Chapter Five

Discussion

5.1 Perspective

Importance of studying the Trans Himalayan zone to understand the evolution of the spectacular mountain ranges of Himalaya and the vast Tibetan plateau has been realized ever since the early explorers dared to penetrate the Himalaya (Lydekker, 1883; Hayden, 1907; Auden, 1935; Wadia, 1937; Heim and Ganser, 1939).

Geological information gathered over the years from the different parts of the Himalaya-Tibet orogen system has helped in establishing the stratigraphical and structural relationships and developing a broad scenario of the development of the system. However, a complete understanding of the response of the continents to collision and the subsequent deformation leading to the uplift of a vast area requires not only information regarding the spatial relationships but also information on the time scales involved in the various events, as well as on the exhumation and uplift of the deep crustal rocks to a very high altitude at present. The use of radio-isotopes for obtaining the time information has vastly helped to this end. The temperature sensitive radio chronometers such as ^{40}Ar-^{39}Ar have turned out to be especially useful in this context. The key to understand the collision related process, as pointed out earlier, lies in the Trans Himalayan Zone which not only contains the suture between the two continents but also has witnessed the pre-,syn-, and post-collision magmatic and deformation activities.

The Ladakh region in India of N-W Trans-Himalaya, bounded by the Karakoram batholith in the north and the Zanskar and Tso-Morin crystallines in the south has preserved almost the complete geological history from Paleozoic passive margin sediments to subduction related magmatism and post collision molasses (Fig.2.2). From south to north, Ladakh provides a complete section through shelf deposits, trench zone, fore-arc basin, calc-alkaline intrusive and back arc deposits (Virdi, 1987) In the following I discuss the results obtained (summarized in Table 5.1) from the four major units of the Ladakh, viz. Indus Suture Zone, Ladakh batholith, Shyok volcanics and Khardung volcanics of the Shyok Sututre Zone in the Northern Ladakh, in the perspective of available information and unanswered problems of the Ladakh sector.

***Table 5.1** Summary of the results.*

Geological Unit	**Sample and Location**	**Age Ma**	**Remark**	**Implication**
INDUS SUTURE ZONE	LK182 Sumdo	38.3 ± 0.6	Highest temp. plateau-like	Reset or syn-collisional?
	LK176 Sumdo	46.75 ± 0.7	Mid temp. plateau	Resetting event
	LK209 Chiktan	128.2 ± 2.6	Plateau age*, Isochron and the Integrated age	Age of the formation
DRAS VOLCANICS	LG290 Dras	85.6 ± 0.6	Plateau like	Formation age
LADAKH BATHOLITH	LK198 Himia	36.04 ± 0 4	Cooling pattern	Slow exhumation
	LK198-Muscovite	29.82 ± 0.2	Plateau age*	High thermal regime
	LK24 Leh	46.25 ± 0.6	Mid temp. Plateau-like	Upper limit for the end of Subduction
	LK24-Biotite	44.63 ± 0.6	Plateau age*	High thermal regime
KARAKORAM FAULT ZONE	LK47 Murgi	13.9 ± 0.1	Plateau Age*	Age of Karakoram fault activation
SHYOK SUTURE ZONE	LG166 Hunder		Excess Argon Pattern	
	Lg197 Tegar	~ 30 Ma	Excess Argon Pattern	The maximum limit
	LG188 Tegar	Min age ~12 Ma, Max. age ~30 Ma	Cooling Pattern	Reset signatures

	LK48 Murgi	Min. age ~12 Ma, Max. age ~ 20 Ma	Cooling pattern	Reflecting a major tectonothermal event at ~20 Ma
	LK57 Panamik	Max. age ~20 Ma at intermediate Temperatures	Two cooling patterns, the higher temperatures giving very high age	Overprinting of a Tectonothermal event at ~20 Ma
	LK67 Tegar	Max. age ~20 Ma at intermediate Temperatures	Two cooling patterns, the higher temperatures giving very high age	Overprinting of a Tectonothermal event at ~20 Ma
	LK68 Tegar	Max age ~30 Ma at intermediate Temperatures	Two cooling patterns, the higher temperatures giving very high age	Overprinting of a Tectonothermal event at ~20 Ma
	LK70 Tirit	Max. age ~35 Ma at intermediate Temperatures	Two cooling patterns, the higher temperatures giving very high age	Overprinting of a Tectonothermal event at ~20 Ma
KHARDUNG VOLCANICS	LK86 Tirit	Max. age ~60 Ma at intermediate steps.	Two cooling patterns	Overprinting of a tectonothermal event at ~ 60 Ma.
	LK88 Khardung	52.4 ± 0.4	Plateau age*	Age of the volcanism

LK90 Khardung	56.4 ± 0.4	Plateau age*	Age of the volcanism
LG87 Chushul	57.0 ± 0.3	Plateau age*	Age of the volcanism
LG601, Dungti	64.0 ±1.2	Plateau age*	Age of the volcanism

- *Trapped $^{40}Ar/^{36}Ar$ ratio for the Plateau age is atmospheric within error
- The MMHb-1 of 520.4 ± 1.7 Ma standard used for all the samples
- The errors quoted are 2σ

5.2 Indus Suture Zone

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 Lamayaru complex while the fore-arc sediments are grouped into Nindam formation (Sinha and Upadhyay, 1993). The well-preserved sections of continental passive margin sediments are exposed in the Spiti and Zanskar sections. The back arc sediments are found along the northern margin of Ladakh batholith.

5.2.1. The Ophiolitic melange of Indus Suture Zone

The southern margin of the Ladakh batholith is separated from the Tethyan sequences by Indus Suture characterized by the ophiolitic melange. Discontinuous ophiolitic melanges can be traced throughout Ladakh from west to east. The Zildat melange is believed to be the eastern continuation of western Shergol ophiolite and is overlain by Nidar ophiolites. It is exposed mainly in the Sumdo Nala (Fig.2.4). This ophiolitic melange is characterized by pillow lavas, basalts, peridotites, serpentinites associated with chert and exotic limestone blocks. I have analyzed two samples (LK176 and LK182) from the Sumdo nalla section of this ophiolitic melange and pillow lava (LK209) of the western Shergol ophiolitic melange from Chiktan village (Fig.2.3), which lies between Bodhkharbu and Shergol.

