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The Timing of Metamorphism, Magmatism, and Cooling in the Zanskar, Garhwal, and Nepal Himalaya

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ABSTRACT

Following India-Asia collision, which is estimated at ca. 54-50 Ma in the Ladakh-southern Tibet area, crustal thickening and timing of peak metamorphism may have been diachronous both along the Himalaya (pre-40 Ma north Pakistan; pre-31 Ma Zanskar; pre-20 Ma east Kashmir, west Garhwal; 11-4 Ma Nanga Parbat) and crsoss the strike of the High Himalaya, propagating S (in Zanskar SW) with time. Thrusting along the base of the High Himalayan slab (Main Central Thrust active 21-19 Ma) was synchronous with N-S (in Zanskar NE-SW) extension along the top of the slab (South Tibet Detachment Zone). Kyanite and sillimanite gneisses in the footwall formed at pressure of 8-10 kbars and depths of burial of 28-35 km, 30-21 Ma ago, whereas anchimetamorphic sediments along the hangingwall have never been buried below ca. 5-6 km. Peak temperatures may have reached 750° on the prograde part of the P-T path. Thermobarometers can be used to constrain depths of burial assuming a continental geothermal gradient of 28-30° C/km and a lithostatic gradient of around 3.5-3.7 km/kbar (or 0.285 kbars/km). Timing of peak metamorphism cannot yet be constrained accurately. However, we can infer cooling histories derived from thermochronometers using radiogenic isotopic systems, and thereby exhumation rates. This paper reviews all the reliable geochronological data and infers cooling histories for the Himalayan zone in Zanskar, Garhwal, and Nepal. Exhumation rates have been far greater in the High Himalayan Zone (1.4-2.1 mm/year) and southern Karakoram (1.2-1.6 mm/year) than along the zone of collision (Indus suture) or along the north Indian plate margin. The High Himalayan leucogranites span 26-14 Ma in the central Himalaya, and anatexis occurred at 21-19 Ma in Zanskar, approximately 30 Ma after the collision. The cooling histories show that significant crustal thickening, widespread metamorphism, erosion and exhumation (and therefore, possibly significant topographic elevation) occurred during the early Miocene along the central and eastern Himalaya, before the strengthening of the Indian monsoon at ca. 8 Ma, before the major change in climate and vegetation, and before the onset of E-W extension on the Tibetan plateau. Exhumation, therefore, was primarily controlled by active thrusts and normal faults, not by external factors such as climate change.

INTRODUCTION

The mountains of central Asia, particularly, the Himalaya, Karakoram, Hindu Kush, and Pamirs, together with the high plateau of Tibet are amongst the most actively deforming parts of the continental crust (Fig. 1). The collision of India into Asia approximately 65-50 Ma ago created most of the topography of central Asia between the Indian Shield, and the Siberian craton. Most kinematic models of the deformation of Asia are two-dimensional relying on slip rates along Quaternary strike-slip faults, palaeomagnetic rotations about a vertical axis and seismic moments of earthquakes. These show that the convergence rate between India and Siberia, around 50-60 mm/year, is partitioned roughly equally between convergence within the Himalaya and internal deformation within the Tibetan Plateau with a relatively minor amount of compression across the Tien Shan (Molnar and Lyon-Caen 1989). This paper discusses another dimension, the vertical dimension, notably the exhumation of rocks, the erosion of the mountain belts, and the Tibetan Plateau, and inferences about surface uplift.

There are no reliable quantitative estimates of the rate of surface uplift in mountain belts (England and Molnar 1990). There are, however, reliable methods of quantifying exhumation in mountain belts. Middle to deep crustal rocks now exposed at the Earth's surface require very large amounts of exhumation, either by mechanical or chemical erosion, or by tectonic removal of overburden by normal faulting. The amount of material removed must also be accounted

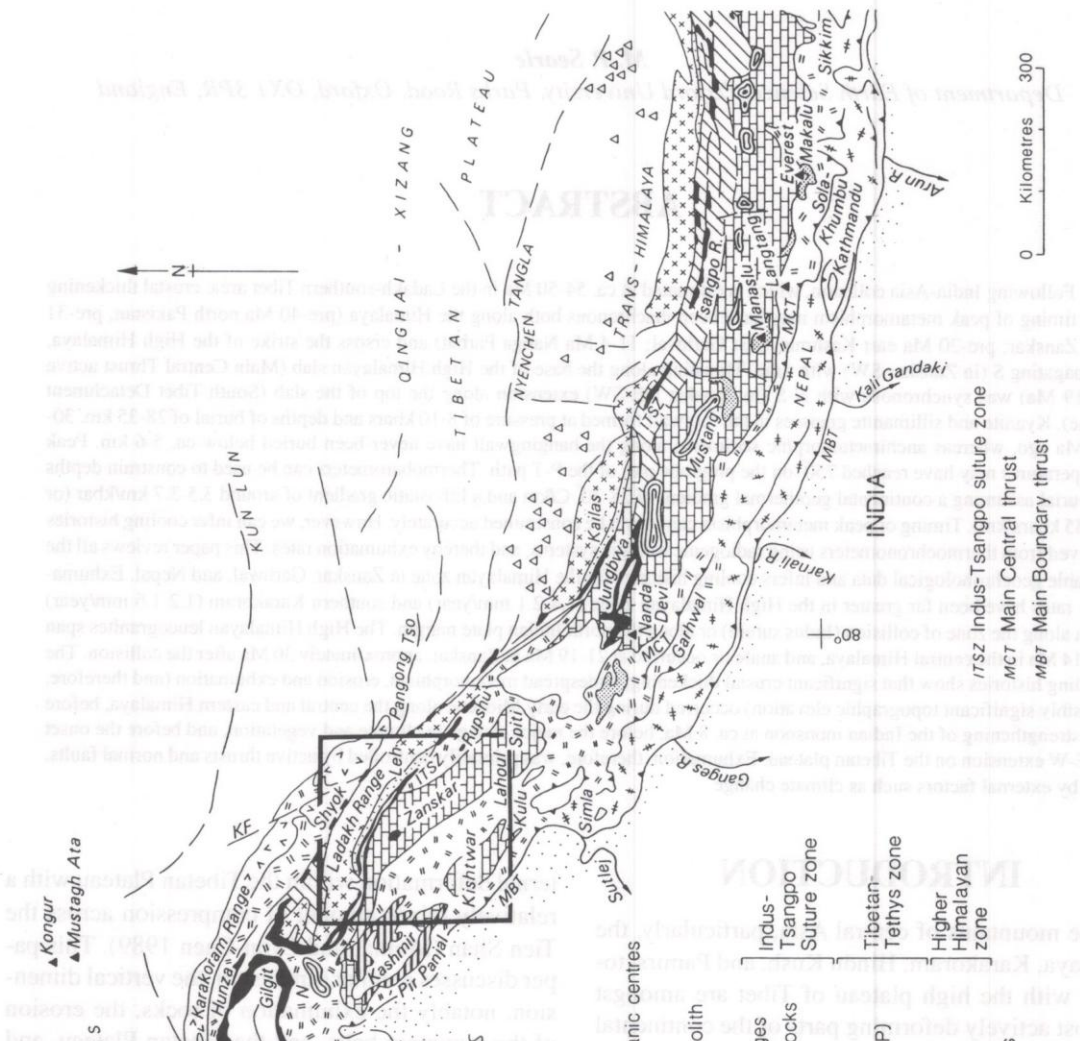


Fig. 1 Map of the Himalaya and Central Asia showing the major structures and tectonic zones

for in any mass balance of crustal material in kinematic interpretations. Using thermobarometric data from metamorphic rocks it is possible to estimate the depths of burial of formation, and therefore the amount of material that must have been removed in order to exhume the rock to the Earth's surface, at whatever altitude that may be. Using thermochronometers, based on radiogenic isotope systems, it is possible to constrain the timing of metamorphism, melting, and cooling. Using the pressure, temperature, and time constraints, a cumulative erosion amount and cooling rate can then be inferred. The two-dimensional kinematics of the Himalaya-Tibet region have been discussed by Molnar and Lyon-Caen (1989) and Avouac and Toppoinnier (1993). This paper discusses the third (depth) and fourth (time) dimensions only in the Zanskar, Garhwal, and Nepal sectors of the Himalaya. The far western Himalaya in the Pakistan area is more complicated with both older (<50 Ma) and younger (Neogene) metamorphic episodes.

