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Fission track geochronology of India*

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Abstract. The fission track ages of cogenetic/co-existing minerals namely garnet, muscovite and apatite from three mica belts *i.e.*, Bihar, Rajasthan, Nellore of peninsular India and Himalayan region, coupled with the corresponding closing temperatures of the minerals have been used to reveal the thermal and uplift histories of these regions. The data show that the extra-peninsular part of the subcontinent during Himalayan orogenic cycle (upper cretaceous-tertiary) witnessed the highest cooling and uplift rates in comparison to the older cycles in peninsular India.

Keywords. Fission tracks; geochronology; closing temperature; cooling and uplift rates; orogenic belts.

1. Introduction

The term geochronology, used earlier for geological time estimates by sedimentation rates, is now commonly applied to geological dating based on the radio-active decay of elements. The field of geochronology is of interdisciplinary nature involving earth scientists, physicists and chemists and is therefore an ideal discipline for team-work. The science of geochronology, in general, is associated with two types of problems: (i) technical and (ii) correct interpretation of the age data. The primary answer to geochronological work is time, the date of the geological event. However, the question of whether a mineral or rock reacted to a later event, and to what extent, can also be answered by geochronology. The most important parameters that control the age results are temperature and the presence of fluid phases. Therefore, these parameters can be evaluated by geochronological work and geochronological data can be used for the construction of metamorphic isogrades.

It is widely accepted that radiometric ages determined on metamorphic minerals from orogenic belts generally reflect their cooling history rather than their primary crystallisation. Armstrong (1966) first developed this concept in detail, while Harper (1967) pioneered its application to the British cadenonian. Its general acceptance, however, stems largely from the investigations of the Central Alps by Prof. Jager and her colleagues at Bern. The time span over which the thermal history of any geological region can be built up will depend upon whether (i) different minerals have been dated by the same method, (ii) the same mineral if possible is dated by different techniques, or (iii) different minerals are dated by different methods.

In this paper we discuss the first possibility in detail as we have dated different minerals collected from various mica belts and the Himalayan region of India by the same fission track etch technique.

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2. Age equation

The speed of radioactive decay, and thus the speed of the geochronological clock, depends only on the stability of the radioactive nucleus; it cannot be changed by outside parameters such as pressure and temperature. Actually, the nature of chemical bond has been found to exert a slight influence on the decay constants of several radioactive isotopes, but this influence is much smaller than the precision of age measurements. Thus we can state that the radioactive clock has a constant speed, independent of the different geological conditions.

We know that the radioactive decay is governed by the well-known formula

$$N = N_0 \exp(-\lambda t).$$

This equation leads to the age formula

$$t = \frac{1}{\lambda} \ln \frac{N_0}{N}.$$

At time $t = 0$, only the parent isotopes are in the system, the number being N_0; after time t, a certain number of parent isotopes P are left and the daughter isotopes D have been formed. Thus we can write

$$P + D = N_0 \ (N = P),$$

$$t = \frac{1}{\lambda} \ln \left(1 + \frac{D}{P}\right).$$

In fission track dating technique, D is measured in terms of fossil fission tracks which are produced due to the spontaneous fission of U^{238} whereas P is estimated in terms of the uranium present in the mineral. The equations used are as given below:

$$\rho_s = \frac{\lambda_F n^{238} F (\exp(\lambda_D T - 1)}{\lambda_D}, \tag{1}$$

$$\rho_i = n^{235} \phi \sigma F. \tag{2}$$

Combining equations (1) and (2), we obtain

$$T = \frac{1}{\lambda_D} \ln \left(1 + \frac{\rho_s \lambda_D}{\rho_i \lambda_F} \phi \sigma I\right),$$

where ρ_s = fossil track density, ρ_i = induced track density, λ_D = total decay constant of uranium, λ_F = spontaneous decay constant of uranium, n^{238} = number of U^{238} atoms/cm^3 of the mineral, n^{235} = number of U^{235} atoms/cm^3 of the mineral, F = a constant depending upon the etchable range of fission tracks, etching efficiency and geometry etc., ϕ = thermal neutron dose, σ = thermal neutron cross-section for fission of U^{235}, and I = isotopic abundance ratio of uranium.

