Tectono-thermal evolution of the India-Asia collision zone based on ^{40}Ar - ^{39}Ar thermochronology in Ladakh, India

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New ^{40}Ar - ^{39}Ar thermochronological results from the Ladakh region in the India-Asia collision zone provide a tectono-thermal evolutionary scenario. The characteristic granodiorite of the Ladakh batholith near Leh yielded a plateau age of 46.3 ± 0.6 Ma (2σ). Biotite from the same rock yielded a plateau age of 44.6 ± 0.3 Ma (2σ). The youngest phase of the Ladakh batholith, the leucogranite near Himya, yielded a cooling pattern with a plateau-like age of ~ 36 Ma. The plateau age of muscovite from the same rock is 29.8 ± 0.2 Ma (2σ). These ages indicate post-collision tectono-thermal activity, which may have been responsible for partial melting within the Ladakh batholith. Two basalt samples from Sumdo Nala have also recorded the post-collision tectono-thermal event, which lasted at least for 8 MY in the suture zone since the collision, whereas in the western part of the Indus Suture, pillow lava of Chiktan showed no effect of this event and yielded an age of emplacement of 128.2 ± 2.6 Ma (2σ). The available data indicate that post-collision deformation led to the crustal thickening causing an increase in temperature, which may have caused partial melting at the base of the thickened crust. The high thermal regime propagated away from the suture with time.

1. Introduction

The Ladakh region of India, in the NW trans-Himalaya, bounded by the Karakoram batholith to the north and the Zaskar and Tso Moriri crystallines to the south (figure 1), provides an excellent opportunity to study an almost complete succession from Paleozoic passive margin sediments to subduction related magmatism and post-collision molasses (Virdi 1987). From south to north Ladakh has a complete section through shelf deposits, trench zone, fore-arc basin, calc-alkaline intrusives and back arc deposits (Sharma and Gupta 1978; Virdi 1987; de Sigoyer *et al* 2004). Indus Suture, with its characteristic ophiolitic mélanges, marks the line of closure of the Tethys ocean. The deep-sea Tethys sediments are grouped into the Lamayuru complex while the

fore-arc sediments are grouped into the Nindam formation (Sinha and Upadhyay 1993; Upadhyay 2002). Well-preserved sections of continental passive margin sediments are exposed in the Spiti and Zaskar sections. The back arc sediments are found along the northern margin of the Ladakh batholith. The estimates for the age of the initiation of collision vary from 60 Ma to 45 Ma (Patriat and Achache 1984; Dewey *et al* 1989; Beck *et al* 1995; Rowley 1996; Searle *et al* 1997; de Sigoyer *et al* 2000; Guillot *et al* 2003); however, for the NW Himalaya, the age of the initiation of the collision is estimated to be 55 ± 2 Ma (de Sigoyer *et al* 2000; Guillot *et al* 2003). Honegger *et al* (1982) gave some Rb-Sr and U-Pb isotopic ages from western Ladakh, concluding that the main plutonic batholith was emplaced from ~ 100 Ma to 60 Ma though some much younger cooling ages

Keywords. India-Asia collision; ^{40}Ar - ^{39}Ar thermochronology; deformation; trans-Himalaya.

Figure 1. Geological map of Ladakh (modified from Sharma 1990 and Mahéo *et al* 2004), showing the sample locations (1- LK 24, 2- LK 198, 3- LK 176 & LK182, 4- LK209).

were also obtained. Other geochronological studies (Brookfield and Reynolds 1981; Reynolds *et al* 1983; Petterson and Windley 1985; Reuber 1989; Sharma 1990; Sorkhabi *et al* 1994) from this area essentially give pre- to syn-collision crystallization ages related to the subduction along an Andean-type margin. Some recent studies (e.g., Weinberg and Dunlap 2000) have reported melting in Ladakh batholith between 50 and 46 Ma. Kohn and Parkinson (2002) and Guillot *et al* (2003) propose that the reheating responsible for the melting is related to the break-off of the Indian plate.

From the Kohistan batholith of Pakistan, the western continuation of the Ladakh batholith, younger crystallization ages (as young as 29–25 Ma) have been reported (Treloar *et al* 1989; George *et al* 1993). We report here the results of geochronological and thermochronological studies

of two important rock units of the India-Asia collision zone from Ladakh region, viz., the ophiolites of the Indus Suture and Trans Himalayan granitoids of the Ladakh batholith.

2. Samples

2.1 The Ladakh batholith

The Ladakh batholith is generally calc-alkaline in composition, ranging from gabbro to granodiorite to tonalite-granite; granodiorite is the major constituent of the Trans-Himalayan batholith (Honegger *et al* 1982; Sharma and Choubey 1983). The interrelationships of different magmatic units of this batholith are complex (Ahmad *et al* 1998). During our fieldwork a muscovite-bearing leucogranite phase was observed intruding into the

Figure 2. Detailed geological map of western Ladakh, showing the sample location of LK209 (modified from Thakur and Mishra 1983).

main body of the batholith at places particularly in the eastern Ladakh. This may be similar to the Pari and Jagot granites of the Kohistan batholith. The best exposure of this leucogranite is found near the village Himya east of Leh. This Himya leucogranite (sample LK198) and a biotite-granodiorite (LK24) near Leh (figure 1) were sampled for ^{40}Ar - ^{39}Ar work.

2.2 The Ophiolitic *mélange* of Indus Suture zone

The southern margin of the Ladakh batholith is separated from the Tethyan sequences by the Indus Suture, characterized by the ophiolite *mélange*. A discontinuous ophiolitic *mélange* outcrops in western Ladakh near Shergol and Chiktan villages, whereas in eastern Ladakh, it is exposed mainly in Sumdo and Nidar Nala sections (figure 2). The ophiolitic *mélange* in Sumdo Nala is made up of basalts, pillow basalts, peridotites and serpentinites associated with chert and exotic limestone blocks. We collected two samples (LK176 and LK182) from the Sumdo Nala section of this ophiolitic *mélange* and a sample of pillow basalt (LK209) of the western Shergol ophiolitic *mélange* near Chiktan village along Chiktan Nala section (figure 2).