Ophiolite obduction onto the continents has been a major phenomenon associated with a collisional orogeny. They mark the plate boundaries along which the collision of two continents takes place. The knowledge of the age of the obduction is very crucial to understand whether ophilolite emplacement marks the initiation of the collision (syn-collision) or it precedes the colloision. However the timing of obduction remains a matter of debate in the Ladakh -Zanskar region. Colchen et al. (1986) and Reuber (1986), suggested it to be of post-early Eocene age coinciding with the collision, while Searle (1986, 1988) and Searle et al. (1997) advocated it to be of Late Cretacious i.e Pre-collision age. This ambiguity results from the fact that the obduction timing is mainly deduced from the reconstructed stratigraphic sequences.

The effect of the ongoing collision on the trapped ophiolite with respect to their radioactive clocks has not yet been explored. Absolute dating of the rocks from the ophiolitic melange in principle should give the age of the formation of the ocean floor. The variable absolute ages from the ophiolites have been interpreted to be showing the variable environments of formation, eventhough the consequent geochemical signatures have not been unambiguous (Thakur and Bhatt 1983). Alternatively, their variable absolute ages could be because of variable degree of resetting due to the collision-related deformation. I propose here that most of the ophiolites get reset during the continent-continent collision. This is reflected by the results of the two samples of the presumably upper parts of the ophiolite suite of Ladakh. While 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 (Fig. 4.2) and the sample LK 176 yielded a plateau at intermediate temperature steps giving an age of ~ 46 Ma (Fig.4.3). These samples, from the ophiolitic melange of the Indus Suture, are reset by post-collision tectono-thermal activity. To retrieve the thermal history experienced by these two samples, their age spectra are modeled using the Multi Diffusion Domain model (Lovera et al. 1989).

5.2.2. Modeling the whole rock age spectra for basalts

Ar-Ar age spectrum obtained in a laboratory step heating experiment essentially follows the same laws of volume diffusion for the loss of Argon by which it has been retained 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 for the whole rock if the 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 activation 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 model has not been used so far to derive the cooling histories from the whole rock samples. One of the reasons may be that many rocks may contain mineral phases which breakdown during the vacuum heating in the laboratory. For example biotite has been demonstrated to break down during the laboratory experiment (Harrison et al., 1985; Lo Ching-Hua et al , 2000) Therefore, I applied this MDD approach on the basalt samples and not to the granodiorite and granite samples of Ladakh batholith, which may have a significant amount of biotite. I used the FORTRAN programmes given by Lovera (http://oro.ess.ucla.edu/argonlab/programs.html) to calculate the diffusion parameters and cooling history of these samples, with necessary modification.

The monotonic cooling model has been used to generate the age spectra for the two basalt samples, which exhibited cooling patterns. For the sample LK182 the model calculated age spectrum exactly matches with the experimentally derived age spectrum. The diffusion parameters and other model parameters used to calculate this age spectrum are given in the table 5.2.

Table 5.2. *Parameters used to model the cooling history of the two basalt 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	00.06231
	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 the 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 the sample LK176.

The activation energy and $\log(D_o/r_o^2)$ are calculated using the laboratory obtained data and correspond to the linear portion of the Arrhenius curve at initial low temperatures. Number of domains and their corresponding domain sizes and volumes are estimated using the $\log(r/r_o)$ plot as discussed in chapter 3 (Section 3.3). The various cooling histories corresponding to the age spectra are given in the figs.5.1 & 5.2 Sample LK176 has low 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 with the model generated age spectrum for about the 80 % of total gas released. Hence the model gives a fairly good estimate of the cooling histories of these samples Both the samples show a rapid cooling initially and slower subsequent cooling. A plausible interpretation for this kind of cooling history could be that both the samples have experienced a large tectonic event, with an associated temperature increase sufficient to reset the argon clock for these older suture ophiolitic basalts The initial rapid cooling indicates a quick termination of that event. The subsequent slow cooling could be due to their exhumation by erosion if these samples were subjected to burial by that event. Such an event is most likely a 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, indicate that by that time they cooled sufficiently below the closure temperatures of their most retentive phase. This difference in age (~ 8 Ma) for this event probably reflects it's protracted nature, not unexpected for large-scale thrusts.

Another sample, LK 209 from western part of the Indus Suture ophiolite, however doesn't appear to have been affected by the post collision tectono-thermal activity. The sample LK 209, Chiktan pillow lava is exposed north of the main Shergol ophiolitc melange exposure. The plateau age of ~128 Ma yielded by this sample is indistinguishable from its integrated Ar-Ar age, indicating no post crystallization effects (Fig.4.1). The 128 Ma age of this pillow basalt therefore, provides an estimate of the time of formation of the part of the ocean which was subsequently trapped between the continents as ophiolites; however, the tectonic setting of formation of this ocean floor remains to be ascertained. This is the only age so far obtained from the ophiolites of Indus Suture which provides the timing of formation of the ocean floor.

5.3 The Ladakh batholith

The Ladakh batholith is generally calc-alkaline in nature ranging from gabbro to granodiorte to tonalite-granite, with granodiorite being the major constituent of the Trans-Himalayan batholith (Honegger et al., 1982; Sharma and Choubey, 1983).