Fission track age determination thus requires essentially the fission track densities before and after the thermal neutron irradiation of the samples and thermal neutron dose measurements.

3. About various constants

The values of the constants are listed below:

$$I = 7{\cdot}25 \times 10^{-3},$$

$$\lambda_D = 1{\cdot}55 \times 10^{-10}\mathrm{yr}^{-1},$$

$$\sigma = 580 \times 10^{-24}\ \mathrm{cm}^2.$$

The value of λ_F *i.e.* the spontaneous fission decay constant is still a matter of debate among trackologists. The values used by various workers are:

$(6{\cdot}9 \pm 0{\cdot}2) \times 10^{-17}\ \mathrm{yr}^{-1}$, (Fleischer and Price 1964);

$(7{\cdot}03 \pm 0{\cdot}11) \times 10^{-17}\ \mathrm{yr}^{-1}$, (Roberts *et al* 1968);

$(7{\cdot}00 \pm 0{\cdot}28) \times 10^{-17}\ \mathrm{yr}^{-1}$, (Hurford and Gleadow 1977);

$(8{\cdot}42 \pm 0{\cdot}10) \times 10^{-17}\ \mathrm{yr}^{-1}$, (Spadvechhia and Hahx 1967);

$(8{\cdot}7 \pm 0{\cdot}6) \times 10^{-17}\ \mathrm{yr}^{-1}$, (Wagner *et al* 1975).

Though we have been calculating the ages using the value of λ_F by Roberts *et al* (1968), yet this point is a matter of controversy and it should be resolved to assign a single value to λ_F. (See discussion in the article by Poupeau 1981).

4. Experimental procedure

4.1 *Optimization of etching conditions*

In progressive etching, there exists a considerable time difference when the tracks, intersecting the surface under investigation, are just revealed and are fully revealed. Prolonged etching widens these channels to sizes that may adversely affect resolution either because of their large size or overlapping due to higher number of track events. It is therefore necessary to use those etching times at which the optical detection efficiency for all the etched events is maximum. Optimum etching conditions to meet this requirement can be obtained from the plots of track density variation with etching time by choosing the etching times corresponding to peak revelation or plateau of tracks (Nagpaul and Nand Lal 1980).

4.2 *Dating methods*

There are various dating methods employed by various workers in the field. These methods are summarised by Gleadow and Lovering (1975), and also discussed by Poupeau (1981). In our laboratory we have mostly used the subtraction method. The details of the technique are given in Nagpaul and Nand Lal (1980).

4.3 *Annealing studies of minerals*

4.3 a *The concept of closing temperatures:* The idea of closing temperatures is very important from the interpretation point of view of fission track ages. An elaboration of this concept is given below:

The concept of closing temperature is applicable only if the rocks have cooled slowly. In fast cooling rocks the fission track ages give the formation time of the samples. When co-existing minerals from such rocks are dated, concordant ages are found. The fast cooling model is characteristic of volcanic rocks.

The concept of closing temperature is illustrated in figure 1. It is assumed that, while the system is near the temperature of crystallization, the daughter nuclide diffuses out as fast as it is produced by radioactive decay. As the system cools, it enters a transitional temperature range within which some of the daughter product accumu-

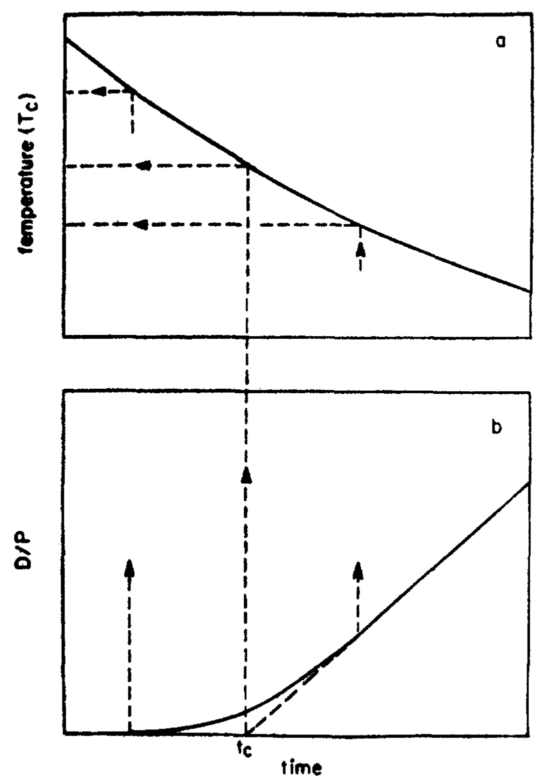

Figure 1. Definition of closure temperature; (a) cooling curve, (b) accumulation curve. *D/P* is the daughter/parent ratio. Broken lines show approximate limits of transitional time-temperature range.