3. Experimental details

Both whole rock and mineral separates were analyzed. The whole rock samples were prepared following Venketesan *et al* (1993) and mineral

separations were carried out following the standard techniques of magnetic separation and density separation using heavy liquid. Mineral separates were then hand picked under a stereomicroscope.

^{40}Ar - ^{39}Ar analysis was carried out following procedures outlined by Venketesan *et al* (1993). Samples were sealed in quartz capsules and irradiated for 100 hours cumulative along with the flux monitor mineral, Minnesota hornblende (MMHb-1), of age 520.4 ± 1.7 Ma, 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}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_2SO_4 salts irradiated with each batch of samples. The values for $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$, $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$, and $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ are 0.00033930, 0.00071120, and 0.045910 respectively. For each sample argon was extracted in a series of twelve to nineteen steps of increasing temperature up to 1400°C , in an electrically heated ultra-high vacuum furnace. After two-stage purification, the isotopic composition of argon released in each step was measured using an AEI MS10 mass spectrometer in static mode. ^{40}Ar blanks were less than 10% of sample ^{40}Ar for the lower temperature steps up to 1000°C and increased gradually to 50% of sample ^{40}Ar at 1400°C . The typical value for the irradiation parameter J is 0.002278 ± 0.00002 .

4. Results

The results are presented in figures 3 to 5 and the tables of analytical data are given in the Appendix. The “plateau” in the age spectrum is defined as a portion that has four or more consecutive steps with apparent ages within 2σ comprising of at least 50% of the total ^{39}Ar released. While the apparent ages do not include error in J , the “plateau-age” is calculated by taking a weighted mean of apparent ages including the error in J . “Plateau-like” ages are calculated wherever there are plateau-like features but the above criterion for plateau is not strictly met. All the ages are reported here with errors at 2σ level.

Two of the basalt samples (LK176 and LK182) from the ophiolitic mélangé show age spectra affected by post-crystallization thermal activity. Sample LK182 (figure 3) yielded a cooling pattern with a maximum age of 38.3 ± 0.6 Ma obtained from the plateau-like part of the age-spectrum consisting of five consecutive steps at high temperatures. The isochron for these five steps yielded an age of 38.7 ± 1.3 Ma consistent with the plateau-like age. The sample LK176 (figure 3) yielded a plateau age for four consecutive middle-temperature steps as 46.8 ± 0.7 Ma comprising 64.4% of ^{39}Ar released. The isochron age of 46.8 ± 1.3 Ma for this sample is the same as its plateau age and the trapped $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 295.8 ± 11.9 is equal to the atmospheric ratio.

The Chiktan pillow lava LK209 (figure 3) yielded a plateau age for six consecutive temperature steps as 128.2 ± 2.6 Ma consisting of 62% of the ^{39}Ar released. Its trapped $^{40}\text{Ar}/^{36}\text{Ar}$ ratio is 296.9 ± 8.4 with an isochron age 126.9 ± 7.6 Ma. The plateau and isochron ages for this sample are indistinguishable. The higher temperature steps yield apparent ages as high as ~ 200 Ma and some intermediate steps show ages even lower than plateau age. These disturbances in the spectrum probably indicate some post-crystallization thermal disturbances, not very significant as the total fusion argon age of the sample (140.7 ± 4.4 Ma) is also close to the plateau age. The age of formation or eruption for this basalt is therefore taken to be 128.2 ± 2.6 Ma. Very recently Maheo *et al* (2004) reported ages of ~ 130 Ma for the Spong tang ophiolite and ~ 124 Ma for the Nidar ophiolites based on ^{40}Ar - ^{39}Ar studies. Ahmad *et al* (2003) also proposed a similar Sm-Nd isochron age of 140 ± 32 Ma for the Indus Suture ophiolites.

Whole-rock samples from the Ladakh batholith yielded complex age spectra reflecting their complex tectono-thermal histories. The sample LK24 (figure 4) yielded a plateau-like age of 46.3 ± 0.6 Ma for the middle temperature steps consisting of 51.4% of ^{39}Ar released. The higher

temperature steps for this sample show the post melting release of argon. The biotite separate, LK24B (figure 4), from the same sample yielded a good plateau age of 44.6 ± 0.3 Ma for ten consecutive steps consisting of more than 93% of ^{39}Ar released. The trapped $^{40}\text{Ar}/^{36}\text{Ar}$ ratio for the plateau steps is 309.5 ± 47.8 and the isochron age 44.6 ± 0.7 Ma. The age spectrum for the leucogranite LK198 (figure 5) yielded a saddle-shaped pattern, the apparent ages from the initial steps being very high starting with ~ 80 Ma and then decreasing progressively. Such a pattern is a clear signature of excess argon. Though most of the excess argon gets released at low temperatures, a significant amount of it is found to be released at high temperature steps as well (Zeitler and Fitz Gerald 1986) giving rise to characteristic saddle-shaped spectrum (McDougall and Harrison 1999).

The intermediate steps for this sample LK198, however, yielded a cooling pattern with apparent ages ranging from ~ 36 Ma to ~ 18 Ma. The ~ 36 Ma age can be taken as the upper limit for the crystallization of this sample. A muscovite separate from this rock, LK198M (figure 5) has yielded an excellent plateau age of 29.8 ± 0.2 , Ma consisting of 100% of argon released. The isochron for this sample yielded a trapped $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 288.9 ± 5.3 , very close to the atmospheric value, with an age of 29.8 ± 0.4 Ma. The existence of an excellent plateau comprising 100% of ^{39}Ar released, and the absence of a cooling pattern indicates that the sample has not undergone slow cooling through its closure temperature. It must have been brought down below its closure temperature immediately after its crystallization at 29.8 ± 0.4 Ma.