Geochronological data from Ladakh batholith are rather scarce. Honegger et al. (1982) had given some Rb/Sr and U-Pb ages from western Ladakh, concluding that the main plutonic batholith intruded from ~ 100 Ma to 60 Ma though some much younger cooling ages were also obtained. The other geochronological studies from this area (Petterson and Windley, 1985; Weinberg and Dunlap, 2000) essentially give the pre-, to syn-collision crystallization ages related to the subduction along an Andean type margin. From 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). The interrelationship of different magmatic units of this batholith is complex (Ahmad et al., 1998). A muscovite bearing leucogranite phase has been identified during the field work to be intruding into the main body of batholith at some places particularly in the Eastern Ladakh. This leucogranite phase may be similar to the Pari and Jagot granites of the Kohistan batholith. The best exposure of this leucogranites is found near the village Himia east of Leh (Figs.2.2 & 2.5). This Himia leucogranite and a biotite-granodiorite (LK24) from the base of *Shanti-stupa* near Leh have been analyzed for the present study.

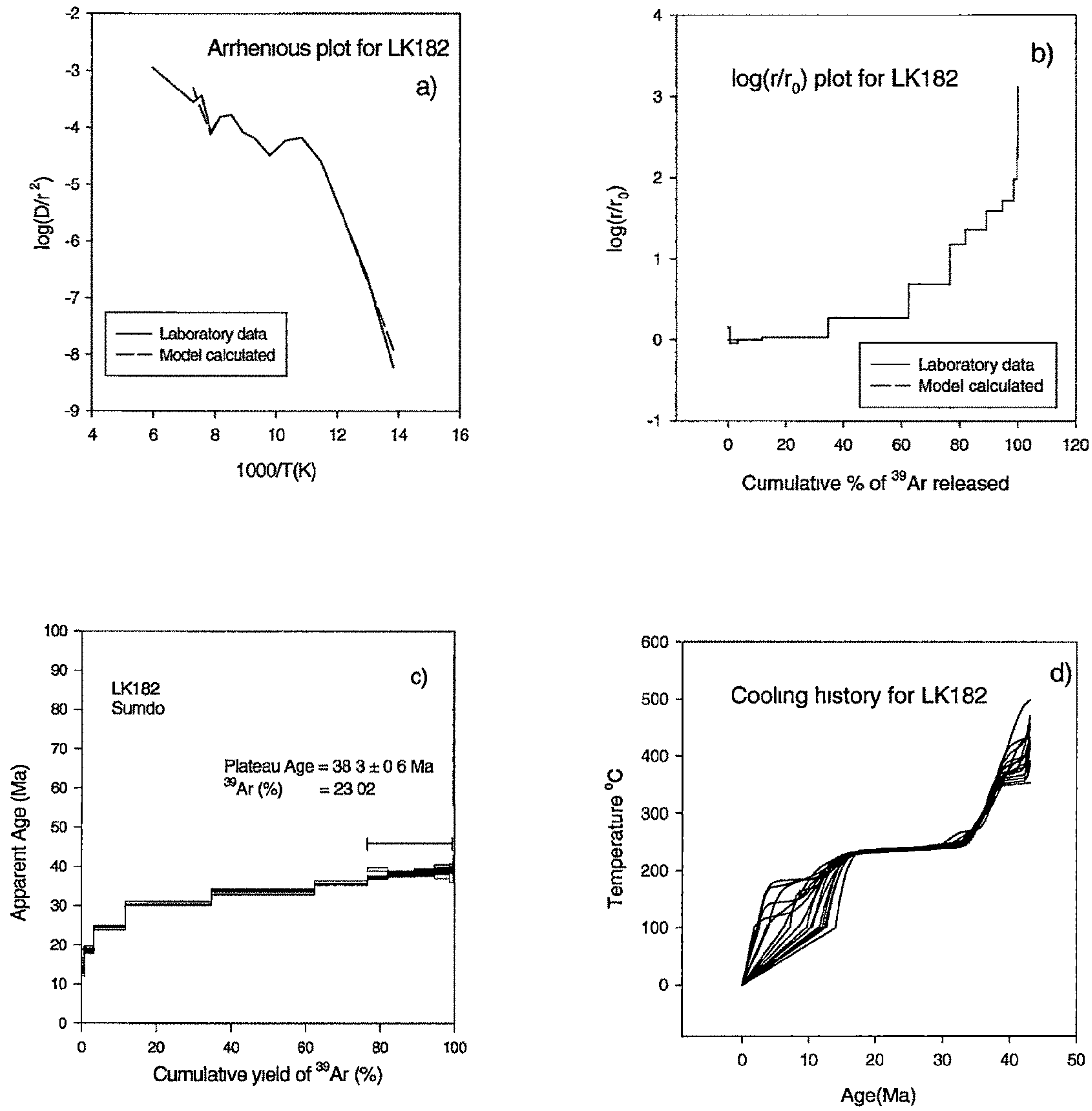

Fig.5.1 *(a) Arrhenius plot; linear portion at initial low temperatures corresponds to the activation energy and log* (D_o/r_o^2) *values used in the model (b)* $\log(r/r_0)$ *plot to estimate the diffusion parameters e.g. number of domains, volumes and sizes. (c) Laboratory obtained and modeled spectra corresponding to different cooling histories. (d) Cooling histories obtained by iteratively varying the initially assumed cooling history. The family of curves represents the total number of possible cooling paths to reproduce the laboratory obtained age spectrum.*

