Chapter Six

Evolution of the India-Asia collision zone in space and time: a synthesis of thermochronological data

6.1 Introduction

India-Asia collision has resulted in contrasting styles of deformation in the two continents involved, as manifested by the Himalayan mountain chain on the Indian continent and the Tibetan plateau on the Asian continent. These spectacular results of the ongoing collision between the two continental plates have attracted the attention of many earth scientists and wealth of information has been generated over the years (Allegre et al, 1984; Yin and Harrison, 2000). Several review papers have attempted to synthesize the available information to build a general understanding of the evolution of the India Asia collision zone (Harrison et al, 1992; Le fort, 1996; Searle, 1996; Hodges, 1999; Pande, 1999; Yin & Harrison; 2000). However, these reviews have been founded on the studies conducted in the Tibetan plateau (north of the Trans Himalaya) and that of Himalayan mountain chain (south of the Trans Himalaya). Little emphasis has been given to the Trans Himalayan Tethys zone which consists of the suture and the pre-, syn- and post-collision magmatic rocks, mainly due to absence of information about this zone except from a couple of isolated patches as of Kohistan sector in western part and Gangdese sector in central part, which are mainly studied for stratigraphy, structure and neotectonics (Garzanti and Van Haver, 1988; Beck et al., 1995; Rowley, 1996; Treloar et al., 1996; Bilham, et al., 1997; Aitchison et al., 2000; Clift et al., 2000.) .

Rowley (1996) has highlighted the importance of the suture zone in constraining the timing of initiation of the collision, which is the fundamental question to be answered, in any attempt to build a scenario of the evolution of the collision zone. The age of initiation of the collision has still remained debatable because of the problem of correlation of the highly jumbled up stratigraphy of the suture zone. The stratigraphic estimates of the age of initiation of the collision range from 56 Ma to 40 Ma (Beck et al, 1995; Rowley, 1996). The approach of paleomagnetism assumes that the sudden decrease in the northward velocity of the Indian plate is due to the initial contact between the two continents (Klootwijk and Pierce, 1979; Dewey et al., 1989). This has been doubted (Butler, 1995), because the lithospheric response to the collision is not well understood. The approach of dating the youngest rock of the Trans Himalayan batholith, to constrain the age of the collision, has also been challenged in the light of new younger dates obtained for the batholith (Yin & Harrison 2000). The problem of the age of initiation of the collision has implications for our understanding of crustal accommodation in the collision zone since the collision started (Patriat and Achache, 1984). It is obvious that crustal accommodation in Himalaya and Tibet led to high mountain chains and the uplifted plateau but the calculated amount of crust to be accommodated, using the northward drift of Indian plate since collision, exceeds the amount that existed in these region (Coward and Butler, 1985, Ratschbacher et al., 1994, Guillot et al 2000). Various theoretical models have been proposed to explain the mechanisms of crustal accommodation (Davis et al., 1983; England and Houseman, 1986; Dalhen and Barr, 1989, Houseman and England, 1996). However, it has been soon realized that process of crustal accommodation, leading to deformation and uplift, has been highly variable in time and space as revealed by chronological and thermochronological studies (Harrison et al. 1992; Krol, et al., 1996; Chung et al., 1998). Chronology of different tectonic events and cooling histories of the magmatic and metamorphic rocks, as determined using temperature sensitive radiogenic isotope systems, provide useful information on the exhumation rates and the tectonic control of the deformation. This ^{40}Ar-^{39}Ar study of Ladakh sector of Trans Himalaya provided some information regarding the thermal state of different units through time. I have already discussed these results regarding the chronology of different tectonic events and its implication for the regional tectonic evolution in chapter 5. Here, I focus on the temperature data from the present study, in light of available thermochronological data from the other regions of the India-Asia collision zone, to build up a broad scenario for the evolution of India-Asia collision zone through time. This synthesis also attempts to throw light on the problem of crustal accommodation in the collision zone since the collision, and attempts to highlight the importance of thermochronology to understand the process of crustal accommodation through time.

6.2 Review of Thermochronological data

6.2.1. Thermochronology of Indus Suture

The basalts (samples LK176 & LK182) of Indus Suture, from Ladakh, yielded rapid cooling rates between ~ 46 Ma to ~ 35 Ma, followed by a slower cooling (Figs. 5.1 & 5.2). The cooling rate around ~ 46 Ma was > 150°C/Ma and between 38 to 35 Ma it was around ~ 30°C/Ma (Table 6.1). This is interpreted to reflect the large scale thrusting along the plate boundaries, resetting the Ar clock of the older ophiolite basalts of the suture, soon after the collision as discussed in chapter 5.