4.1 Modeling the whole rock age spectra for basalts

The release of argon during step-heating experiments in a laboratory essentially follows the same laws of volume diffusion as the retention of argon during the cooling of the rock in nature. In principle, an age spectrum can be translated into the cooling history experienced by the sample. Lovera *et al* (1989) proposed a method of retrieving this cooling history from the K-feldspars that have discrete non-interacting multi-diffusion domains (MDD). The MDD model proposed for the K-feldspar can be extended to the whole rock if its different mineral phases are considered as different non-interacting diffusion domains. These domains corresponding to different minerals in a whole rock sample will have different kinetic energies; however, Lovera *et al* (1993) showed that the calculation of cooling histories is not very sensitive to the choice of single or multiple activation energy models. This

Figure 3. Age spectra and isochron plots for Indus Suture basalts.

model has not been used so far to derive cooling histories from the whole rock samples. We applied this MDD approach on the basalt samples. We used the FORTRAN programmes given by O M Lovera

(<http://oro.ess.ucla.edu/argonlab/programs.html>) to calculate the diffusion parameters and cooling history of these samples. The monotonic cooling model has been used to generate the age

Figure 4. Whole rock and biotite age spectra and isochron plots for Lehigh granodiorite LK 24.

spectra for the two basalt samples, which exhibited cooling patterns. For the sample LK182 the model-calculated age spectrum exactly matches the experimentally derived age spectrum (figure 6). The diffusion parameters and other model parameters used to calculate this age spectrum are given in table 1. Various cooling histories corresponding to the age spectra are given in figure 6. Sample LK176 has low apparent-ages at higher temperatures after yielding a plateau for the four middle temperature steps. This disturbed pattern at higher temperatures is not reflected in the model generated age spectrum.

However, the experimentally obtained age spectrum matches the model generated age spectrum for about 80% of total gas released (figure 7). Hence the model provides a fairly good idea about the

cooling histories of these samples. Both the samples show rapid initial cooling and slow subsequent cooling. A plausible cooling history interpretation of this kind of pattern is that both the samples have experienced a large tectonic event, with associated temperature increase, sufficient to reset the argon clock for these older ophiolitic basalts. The initial rapid cooling indicates the quick termination of that event. The subsequent slow cooling could be due to their exhumation if these samples were subjected to burial by that event. Such an event is most likely large scale thrusting induced by the ongoing collision. The ages for this event registered by these two samples are ~ 38 Ma and ~ 46 Ma respectively, a difference of 8 MY. The differences in age for this event reflect its protracted nature, not unexpected for large scale thrusts.

B Figure 5. (A) Whole rock age spectrum for Himya leucogranite LK198. (B) Age spectrum and isochron plot of muscovite separated from the Himya leucogranite.

5. Discussion

Ophiolite obduction onto continents is a major phenomenon associated with collisional orogeny. The knowledge of the age of the obduction is crucial to understand whether ophiolite emplacement marks the initiation of the collision (syn-collision) or it precedes the collision. However the timing

of obduction is often a matter of debate. In the Ladakh-Zaskar region the timing of ophiolite obduction has not been unanimously agreed upon. Colchen *et al* (1986) and Reuber (1986) suggested it to be of post-early Eocene age coinciding with the collision, while Searle *et al* (1997) and Guillot *et al* (2003) advocated it to be of late Cretaceous age i.e., pre-collision. This ambiguity results from

Figure 6. (a) Arrhenius plot; (b) $\log(r/r_0)$ plot; (c) age spectrum; (d) modeled cooling history, for the basalt sample LK182 from Sumdo Nala of Indus Suture.

the fact that obduction timing is mainly deduced from the reconstructed stratigraphic sequences. The effect of tectono-thermal events due to the ongoing collision on the radioactive clocks in the trapped ophiolites has been demonstrated for the Shyok suture zone (Bhutani *et al* 2003). Absolute dating of rocks from an ophiolitic mélangé should in principle provide the age of formation of the ocean floor. Variable absolute ages from the

ophiolites have been interpreted as showing variable environments of formation, even though the geochemical signatures have not been unambiguous (Thakur and Bhat 1983; Hébert *et al* 2000). Alternatively, their variable absolute ages could be because of variable degrees of age-resetting due to collision-related deformation. We propose here that ages of most of ophiolites get reset during continent-continent collisions. This is evidenced by

Table 1. Parameters used to model the cooling history of the two basalts samples.

Sample	Domain #	Volume fraction	Domain size
LK182 ^a	1	0.05908	0.00131
	2	0.15615	0.00170
	3	0.26910	0.00456
	4	0.16335	0.00578
	5	0.10135	0.01182
	6	0.13093	0.06231
	7	0.11352	0.20015
	8	0.00652	1.000
LK176 ^b	1	0.08492	0.13277
	2	0.72296	0.32086
	3	0.19212	1.0000

^a Activation energy $E = 65.3$ kcal/mol and $\log(D_0/r_0^2) = 11.82$ s⁻¹ used to calculate the cooling histories for sample LK182.

^b Activation energy $E = 28.3$ kcal/mol and $\log(D_0/r_0^2) = 1.95$ s⁻¹ used to calculate the cooling histories for sample LK176.

the results on the three samples of the presumably upper part of the ophiolite suite of Ladakh. The basalts from Sumdo Nala of the eastern Ladakh yielded complex age spectra. Sample LK182 gave a cooling pattern with the maximum age of ~ 38 Ma while sample LK 176 yielded a plateau for intermediate temperature steps with an age of ~ 46 Ma. These samples, from the ophiolitic melange of the Indus Suture, unlike the corresponding units of Chiktan from west, have been reset by post-collision tectono-thermal activity. This thermal event affecting the Indus Suture at ~ 46 Ma is also recorded by de Sigoyer *et al* (2000) in Tso Morari and by Weinberg and Dunlap (2000) in the Ladakh batholith as causing melting within the batholith. The regional extent of the thermal disturbance in the suture zone at ~ 46 Ma indicates a major tectono-thermal process. Guillot *et al* (2003) proposed that the heating could be related to the break-off of the Indian plate slab. Chiktan pillow lava is exposed north of the main Shergol ophiolitic mélangé exposure. The plateau age of 128.2 ± 2.6 Ma yielded by this sample is indistinguishable from its isochron age and close to its total fusion Ar age of 140.7 ± 4.4 Ma (functional equivalent of K-Ar age), indicating no significant post crystallization effects. The 128 Ma age of this pillow basalt, therefore, provides an estimate of the time of formation. The other estimates for the age of formation of the Indus Suture ophiolites also range from 130 Ma to 124 Ma (Ahmad *et al* 2003; Maheo *et al* 2004).