MINERAL CLOSURE TEMPERATURES AND COOLING PATHS

Cooling ages are best obtained from thermochronometers using radiogenic isotope systems such as U-Pb, Sm-Nd, Rb-Sr, K-Ar or ^{40}Ar/^{39}Ar, for which the retention of the daughter isotopes is temperature dependent. Each mineral within a given isotopic system has a critical temperature at which the mineral cools to become stable (eg: Cliff 1985). Dating several different minerals in one rock with different blocking or closure temperatures should result in a number of points in time on several different isotherms, to give a cooling curve on a temperature-time plot. For example, using the ^{40}Ar/^{39}Ar and K-Ar methods on hornblende, muscovite, and biotite, and the fission track method on zircon and apatite, the thermal history of that rock can be dated at blocking temperatures within the range 500-120° C.

A "fission track", or charged particle track, is the damage zone formed as the two nuclei of a spontaneous fissioning heavy element, such as uranium, pass through a solid (Fleischer et al. 1975). Annealing of fission tracks is both a time and temperature dependent process, and the low annealing temperatures of apatite and zircon make fission track dating a particularly useful tool for dating the cooling and exhumation histories of mountain belts. Fission tracks in zircon will start to accumulate below its closure temperature which is thought to be 200° ± 50° C and in apatite around 120° C (Zeitler 1985). Fission track ages decrease with depth, due to increasing temperature and pressure, as tracks enter the zone of partial annealing and become shortened. Fission track ages should therefore increase with increasing elevation. If these ages are plotted against elevation, the gradient of the cooling curve has been termed the "apparent uplift rate" (Lewis 1990). The decrease of mineral ages with time may not necessarily reflect the rise of the rock towards the surface, but it could also reflect a relaxation of the geothermal gradient in a stable continental block, together with normal erosion. In this case "uplift rates" are apparent not real, and the term "surface approach rates" or "exhumation" is more accurate.

The argon blocking temperature for hornblende is 500-525° C, for muscovite 350-400° C, and for biotite 275-325° C (see Cliff 1985 and Zeitler 1989 for reviews). The ^{40}Ar/^{39}Ar step heating method provides additional constraints on the interpretation of the thermal history, by the flatness of the plateau and the shape of the spectrum (Harrison 1983). Both total fusion and step-heating ages can now also be ascertained using a laser probe, which has the capacity to measure the argon release on a single point. Rb-Sr blocking temperatures are about 500° C for muscovite and 250-300° C for biotite (Dodson and McClelland-Brown 1985). The full range of mineral dating methods has been successfully used in the Alps for unravelling the thermal evolution (Hurford et al. 1989), and we are now in a position to be able to do a similar study of selected parts of the Himalaya.

Since most granites crystallise at temperatures above 650-700° C, these isotopic systems are clearly not useful for dating crystallisation, but they are useful for inferring ages of metamorphism and cooling. U-Pb dating of zircon, which has a closing temperature of over 750° C (Parrish and Tirrul 1989) is the only reliable method of dating the crystallisation of granites. Other U and Th bearing minerals used for high-temperature U-Pb dating are monazite, allanite, xenotime and baddelyite. Monazite is a light rare-earth element phosphate (LREE)PO_4, which has an average of 6% Th and 1% U, and forms a common accessory mineral in leucogranitic rocks and also in high-grade metamorphic rocks. The closing temperatures of both monazite and thorite are thought to be about 700° C (Copeland et al. 1988, Parrish and Tirrul 1989).

Dating peak metamorphism remains one of the major goals of geochronology (Zeitler 1989). U-Pb ages of zircon or monazite in granitic rocks are widely interpreted as dating the timing of crystallisation (Scharer and Allègre 1983, Scharer 1984). Recently, monazite has also been recognised as a metamorphic mineral in metapelites at, or slightly below, the conditions for staurolite metamorphism. U-Pb dating of monazite records the timing at which the rocks attained temperatures of 525 ± 25° C and pressures of 3.1 ± 0.25 kbars during prograde metamorphism (Smith and Barreiro 1990). Garnet also has high U/Pb and Sm/Nd ratios (with corresponding low Rb/Sr ratios), relative to coexisting phases, and can therefore be useful for geochronology. P-T estimates derived from major element partitioning can be directly related to the timing of garnet crystallisation, because the diffusion rates for Sm-Nd, Rb-Sr, and U-Pb garnets are low (Vance and O'Nions 1990).

In the following sections the full range of isotopic dating results from metamorphic and magmatic rocks across the Himalaya is used to deduce exhumation rates. Although it does not necessarily follow, many of the terrains with high exhumation rates also have presently high average surface elevations, which are in turn reflected in the dynamic geomorphology of the mountain belt. However, the Tibetan Plateau at a mean elevation of 5200 m has extremely low erosion and exhumation rates, yet it is apparently the major cause of the high precipitation along the High Himalaya mountains to the south, in particular the Indian monsoon.

KASHMIR ZANSKAR HIMALAYA

Southeast of Nanga Parbat the High Himalayan zone extends into north Kashmir, western Zanskar, and the Kishtwar, Chamba, and Kulu districts of NW India (Fig. 2). The zone includes Precambrian, Palaeozoic, and Mesozoic rocks metamorphosed in the Tertiary. Regional Barrovian metamorphism affected all the rocks of the High Himalayan Zone, and reconnaissance mapping has demonstrated that metamorphic isograds are folded around giant SW-verging recumbent nappe structure (Searle 1986; Searle et al. 1988; Searle and Rex 1989). Isograds are inverted and structurally telescoped around the Kishtwar Window along the Main Central Thrust (MCT) zone at the base of the High Himalayan Slab (Staubli 1989). At the top of the slab, isograds are the right way-up and also structurally telescoped along the Zanskar normal fault zone (Searle 1986; Herren 1987; Searle and Rex 1989). Between the MCT and the Zanskar normal fault zone, metamorphic assemblages indicate a single prograde reaction series from chlorite through biotite, garnet, staurolite, kyanite to sillimanite grade. Temperatures increase structurally upwards from the MCT at the base and structurally downwards from the Zanskar normal fault at the top into the sillimanite grade core of the High Himalaya (Searle et al. 1992). This core zone corresponds to the topographically highest part of the whole Himalaya. Pressures increase structurally upwards across the MCT zone then show an apparent decrease from 7.5 to 4.5 kbars (Staubli 1989). Along the Suru valley in western Zanskar thermobarometry indicates that maximum P-T conditions attained were 750° C and 5-12 kbars (Searle et al. 1992). Preliminary Ar-Ar geochronology shows that peak metamorphism occurred between 20 and 30 Ma ago (Fig. 3). This indicates a time-averaged exhumation rate of 2.1-1.4 mm/year. Geobarometers give a wide range of pressure estimates across eastern Kashmir and western Zanskar so this exhumation rate should probably be regarded as a maximum. However, very rapid exhumation is required in order to preserve the inverted metamorphic gradient along the MCT zone at the base of the High Himalayan slab.

