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An overview of the metamorphic evolution in Central Nepal

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Abstract

This paper summarizes the studies of the metamorphic evolution of Central Nepal carried out by Nepali and international teams in the last 25 years. In Central Nepal, three metamorphic units are recognized. (1) The southernmost zone is the Lesser Himalaya, which is characterised by an inverted mineral zoning towards the Main Central Thrust (MCT) zone; (2) the Kathmandu nappe corresponds to an early (< 22 Ma) out-of-sequence thrusting zone over the Lesser Himalaya along the Mahabharat thrust (MT) and is characterised by a Barrovian metamorphic evolution; (3) the Higher Himalayan Crystalline unit (HHC) is bounded at its base by the MCT and at its top by the South Tibetan Detachment system (STDS). It is characterised by successive tectonometamorphic episodes during the period spanning from 35–36 Ma to 2–3 Ma. Recent investigations suggest that the apparent metamorphic inversion througout the MCT zone does not reflect geothermal inversion. Instead, these investigations suggest successive cooling of the HHC along the MCT and the local preservation, above the MCT, of high-grade metamorphic rocks. The overall metamorphic history in Central Nepal from Oligocene to Pliocene, reflects the thermal reequilibration of rocks after thickening by conductive and advective heating and partial melting of the middle crust. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Himalayan orogen, (Fig. 1) which began with the collision of India and Eurasia at the Palaeocene/Eocene boundary (Rowley, 1996; de Sigoyer, 1998 and references cited therein), provides an excellent natural laboratory for the study of metamorphic processes. Since 55 Ma, the shortening due to convergence produced intra-upper crustal shear zones, that thickened the Indian crust to its present thickness of 70 km (Le Fort, 1975a; Molnar, 1988; Zhao et al., 1993). A main consequence of this thickening is the concentration of radioactive heat-producing elements (K, U, Th) possibly responsible for the development of a Barrovian metamorphism and associated anatexis within the HHC. Due to the compressional and extensional faulting, different tectonometamorphic units have been juxtaposed along the Himalayan belt.

The Central part of Nepal, from the western Kali Gandaki river to the east of the Indrawati river contains good exposures of the core of the Himalayan orogenic belt (Fig. 2). Although the tectonometamorphic history of the area has been well investigated (e.g. Le Fort, 1975a; Pêcher, 1989; Vannay and Hodges, 1996), the metamorphic evolution of Central Nepal is rather complex (MacFarlane, 1995 and this issue) and a mountain belt could be described as a complex thermodynamic system in which a simple unifying theory of orogenesis is not sufficient to explain many features (Hodges, 1998). This paper attempts to review the present knowledge of the metamorphic evolution of the Central Himalayan belt in Nepal and summarizes geological data collected during the last 25 years.

2. Petrological studies

Field and petrological studies indicate that a zone 15–30 km thick in the Central Himalaya is affected by middle-pressure, middle-temperature metamorphism. This zone includes the Lesser Himalaya, the

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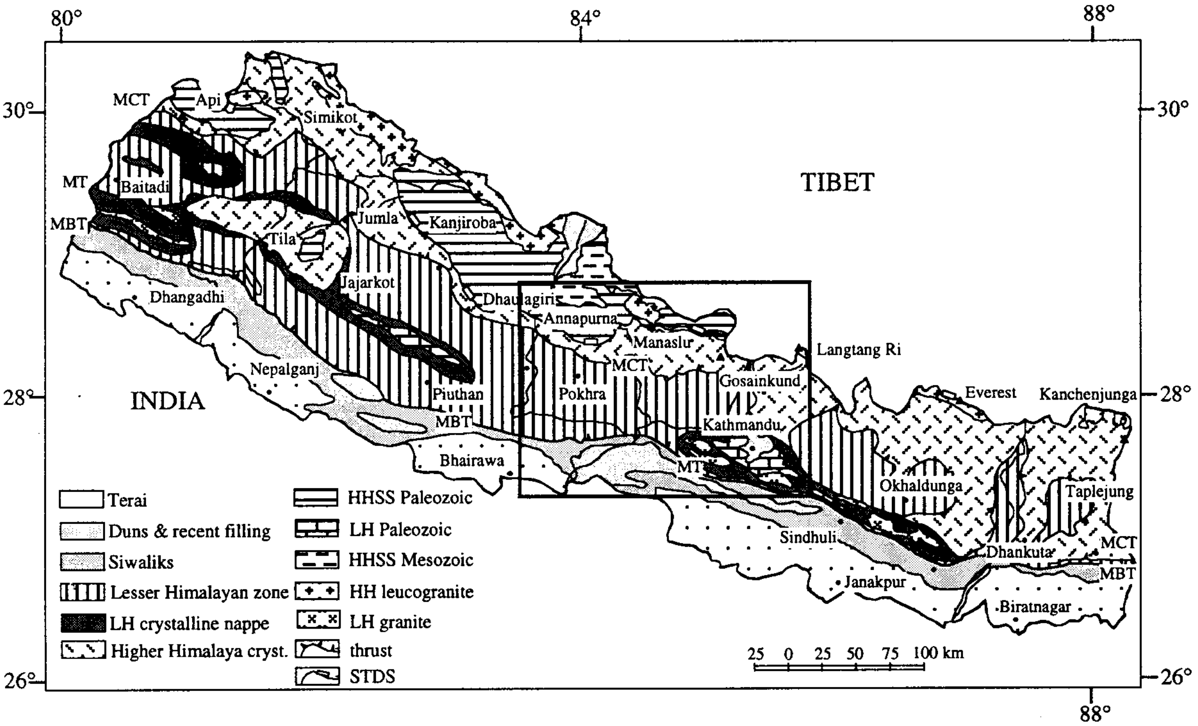