The above observations on the Indus Suture ophiolitic basalts need to be noted in the light of

results from the Ladakh batholith. The Leh granodiorite has given a plateau-like age of ~ 46 Ma and the Himya leucogranite has given a maximum plateau-like age of 36 Ma. Both these samples exhibit post-collision tectono-thermal effects. The biotite from the Leh granodiorite yielded a plateau age of 44.6 ± 0.3 Ma. Clift *et al* (2002) have also reported Ar-Ar ages on biotite ranging between 49 and 44 Ma, from the Ladakh batholith. Furthermore, this also supports the proposition of Weinberg and Dunlap (2000) of re-melting of the Ladakh batholith between 50 and 46 Ma. The muscovite from the Himya leucogranite yielded a plateau age of 29.8 ± 0.2 Ma. The whole rock and muscovite ages from the Himya leucogranite indicate that the crystallization was certainly much later than the collision. Similarly young post-collision ages have been reported from the leucogranites of the Kohistan batholith. Searle *et al* (1999) reported high Himalaya-type leucogranites from the Kohistan batholith of Pakistan. These leucogranites are muscovite-garnet-tourmaline granites, clearly anatectic in origin. Most U-Pb ages obtained from these granites yield the crystallization age as 30.2 ± 0.3 Ma (Krol *et al* 1996). Pari apatite and Jagot granites are reported to be 29 to 24 Ma in age (Treloar *et al* 1989; George *et al* 1993.) The present results on the Himya granite from the Ladakh batholith shows that the post-collision magmatism was not only restricted to Kohistan but was widespread throughout the Trans-Himalayan batholith, since the Gangdese batholith also contains such rocks. The northern Himalayan leucogranites, which cover an area of 4000 km², in the eastern Himalayas, may also be related to the crustal thickening-induced melting caused by the post collision compressive tectonics as discussed by Le Fort (1986).

5.1 Post-collision magma generation: Partial re-melting of batholith granitoids

The post-collision history of convergent plate margins is dominated by compressive tectonics, which leads to crustal thickening. Dewey and Burke (1973) suggested that thickening of the crust can induce melting. Wyllie (1984) has demonstrated that crust thickened to 50 km at active continental margins have the 750°C geotherm at its base. At that depth crustal melting can take place in the presence of fluids. The crustal thickening coupled with large scale thrusting produces heat and causes hydrous minerals to break down. The granitoids of the Trans-Himalaya batholith have amphibole as a common phase. Breakdown of this amphibole can release sufficient fluid to lower the solidus and generate partial melt at the base of thickened crust. These partial melt then slowly intrude the

Figure 7. (a) Arrhenius plot; (b) $\log(r/r_0)$ plot; (c) age spectrum; (d) modeled cooling history, for the basalt sample LK176 from Sumdo Nala of Indus Suture.

earlier granitoids and cool slowly by conduction. This is reflected well in the whole rock age spectrum of anatectic Himya granite, which gives a slow cooling pattern from 38 Ma to 18 Ma. Muscovite from the same rock yields a good plateau age of 29 Ma indicating that it had cooled below $\sim 350^{\circ}\text{C}$ by that time. Guillot *et al* (2003) (and references therein) also concluded, based on the available Ar-Ar, Rb-Sr and U-Pb thermochronological data, that the temperature in suture zone

was below 500°C by 40 Ma. A similar scenario has been suggested for the generation of the Higher Himalaya leucogranite—the thrusting along the Main Central Thrust (MCT) is supposed to cause sufficient heat from friction and burial for partial re-melting and emplacement of leucogranites in the Higher Himalaya. Another probable scenario for heat generation in the Higher Himalaya is suggested by Guillot *et al* (2003) in terms of subduction of the Indian plate and then decoupling

along the MCT and South Tibet Detachment System (STDS). They concluded that temperatures as high as 700°C can be achieved and maintained for short periods by this mechanism, which apparently is consistent with geochronological records of brief periods of high-temperature activity along the MCT from 25 Ma to 18 Ma, reflected in leucogranite emplacements. We here propose that the high thermal regime has affected even the pre-collision trapped ophiolites of the suture zone, such that these yield much younger ages. The tectonically induced heating soon after the collision at ~ 50 Ma slowly propagated away from the plate suture with deformation diffusing into both continental plates. The ages obtained on the two samples of basalts from the suture zone ophiolites indicate the protracted duration of the thermal event, which is also recorded by the Himya granite.

U-Pb crystallization ages of Baltoro granites from the Karakoram batholith are 21 ± 0.5 Ma (Parrish and Tirrul 1989) and 25.5 ± 0.8 Ma (Scharer *et al* 1990). These granites lie north of the Indus Suture and their anatectic origin and post-collision ages suggest that they might also have resulted from the crustal thickening-induced melting. It, therefore, appears that post-collision compressive tectonics have affected the pre-existing rocks on both sides of the Indus Suture.