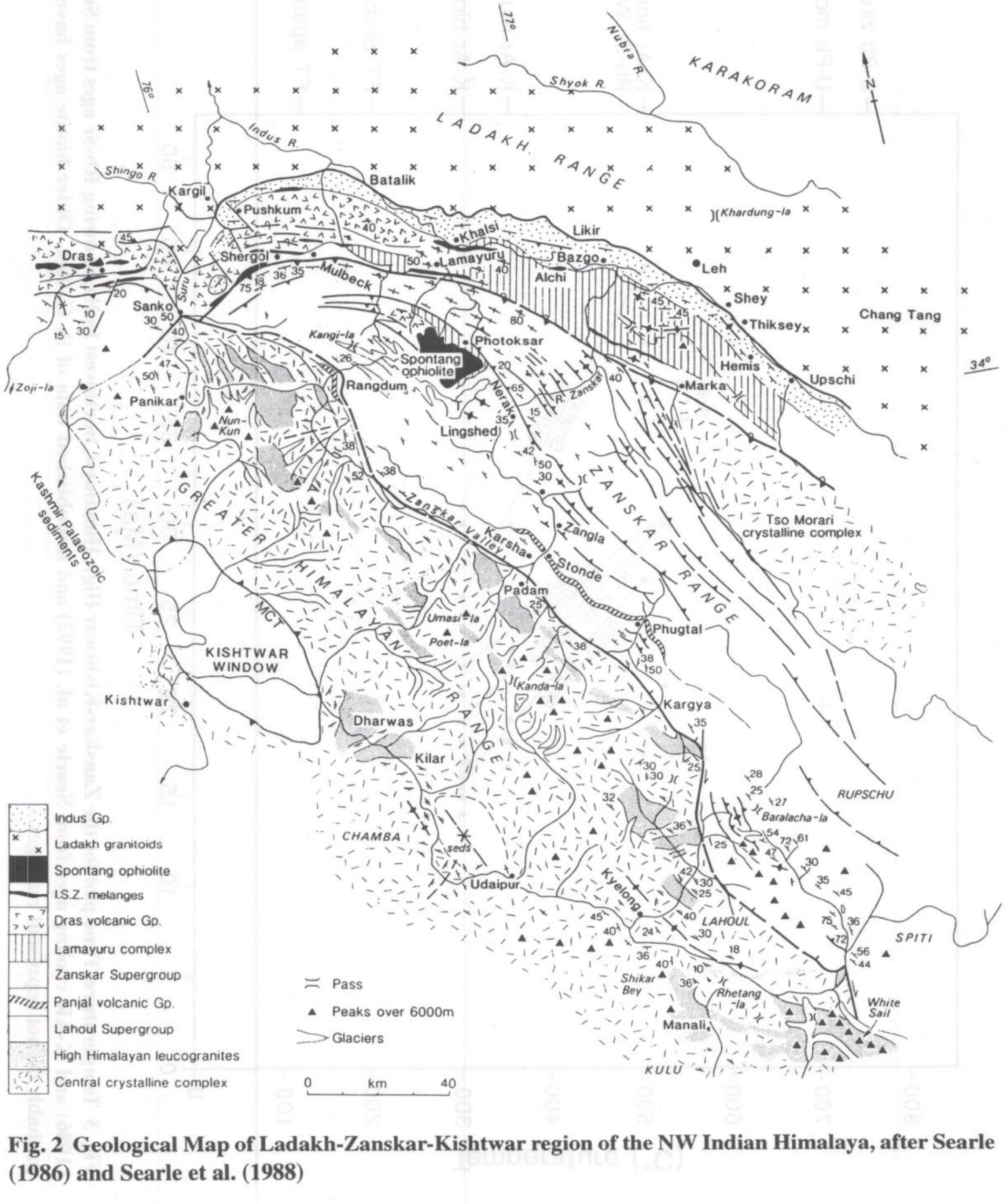


Fig. 2 Geological Map of Ladakh-Zanskar-Kishtwar region of the NW Indian Himalaya, after Searle (1986) and Searle et al. (1988)

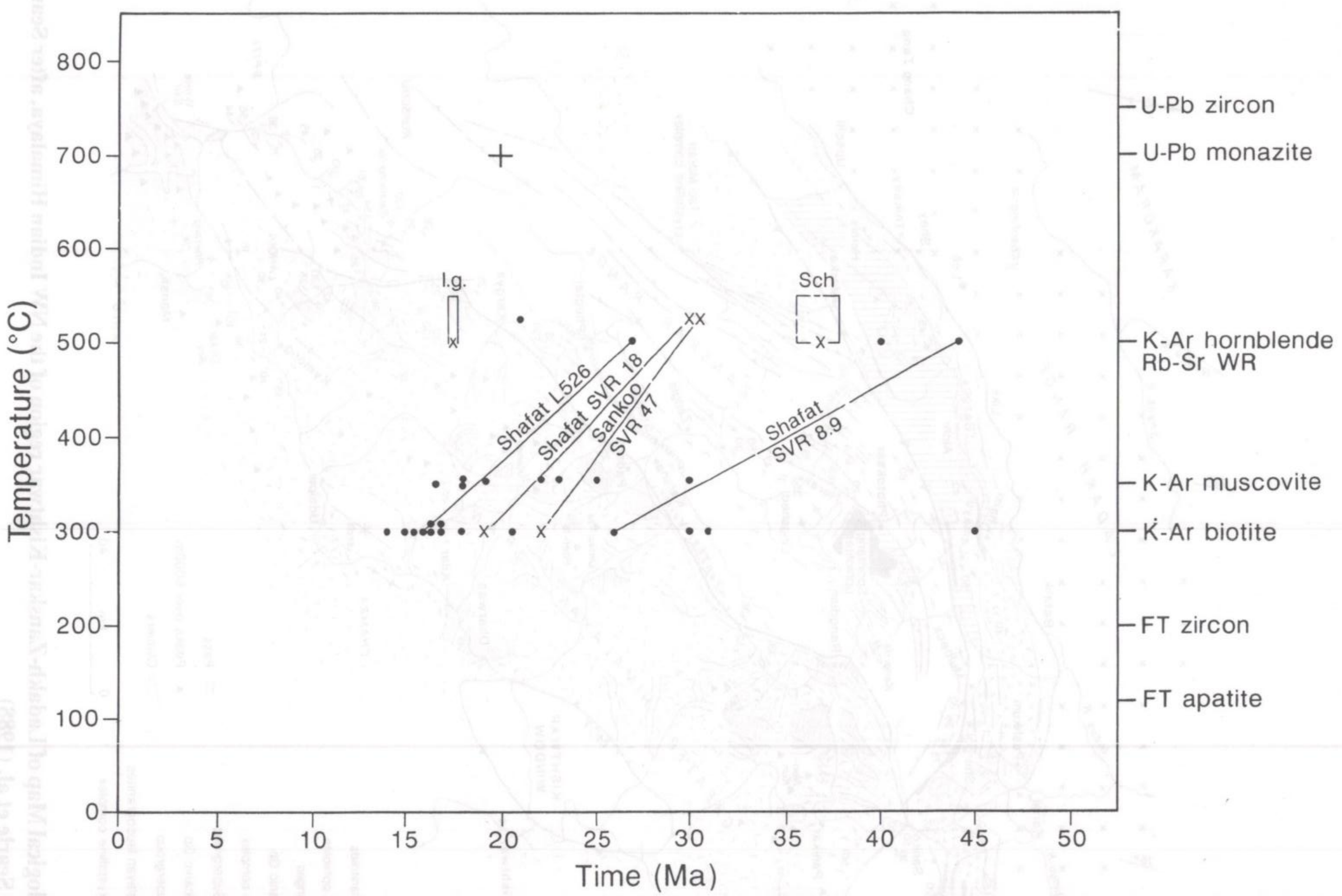


Fig. 3 Temperature-Time plot for the Zanskar-Kishtwar High Himalaya, northwest India, showing Rb-Sr ages from Searle and Fryer (1986) and K-AR cooling ages from Searle et al. (1992) and unpublished data of D. C. Rex. Older biotite ages have excess Ar and probably do not represent real ages.

