ar step heating experiment. Detailed chemistry of Shyok volcanics between Panamik and Tirit shows that they range from basalt to basaltic andesite to andesite\textsuperscript{5,21}, with their SiO\textsubscript{2} (wt)% ranging from ~ 42 to 62% and the total alkali (Na\textsubscript{2}O + K\textsubscript{2}O) ranging from ~ 2 to 8 (wt)% (ref. 5). Thin sections show that all the samples are essentially composed of plagioclase, hornblende and augite.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Geological map of northern Ladakh (modified from Upadhyay \textit{et al.}\textsuperscript{4}), showing different units of Shyok suture zone and sample locations. Shyok volcanics lie in discontinuous outcrops along the Nubra river in the vicinity of Karakoram fault zone. Inset shows a regional-scale map of Himalaya-Tibet orogeny (modified from Harrison \textit{et al.}\textsuperscript{32}), depicting important strike slip faults including Karakoram Fault, which are mainly along the margins of the Tibetan plateau. Location of the study area is also shown. MBT, Main Boundary Thrust; MCT, Main Central Thrust; MMT, Main Mantel Thrust; ITS, Indus Tsangpo Suture; SSZ, Shyok Suture Zone and STD is South Tibet Detachment.}
\end{figure}
with biotite, sphene, and chlorite being the accessory minerals, while in some basalt samples, olivine is present as an accessory mineral. Care is taken to avoid the samples with secondary hydrothermal veins.

The $^{40}\text{Ar} - ^{39}\text{Ar}$ analysis has been carried out following the procedures outlined by Venkatesan et al.\textsuperscript{22} Samples were sealed in quartz capsules and irradiated for 100 h cumulative along with the flux monitor mineral, Minnesota hornblende (MMHb-1), in the central core of the light-water moderated APSARA reactor at the Bhabha Atomic Research Centre, Mumbai. The APSARA reactor was not run continuously and consequently appropriate correction for $^{37}\text{Ar}$ decay for segmented irradiations was made. Pure nickel wires were included in both sample and monitor capsules to measure neutron fluence variations. Interference corrections were based on measurements of pure CaF$_2$ and K$_2$SO$_4$ salts irradiated with each batch of samples. The samples used in the present study have been irradiated in two batches. The values for ($^{36}\text{Ar}/^{37}\text{Ar})_{Ca}$, ($^{39}\text{Ar}/^{37}\text{Ar})_{Ca}$, and ($^{40}\text{Ar}/^{39}\text{Ar})_{K}$ for sample LK 48 are 0.00034, 0.00071 and 0.046 and for the rest of the samples are 0.00016, 0.00075 and 0.069 respectively.

For each sample, argon was extracted in a series of twelve to nineteen steps of increasing temperatures up to 1400°C, in an electrically heated ultra-high vacuum furnace. After two stage purification, the argon released in each step was measured for its isotopic composition using an AEI MS10 mass spectrometer in static mode. $^{40}\text{Ar}$ blanks were less than 10% of sample $^{40}\text{Ar}$ for the lower temperatures up to 1000°C and increased gradually to 50% of sample $^{40}\text{Ar}$ at 1400°C. The typical value for the irradiation parameter $J$ is 0.002278 ± 0.00002. The ages have been reported with respect to MMHb-1 of 520.4 ± 1.7 Ma (ref. 23).

Sample LK 48 is a basalt in tectonic contact with the ophiolitic mélangé of the Shyok suture zone near the village Murgi (Figure 1). This has yielded cooling pattern of the rising apparent ages from ~ 13 Ma to ~ 20 Ma from 650°C to 950°C (Figure 2). A very insignificant amount of gas (< 1%) released in the first and last step yielded high apparent ages, ~ 30 Ma and ~ 80 Ma respectively.

Sample LK 57 from near the village Panamik (Figure 1) yielded a complex age spectrum (Figure 2). Overprinting of subsequent tectono-thermal events can be made out from the age spectrum. The apparent ages start from ~ 10 Ma (at 450°C) and go up to ~ 20 Ma (at 650°C) for the first ~ 40% of the gas released. The apparent ages again become as low as ~ 14 Ma at the seventh temperature step (700°C) and then rise up to as high age as ~ 100 Ma at the maximum temperature step indicating perhaps a superposition of two events. A similar pattern gets repeated for the sample LK 67 which also yielded a disturbed age spectrum. Figure 2, looks like two separate cooling patterns. The first cooling pattern starts from

![Figure 2](image-url). Age spectra (a–f) of Shyok volcanics in the vicinity of Karakoram fault zone. All the spectra show superimposition of subsequent tectono-thermal events between ~ 10 to ~ 20 Ma. The last plot (f) is an overlap of all the five samples demonstrating the similarity of age spectra.
~ 12 Ma (at 500°C) and goes up to ~ 18 Ma (650°C) consisting ~ 30% of the total gas released. The second pattern of the rising ages starts at middle temperature steps from ~ 11 Ma age and goes up to ~ 60 Ma consisting of the remaining 70% of the gas released.