6. Conclusions

^{40}Ar - ^{39}Ar data for the Ladakh batholith and Indus Suture ophiolites provide a thermochronological sequence for the evolution of the India-Asia collision zone. Consequent to the India-Asia collision at ~ 55 Ma, deformation started at the plate boundaries producing a sufficient crustal thickness for partial-melting of the Ladakh batholith in the presence of fluids at ~ 46 Ma. The last-stage melt intruded the main plutonic mass in the form of leucogranites and cooled through a temperature of 350°C by around 29 Ma. The high thermal regime (temperature > 500°C) at the Indus Suture lasted at least till ~ 38 Ma, as registered by the basalts of ophiolites in Sumdo. The trapped

ophiolites of this suture are clearly affected by the post-collision tectono-thermal activity though its intensity and extent varied between different units of the ophiolite as well as different geographical locations. Basalts from the Sumdo indicate a minimum duration of ~ 8 MY for the high thermal regime since the collision, while the ~ 128 Ma old pillow basalt from Chiktan, from the western part of the Indus Suture, has remained unaffected from the post-collision thermal event. As the deformation with the associated high thermal regime propagated away from the suture and into the continental plates it led to widespread leucogranite emplacement in the form of 25–20 Ma granites of the Karakoram batholith in the north and ~ 20 Ma granites of the Higher Himalaya along the MCT south of the suture. However, the spatial position of the major thrusts could have been controlled by the pre-collision history of the continents (Dubey 2004). This tectono-thermal activity along the MCT in the Higher Himalaya, south of the suture, and in the Karakoram batholith, north of the suture, therefore appears to be a large scale manifestation of the process which started with collision at the plate boundaries in the Trans-Himalaya.

Acknowledgements

This work was carried out by us at the Physical Research Laboratory, Ahmedabad. The authors are thankful to Drs. Mark Harrison, Igor Villa and Mike Searle for their useful suggestions during discussions in different HKT meetings. The authors also thank Dr. O M Lovera whose FORTRAN programmes they have used in the present work. The manuscript has been greatly improved by critical reviews and useful suggestions by Dr. Stephane Guillot, Dr. Ashok Dubey and an anonymous reviewer. The authors would also like to thank Mrs. Tahira Meer and Janaab Yasin Chaunka and their family at Leh and Janaab Abdul Kayyum Kotidaar and Janaab Raoof and their family at Choglamsar in Ladakh for their kind help and hospitality during field work.

(Appendix follows)

Appendix

Table A1. Argon isotopic composition and apparent ages of sample LK97/182 (Sumdo Nala) at different temperature steps. The errors in ages are without and with (bracketed) errors in *J*. **J = .002113 ± .000032.**

Temp. °C	³⁶ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁹ Ar ±1σ	Age (Ma) ±1σ	³⁹ Ar%	⁴⁰ Ar*%	³⁷ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁶ Ar ±1σ
450	0.011013	6.89	13.79	0.47	52.74	0.2477	625.3
	0.000087	0.10	0.39(0.44)				
500	0.003397	5.973	18.85	2.90	83.20	0.2650	1758.5
	0.000030	0.038	0.13(0.31)				
550	0.001864	6.907	24.07	8.45	92.03	0.15152	3706.1
	0.000012	0.040	0.13(0.38)				
600	0.000763	8.369	30.78	22.90	97.30	0.05572	10961.4
	0.000012	0.048	0.16(0.49)				
650	0.003079	9.728	33.30	27.72	90.65	0.05015	3159.0
	0.000025	0.056	0.18(0.53)				
700	0.0008544	9.815	36.09	14.19	97.43	0.06657	11487.1
	0.0000074	0.057	0.18(0.57)				
750	0.001927	10.988	39.28	5.37	94.82	0.13536	5701.1
	0.000050	0.064	0.22(0.63)				
800	0.002510	10.94	38.48	7.27	93.22	0.2452	4360.8
	0.000038	0.10	0.21(0.61)				
850	0.003676	11.182	38.08	5.40	90.28	1.3069	3041.4
	0.000080	0.065	0.23(0.61)				
900	0.00242	10.674	37.57	3.92	93.30	1.5736	4412.4
	0.00015	0.063	0.26(0.62)				
950	0.01440	14.31	37.95	1.06	70.28	10.783	994.2
	0.00067	0.39	0.98(1.13)				
1000	0.0438	32.96	74.77	0.15	60.75	72.91	752.9
	0.0053	2.07	9.48(9.54)				
1050	0.064	48.16	107.9	0.08	60.58	89.06	749.7
	0.014	4.01	20.7(20.7)				
1100	0.131	99.1	216.9	0.07	61.00	90.05	757.8
	0.049	12.4	64.7(64.7)				
1400	0.126	153.4	396.3	0.08	75.77	57.27	1219.7
	0.082	16.3	86.3(86.5)				
Total	0.002494	9.629	33.58	100.00	92.35	0.6195	3860.2
	0.000075	0.028	0.12(0.52)				

Table A2. Argon isotopic composition and apparent ages of sample LK176 (Sumdo Nala) at different temperature steps. The errors in ages are without and with (bracketed) errors in *J*. **J = .002256 ± .000027.**

Temp. °C	³⁶ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁹ Ar ±1σ	Age (Ma) ±1σ	³⁹ Ar%	⁴⁰ Ar*%	³⁷ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁶ Ar ±1σ
450	0.0506	39.48	97.13	0.60	62.13	2.274	780.2
	0.0013	0.55	2.18(2.45)				
500	0.03385	16.66	26.87	3.95	39.94	3.398	491.99
	0.00038	0.11	0.59(0.67)				
550	0.017570	12.965	31.36	7.57	59.96	1.784	737.94
	0.000091	0.088	0.33(0.50)				
600	0.01230	15.077	45.97	12.48	75.90	1.2575	1226.0
	0.00023	0.089	0.41(0.68)				
650	0.04560	25.21	47.14	17.46	46.56	0.7514	552.91
	0.00059	0.15	0.84(1.00)				

Table A2. (Continued)