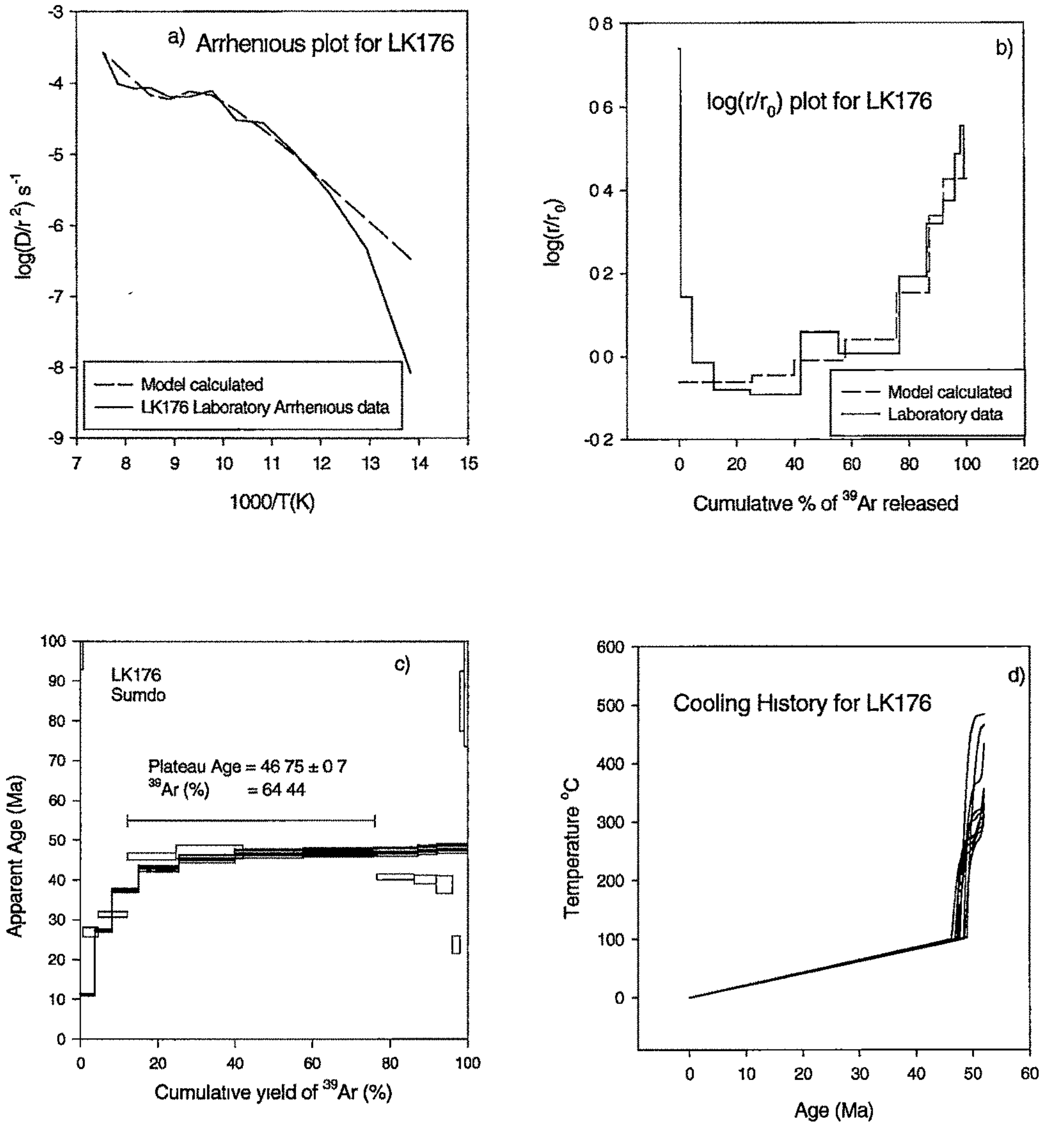

Fig.5.2 *(a) Arrhenius plot; linear portion at initial low temperatures corresponds to the activation energy and log (D_o/r_o^2) values used in the model (b) log(r/r_0) plot to estimate the diffusion parameters e.g. number of domains, volumes and sizes. (c) Laboratory obtained and modeled spectra corresponding to different cooling histories. (d) Cooling histories obtained by iteratively varying the initially assumed cooling history. The family of curves represents the total number of possible cooling paths to reproduce the laboratory obtained age spectrum.*

The results from these samples of the Ladakh bathoilth are discussed in the light of the results from Indus Suture Zone, already discussed in the previous section and the existing literature from different geographical locations. Leh granodiorite gives plateau-like age of ~ 46 Ma (Fig. 4.5) and Himia leucogranite gives a maximum plateau-like age of 36Ma (Fig. 4.7). These samples exhibit syn-, to post-collision tectono-thermal effects. The muscovite from the Himia leucogranite yielded a plateau age of ~29 Ma (Fig.4.8). The whole rock and muscovite ages for the Himia leucogranite indicate that these samples have certainly experienced temperatures, higher than ~ 350°C (closure temperature for muscovite), and probably represent the cooling after the post-collision crystallization. Such young post-collision cooling and crystallization ages are reported from the Kohistan batholith leucogranites. Searle et al. (1999) demonstrated that the leucogranites from the Kohistan batholith of Pakistan are similar to High Himalaya leucogranites.. These leucogranites are muscovite-garnet- tourmaline granite, which are clearly anatectic in origin. Most recent U-Pb ages obtained from these granites give crystallization time as 30.2 ± 0.3 Ma (Krol et al., 1996). Pari apatite and Jagot granites are reported to be 29 to 24 Ma (Treloar et al., 1989; George et al., 1993.) The present result from Himia granite from Ladakh batholith, shows that the post -collision magmatism was not only restricted to Kohistan but was widespread through out the Trans Himalayan batholith, as Gangdese batholith also contains such rocks. The N-Himalyan leucogranites, which cover an area of 4000 km^2, in the Eastern Himalayas also may be related to the crustal thickening induced melting caused by the post collision compressive tectonics as discussed by Le Fort (1986).