The same cooling pattern is reproduced by another sample from the nearby area, LK 68 for the first ~ 60% of the total gas released. However, there is another cooling pattern superimposed, starting from the middle temperature steps at the apparent age ~ 20 Ma to a very high age of more than 200 Ma, for the remaining ~ 40% of the gas released (Figure 2). Sample LK 70 from near the village Tirit (Figure 1) also yielded a complex age spectrum and appeared to have two superimposed cooling patterns (Figure 2). The first spectrum starts from the apparent age of ~ 20 Ma (450°C step) and goes up to ~ 35 Ma (650°C) for the first ~ 55% of the gas released and again the ages become lower than ~ 25 Ma and then rise to as high values as ~ 100 Ma.

A mica-segregate from a sheared granite from the Karakoram batholith, LK 47 was collected near the village Murgi (Figure 1). Being crushed and segregated in a fault zone, this sample had a large amount of trapped gases, and had to be degassed up to 700°C. It could be analysed starting from temperature 750°C. However it yielded a very good plateau age of 13.9 ± 0.1 Ma consisting of nine consecutive steps and 99.5% of 39Ar released (Figure 3). The isochron of this sample yielded an age of 14.0 ± 0.3 Ma with trapped ratio as 283.6 ± 24.2 and MSWD of 0.2.

40Ar/39Ar plateau ages usually provide the timing of cooling below the closure temperature of the phase dated22. The disturbed age spectra, which do not yield any plateau age, indicate inhomogeneous isotopic distribution within the sample. Attributing this inhomogeneity in whole rock samples to any phenomenon is difficult in the absence of independent geological evidences. However, in a tectonically-disturbed terrain the disturbed age spectra provide vital information if interpreted in the light of well-constrained geological history. The samples from the Shyok suture zone are expected to yield disturbed age spectra because of their being in a highly tectonized zone. These age spectra show the multi-tectono-thermal events experienced by these samples. The high apparent ages obtained for the higher temperature steps for the Shyok volcanics suggest cooling below green-schist facies metamorphism, probably related to the suturing in Cretaceous, an observation also made by Dunlop and Wysocki35 in a recent study. Rolland et al.31 and Upadhyay36, suggested the age of the base of the Nubra-Shyok volcanics unit to be Middle Cretaceous ~ 108 to 92 Ma, on the basis of foraminifer Orbitolina bearing limestone interbedded with the Shyok basalts and andesites of the Shyok volcanics. In the light of these geological evidences, we explain that the higher ages at high temperature steps actually indicate the formation ages or the earlier deformation events experienced by these samples, and the lower ages at the low temperature steps reflect the later tectono-thermal events. The remarkable consistency in the patterns of their age spectra (Figure 2) suggests that they are affected by a regional-scale tectono-thermal event. The age spectra of these Shyok volcanics indicate that the strong tectono-thermal event has taken place somewhere between ~ 10 to ~ 20 Ma ago. We could pinpoint this event with the help of sample LK 47. The fault movement directly affects this sample taken from a fault gauge. It has yielded a plateau age indicative of the fault activation timing, i.e. 13.9 ± 0.1 Ma. This age explains the tectono-thermal event reflected by the fault vicinity samples. We, therefore, conclude that Karakoram fault got activated at 13.9 ± 0.1 Ma ago in the Shyok suture zone. This age of Karakoram fault activation is in good agreement with the earlier estimates15-17,19. Murphy et al.16, based on the slip history across South Kailas thrust system estimated Karakoram fault to be younger than ~ 13 Ma, i.e. the cessation of the South Kailas thrust system. They further noted that in central portion, the Karakoram fault initiated at ~ 17 Ma, suggesting southward propagation of it.

![Figure 3](Image)  
Figure 3. Age spectrum and isochron of sample LK 47. The vertical side of the each box in the age spectrum plot is 2σ error in apparent age without including error in J. Error in plateau-age includes error in J. 40Ar/39Ar vs 39Ar/36Ar correlation diagram is also shown with isochron age, 40Ar/39Ar trapped ratio and MSWD value.
Our results thus provide an estimate of timing of its activation in the Nubra-Shyok region of the Shyok suture zone. The present-day tectonic disposition of Shyok suture zone is due to the strike-slip movement along the Karakoram fault. A significant amount of crustal shortening might have been accommodated along this fault zone as evidenced by the highly tektonized rocks of Shyok suture. At almost the same time (~14 Ma) the east-west extension in Tibet also commenced, as estimated earlier. Recently, Blišniuk et al. reported a minimum age of ~13.5 Ma for the normal faulting in central Tibet based on the mineralization ages determined with Rb-Sr and Ar-Ar data. Williams et al. estimated that the extensional regime in Tibet started between ~18 Ma and ~13 Ma ago based on the Ar–Ar dating of the north-south trending dykes in southern Tibet. These early extensional activities in Tibet are usually linked with the processes occurring beneath the plateau. However, recently Murphy et al. indicated the kinematic relationship between the tectonic movement along the Karakoram fault and the Gurla Mandhata detachment zone of south-west Tibet. Our new age data on the Karakoram strike-slip fault activation also support causal relationship between the strike-slip movement along the margins of the Tibetan plateau and the extensional normal faulting in the plateau.

The Shyok suture zone has been affected by the strike-slip movements along Karakoram fault, which got activated in this region at 13.9 ± 0.1 Ma. The 40Ar/39Ar age spectra of the whole rock volcanics in the vicinity of the fault zone reflect this event. This age provides the timing of major phase of deformation and crustal shortening in Shyok suture zone. Furthermore, the simultaneity of the Karakoram fault activation and the initiation of the extensional regime in Tibetan plateau suggest causal relationship between the two phenomena.


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