Temp. °C	$^{36}\text{Ar}/^{39}\text{Ar}$ $\pm 1\sigma$	$^{40}\text{Ar}/^{39}\text{Ar}$ $\pm 1\sigma$	Age (Ma) $\pm 1\sigma$	$^{39}\text{Ar}\%$	$^{40}\text{Ar}^*\%$	$^{37}\text{Ar}/^{39}\text{Ar}$ $\pm 1\sigma$	$^{40}\text{Ar}/^{36}\text{Ar}$ $\pm 1\sigma$
700	0.00809	14.154	47.24	13.16	83.10	0.5357	1748.8
	0.00014	0.084	0.34(0.65)			0.0023	32.6
750	0.006743	13.642	46.79	21.34	85.39	0.5559	2023.1
	0.000024	0.080	0.28(0.61)			0.0022	12.6
800	0.01642	14.996	40.81	9.63	67.64	3.036	913.27
	0.00013	0.092	0.35(0.59)			0.019	8.72
850	0.03232	19.53	40.14	5.75	51.09	16.111	604.14
	0.00026	0.13	0.53(0.71)			0.032	5.92
900	0.03061	18.70	38.88	4.06	51.64	21.584	611.0
	0.00085	0.14	1.11(1.20)			0.043	17.4
950	0.08201	30.10	23.72	2.00	19.49	38.786	367.04
	0.00058	0.24	1.10(1.14)			0.078	3.80
1000	0.0597	39.02	84.96	1.10	54.79	126.80	653.6
	0.0032	0.24	3.76(3.88)			0.49	35.3
1050	0.0339	32.98	91.13	0.90	69.64	211.15	973.4
	0.0057	1.80	8.77(8.83)			2.31	171.1
Total	0.02226	17.588	44.26	100.00	62.61	6.930	790.30
	0.00013	0.041	0.21(0.56)			0.022	4.94

Table A3. Argon isotopic composition and apparent ages of sample LK97/209 (Chiktan Pillow Lava) at different temperature steps. The errors in ages are without and with (bracketed) errors in J . $J = .002369 \pm .000028$.

Temp. °C	$^{36}\text{Ar}/^{39}\text{Ar}$ $\pm 1\sigma$	$^{40}\text{Ar}/^{39}\text{Ar}$ $\pm 1\sigma$	Age (Ma) $\pm 1\sigma$	$^{39}\text{Ar}\%$	$^{40}\text{Ar}^*\%$	$^{37}\text{Ar}/^{39}\text{Ar}$ $\pm 1\sigma$	$^{40}\text{Ar}/^{36}\text{Ar}$ $\pm 1\sigma$
450	1.182	376.17	111.0	3.11	7.12	3.470	318.16
	0.021	7.01	13.0(13.1)			0.067	6.10
500	0.4038	148.66	121.14	9.44	19.73	2.9371	368.12
	0.0049	0.87	6.33(6.48)			0.0059	4.81
550	0.2638	110.28	133.06	17.84	29.31	2.5796	418.01
	0.0010	0.64	2.34(2.79)			0.0074	2.64
600	0.1954	89.49	130.80	12.30	35.48	11.123	458.00
	0.0016	0.56	2.44(2.86)			0.037	4.34
650	0.16612	79.23	124.40	12.37	38.04	13.114	476.96
	0.00059	0.47	1.68(2.20)			0.081	2.99
700	0.1394	72.46	128.89	7.07	43.16	12.421	519.85
	0.0017	0.54	2.43(2.84)			0.025	6.96
750	0.10206	53.83	98.41	4.07	43.97	26.805	527.44
	0.00079	0.40	1.41(1.81)			0.054	5.02
800	0.2241	86.74	85.58	2.17	23.65	33.68	387.03
	0.0030	0.58	4.16(4.27)			0.15	5.74
850	0.4885	168.58	100.7	1.53	14.37	16.70	345.11
	0.0089	1.42	10.7(10.7)			0.31	6.58
900	0.5825	194.10	91.53	1.29	11.32	21.77	333.22
	0.0031	1.22	5.44(5.54)			0.20	2.58
950	0.3772	147.46	147.58	2.08	24.41	48.01	390.92
	0.0045	1.17	6.10(6.33)			6.93	4.77
1000	0.2154	101.18	153.64	2.92	37.10	89.39	469.79
	0.0022	0.88	3.59(3.99)			0.43	5.85
1050	0.2312	112.52	179.61	7.70	39.28	38.99	486.69
	0.0020	0.69	3.16(3.75)			0.11	4.91

Table A3. (Continued)

Temp. °C	³⁶ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁹ Ar ±1σ	Age (Ma) ±1σ	³⁹ Ar%	⁴⁰ Ar*%	³⁷ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁶ Ar ±1σ
1100	0.2401	120.21	199.10	7.19	40.98	22.525	500.72
	0.0019	0.77	3.31(3.99)			0.045	4.88
1150	0.2168	114.63	204.02	2.57	44.10	20.84	528.7
	0.0048	1.44	7.44(7.78)			0.16	13.2
1200	0.128	81.13	175.8	2.19	53.26	26.43	632.2
	0.013	4.09	22.0(22.1)			0.28	73.0
1250	0.038	56.59	184.3	1.63	80.24	31.14	1495.5
	0.022	6.58	35.9(36.0)			0.21	897.1
1300	0.017	51.87	189.5	2.54	90.14	32.14	2995.7
	0.021	6.36	34.5(34.6)			0.10	3724.6
Total	0.25903	110.78	140.65	100.00	30.90	17.74	427.67
	0.00098	0.31	1.57(2.24)			0.15	1.96

Table A4. Argon isotopic composition and apparent ages of sample LK24 (Leh, Ladakh Batholith) at different temperature steps. The errors in ages are without and with (bracketed) errors in J. **J = .002256 ± .000016.**