5.3.1. Post-collision magma generation: partial re-melting of batholith granitoids ?

The post- collision history of plate margins is dominated by the compressive tectonics, which leads to the crustal thickening. Dewey and Burk (1973), suggested that thickening of the crust can induce melting. Wyllie (1984) has demonstrated that a thickening of the crust at the active continental margin upto 50km will have 750°C geotherm at its base. At that depth crustal melting can take place in the presence of fluids. The crustal thickening coupled with the large scale thrusting produces heat and causes the hydrous minerals to breakdown. The granitoids of Trans-Himalaya batholith have amphibole as a common phase. This amphibole can produce sufficient fluid to lower the solidus and generate the partial melt at the base of thickened crust. These partial melts then slowly intrude the earlier granitoids and cool slowly by conduction. This is reflected well in the whole rock age spectrum of anatectic Himia granite, which gives a slow cooling pattern from ~ 38 Ma to 18 Ma. The maximum age provides the lower bound on the crystallization time and indicates that it cooled through ~500°C (closure temperature for hornblende) at ~38 Ma. The muscovite of the same rock yields a good plateau age as 29 Ma indicating that it was at least at 350°C at that time. However, the amphibole granodiorites may need temperatures as high as 850°C to 900°C, to remelt. Hence, the exact heat source and mechanism for the post- collision magma generation remains to be established. For the generation of higher-himalaya leucogranites- the thrusting along the MCT is supposed to cause sufficient heat from friction and burial for partial re-melting and emplacement of leucogranites in the Higher-Himalaya (Le Fort, 1986). The resetting signatures obtained from the ophiolites further indicate the wide spread post-collision thermal regime. De Sigoyer et al. (2000) record a strong heating of Tso Morari crystallines and attributed it to the crustal thickening. I propose that the tectonically induced heating soon after the collision at ~ 50 Ma slowly propagated away from the plate suture with deformation getting diffused into both the continental plates. The ages obtained from the two samples of basalts from the suture zone ophiolites indicate the protracted duration of the thermal event, which is also recorded by the Himia granite. There are evidences of deformation related strong heating and magma generation similar to the higher Himalayan leucogranites in the north of the suture zone too. In the north the U-Pb crystallization ages from Baltoro granites from Karakoram batholith are 21 ± 0.5 Ma (Parrish and Tirrul, 1989) and 25 .5 ± 0.8 Ma (Scharer et al., 1990). These granites are to the north of the Indus Suture, their anatectic origin and post-collision ages suggest that they might also have resulted from melting induced by crustal thickening. It therefore appears that the post-collision compressive tectonics have affected the pre existing rocks on both of the sides of the Suture.

5.4 Northern Ladakh (North of the Ladakh batholith)

North of the Ladakh batholith is characterized by the linear volcanic belts, and ophiolitic mélange, which separate it from the Karakoram batholith in the north (Figs. 2.2 & 2.5). The ophiolitic mélange of Nubra-Shyok valley and associated flyschoidal and Molassic sediments are believed to be representing the line of a subduction named as the Shyok Suture. This is the eastern extension of the Kohistan sector of Pakistan. Unlike the main suture between Indian and Asian plates, viz., the Indus Suture, the Shyok suture could not be traced all along the northern margin of the Trans Himalayan batholith. The Shyok suture ends in the Nubra-Shyok valley in the northern Ladakh.

Since the first reporting of the Shyok suture (Frank et al., 1977), several models have been proposed to explain the evolution of the island-arc terrain and its suturing with the Indian and Asian plates (Brookfield and Reynolds, 1981; Rai, 1983; Reynolds et al., 1983; Coward & Butler, 1985; Petterson & Windley, 1985; Sharma, 1987; Treloar et al., 1989; Searle et al., 1997). These models have usually been assumed to be valid for the whole Himalayan-Tibetan arc even though the Shyok suture could not be extended to east of the Ladakh sector. Shyok suture in Pakistan has been studied rather in detail with only a few studies carried out in the Ladakh sector of India. 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 (1981), & Reynolds et al. (1983) suggested that the Shyok suture didn't close until Miocene and the Indus suture closed earlier in the Late Cretaceous. Coward & Butler (1985), Petterson & Windley (1985), Treloar et al. (1989), and Searle et al. (1997) favored an early closure of the Shyok suture in Cretaceous. The mode of the subduction and closure also remained a matter of debate. Rai (1982) argued against any subduction along the Shyok suture. Rai (1983) reported upper Cretaceous to Eocene marine fossils from the flycsh of the Shyok suture zone. This makes it almost synchronous with the Indus suture zone flycsh.

Furthermore, the significance of the pyroclastic acidic Khardung volcanics of the northern Ladakh (Figs. 2.2 & 2.5) could not be realized fully as its age remains controversial While it appears to be overlain by the Eocene Shyok Molasse (Rai, 1983) on the basis of K-Ar ages (Sharma & Gupta, 1978) they have been assigned to Oligocene (Thakur and Mishra, 1984). Raz and Honegger (1989) described these pyroclastic volcanics from near the Teah village north of Khalsi, which are exposed in a 16 km^2 area and form 500m thick dome. These rhyolites and rhyodacites follow the trachy basalts and trachy andesites interbedded with the basalt-andesitic flows.

5.4.1. The Shyok Suture Zone

Apart from the sporadic occurrences of the ophiolitic melanges of serpentinites and ultra basics, intercalated with flycsh, mollase and volcano-sedimentary sequences, a variety of volcanic rocks ranging from basalts to basaltic andesites to andesites are reported from the Nubra-Shyok valley and are grouped into the Shyok volcanics. Shyok volcanics are a very heterogeneous sequence comprising of basalts to andesites. The heterogeneity is maximum near the village Murgi, where an isolated outcrop of serpentinites of the Shyok ophiolite is present in the Shyok volcanics. The Shyok volcanics are in contact with flycsh, metasediments and mollases at different places. At most of the places the volcanics are greenish gray, fine grained and massive in nature. The andesites are widely distributed and look tectonically transposed at many places.

A total of the 14 whole rock samples from northern Ladakh (Figs. 2.2 & 2.5) were analyzed by the step heating experiment. Four of these samples are of the Khardung volcanics, two from the type locality near the Khardung village and the two from its eastern most extension, near the Chushul and Dungti areas. The samples of the Shyok volcanics are collected mainly along the Nubra River, comprising the major geochemical varieties of this suit, including the mélange unit of Murgi.