lates in the mineral and some is lost. Eventually, at temperatures near ambient, the losses are negligible and the daughter product accumulates without any loss whatsoever. In calculating an ' age ' for the system, we in effect extrapolate the last portion of the curve back to the time axis, as shown by the broken line. According to this picture, the closure process is not a sharply defined event. Nonetheless closing temperature T_c can be given a simple and precise definition as illustrated in figure 1 namely the temperature of the system at the time given by its apparent age; on this basis it can be directly related to cooling history.

It is easy to imagine that closing temperature may vary with cooling rate; the slower the rate of cooling, the longer will be the time during which total or partial loss of daughter product may occur, and the lower will be both the apparent age and the corresponding closure temperature. Incorporating the idea of cooling rates, Haack (1977) proposed a model to calculate the closing temperatures of various minerals. He has integrated the opposing effects of track production and fading over time for a series of cooling rates. We have obtained the track growth curves *vs* temperature for various minerals for different cooling rates and estimated T_c following the approach of Haack (Sharma *et al* 1980). These are given in table 1.

According to Wagner (1972), the fission track age can be taken to represent the time when the rock cools down to a temperature at which 50% of the tracks are stable. In reality the stable conditions for the tracks to be recorded arrive progressively over a wide range of temperatures called partial stability zone. The simplest estimate of the effective closing temperature can be obtained by extrapolating the results of laboratory annealing data to the times of the order of $10^7 - 10^8$ years and taking the temperatures at which 50% of the tracks are stable. Using this procedure the T_c values obtained are given in table 1. If we compare T_c by two approaches we find that the two values agree only if the cooling rates are of the order of 100°C/m.y. which are rarely encountered in geological set-ups.

Table 1. Closing temperature of various minerals

Mineral	Fission track closing temp. (°C) for cooling rates					Closing temp. by other radiometric methods*		
	0.1°C/m.y.	1°C/m.y.	10°C/m.y.	100°C/m.y.	**	Rb-Sr	K-Ar	U-Pb
Apatite	83	100	117	134	130±30	—	—	—
Biotite	22	39	56	73	100±20	300	300	—
Epidote	165	185	205	225	240±25	—	—	—
Garnet	258	276	296	317	350±50	—	—	—
Hornblende	99	117	135	155	145±25	—	—	—
Muscovite	105	125	145	165	170±25	500	350	—
Monazite	—	—	—	—	—	—	—	530
Phengite	—	—	—	—	—	500	350	—
Sphene	282	302	322	342	340±25	—	—	—
Zircon**	—	—	—	—	350	—	—	—

*Data from Wagner *et al* (1977).

**Temperature corresponding to 50% track-retention for 10^6–10^7 years (Saini 1978).

***The closing temperatures at various cooling rates for zircon could not be calculated as its annealing characteristics are available only for 0% and 100% track retention (Krishnaswami *et al* 1973).

4.3 b *Age correction due to geological annealing of fossil tracks:* There are two methods to assess the age correction due to shortening of fossil tracks over geological times at low ambient temperatures. One which is mostly followed by our group is to measure the length reductions of fossil tracks with respect to induced tracks and then convert this length reduction to density reduction through translation curves obtained in the laboratory (Nagpaul and Nand Lal 1980). Another method for finding out the model ages is due to Poupeau *et al* (1980) and is known as plateau age method. Though the plateau method is more accurate, a large number of analysis is required to calculate the plateau age. Poupeau (1981) has discussed the age correction method in detail.