Temp. °C	³⁶ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁹ Ar ±1σ	Age (Ma) ±1σ	³⁹ Ar%	⁴⁰ Ar*%	³⁷ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁶ Ar ±1σ
500	0.16419	55.00	26.19	1.47	11.78	0.1967	334.98
	0.00088	0.33	1.45(1.46)			0.0072	2.50
550	0.06299	26.43	31.53	2.53	29.57	0.12480	419.59
	0.00022	0.15	0.56(0.60)			0.00057	2.59
600	0.04755	23.55	38.25	4.94	40.34	0.09223	495.27
	0.00025	0.14	0.53(0.59)			0.00063	3.59
650	0.010805	12.927	39.18	5.82	75.30	0.07354	1196.39
	0.000037	0.075	0.26(0.38)			0.00074	7.36
700	0.01417	13.656	38.12	4.27	69.33	0.1060	963.4
	0.00019	0.079	0.35(0.44)			0.0023	14.1
750	0.023864	16.825	39.34	4.02	58.09	0.16382	705.06
	0.000083	0.098	0.35(0.44)			0.00050	4.36
800	0.03880	20.84	37.73	4.76	44.97	0.2734	536.98
	0.00018	0.12	0.45(0.52)			0.0011	3.70
850	0.05378	26.03	40.78	6.02	38.94	0.5569	483.99
	0.00019	0.15	0.54(0.61)			0.0022	2.96
900	0.018589	16.886	45.78	12.31	67.47	1.8963	908.39
	0.000086	0.098	0.35(0.47)			0.0038	6.20
950	0.006169	13.500	46.90	26.61	86.50	4.0312	2188.4
	0.000025	0.080	0.28(0.43)			0.0081	14.4
1000	0.00984	14.33	45.90	12.43	79.71	2.0099	1456.7
	0.00015	0.11	0.40(0.51)			0.0040	24.5
1050	0.03253	19.30	38.99	8.25	50.18	2.2158	593.18
	0.00025	0.15	0.57(0.63)			0.0044	6.01
1100	0.04551	22.25	35.46	3.70	39.56	1.2352	488.89
	0.00064	0.24	1.18(1.20)			0.0025	8.51
1150	0.0600	25.42	31.07	1.26	30.29	2.534	423.9
	0.0021	0.64	3.51(3.51)			0.021	18.0

Table A4. (Continued)

Temp. °C	$^{36}\text{Ar}/^{39}\text{Ar}$ ±1σ	$^{40}\text{Ar}/^{39}\text{Ar}$ ±1σ	Age (Ma) ±1σ	$^{39}\text{Ar}\%$	$^{40}\text{Ar}^*\%$	$^{37}\text{Ar}/^{39}\text{Ar}$ ±1σ	$^{40}\text{Ar}/^{36}\text{Ar}$ ±1σ
1200	0.0414	21.45	37.16	0.76	43.01	3.424	518.6
	0.0031	1.13	5.78(5.79)			0.063	47.7
1250	0.0453	21.65	33.29	0.58	38.13	3.634	477.6
	0.0047	1.58	8.38(8.38)			0.019	60.3
1300	0.0237	16.50	38.23	0.27	57.54	4.244	695.9
	0.0055	1.64	9.21(9.21)			0.028	176.3
Total	0.024546	17.731	42.14	100.00	59.09	1.9476	722.35
	0.000068	0.040	0.16(0.33)			0.0024	2.45

Table A5. Argon isotopic composition and apparent ages of sample LK24B (Biotite, Ladakh Batholith, Leh) at different temperature steps. The errors in ages are without and with (bracketed) errors in J . $J = .002237 \pm .000016$.

Temp. °C	$^{36}\text{Ar}/^{39}\text{Ar}$ ±1σ	$^{40}\text{Ar}/^{39}\text{Ar}$ ±1σ	Age (Ma) ±1σ	$^{39}\text{Ar}\%$	$^{40}\text{Ar}^*\%$	$^{37}\text{Ar}/^{39}\text{Ar}$ ±1σ	$^{40}\text{Ar}/^{36}\text{Ar}$ ±1σ
450	0.06023	22.24	17.85	0.34	19.99	0.1738	369.32
	0.00027	0.20	0.82(0.83)			0.0060	3.65
500	0.02256	11.99	21.36	0.70	44.41	0.08516	531.59
	0.00013	0.11	0.43(0.45)			0.00065	5.49
550	0.013291	12.732	35.18	1.84	69.15	0.01369	957.97
	0.000062	0.081	0.29(0.38)			0.00061	7.04
600	0.004585	11.755	41.48	3.57	88.47	0.0107	2563.7
	0.000091	0.070	0.27(0.39)			0.0021	52.7
650	0.003647	12.296	44.70	8.87	91.24	0.02706	3371.6
	0.000065	0.071	0.26(0.40)			0.00028	62.4
700	0.000815	11.444	44.65	12.28	97.90	0.003521	14044.5
	0.000023	0.066	0.23(0.39)			0.000048	410.6
750	0.001454	11.652	44.72	10.20	96.31	0.01581	8014.0
	0.000038	0.068	0.24(0.39)			0.00026	211.3
800	0.001522	11.734	44.96	6.03	96.17	0.01021	7709.0
	0.000050	0.069	0.24(0.40)			0.00049	253.9
850	0.003075	12.147	44.78	7.67	92.52	0.04084	3950.0
	0.000039	0.071	0.25(0.40)			0.00077	53.8
900	0.00231	12.042	45.26	8.45	94.33	0.04149	5211.0
	0.00034	0.070	0.47(0.56)			0.00017	773.5
950	0.001437	11.580	44.46	15.36	96.33	0.05667	8059.5
	0.000033	0.067	0.23(0.39)			0.00011	188.8
1000	0.000874	11.408	44.43	16.25	97.74	0.0402	13049.0
	0.000063	0.066	0.24(0.39)			0.0015	949.6
1050	0.000610	11.360	44.55	8.17	98.41	0.07106	18632.4
	0.000042	0.067	0.24(0.39)			0.00048	1301.9
1150	0.0019	11.08	41.97	0.20	94.96	2.946	5858.3
	0.0018	0.80	3.79(3.80)			0.055	5560.3
Total	0.002374	11.762	44.082	100.00	94.04	0.04864	4954.5
	0.000034	0.022	0.086(0.318)			0.00029	70.6

Table A6. Argon isotopic composition and apparent ages of sample LK97/198 (Himya, Ladakh Batholith) at different temperature steps. The errors in ages are without and with (bracketed) errors in *J*. **J = .002429 ± .000015.**