6.2.2. Thermochronology of Trans Himalayan Batholith

K-feldspar thermochronology of the plutonic rocks of the Kohistan batholith, western continuation of Ladakh Batholith, has yielded a variety of cooling rates for the different time periods (Krol et al., 1996). In the western Kohistan, the cooling rates were of the order of 40°C/Ma between 44 to 41 Ma. At 41 Ma cooling rates increased dramatically to 80°C/Ma (Krol et al., 1996). In eastern Kohistan, muscovite crystallization age from the Indus confluence aplites was found to be ~ 30 Ma (Krol et al., 1996). This is consistent with the $^{40}Ar/^{39}Ar$ age of muscovite from the Himia leucogranite of Ladakh batholith and indicates a cooling through ~ 350°C at that time (Table 6.1). The whole rock age spectrum of this rock yielded a cooling pattern from 38 to 18 Ma (Fig. 4.7). This indicates that the thermal regime was sufficiently high at ~ 38 Ma to partially re-melt the pre-existing subduction related granodiorites of Ladakh Batholith and form the leucogranite with constituent muscovite being at 350°C at ~ 30 Ma. The $^{40}Ar/^{39}Ar$ dating along the normal faults of South Tibet Detachment (STD), in the Gangdese batholith, east of Ladakh, yielded a rapid cooling episode between 8 to 4 Ma (Harrison et al, 1992), indicating the formation of the STD at ~ 8 Ma. Since the STD is supposed to be gravitational collapse structure due probably to the relaxation of stress during the eastward movement along the Red River fault, the Tibetan plateau is believed to have attained its full elevation by that time (Harrison et al, 1992).

Table 6.1 *Summary of time and temperature information derived from the present study*

Tectonic setting	***Time (Ma)***	***Cooling rate / Temperature***	***Remark***
Indus Suture Zone (ISZ)	46	150°C/Ma	Derived using the MDD model (Fig. 5.2) on the basalt (LK176) from ISZ ophiolite.
	38 to 31	30°C/Ma	Derived using the MDD model (Fig. 5.1) on the basalt from ISZ ophiolite (LK182).
Ladakh batholith	46	550 °C	Closure temperature of the hornblende, a major phase of the sample, and the maximum apparent age (Fig.4.5) of the whole rock granodiorite sample LK24.
	36	More than 350 °C	Maximum closure temperature of muscovite, a major phase of the two-mica leucogranite(LK198) and the maximum apparent plateau-like age of the leucogranite (Fig. 4.7)
	30	350°C	Closure temperature of the muscovite and the plateau age of the muscovite LK198M (Fig. 4.8)
	44	300°C	Closure temperature of the biotite and the plateau age of the biotite LK44B. (Fig. 4.6)
Shyok Suture Zone (SSZ)	60-52	700°C	Minimum temperature of eruption of Khardung volcanics (LK88,99 &LG 87, 601) and their plateau ages, interpreted as duration of emplacement/eruption , (Figs. 4.19 to 4.22)

	20	500°C	Minimum closure temperature of the highest retentive phase (pyroxene in these samples) of the shyok volcanics(LK 48,57,67 68, 70) , and their reset apparent age (Fig. 5.3).
	14	350°C	Closure temperature of the mica and plateau age (Fig. 4.18) of the micaceous segregate LK47 from the Karakoram fault zone.