4.4 *Cooling and uplift rates*

The uplift rates in the present work have been derived according to the equation:

$$\text{Uplift rate} = \frac{\text{Cooling rate}}{\text{Geothermal gradient}},$$

where cooling rates are calculated from the closing temperatures and apparent ages of the various minerals, and an average geothermal gradient of the order of 30°C/km has been adopted. The above relation gives only an average uplift rate, and may not be valid if the uplift is not a continuous one but related to tectonic pulses of short durations. However, as a first order approximation, the results obtained using this relation are extremely useful for understanding the thermal and tectonic history of the various orogenic belts in the Indian subcontinent.

5. Geochronology and cooling rates of various geological regions

Although the available geochronological data, particularly the mineral ages, for the peninsular and the extra-peninsular India are far too meagre for arriving at the final conclusion regarding the cooling and the uplift rates of different geological regions, an attempt has been made to synthesize and correlate the information available from various pegmatitic belts *viz.* Bihar, Nellore, Rajasthan, South India and the Himalayan region.

5.1 *Rajasthan mica belt*

A large number of pegmatites from which the samples were collected which have been dated by fission track method, occur in the region around Gangapur in Bhilwara district. The salient features of the tectonic-metamorphic history of this region which has been investigated in detail by Sharma (1978) are as follows:

The metasediments represented by staurolite-kyanite schist, sillimanite-kyanite schist, garneti-ferrous mica schist, gneisses, calc-silicate rocks and crystalline limestone belonging to Aravalli Group have been intruded by granites, pegmatites and quartz veins. Originally, these rocks might have been argillaceous, arenaceous and calcareous sediments which through regional folding and associated metamorphism have resulted into the present form of metasediments. Three phases of folding have been recognised in the area. The tectonic history of the area began with the formation of first generation F_1 folds which have a regional NNE-SSW trend. The most prevalent planar structure associated with this folding was the axial plane foliation. Simultaneous to the development of this foliation, the regional metamorphism also progressed to a high grade amphibolite facies. The pegmatites and quartz veins which represent a differentiated fraction of the granite magma intruded along the structurally favourable locales formed during this tectonic episode, particularly the axial plane foliation and F_1 folds. Most of the pegmatites in the present area belong to this period and have been affected by subsequent deformations.

The second tectonic event which closely followed the F_1 resulted in the development of a set of second generation folds designated as F_2 which are tight and isoclinal and plunge at moderate angle towards NE or SW. This fold movement caused the development of fractures in partially or completely solidified pegmatites emplaced during the first tectonic phase.

The third and the last tectonic episode in the area is represented by broad open cross folds F_3 which are accompanied by fracture cleavages that occur roughly parallel to the axial plane of these folds. Otherwise, this movement was not intensive enough and did not result in any recrystallization of minerals, nor of any intensive foliation.

5.1a *Fission track age data and their interpretation:* The fission track age data of garnet, muscovite and apatite, analysed in our laboratory are disucussed by Nagpal and Nagpaul (1974) and Sharma *et al* (1975). The apparent fission track ages of garnet from pegmatites lie between 960 m.y. and 1100 m.y., muscovite between 745 m.y. and 835 m.y. and apatite between 410 m.y. and 555 m.y. The mean f.t. ages of the cogenetic minerals are given in table 2. The errors in the age data represent the standard error of the mean.

Three major orogenic cycles have been recognised in Rajasthan—The Delhi Cycle, the Aravalli Cycle and the Banded Gneissic Group Cycle, which are assigned different ages by different workers (Holmes 1949, 1955; Aswathanarayana 1956; Rama Rao 1964; Sarkar *et al* 1964; Vinogradov *et al* 1964; Crawford 1970; Pichamuthu 1971; Balasundram and Balasubrahmanyan 1973).

The ages of Untala granite, Erinpura granite and muscovite from Lower Alwar Schists ($\sim$ 900 m.y.) by Rb-Sr method (Crawford 1970); uraninite from the Danta mine (906 $\pm$ 20 m.y.) and monazite from the Soniana pegmatite (735-865 m.y.) by U-Th-Pb method (Holmes 1949; Chauduri *et al* 1967) and those of cogenetic minerals from the pegmatites of this region by f.t. method are comparable and suggest that all of them may be related to the same tectonic episode. The discrepancy in the fission

Table 2. Fission track age data of minerals from mica belts

Region	Number of samples analysed for			Mean fission track ages (m.y.) of		
	garnet	muscovite	apatite	garnet	muscovite	apatite
Rajasthan mica belt	4	7	5	982$\pm$78	793$\pm$31	493$\pm$71
Bihar mica belt	6	7	8	834$\pm$35	763$\pm$30	454$\pm$52
Nellore mica belt	5	—	5	1065$\pm$55	—	424$\pm$8

track ages of these minerals from the same pegmatite is attributed to the differences in their thermal track stability and has been elaborated in the following paragraph.