The age spectra are disturbed, but show a consistent pattern. Two samples LG166 (Fig. 4.16) and LG 197(Fig. 4.15) from Hunder and near Tegar villages respectively yielded saddle-shaped age spectra characteristic of the excess argon. The minimum ages of ~50 Ma and 30 Ma could be the upper bound on the formation of these samples. Two samples LG 188 & LK48 from near Tegar & Murgi villages respectively yielded similar pattern of continuously rising ages, starting from ~13 Ma and going as high as ~ 20 to 30 Ma (Figs. 4.16 & 4 9).

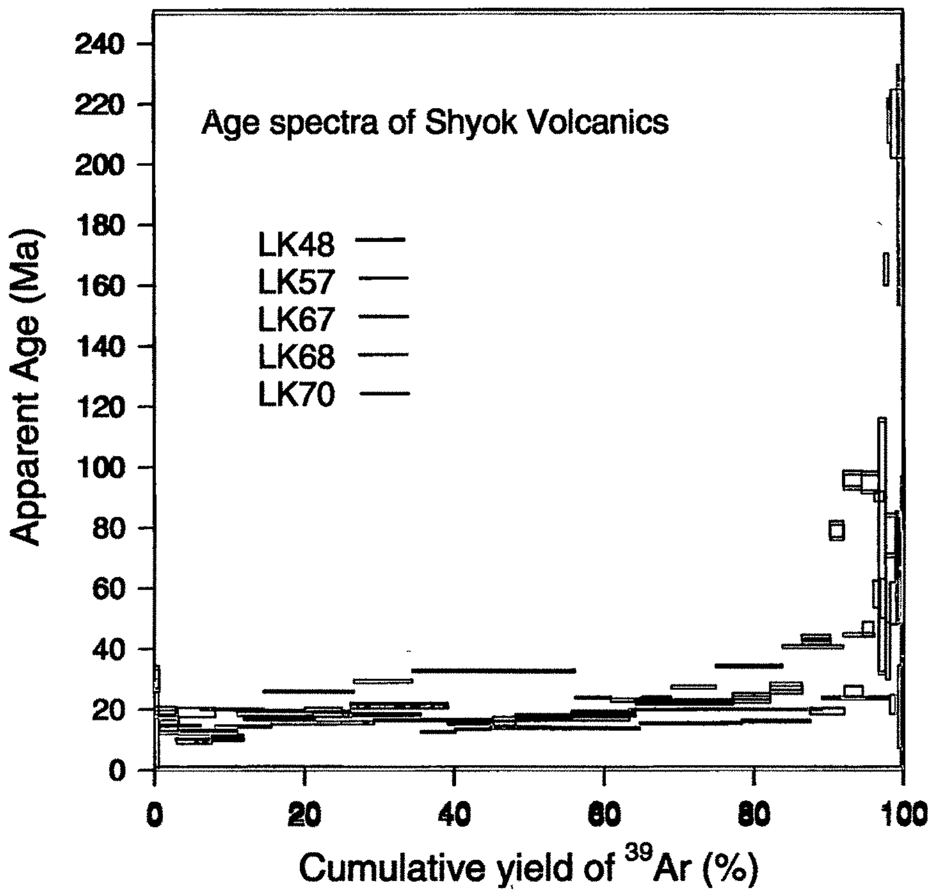

***Fig.5.3** Age spectra of Shyok Volcanics plotted together to show the consistency in their pattern*

Four samples LK57 from Panamik, LK67 and LK68 near Tegar and LK70 from near Tirit village's yield similar age spectra Figs. (4.10 to 12), which are characterized by the two distinct increasing-age patterns. The age spectra of these samples, when plotted together overlap and show two distinct patterns (Fig. 5.3) The first rising-age pattern from ~ 10 ma to 12 Ma, and going up to ~ 20 to 30 Ma for the first 40 to 50 % of the ^{39}Ar released. The second pattern also starts from the low age ~ 14 Ma and goes very high (> 70Ma)at the highest temperature..

The samples also show a systematic change with location: as the distance from the Khardung volcanics decreases (Fig.2.2), the ages in the first pattern become higher. The sample near Tirit, which is the nearest to Khardung volcanics of all the samples analyzed, yields as a high an age as ~40 Ma for the first 50% of the gas released.

The age spectra show the multi-tectonothermal events experienced by these samples. The high ages obtained for the higher temperature steps for the Shyok volcanics suggest that these may be pre-existing rocks. Rolland et al. (2000), suggest the age of the base of the Nubra-Shyok volcanics unit to be Middle Cretaceous ~108 to 92 Ma, on the basis of forminifera *Orbitolina* bearing limestone interbedded with the Shyok basalts and andesites of the Shyok volcanics. Rai (1983) also suggested that the Shyok volcanics are older than the overlying Saltoro flycsh, which yielded upper Cretaceous to Eocene fossils such as *Cyclammina* sp. of upper Cretaceous & *Numulites* sp. of Eocene. These evidences indicate that the older Shyok volcanics are affected by the later tectono-thermal events. The remarkable consistency of their age spectra (Fig. 5.3) suggests that they reflect a large-scale tectono-thermal event which had effects on a regional scale.

5.4.2. Khardung Volcanics

These basic Shyok volcanics are in contrast with the acidic & rhyolitic Khardung volcanics of the Nubra-Shyok. Khardung volcanics are pyroclastic in nature. They form a linear and irregular belt along the northern margin of the Ladakh batholith and appear to be directly overlying the batholith. These volcanics consist of rhyolite, rhydacite, dacite, tuffs, ignimbrites and volcano-sedimentary sequences. Spheroidal to ovoidal lappilii are reported from the topmost tuffaceous bed of these rocks. These tuffaceous rocks are conformably overlain by the thick lahar unit consisting of unsorted boulders and pebbles derived from the acidic volcanics. The acidic volcanism is supposed to be continuous further east up to Chushul in eastern Ladakh. The presence of lapiili, tuffs and lahar indicate the near-surface explosive eruption of these rocks.