6.2.3. Thermochronology of north of the Suture

$^{40}Ar/^{39}Ar$ analyses of K-feldspar samples from the northwest of Lhasa yielded age gradients between 55 and 40 Ma that are suggestive of slow cooling (~ 10°C per million year) during the initial phase of collision (Copeland et al., 1990). The corresponding low average unroofing rates (<0.3 mm/yr), indicate a slow thickening during the initial period of post-collision. Similar K-feldspar analyses of several other plutons north of the Lhasa did not reveal fast cooling rates. Uplift rate for the Quxu pluton near Lhasa, derived by plotting the ages with elevation, yielded a sharp change in the rate at ~ 20 Ma from 0.08 ± 0.02 mm/yr, to > 2 mm/yr (Zeitler, 1985). The same unroofing rates were derived by the K-feldspar thermochronology by Richter et al. (1991), for the Quxu pluton, reinforcing the conclusion that a sharp change in the unroofing rate has occurred in this region of Tibet at ~ 20 Ma. This is interpreted to be due to the rapid uplift, and hence greater crustal accommodation during this time period in the southern Tibet. The thermochronological studies in the far north of the suture, near central Kunlun, revealed the fast unroofing rates at ~ 20 Ma (Arnaud et al., 1991). In the western region the Karakoram batholith, north of the suture, yielded rapid cooling rates between 17 Ma to 5 Ma (Searle, 1996). These are related to the intrusion of Baltoro leucogranite above 750°C at 25 -21 Ma into the already hot country rock and cooled slowly for 4 Ma till ~ 17 Ma ago (Searle, 1996).

6.2.4. Thermochronology south of the Suture

In the south of the suture, the Main Central Thrust, separating the Higher Himalayas from the Lesser Himalaya, has been found to be active between ~ 25 Ma to 18 Ma from the crystallization ages of Higher Himalaya anatectic granites and the deformation along the hanging wall of MCT (Copeland et al., 1991; Harrison et al., 1998). $^{40}Ar/^{39}Ar$ dating of the individual detrital grains from the Bengal fan also confirms rapid denudation and erosion rates in the early Miocene (Copeland et al., 1990). Recently Najaman et al. (2001) showed detrital muscovites from the foreland basin of Pakistan to be between 40 to 36 Ma, indicating rapid uplift and erosion since then. Further younging of deformation towards south was supported by the fission track cooling ages from the Main Boundary Thrust (MBT) near Kohat region of northwest Pakistan, indicating a rapid cooling episode between ~ 10 to 8 Ma, related to the uplift of the MBT. The youngest thrust system in the southern most Himalaya, the Main Frontal Thrust (MFT) (Baker et al., 1988), separating the foreland sediments from the Himalaya, is shown to be active at 2.1 -1.6 Ma using magnetostratigraphy by Johnson et al. (1986) and Baker et al. (1988). The present day convergence is presumably accommodated in the east -west extension of the southern Tibet along the South Tibet Detachment (STD) zone (Armijo et al., 1986).

6.3 Propagation of deformation through time

The present day strain partitioning into various regions in the collision zone provides very important clues to understanding of the crustal accommodation. The development of GPS technology has helped in quantifying the present day relative plate motions. Out of the present day convergence rate of ~ 50 mm/yr, the total shortening rate in the Himalaya is estimated to be 18 ± 7 mm/yr (Lyon-Caen and Molnar 1985; Molnar 1988). This is consistent with the recent GPS measurements (Bilham et al., 1997), which give the convergence rates across Himalaya to be between 17.5 ± 2 mm/yr to 20.5 ± 2mm/yr Most of the present day convergence is estimated to be partitioned in the east-west extension along the strike slip faults. The major among them are Karakoram - Jiale - Red River fault system in the south, accommodating ~ 20 to 32 mm/yr and Altyn Tagh in north, accommodating ~ 30 mm/yr (Avouac and Tapponier, 1993). The rest of the convergence is being partitioned across the Tien Shan, north of the Tarim Basin in China. However, these present day estimates as such can not be extrapolated back in time. Thermochronological data from different regions of the collision zone indicate that the mode and rate of crustal accommodation have been highly variable in space and time. The rapid cooling rates in suture zone in Ladakh and Kohistan starting soon after the collision (~50 Ma) and the cooling ages of ~ 30 Ma from these region clearly indicate that most of the collision-related deformation was accommodated along the plate boundaries then. Thermochronological data from Tibetan plateau and Karakoram batholith, (north of the suture) and from the higher Himalaya (south of the suture), cluster around ~ 20 Ma. This indeed has been a major period of deformation and most of the present day features of the collision zone probably initiated at this time, by brittle crustal-stacking according to the critical taper wedge model for Himalaya (Dalhen and Barr, 1989; Davis et al., 1983) and by viscous thickening according to the thin viscous sheet model for Tibet (England and Houseman, 1986; Houseman & England 1996). These data also indicate the propagation of deformation away from the suture into both the continents with time. The southward younging of the thrusts in Himalaya, in the form of MBT activation at ~ 10 Ma and MFT activation at ~ 2 Ma, and similarly the northward younging of the thickness in the Tibetan Plateau as predicted by the thin viscous sheet model and as seen in the thermochronological data, also substantiate the proposition that the deformation and crustal accommodation has propagated away from the suture with time and has now reached up to the Tarim basin as reflected in by the Tien Shan fault activity. The ~ 8 Ma date from the STD and those of the other strike slip faults, indicates that lateral extrusion of the South Asian block started late in the history to further accommodate the crust. The lateral extrusion has since become the major mode of crustal accommodation with time as reflected in the present day estimate of strain partitioning.