As is evident from the above discussion the granite magma and its differentiated pegmatitic melt after its emplacement into the Aravalli metasediments during the closing stage of the first tectonic episode started crystallizing around 1000–1100 m.y. The temperature-pressure conditions during that period had sufficiently increased resulting in a high grade regional metamorphism (amphibolite facies) and anatectic magmatism in the area. A fall in the temperature after the emplacement of the melt resulted in crystallization of the pegmatitic bodies. The second tectonic episode which fractured these pegmatites and albitized the already consolidated primary zones, might have been active between 900–950 m.y. as indicated by dating of uraninite and monazite of the replacement zones. After this tectonic event, the pegmatite bodies gradually cooled down so as to reach firstly the closing temperature of garnet and subsequently to that of muscovite and apatite. The cooling and uplift rates of the pegmatites calculated by using the closing temperatures and the corresponding mineral ages, are given in table 3.

5.2 *The Bihar mica belt*

The geology of these pegmatites has been described in detail by Mahadevan (1965) and Anandalwar and Mahadevan (1968).

The Bihar mica belt and the adjoining areas of eastern India have been affected by various orogenies such as Older Metamorphics, Iron-Ore, Singhbhum, Satpura and Monghyr. The imprint of the oldest orogeny in the area is recorded by muscovite (~ 3035 m.y.) from pegmatite near Jorapokar emplaced into the metamorphic rocks older than those of the Iron-Ore series from which it differs in higher degree of metamorphism (Sarkar *et al* 1964). According to Sarkar *et al* (1964), the Iron-Ore Orogeny, regional metamorphism and emplacement of the Singhbhum Granite and Soda Granite from Bihar took place around 2100 m.y.

A number of minerals from pegmatites of the Bihar mica belt dated by various workers (Holmes 1950; Sarkar 1941; Sarkar and Sen Sharma 1946; Nandi and Sen 1950 a, b; Aswathanarayana 1956; Venkatasubramanian and Krishnan 1960; Sarkar and Saha 1962) suggest that these pegmatites were emplaced during the closing stage of the Satpura Orogeny which is considered by Holmes (1950) to be around 950 m.y.,

Table 3. Cooling and uplift rates of various mica belts.

Region	Time span (m.y.)	Cooling rate* (°C/m.y.)	Uplift rate (m/m.y.)
Rajasthan mica belt	982–793	1.7	57
	793–493	0.8	2·8
Bihar mica belt	834–763	2.1	70.9
	763–454	0.8	2.8
Nellore mica belt	1065–424	2.7	90

*Cooling rates have been calculated by using the closing temperatures corresponding to cooling rate of 1°C/m.y.

and they are genetically related to the Chotanagpur granite-gneiss, a part of which has been dated at 1000 m.y. (Crawford 1968). According to Sarkar *et al* (1964), the age data from the Bihar mica belt is comparable with that of the Muri (890–970 m.y.) Singhbhum (934–940 m.y.), Gangapur (912–993 m.y.) and Ranchi (980 m.y.) belts and all belong to the Satpura cycle.

A mild metamorphism followed by emplacement of granite in the Monghyr district (located $\sim$ 200 km NE of the area under study) around 400 m.y. has also been reported by Sarkar *et al* (1964). The f.t. age data of all the three cogenetic minerals analysed in our laboratory by Nand Lal *et al* (1976) and given in table 2 suggest the emplacement of pegmatites in the Hazaribagh district of the Bihar mica belt during the Satpura orogeny. Further the data also indicate that the fission tracks even in the most sensitive mineral (apatite) were not affected by the Monghyr orogeny ($\sim$ 400 m.y.), thus suggesting it to be of mild nature and local extent.