The signatures of the younger tectono-thermal event reflected in the Shyok volcanics age-spectra is absent in the Khardung volcanics. Rhyolite samples LK 88 and LK90 from the vicinity of the village Khardung (Figs. 2.2 & 2.5) yielded good plateau ages of 52 .0 ± 0.4 and 56.4 ± 0.4 Ma respectively for more than 80 % of ^{39}Ar released and with atmospheric trapped ratios (Figs. 4.19 & 4.20). Sample LG 87 from the eastern extension of the Khardung volcanics near Chushul (Fig. 2.2) also yielded a plateau age of 57.0 ± 0.3 Ma more than 90% of ^{39}Ar released and with atmospheric ratio (Fig 4 22). Sample LG601, from the further east, near Dungti (Fig 2.2) didn't yield any plateau age, however a plateau-like age of 64.0 ± 1.2 Ma was obtained from the middle temperature steps (Fig. 4.21). All the four age spectra of the Khardung volcanics show higher apparent ages at higher temperature steps. These results indicate that explosive acidic volcanism continued at the southern margin of Asian plate atleast between 64 to 52 Ma. This is consistent with the observation that these are overlain by the Eocene Shyok molasse (Rai 1983). These volcanics are not affected by the younger tecono-thermal events which affected Shyok volcanics. The strikingly different results from the two adjacent volcanic belts indicate that these two belts formed in two different tectonics settings and evolved independently and were later juxtaposed by some large scale tectonic event, probably the activation of the Karakoram fault.

5.4.3. Simultaneous and independent evolution of the island and continental arc along the southern margin of the Asian plate

Recently Rolland et al. (2000), showed that the back-arc like geochemical signatures of the northern suture of Kohistan sector are not present in the Shyok Suture zone of the Ladakh sector. They further noted that the acidic volcanism of Khardung represents an Andean type margin like Tibet, while the Kohistan sector's northern suture represents the suturing of an island arc with the continent. Raz and Honegger (1989) provided field evidences for the presence of continental crust before the calc-alakline magma intrusion in the northern Ladakh They reported meta-sediments, shale, sandstone, quartzites, and marbles indicating of the continental crust. A 50 m thick layer of calc-silicates yielded *Megalodan & Lithiotis,* the characteristic fossils of Late Triassic to Early Jurassic, which are also reported from Kashmir (Fuchs 1982) and Karakoram (Gregan and Pant, 1983). Based on these observations it appears that the island arc setting of Kohistan sector and the northern suture doesn't extend to the east of Nubra-Shyok valley. This means that pre-collision geometry of the south Eurasian margin was such that only western side of it had small oceanic plate/crust, which facilitated the intra-oceanic subduction of the Tethys in the western side around ~ 85 Ma ago as revealed by Dras island arc sample LK290. Jurrasic fossils and older ages of Khardung volcanics indicate Andean type subduction for most of the Plate in the east at the same time (Fig. 5 4). In this scenario the Island arc and continental arc evolved simultaneously but in different tectonic settings. The present day Shyok Suture Zone and island arc type Kohistan sector represent the small portion of oceanic plate at the western part of the southern margin of the Asian plate. The flyshoids and ophiolitic mélange of the Shyok Suture formed after the Indus Suture closed along the continental part of the Asian plate. Though, according to this model, the suturing along Shyok is younger than the Indus Suture, the time difference doesn't seem to be significant, given the very small volume of the oceanic part of the Asian plate.

Sample LK 47, taken from a sheared zone along the Karakoram Batholith, in tectonic contact with the Shyok ophiolitic mélange near village Murgi (Figs. 2.2 & 2.5), yielded a very good plateau age of 13.9 ± 0.1 Ma with atmospheric trapped ratio (Fig 4.18). I have interpreted this age to be the activation age of Karakoram Fault. This is supported by Searle et al. (1998) who suggested that the activation of the Karakoram fault is post-leucogranite generation in the Karokarm batholith, i.e. younger than 18-15 Ma.
This further substantiates the model proposed here for the evolution of the northern Ladakh as Karakoram fault activation appears to be responsible to bring the Shyok volcanics in juxtaposition with the Khardung volcanics. The age spectra of Shyok volcanics also indicate an event at 12-14 Ma. Furthermore the proposed model also explains the positioning of the Karakoram fault (Fig. 5.4), which appears to have been facilitated by the weak zone between the continent-oceanic transition at the southern margin of the Asian plate.