6.4 Late accommodation of crust within the NW Trans Himalaya: Deformation in Shyok Suture Zone

The sequence of deformation and mode of crustal accommodation discussed above brings out that on a larger spatial scale the deformation propagated away from the plate boundaries into the continents with time.

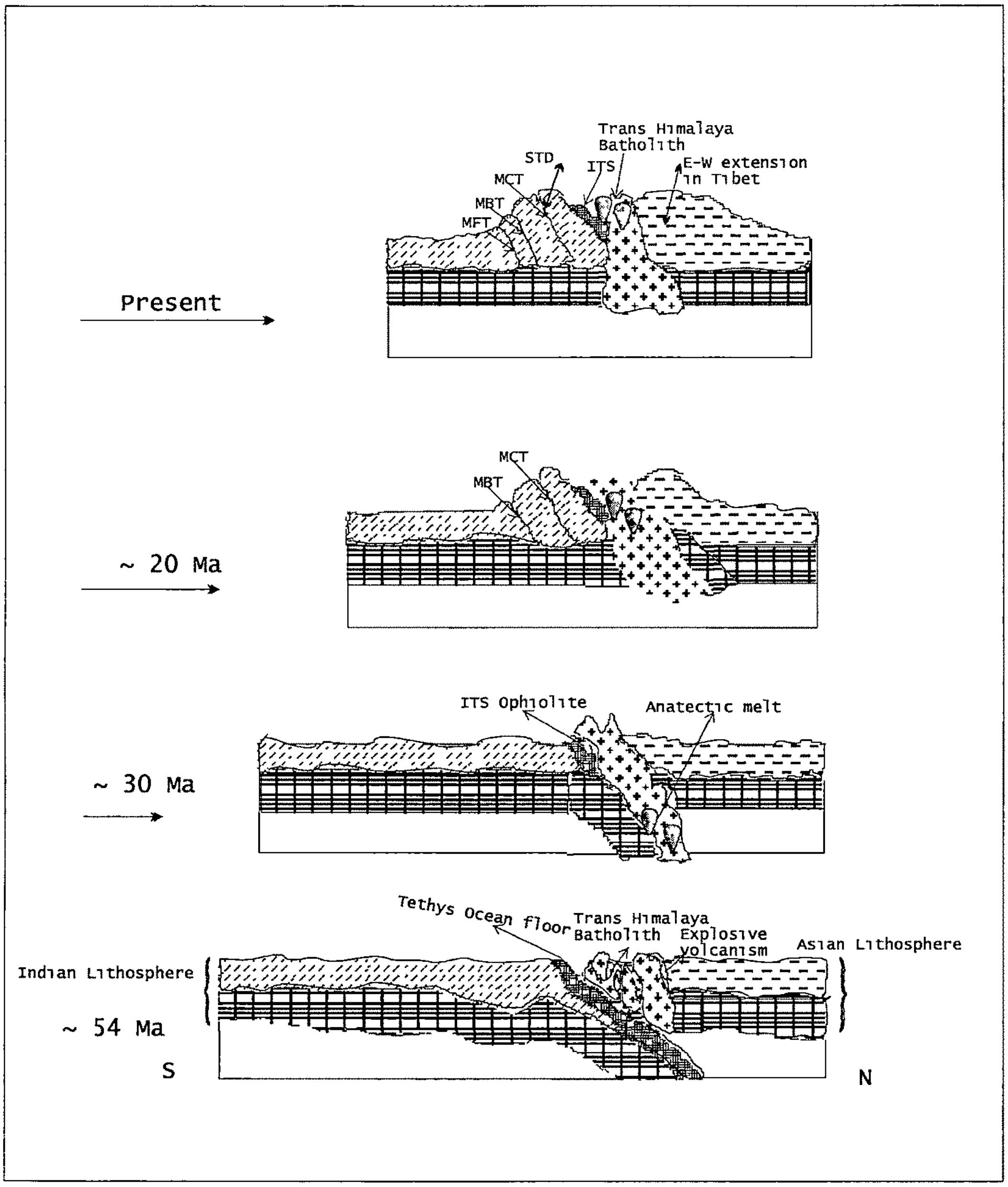

Fig. 6.1 *Cartoon diagram showing the evolution of India-Asia collision zone with time. Four main stages are shown here. Collision started at ~54 Ma ago and depicted here as showing the completion of suturing of the continents with trapped/obducted Tethys ocean and cessation of subduction related magmatism forming the Trans Himalayan batholith. Till ~ 30 Ma ago most of the deformation and crustal accommodation was restricted to plate boundary, resulting southward thrusting of the ophiolites and thickening of the Trans Himalayan batholith and southern margin of the Tibet. The thrusting at boundary and thickening of the crust generated partial anatectic melt at this time. In the next stage ~ 20 Ma ago, widespread deformation took place in the south as well as north of the plate boundary. Most of the crust accommodated in thrusting along the MCT(Main Central Thrust) in Himalayas and uplifting the Tibetan plateau in the north. (* *Fig. caption continued on next page**)*

Later stage the deformation propagated farther away from the boundary and manifested in the form of MBT(Main Boundary Thrust), and MFT(Main Frontal Thrust)/HFF(Himalayan Frontal Fault) in the south and thickening of the northern margin of the Tibetan plateau. Accommodation of the crust is now taking place mostly in the strike slip movement of large faults in Tibetan region and E-W extension of Tibet

The synthesis of the available results indicates that most of the deformation and uplift of the Tibetan Plateau in north as well as that of Higher Himalaya along MCT took place around 20Ma. However, the results of the present study obtained from the Shyok Suture Zone of northern Ladakh indicate towards a strong tectono-thermal event around ~20 Ma in this region. These results, and other various geological and geochemical evidences as discussed in detail in chapter 5, further reveal that the regions east of Karakoram Fault was not much affected by this event, and the island arc in west of Karakoram fault and the continental arc in the east evolved independently and simultaneously. This points towards an internal adjustment of the NW Ladakh sector of the Trans Himalaya, which could have accommodated a significant portion of the crust, which when taken into consideration, can account for some of the amount exceeding the theoretical estimates of the crustal accommodation