The discordance of f.t. ages of the three cogenetic minerals is attributed to the uplift and cooling of rocks in which these pegmatites were emplaced and is discussed below:

Since the pegmatites were emplaced in the rocks of the upper amphibolite facies, the temperature of about $595 \pm 10°C$ might have been reached in the region (Winkler 1967) though the initial temperature of the pegmatitic melt at the time of emplacement may be higher. After their emplacement the pegmatitic bodies started crystallizing and cooling down. The rate of initial cooling might have been greater until the temperature of the pegmatites reached the regional temperature prevailing in the area (*i.e.* $\sim 600°C$) which was not favourable for retention of tracks in any of the minerals. The pegmatite bodies along with country rocks started uplifting and cooling simultaneously. The spectrum of cooling and uplift rates for the region is indicated in table 3.

The model f.t. age of apatite has tectonic significance in relation to the development of the Narmada-Son deep-seated fracture lineament which cuts across the Indian Peninsula and passes adjoining to the Bihar mica belt. This lineament is believed to be of different ages; Proterozoic by Auden (1949), and Naqvi *et al* (1974); Permian by Fox (1931) and Tertiary by Ahmed (1966). Our data (Nand Lal *et al* 1976) suggest that there was no significant tectonic activity along this fracture lineament, at least subsequent to 600 m.y., the model f.t. age of apatite.

5.3 *The Nellore mica belt*

A number of minerals from pegmatites of the Nellore mica belt have been dated by various workers by mass spectrometric method. Venkatasubramanian *et al* (1968) have reported the age value of 1500 m.y. for muscovite from the Nellore mica belt, which is in good agreement with lead ages for Samarskites from associated pegmatites (Holmes 1955). From this data, the pegmatitic intrusion of the Nellore mica belt is regarded as associated with the cooling stages of the Eastern Ghats Orogeny (1500–1600 m.y.).

A metamorphism, folding and uplift of the Eastern Ghats around 500 m.y. ago has been reported by Aswathanarayana (1964). The model f.t. age of 440 m.y. for apatite (Parshad *et al* 1979) indicates that the thermal event associated with metamorphic cycle affected this mineral and set a new fission clock. The new f.t. age of 1065 m.y. for garnet (table 2, Parshad *et al* 1979) indicates that during the metamorphic event around 500 m.y., though the temperature crossed the closing temperature of apatite (100°C), it was below the closing temperature of garnet (276°C). The cooling and uplift rates calculated for these pegmatites are given in table 3.

5.4 *The Himalayan orogenic belt*

This orogenic belt, unlike other orogenic belts of India, is geologically and geochronologically less understood. The occurrence of pre-cambrian gneisses as old as 2,030 m.y. (Wangtu gneiss), 1,890 m.y. (Munsiari gneiss), 1,430 m.y. (Baragaon gneiss) and 1,220 m.y. (Bandal gneiss) in the crystalline basement suggests some possible magmatic correlation with the adjoining regions of the Aravalli orogenic belt (Bhanot *et al* 1973, 1978, 1979).

The presence of a pronounced unconformity marked between the Martolis and the Ralamas in Kumaun (Heim and Gansser 1939), the Haimantas and the Jadha in Garhwal (Auden 1949) and the Dogras and the Tanawals in the Vihi, Sindh and Banihal areas of Kashmir (Wadia 1957) suggest diastrophic movements towards the end of the Purana Era. The dating of granitic rocks from Mandi, Manali and Rohtang regions around 500–600 m.y. (Jager *et al* 1971; Bhanot *et al* 1973; Mehta 1977) suggests magmatism associated with the closing phase of this episode; however, the information on metamorphism and deformation related to this event is not clear so far. The presence of Caledonian and Hercynian epiorogenic movements in the Himalayas has also been suggested by Valdiya (1964) besides the Tertiary Orogeny which brought about the evolution of the Himalyas in at least four successive phases.

The first diastrophic phase of the Himalayan Orogeny took place towards the Upper Cretaceous during which period marine conditions in Karakoram and Tibet Plateau, marine transgression by the Nummulitic sea in the lesser Himalayan region and emplacement of ophiolites in the Indus-Suture zone took place. This phase has been designated the " Karakoram Orogeny " by De Terra (1933) and Valdiya (1964).