The U-Pb (Noble and Searle 1995) and Rb-Sr (Searle and Fryer 1986) ages of crustal melt leucogranites from the Suru and Chenab valleys at the deeper structural levels of the Zanskar-Kishtwar Himalaya are younger than the surrounding metamorphic rocks supporting the suggestion that the leucogranites are the end products of ultra-metamorphism and crustal thickening processes. Fig. 3 shows that the cooling history of kyanite and sillimanite gneisses at Shafat in the middle of the High Himalayan slab spans a wide period of time (eg: hornblende Ar/Ar and K-Ar ages from 44-21 Ma).

GARHWAL HIMALAYA

In the Garhwal Himalaya of northern India the MCT forms a 10 km thick shear zone composed of mylonitic augen gneiss, amphibolite and metasediments, bounded above by the Vaikrita Thrust in the north and below by the Munsiari Thrust in the south (Fig. 4). Metamorphic grade increases to the north with structural height. The P-T gradient is inverted across the MCT zone but the upper 9 km (horizontal distance) of the Higher Himalayan slab is roughly isothermal (520- 620° C) and isobaric (7-8.9 kbars). Fig. 5 shows a temperature-time plot with the isotopic age data from this area. Hornblende growing along the ductile fabric associated with thrust movement along the MCT gives a plateau age of 19.8±2.6 Ma in the Bhagirathi valley section (Metcalfe 1993) suggesting that this may be recording the timing of slip on the MCT. K-Ar muscovite ages show a steady southwards decrease in cooling ages, mirroring the southwards propagating thrusting with time. Hornblende $^{40}Ar/^{39}Ar$ data show that structurally lower rocks in the biotite grade immediately above the Munsiari Thrust have not been reheated above 500° C since the Precambrian (Metcalfe 1993). There are, as yet, no reliable crystallisation ages from the tourmaline leucogranites at the top of the High Himalayan slab but preliminary fission track ages of zircon and apatite from the Shivling leucogranite suggest a relatively slow cooling from 15 Ma to the present. U-Pb zircon-monazite dating is in progress on these rocks.

NEPAL HIMALAYAN COOLING AND EXHUMATION HISTORY

The High Himalayan zone in the Nepal Himalaya, like the Zanskar and Garhwal sectors to the west, is bounded below by the north-dipping Main Central Thrust with its inverted metamorphic isograds, and above by the South Tibetan Detachment, a noth-dipping low-angle normal fault placing Palaeozoic sediments at the base of the Tethyan shelf on top of high-grade gneisses (Fig. 6). The tourmaline-bearing leucogranites, formed by anatexis of the continental crust, were intruded mainly along the South Tibetan Detachment, although some of the large plutons in Bhutan actually cross the normal fault and intrude up into the Tethyan cover. Fig. 7 summarises all the isotopic age data for the High Himalaya in Nepal, and Fig. 8 compares the age range of the High Himalayan leucogranites and gneisses with the North Himalayan granite gneiss domes. The latter form a series of about eleven domal structures along the hangingwall of a large-scale breakback thrust (Kangmar Thrust) with upward and outward decreasing metamorphic grade (Burg et al. 1984; Searle et al. 1987; Chen et al. 1990). Muscovite and biotite cooling ages from the North Himalayan gneiss domes are early and middle Miocene (Maluski et al. 1988), roughly concomitant with the High Himalayan tourmaline leucogranites.

ANNAPURNA

Parrish and Hodges (1993) dated igneous and metamorphic monazites from the Annapurna Sanctuary, in the western part of the High Himalayan zone in Nepal, using U-Pb isotopes, and concluded that metamorphism occurred at 22±1 Ma in this area. Deformed kyanite grade migmatitic segregations within Formation I above the MCT are 22.5 Ma and contain inherited monazite, whilst pegmatitic dykes which cross-cut Formation II calc-silicate gneisses have 22±1 Ma zircons which have no inheritance (Parrish and Hodges 1993). Formation III consists of augen gneisses containing strongly foliated leucogranites, previously thought to be Cambrian in age. The leucogranites contain igneous monazite 36.2±0.3 Ma old, suggesting that initial crustal melting in Nepal occurred in the Oligocene. Strongly foliated pegmatites within calc-sili-

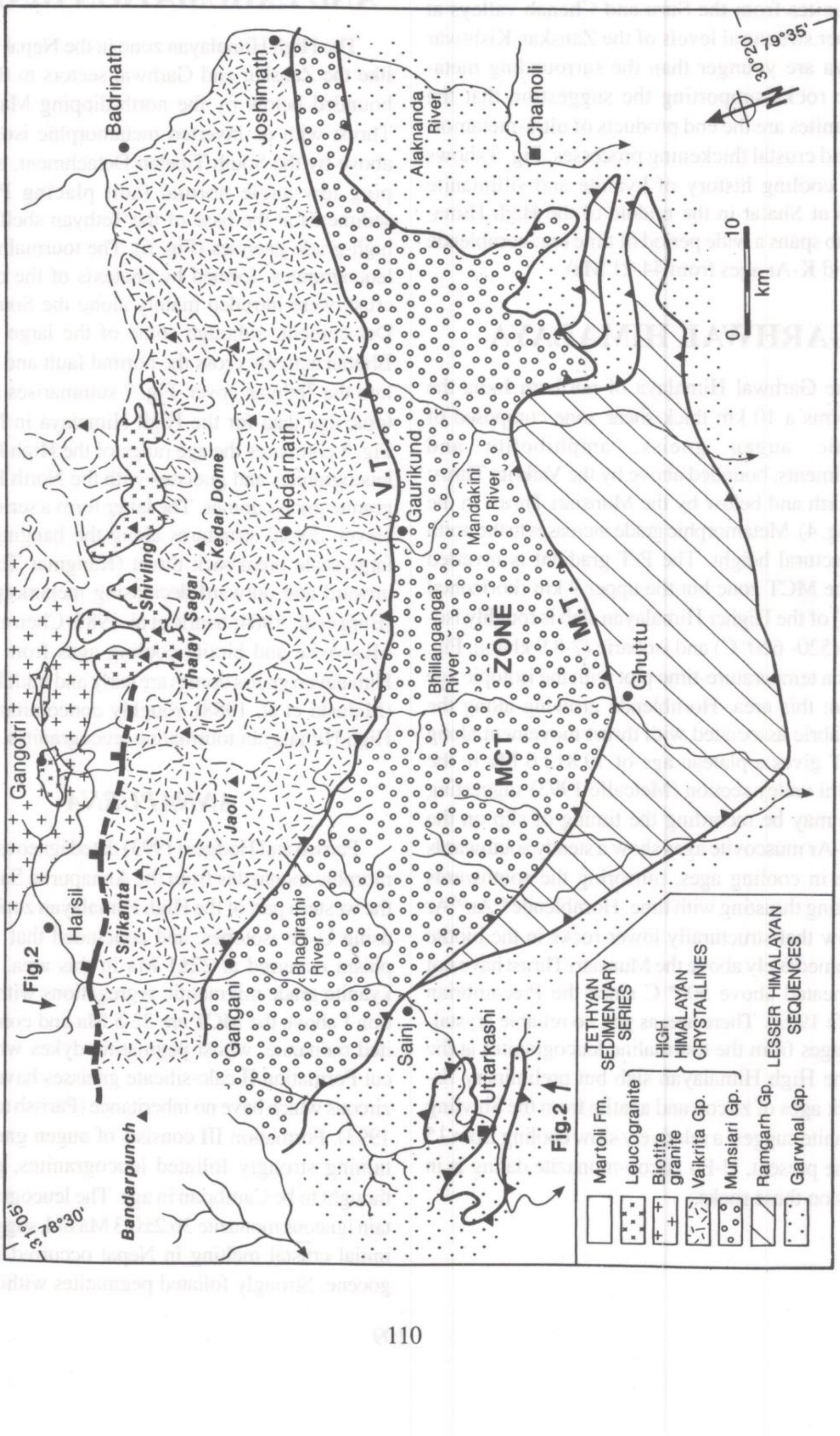


Fig. 4 Geological map of the Garhwal Himalaya from Metcalfe (1993)