Temp. °C	³⁶ Ar/ ³⁹ Ar ±1σ	±1σ ±1σ	Age (Ma) ±1σ	³⁹ Ar%	⁴⁰ Ar*%	³⁷ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁶ Ar ±1σ
450	0.0720 0.0012	39.89 0.24	79.75 1.74(1.80)	1.15	46.65	0.0474 0.0021	553.88 9.92
500	0.02359 0.00012	13.930 0.087	30.24 0.36(0.41)	1.63	49.96	0.1747 0.0037	590.56 4.53
550	0.019120 0.000066	12.198 0.076	28.47 0.30(0.34)	2.20	53.68	0.2064 0.0018	637.97 4.18
600	0.04454 0.00029	18.22 0.11	22.03 0.54(0.55)	2.39	27.76	0.21717 0.00043	409.08 3.45
650	0.006190 0.000064	6.266 0.042	19.34 0.18(0.22)	3.53	70.81	0.1639 0.0010	1012.3 12.1
700	0.004645 0.000019	5.558 0.034	18.25 0.13(0.17)	4.19	75.30	0.1747 0.0024	1196.51 8.02
750	0.006020 0.000026	6.242 0.038	19.45 0.15(0.19)	6.44	71.50	0.12157 0.00024	1036.96 7.15
800	0.005244 0.000018	6.324 0.039	20.80 0.15(0.20)	6.61	75.50	0.08515 0.00017	1206.05 7.79
850	0.004677 0.000020	6.547 0.040	22.49 0.15(0.21)	7.72	78.89	0.09668 0.00019	1399.76 9.62
900	0.004227 0.000015	7.220 0.045	25.98 0.17(0.23)	6.56	82.70	0.10547 0.00048	1707.9 11.1
950	0.005022 0.000026	7.946 0.048	28.10 0.19(0.25)	7.50	81.33	0.1088 0.0011	1582.3 11.8
1000	0.005347 0.000088	9.129 0.054	32.78 0.23(0.31)	9.13	82.69	0.1087 0.0027	1707.4 29.5
1050	0.005641 0.000051	9.999 0.059	36.15 0.23(0.32)	12.00	83.33	0.09653 0.00019	1772.5 18.4
1100	0.005293 0.000029	9.845 0.057	35.93 0.22(0.31)	20.91	84.11	0.08697 0.00059	1860.0 14.0
1150	0.01342 0.00017	13.947 0.090	43.22 0.40(0.48)	4.75	71.57	0.2506 0.0023	1039.5 14.4
1200	0.02458 0.00071	20.19 0.24	55.79 1.33(1.37)	1.09	64.04	0.3486 0.0029	821.6 25.7
1250	0.02958 0.00075	21.09 0.26	53.32 1.41(1.45)	1.11	58.56	0.4562 0.0077	713.0 20.0
1300	0.0354 0.0026	22.65 0.88	52.59 4.99(5.00)	0.49	53.76	0.5031 0.0057	639.1 53.6
1400	0.0686 0.0036	33.30 1.76	56.19 8.71(8.71)	0.61	39.11	0.762 0.021	485.3 36.0
Total	0.008957 0.000036	9.760 0.021	30.905 0.095(0.211)	100.00	72.88	0.12978 0.00037	1089.68 4.85

Table A7. Argon isotopic composition and apparent ages of sample LK97198M (Muscovite, Ladakh Batholith, Himya) at different temperature steps. The errors in ages are without and with (bracketed) errors in *J*. **J = .002429 ± .000015.**

Temp. °C	³⁶ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁹ Ar ±1σ	Age (Ma) ±1σ	³⁹ Ar%	⁴⁰ Ar*%	³⁷ Ar/ ³⁹ Ar ±1σ	⁴⁰ Ar/ ³⁶ Ar ±1σ
550	0.04292 0.00015	19.27 0.17	26.98 0.68(0.70)	0.36	34.19	0.0677 0.0019	448.99 4.13
600	0.04987 0	22.21 0.19	30.57 0.74(0.76)	0.80	33.64	0.03644 0.00085	445.31 3.92

Table A7. (Continued)

Temp. °C	$^{36}\text{Ar}/^{39}\text{Ar}$ ±1σ	$^{40}\text{Ar}/^{39}\text{Ar}$ ±1σ	Age (Ma) ±1σ	$^{39}\text{Ar}\%$	$^{40}\text{Ar}^*\%$	$^{37}\text{Ar}/^{39}\text{Ar}$ ±1σ	$^{40}\text{Ar}/^{36}\text{Ar}$ ±1σ
650	0.010811	10.299	29.08	1.41	68.98	0.0143	952.65
	0.000037	0.070	0.26(0.31)			0.0011	6.73
700	0.003942	8.509	30.05	4.51	86.31	0.011322	2158.5
	0.000014	0.051	0.18(0.26)			0.000062	13.5
750	0.0009092	7.555	29.82	13.93	96.44	0.003287	8309.6
	0.0000034	0.044	0.16(0.24)			0.000054	52.1
800	0.0004053	7.406	29.82	21.44	98.38	0.006099	18271.4
	0.0000026	0.043	0.15(0.24)			0.000064	149.6
850	0.0009839	7.521	29.60	16.77	96.13	0.02830	7644.5
	0.0000097	0.044	0.15(0.24)			0.00040	84.5
900	0.0008032	7.509	29.76	21.34	96.84	0.009458	9349.1
	0.0000062	0.043	0.15(0.24)			0.000042	85.8
950	0.0007518	7.582	30.12	11.21	97.07	0.003839	10085.6
	0.0000054	0.044	0.16(0.24)			0.000052	89.1
1000	0.000137	7.466	30.39	6.15	99.46	0.00605	54394.6
	0.000027	0.045	0.16(0.25)			0.00062	10806.3
1050	0.000850	7.480	29.59	1.74	96.64	0.01092	8799.6
	0.000100	0.061	0.26(0.32)			0.00018	1033.8
1100	0.01977	13.80	32.53	0.34	57.65	0.0628	697.7
	0.00079	0.25	1.37(1.39)			0.0013	30.5
Total	0.0016086	7.766	29.840	100.00	93.88	0.010985	4827.9
	0.0000047	0.018	0.062(0.192)			0.000082	16.9

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