Valdiya (1964) considers that the second phase, known as the " Post Kirthar Orogeny ", took place towards the end of the Eocene and culminated in the Oligocene period. As a result, the Tibetan Plateau emerged from the cradle of the sea, the crystalline basement started ridging up along the Indo-Tibetan border, followed by possible development of exotic nappes of the Kumaun-Tibet border and emplacements of tourmaline-bearing granites of batholithic dimensions.

During the third phase, which took place towards the Middle Miocene period, the Himalayan Orogenic Belt witnessed the strongest upheaval; this brought about tight isoclinal folding, overturning and thrusting and was designated the " Sirmurrian Orogeny ". Recently, Sharma and Nagpaul (1980) have dated the thrusting event in the Satluj Valley at around 15 m.y.

The fourth phase in the tectonic evolution of the Himalayas commenced in the Pliocene and continued down to Middle Pleistocene time. This phase, called the " Siwalik Orogeny ", brought about folding and faulting of the Siwaliks, formation of the Main Boundary Fault, reactivation of the lesser Himalayan thrusts, elevation and tilting of Karewas of Kashmir and development of the Indo-Gangetic depression.

5.4a *Cooling and uplift rates*

The geodetic surveys carried out by the Survey of India (6th Gen. Assembly Meeting IUGG, Grenoble) have revealed that the Himalayas has been rising at a rate of 0·8 mm/year (800 m/m.y. during the past 75 years). Sharma *et al* (1978), using fission-track techniques, calculated a tectonic uplift of 550 m/m.y. for the past 8 m.y. from the Mandi region of the northwest Himalayas. Saini *et al* (1979) have suggested uplift rates of 0·04 mm/year, 0·08 mm/year and 0·15 mm/year for the period 200–46 m.y.; 31–20 m.y. and 20–11 m.y., respectively for the Kinnaur region of the Higher Himalayas. These authors also suggested that this region uplifted at a comparatively much faster rate of 0·8 mm/year between 15–7 m.y. ago during Miocene thrusting. Mehta using Rb-Sr muscovite and biotite ages from Kulu-Manali area, has calculated an uplift rate of 800 m/m.y. during the period 25–10 m.y. (Mehta 1979). The information on the cooling rates from the Himalayan Orogenic Belt is limited to the fission-track data reported by Saini *et al* (1979) and Saini (1978). Sharma *et al* (1978) suggested a cooling rate of 2–3°C/m.y. and 4°C/m.y. for the periods between 200–46 m.y.; 31–20 m.y. and 20–11 m.y., respectively for the Kinnaur region. They also suggested rapid cooling ($\sim$ 25°C/m.y.) subsequent to thrusting in the area. Frank *et al* (1977), using Rb-Sr age data, also suggested rapid cooling in the vicinity of the thrust zone in the Kulu area. The above data obviously suggest faster uplift and rapid cooling after the Middle Miocene (Sirmurian Orogeny) which brought about folding, overturning and thrusting in the Himalayas. The cooling and uplift rates for this region are given in table 4.

An important fact which emerges from the cooling and uplift histories of various geological regions of India discussed above is that the Himalayan Orogenic Cycle (Upper Cretaceous-Tertiary) witnessed the highest uplift and cooling rates as compared to older cycles of the peninsular India and may be attributed to large-scale horizontal shift of the Indian plate from 40°S lattitude to 8°N latitude in the past 71 m.y. as suggested by Molnar and Tapponier (1975) at an average rate of about 50 mm/year (Le Pichon 1968; Minster *et al* 1974).

Table 4. Uplift and cooling rates of Himalayan orogenic belt

Locality/region	Method	Age span	Uplift rate (m/m.y.)	Cooling rate (°C/m.y.)
Outer Himalayan region	geodetic	past 75 years	800	—
Kulu	Rb-Sr-mineral ages	25-10 m.y.	800	—
Mandi	fission track	32-16 m.y.	—	2·0–3·0
		16-8 m.y.	—	3.0–6.0
		past 8 m.y.	550	—
Kinnaur	fission track	200-46 m.y.	30	1.0
		31-20 m.y.	80	2·0
		20-11 m.y.	150	4.0
		15- 7 m.y.	800	25.0

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