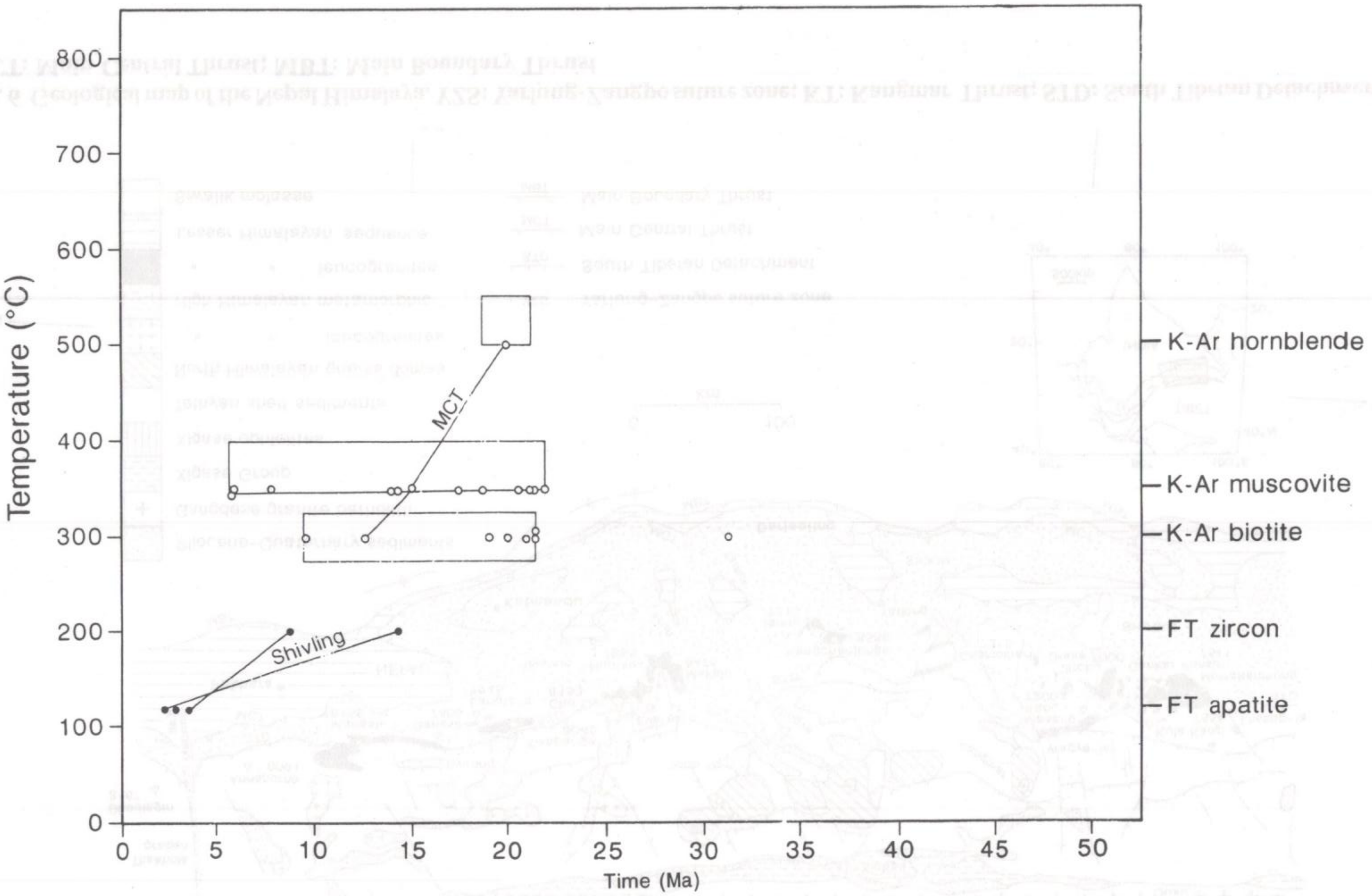


Fig. 5 Temperature-Time plot for the Garhwal Himalaya, northern India, showing the Ar-Ar and K-Ar ages of Metcalfe (1993) and some fission track zircon and apatite ages from A. Hurford (unpublished data) from the Shivling leucogranite. An ^{40}AR/^{39}Ar plateau age of 19.8±2.6 Ma from hornblende growing along syn-deformation fabrics in the MCT zone in the Bhagirathi valley constrains the timing of motion along the MCT in the central Himalaya. Metcalfe (1993) also showed that muscovite thermochronology reveals a southwards decrease in cooling ages across the High Himalayan slab, consistent with the model of southward propagation of metamorphism across the Himalaya.