Plateau age of ~14 Ma obtained by the fault zone sample from Karakoram batholith (LK47) is the age of fault activation. I propose here that internal adjustment of the crust in the Shyok Suture Zone was facilitated by this fault activation, which brought in juxtaposition the Kohistan-Shyok island arc with the Ladakh-Gangdese continental arc (Fig. 5.4). Recently Weinberg and Dunlop (2000) proposed on the basis of the cooling history of the shear zone samples, that shearing took place in NW Ladakh around ~22 Ma. They further stated that this dextral shearing took place within a zone of approximately 100 km-width including Ladakh batholith and a portion of Karakoram batholith and was responsible for the regional trend of the Ladakh batholith. This is in agreement with my results and interpretation of deformation in northern Ladakh.

6.5 Scope for further work

The response of continents to collision and consequent mountain building process is fundamental geological problem and deserves detailed study to fully understand the phenomenon to be able to apply it to older inactive orogens. Thermochronological studies provide complementary and much needed information about rate of exhumation/uplift and time sequence for the various tectono-thermal events. Though the data in this field is fast accumulating, the proper theoretical framework to understand and interpret it, is still lacking.

Collision is major process of continental crust building and making continents to supercontinents which affects the overall global climate and biosphere. However, very few isotopic studies using oxygen, strontium, neodymium, lead etc. have been carried out (Srimal et al., 1987) to understand the petrogenetic aspects of collision related magmatic processes. This leads to confusion over the younger post collision ages obtained from the various parts of the collision zone.

In my view any future work on these active collision belt should be on following lines:

1. K-feldspar thermochronology and mineral dating of different magmatic and metamorphic units of the Trans Himalayan zone to understand the complete cooling/exhumation history of this zone.
2. Development of theoretical and numerical simulations incorporating thermochronological data to understand the response of continental crust to collision and controls of deformation and crustal accommodation.
3. Petrogenetic studies of the magmatic rocks of the collision zone.
4. The petrogenetic and chronological correlation to bring out magma evolution in an orogenic belt .