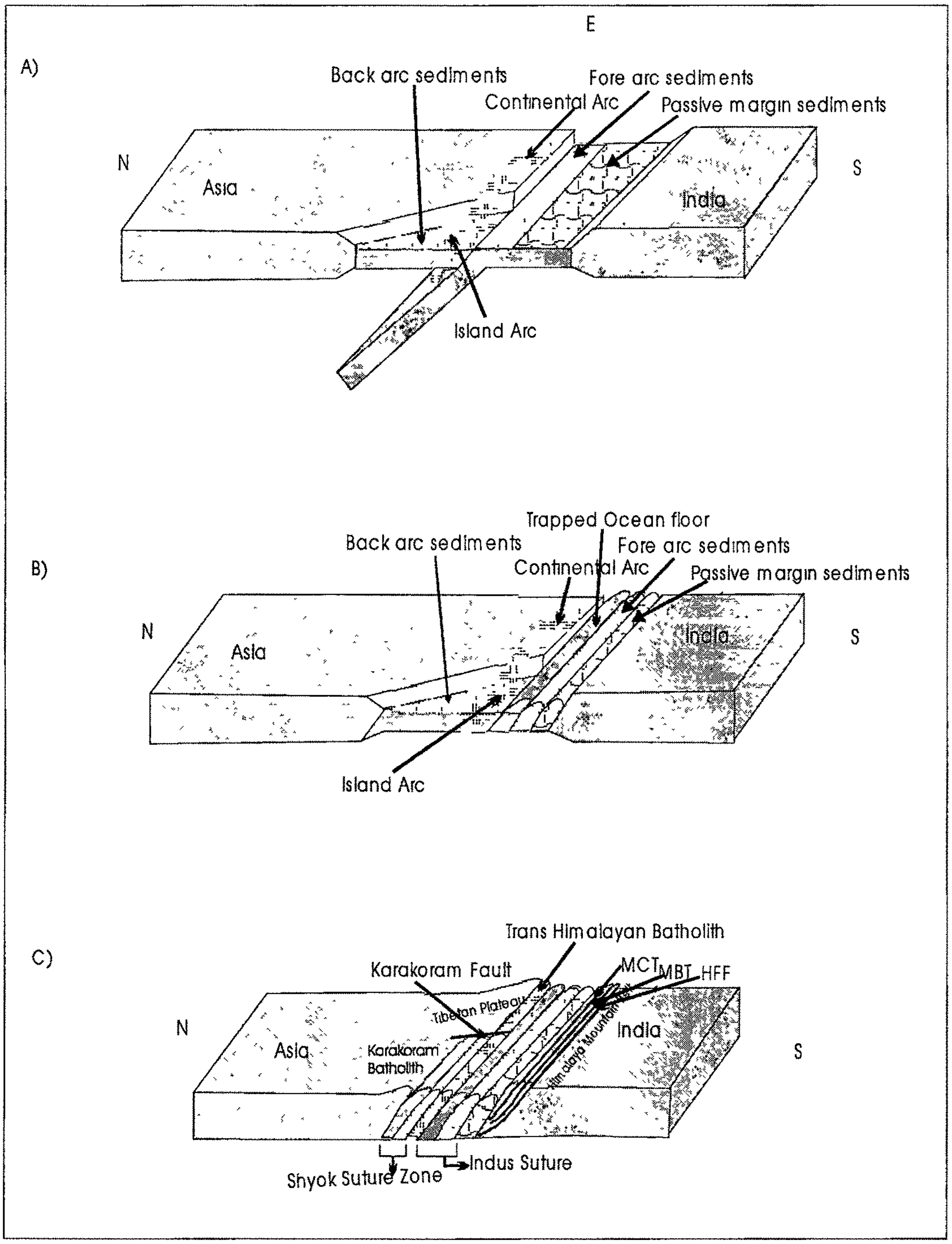

Fig. 5.4 *Cartoon diagram showing the evolution of the southern margin of the Asian plate. (A) Pre-collision boundary of the southern margin of Asian plate was partly oceanic at western end which subsequently gave rise to island arc magmatism and the back arc sedimentation while at the same time the continental margin of the plate was having the continental arc magmatism. (B). The Indus Suture closed as the Tethys ocean completely subducted , it compressed the small part of the*

oceanic crust along the Asian margin and caused the breakage along the continent-oceanic boundary. (C). The small part of the oceanic plate along the Asian continental plate formed the Shyok Suture Zone with the characteristic ophiolites and flyshoids. The boundary between the continent and ocean later acted as plane of weakness to facilitate the formation of Karakoram Fault.

For the most part the Trans Himalaya evolved in an Andean type setting, except for the small portion of intra-oceanic crust in the western side, giving rise to the Kohistan island arc

5.5 Conclusion

The Ar-Ar data from the three main tectonomorphic subdivisions of the Trans-Himalaya in Ladakh region, viz., Ladakh batholith, the Indus suture zone ophiolites and the Shyok Suture Zone volcanics provide a thermochronological sequence for the evolution of the India-Asia collision zone. The age of the collision and tectonization along the northern and southern margins of Ladakh batholith is not significantly different. The end of the subduction-related magmatic activity is represented by the highly differentiated and explosive Khardung volcanics of northern Ladakh, is dated between ~52 to 64 Ma. Consequent to the India-Asia collision at ~52 Ma, deformation started at the plate boundaries producing sufficient crustal thickness for remelting of the Ladakh batholith in the presence of fluids at ~46 Ma. The high thermal regime at the suture lasted at least till ~35 Ma ago, as registered by the basalts of Indus suture ophiolites in Sumdo. The trapped ophiolites of 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 of ~17 Ma duration of the high thermal regime since the collision, while the ~128 Ma old pillow basalt from Chiktan, from the western part of the Indus Suture, remained unaffected by post-collision thermal events. The ages obtained from the Ladakh batholith and particularly that from the Himia leucogranite suggest that the relationship of this with the coeval leucogranites of Higher Himalaya and Karakoram, which are to the south and north of it, needs to be explored. I propose that the continuously propagating deformation into the continental plates away from the suture has emplaced the 25-20 Ma granites of Karakoram batholith in the north and ~20 Ma granites of Higher Himalaya along MCT south of the suture. This tectono-thermal activity along the MCT in the

Higher Himalaya, south of the suture, and in the Karakoram batholith, north of the suture, is therefore the large-scale manifestation of the process, which started with collision at the plate boundaries in Trans-Himalaya. Such a scenario obviates the necessity of separate mechanisms to explain the formation of Trans-Himalaya, Higher Himalaya, and Karakoram leucogranites. The deformational style dominated by the N-S compression was later replaced by the eastward extrusion of the Tibetan plateau along the large-scale strike slip faults. The Karakoram fault is believed to mark the western boundary of the extruding Tibetan block. The ~ 14 Ma age obtained from the micaceous segregation from the Karakoram batholith along the right bank of the Nubra river in the northern Ladakh, is interpreted to be the age of the Karakoram fault activation. This younger large-scale event has disturbed and reheated the volcanics of the Shyok suture zone but the eastern continental arc remained unaffected indicating the separate and independent history and evolution of the two regions. The Karakoram strike slip fault could have juxtaposed these in the present position.