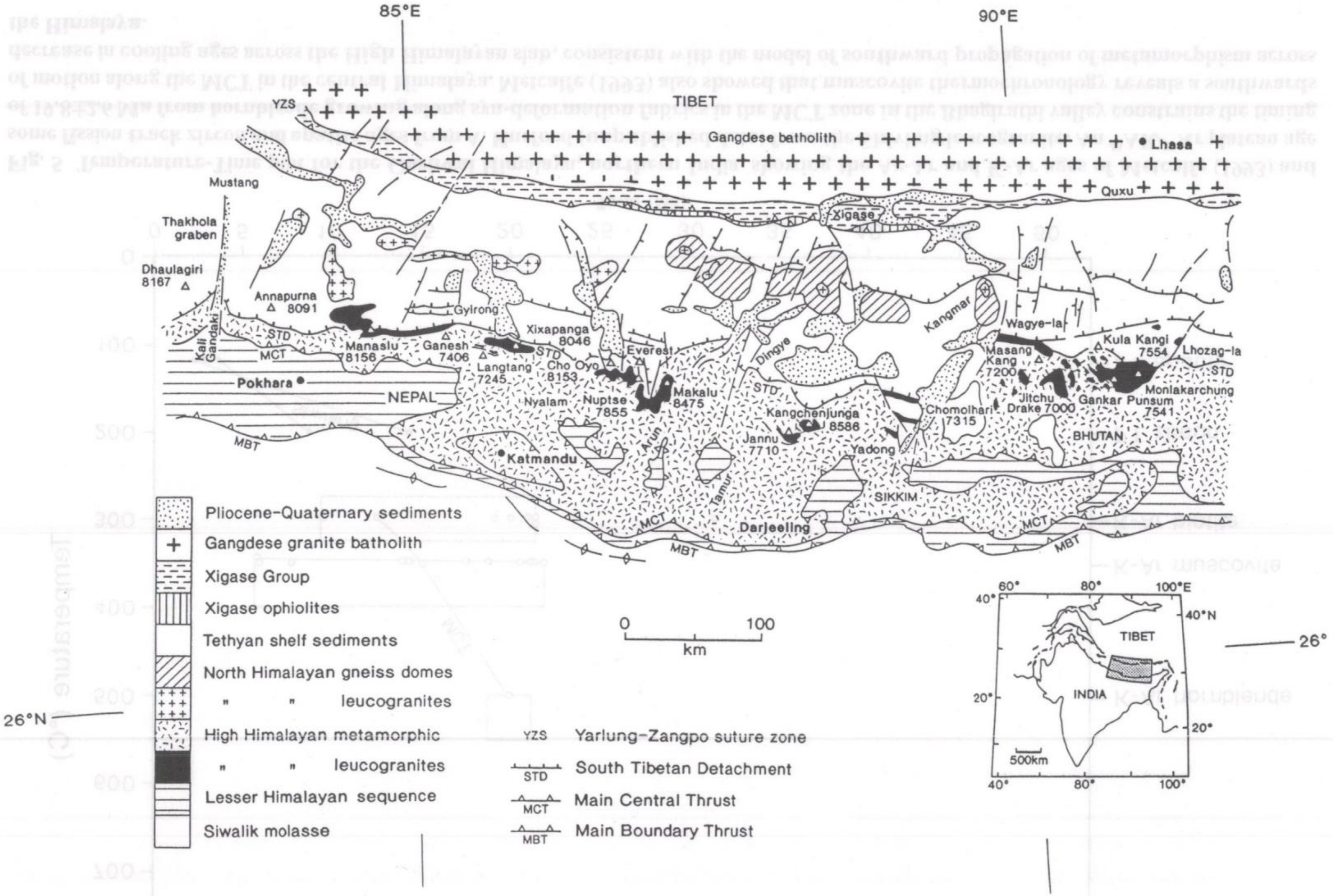


Fig. 6 Geological map of the Nepal Himalaya. YZS: Yarlung-Zangpo suture zone; KT: Kangmar Thrust; STD: South Tibetan Detachment; MCT: Main Central Thrust; MBT: Main Boundary Thrust

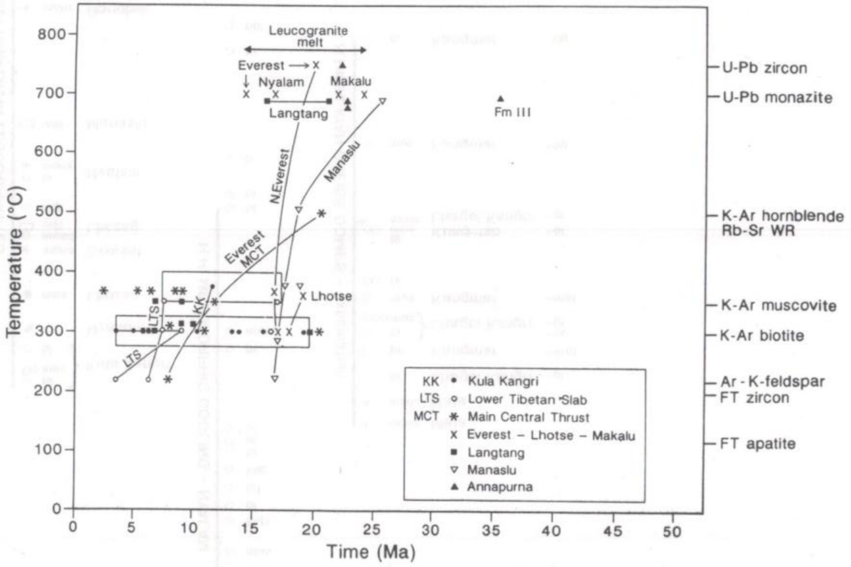
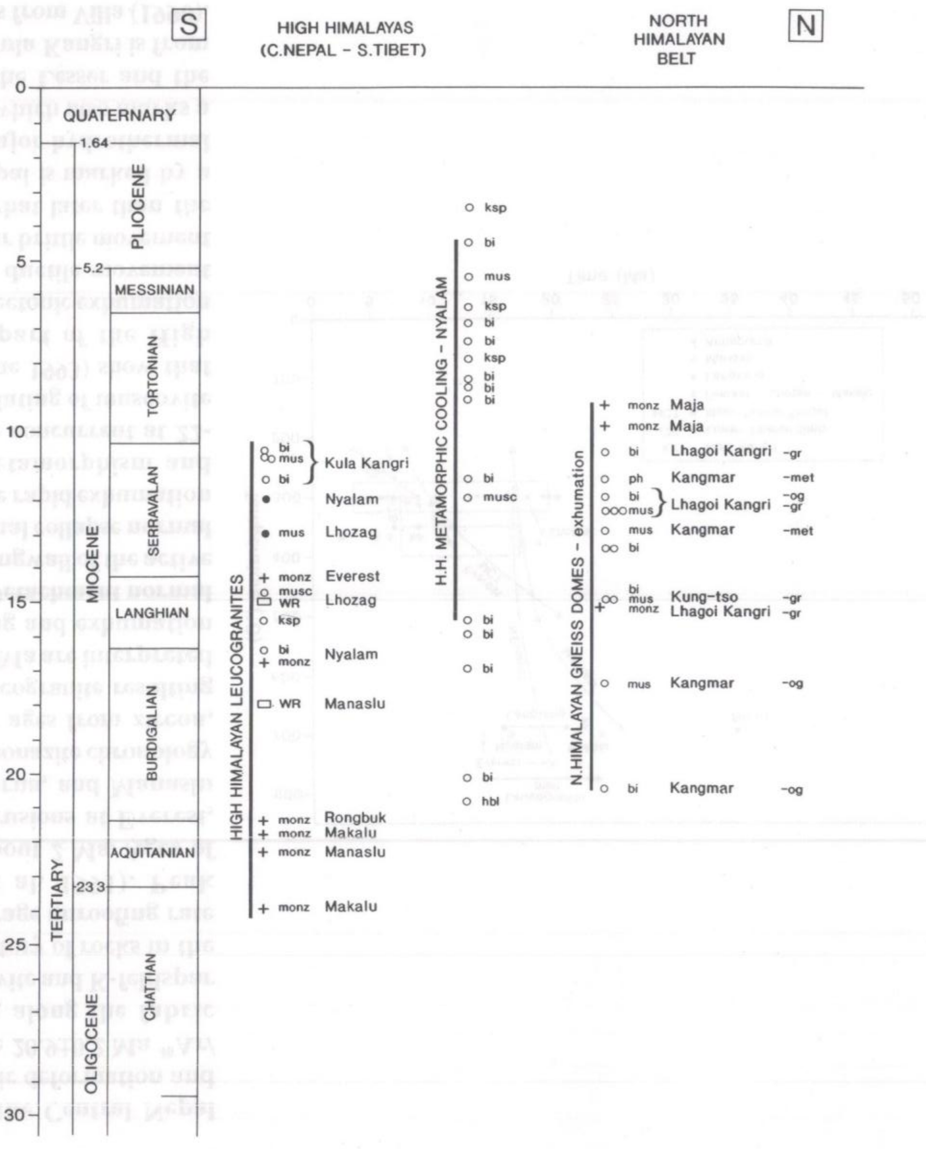


Fig. 7 Temperature-Time plot for the Central Nepal Himalaya. The age of syn-metamorphic deformation and slip along the MCT is provided by the 20.9±0.2 Ma ^{40}Ar/^{39}Ar age from hornblende growing along the fabric (Hubbard and Harrison 1989). Muscovite and K-feldspar ages reflect the subsequent cooling history of rocks in the MCT zone, and together show an average unroofing rate of 1.2±0.6 mm/year (Hubbard et al. 1991). Peak temperatures were maintained for about 2 Ma. Ages of leucogranite crystallisation from intrusions at Everest, Makalu, Nyalam, Langtang, Annapurna, and Manaslu span 24-15 Ma from U-Pb zircon and monazite chronology (see text for source of data). Similar ages from zircon, muscovite, and biotite in the Everest leucogranite resulting in a steep cooling curve between 19-17 Ma are interpreted as resulting from very rapid unroofing and exhumation along the footwall of the South Tibet Detachment normal fault. Uplift of the rock along the hangingwall of the active MCT, tectonic unroofing by gravitational collapse normal faulting and erosion all contribute to the rapid exhumation recorded by the geochronology. Metamorphism and anatexis in the Langtang section were concurrent at 22-16 Ma (Parrish et al. 1992). ^{40}Ar/^{39}Ar dating of muscovite from the Langtang section (Macfarlane 1993) show that early rapid cooling of the upper part of the High Himalayan slab may have been due to tectonic exhumation along the footwall of the STD. Early ductile movement along the MCT was pre-5.8 Ma and later brittle movement was about 2.3 Ma, apparently somewhat later than the Everest section. The MCT zone in Nepal is marked by a line of hot springs, suggesting that major hydrothermal discharge is controlled by this thrust, which also marks a distinct topographic divide between the Lesser and the High Himalaya. ^{40}Ar/^{39}Ar data from Kula Kangri is from Maluski et al. (1988) and Nuptse data is from Villa (1990).

Fig. 8 Tertiary time chart showing all isotopic ages recorded in the High Himalayan belt in central Nepal-southern Tibet, and cooling ages from the metamorphic rocks in the High Himalayan slab. Also shown are the ages recorded from the North Himalayan gneiss domes in the Kangmar and Lhagoi-Kangri belt to the north of the High Himalaya. These domes are metamorphic core complexes uplifted along late stage breakback thrusts cutting up into the Tethyan sediments structurally above the South Tibet Detachment, showing cores of leucogranite and upward and outward decreasing metamorphic grade. Monazite ages from High Himalayan leucogranites span ages from 26-14 Ma and North Himalayan granites from the cores of the gneiss domes are 21-9 Ma. See text for sources of data. Monz: monazite; bi: biotite; mus: muscovite; ksp: K-feldspar; hbl: hornblende; WR: Whole Rock



cate gneisses of the Annapurna Formation structurally above Formation III contain allanites which are also 22±0.5 Ma old showing that south-directed thrusting was post-22 Ma (Parrish and Hodges 1993).

MANASLU

The Manaslu leucogranite has been the subject of numerous geochemical (le Fort 1981; Vidal et al. 1982; France-Lanord and Le Fort 1988) and isotopic dating (Vidal 1976; Vidal et al. 1984; Deniel et al. 1987; Copeland et al. 1990) investigations. It forms a large leucogranite pluton consisting of the assemblage: quartz + plagioclase+ K-feldspar + muscovite + biotite, with tourmaline concentrated mainly in the dykes and sills emanating out of the main body of the granite. The composition is close to a minimum melt with high concentrations of B, F, and Li, and the leucogranite is almost completely unaltered. The Manaslu leucogranite has extremely heterogeneous $^{87}Sr/^{86}Sr$ initial ratios, which make it difficult to date isotopically. Denial et al. (1987) published a Rb-Sr isochron at 18.1±0.5 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7470. However six other samples from the same outcrop fall below the isochron and do not define the ages, making the accuracy of the 18.1 Ma date questionable (Copeland et al. 1990). A single U-Pb monazite age of 25.5 Ma is considerably older, and Deniel et al. (1987) interpreted these data as recording multiple batches of magma in the Manaslu pluton. The heterogeneity of Sr and Nd isotopes show that the magma was very poorly mixed during segregation and transport from the source. $^{40}Ar/^{39}Ar$ ages for hornblendes from the northeastern part of the contact metamorphic aureole of the pluton show that intrusion occurred prior to 22-23 Ma (Guillot et al. 1994). The cooling history is interpreted from the $^{40}Ar/^{39}Ar$ data which show that the Manaslu leucogranite cooled through the 350° C isotherm, the muscovite closing temperature, at 18.4-13.3 Ma, then through 300° C, the biotite closing temperature at 17.0-14.7 Ma, and then through 225° C, the K-feldspar closing temperature at 16.4-3.4 Ma (Copeland et at. 1990). The cooling curve (Fig. 7) shows that a rapid period of exhumation or unroofing occurred during the mid-Miocene.

Copeland et al. (1990) also showed that the rates and times of cooling varied from place to place within the Manaslu pluton. Structurally higher samples cooled earlier and at faster rates than structurally lower samples. Higher samples were intruded into country rocks which were at temperatures of 300-350° C, whereas structurally lower samples were intruded into rocks which were at temperatures of 375-450° C, consistent with the interpretation that the leucogranites were intruded along the South Tibetan Detachment, the major north-dipping normal fault at the top of the High Himalayan slab and base of the Tethyan sedimentary sequence (Guillot et al. 1993; Searle et al. 1993). The Manaslu granite was therefore intruded at depths of 8-15 km along a north-dipping normal fault zone at the highest structural levels of he High Himalayan slab.

LANGTANG

The Langtang Himalaya in north central Nepal shows a 20 km section through the High Himalayan gneisses along the hangingwall of the MCT which is dominated by non-coaxial top-to-south simple shear fabrics. The apparent inverted metamorphic gradient results from post metamorphic thrusting of sillimanite grade rocks over kyanite grade rocks at the higher structural levels (Reddy et al. 1993). The upper levels consist of a massive layered leucogranite sill complex intruded into sillimanite grade gneiss (Langtang Lirung unit), syn- to late kinematic with respect to the main fabric development. Leucogranites contain inherited zircons with mainly Proterozoic ages, as well as igneous monazites and xenotimes which show evidence of crystallization at 21 Ma with no inheritance (Parrish et al. 1992). Metamorphic monazites are common in the semipelitic gneisses and show a range of ages from 15.4-20.7 Ma indicating the probable timing of peak metamorphism in this sector of the Central Himalaya. $^{40}Ar/^{39}Ar$ cooling ages of muscovite and biotite range from 9.7-4.6 Ma and a later period of brittle thrusting along the MCT zone is constrained at approximately 2.3 Ma (Macfarlane 1993). One biotite $^{40}Ar/^{39}Ar$ age of 19.4 Ma from the uppermost part of the High Himalayan slab is closer to the U-Pb monazite ages, suggesting that cooling ages decrease southwards with the younger thrusts, similar to the Garhwal story. The isotopic dating results form this part of the Himalaya seem to suggest that peak metamorphism and crustal anatexis occurred at around 21 Ma, with the upper part of the High Himalayan Slab experiencing rapid cooling and exhumation during the mid-Miocene (21-15 Ma), whilst the lower part of the slab cooled somewhat slower and later (15-5 Ma).

EVEREST-NUPTSE-MAKALU

In eastern Nepal, the MCT forms a 3-5 km thick shear zone which thrusts High Himalayan gneisses in the north over Lesser Himalayan low-grade rocks in the south. The metamorphic grade increases structurally up-section from garnet-staurolite grade through kyanite grade to sillimanite gneisses. Large lourmaline-bearing two-mica leucogranite intrusions form some of the large mountains, such as Makalu an Lhotse at the top of the slab along the Nepal-Tibet border. A network of leucogranitic dykes and sills emanate out of these leucogranite bodies and intrude the sillimanite grade gneisses, magnificently exposed on the south face of Everest, Lhotse and Cho Oyu for example. The top of the High Himalayan (Tibetan) Slab is marked by the low-angle north-dipping normal fault, the South Tibetan Detachment (STD) (Burchfiel et al. 1992). At least 35 km of northward displacement along the STD in the Everest area where low-grade sediments which were never at temperatures higher than 350° C have been faulted on top of sillimanite-grade gneisses metamorphosed at temperatures above 650° C. This indicates that between 10-15 km of stratigraphic section is structurally missing across this normal fault zone. The Rongbuk leucogranite, which gives a U-Pb zircon age of 19.5±0.4 Ma and a monazite age of 20.6±0.2 Ma, cuts across the STD giving an upper age limit on normal fault movement (Copeland et al. 1988; Burchfiel et al. 1992). This is very close to the age of movement along the MCT at the base of the High Himalayan slab, suggesting that the two major bounding faults were active at the same time.

Whereas the Langtang section is thought to have been affected by post-metamorphic thrusts an normal faults distorting the P-T profile, the section through the Solu Khumbu region south of Everest has been interpreted as representing a portion of the palaeo-geotherm at the time of MCT deformation (Hubbard 1989). Thermobarometric and structural data from the MCT zone suggest syn-Metamorphic deformation at temperatures of 500-550° C was active at 20.9±0.2 Ma, the $^{40}Ar/^{39}Ar$ plateau age of hornblende growing along the thrust fabric (Hubbard and Harrison 1989). The pressures recorded by thermobarometry of 7.3 kbars show a depth of metamorphism of approximately 26 km. Biotite ages as old as 20 Ma near the leucogranites show that intrusion was concomitant to deformation and metamorphism in the MCT zone along the base. The cooling history of the MCT rocks are further constrained by the $^{40}Ar/^{39}Ar$ ages of muscovite (Tc=350° C at 12±0.2 Ma) and K-feldspar (Tc= 220° C at 8.0±0.2 Ma) (Hubbard and Harrison 1989) which are plotted on Fig. 7. Hubbard et al. (1991) used their geochronological and thermobarometric data to obtain an average unroofing rate of 1.2±0.6 mm/year for the east Nepal High Himalaya. They emphasised however that the way this exhumation was partitioned through time cannot be accurately determined. Uncertainties in the unroofing history are due to the variation in radiogenic heat production and a continually changing, non-linear geotherm through time. The depth controls through geobarometry do, however, contain useful information about the amounts of erosion. Some 26 km thickness of overburden was eroded and removed from the hangingwall of the MCT since 21 Ma in order to exhume the rocks exposed at the surface today. This eroded material was transported along the major river systems draining the Himalaya into the Ganges-Brhamaputra system in the eastern Himalaya and the Indus river system in the western Himalaya.

DISCUSSION AND CONCLUSIONS

Cooling histories of metamorphic and magmatic rocks from the Himalaya derived from thermochronometers using radiogenic isotope systems, combined with thermobarometers have been used to determine the total amounts of rock material which must have been eroded off different parts of the Himalaya since the Indian plate collision. Time constraints involved in these processes allow us to estimate erosion-exhumation rates. Along most of the Indus-Tsangpo suture zone in the Ladakh and south Tibet there is good geological evidence, in terms of the youngest marine foraminifera in Lower Eocene limestones and the oldest overlying continental red beds, that collision and the closure of the Tethys occurred at the Lower/Middle Eocene boundary, 54-50 Ma ago (Searle at al. 1987). This age coincides with a pronounced slowing down in the rate of the northward drift of India, and a reorganisation of plates in the southeast Asia region (Patriat and Achache 1984).

Whereas peak metamorphism in the far western Himalaya was probably Eocene, peak metamorphism along the entire Himalayan belt east of Nanga Parbat was probably Oligocene- early Miocene. Geochronology in the eastern Kashmir-western Zanskar sector suggests that the age of peak metamorphism was pre-31 Ma, with the possibility of diachronous metamorphism younging towards the southwest, down-structural section with time (Searle et al. 1992). In Garhwal and Nepal peak metamorphism was pre-21 Ma coincident with high temperature shearing along the MCT zone (Hubbard 1989; Metcalfe 1993). The youngest metamorphism is actually within the Nanga Parbat syntaxis where Smith et al. (1992) and Zeitler et al. (1993) have recorded a Pliocene-Pleistocene regional metamorphism and crustal melting event, when the Nanga Parbat gneisses were undergoing rapid denudation at mean rates of 5 mm/year. These exceptionally high exhumation rates were caused by active east-west compression across the syntaxis, where thrusts and fold axial traces swing around into a north-south alignment, and active north-south compression where the north-south striking Nanga Parbat-Harmosh massif impinges on the east-west striking southern Karakoram (Searle 1991).

Exhumation in the Himalaya was accomplished both by erosion and tectonic processes, particularly normal faulting. Thrusting along the base of the High Himalayan slab (MCT) was active at 21-18 Ma ago, synchronously with dip-slip on the South Tibet Detachment normal fault at the top of the slab. Kyanite and sillimanite gneisses in the footwall formed at pressures of 8-10 kbars and depths of burial of 28-35 km, 30-21 Ma ago, whereas low-grade sediments along the hangingwall have never been buried below about 5-6 km. Exhumation rates are far greater in the High Himalayan zone (1.4-2.1 mm/year) than along the actual zone of collision, or along the north Indian continental margin. The High Himalayan leucogranites span a wide range from 24-9 Ma in the central Himalaya and anatexis occurred at 21-19 Ma in Zanskar, approximately 30 Ma after the collision.

The Karakoram underwent high temperature-medium/high pressure metamorphism during the Eocene (50-37 Ma) and widespread lower crustal (Baltoro monzogranite-leucogranite) and upper mantle (lamprophyre dykes melting during the Miocene (25-21 Ma) (Searle 1991). The lower crust beneath the Tibetan plateau has not been uplifted and exhumed, and therefore the composition and thermal state remains unknown. A few mid-crustal metamorphic core complexes such as the Nyainqentanglha massif, have been exhumed along the low-angle normal faults. $^{40}Ar/^{39}Ar$ dating of muscovite, biotite, K-feldspar, and fission track apatite show that rocks within the extensional shear zone cooled from above 350° C to about 100° C between 8-3 Ma ago (Pan and Kidd 1992). They suggested that this late Miocene age may have reflected the beginnings of collapse of the Tibetan plateau when it reached its maximum sustainable elevation. However, the NE-SW aligned Nyainqentanglha massif is something of an anomalous structure on the Tibetan plateau, and is not parallel to the N-S aligned graben systems in southern Tibet. The 8±3 Ma age from Nyainqentanglha undoubtedly marks the time at which these rocks cooled through 350° C, but it does not record the onset of exhumation of these amphibolite facies rocks, which would probably have been earlier at higher temperatures, and it does not necessarily record the timing of the extensional collapse of the whole plateau. We still do not know the age of maximum elevation of the plateau or when it started extending. Likewise, we do not know the age of peak metamorphism or the timing of exhumation in the Kun Lun, Pamirs, or Tien Shan mountains to the north and west of the Tibetan plateau.

Cooling histories of the Himalaya and Karakoram in particular show that significant crustal thickening, widespread metamorphism, erosion, and exhumation (and therefore probably significant topographic elevation) occurred during he Eocene-Oligocene in the Karakoram, and during the early Miocene along the central and eastern Himalaya. This happened before the strengthening of the Indian monsoon at about 8 Ma (Prell and Kutzbach 1992), before the changes in climate and vegetation in north Pakistan (Quade et al. 1989), and before the onset of east-west extension and collapse of the Tibetan plateau (Mercier et al. 1987). The primary influence over exhumation was exerted by tectonic features, particularly thrusts and normal faults, and not by external features such as climate. Kinematic models of the deformation of Asia using 2-D strain rates and slip rates on strike-slip faults should also take into account 3-D exhumation and erosion rates in crustal balancing exercises.

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