Fig. 1. Geological map of Nepal (after Raï, 1998 and Upreti and Le Fort, 1999).

Kathmandu nappe, the HHC and local incursion in the TSS, during leucogranitic intrusion of the HHL (Hagen, 1969; Le Fort, 1971, 1975a; Le Fort et al., 1986; Arita et al., 1973; Pêcher, 1978, 1989; Stöcklin, 1980a; Guillot et al., 1995) (Figs. 1 and 2).

2.1. The Lesser Himalaya

The Lesser Himalaya, also called the Lower Himalaya or the Midland Formations, is a thick (>7 km) section of para-autochtonous crystalline rocks of Nepal, comprised of low (Chl no Bt) to medium (Bt+Grt+St+Ky) grade rocks. These lower Proterozoic clastic rocks (Vidal et al., 1982; Deniel, 1985; Colchen et al., 1986; Parrish and Hodges, 1996) are subdivided into two groups. The lower group consists of argillic-arenaceous rocks (Kuncha sandstones of Bordet, 1961) and the upper group is composed of argillic-calcareous units (Hagen, 1969; Hashimoto et al., 1973; Le Fort, 1975a; Pêcher, 1978; Stöcklin, 1980a) (Fig. 2). The Lesser Himalaya thrusts upon the Siwaliks along the Main Boundary Thrust (MBT) to the south and is overlained by the allochthonous thrust sheets, the Kathmandu and HHC nappes along the MT and the MCT zone, respectively. The Lesser Himalaya is folded into a vast post-metamorphic anticlinal structure with a N110° axis, the Kuncha–Gorkha anticlinorium (Pêcher, 1977, 1978). The southern flank of the anticlinorium is weakly metamorphosed, whereas the northern flank is highly metamorphosed. In the northern flank, the Ulleri augen-gneiss composed of Lower Proterozoic granitic laccoliths is exposed (Le Fort, 1989). The apparent width of the Lesser Himalaya increases eastward, and is related to the erosion level (Pêcher, 1978).

Throughout the Lesser Himalaya, the metamorphic grade increases upwards toward higher structural levels defining an inverse metamorphic mineral zonation as first described in Sikkim (Ray, 1947). Pêcher (1978) defined from south to north, four metamorphic zones: the chlorite zone (Chl+Ms), the biotite zone (Chl+Bt), the garnet zone (Grt+Bt+Pl+Chl) and the staurolite zone (Grt+Bt+Pl ± St). Kyanite, the typical mineral of the HHC, is also found in the eastern part of the upper Lesser Himalaya. There, the main foliation as well as ductile C-S fabrics is defined by Bt and Ms. Grt or St contain synkinematic sigmoidal inclusion trails. The non coaxial fabrics indicate SW directed movement from the Kali Gandaki in the west (Pêcher, 1978; Caby et al., 1983) to the Mailung Khola in the East (Raï et al., 1998). Traces of a retrograde evolution towards greenschist facies conditions are locally observed in the Kali Kandaki valley (Caby et al., 1983; Vannay and Hodges, 1996), in the Buhri Gandaki valley (Guillot, 1993) and in the Langtang valley (MacFarlane et al., 1992; MacFarlane, 1993, 1995).

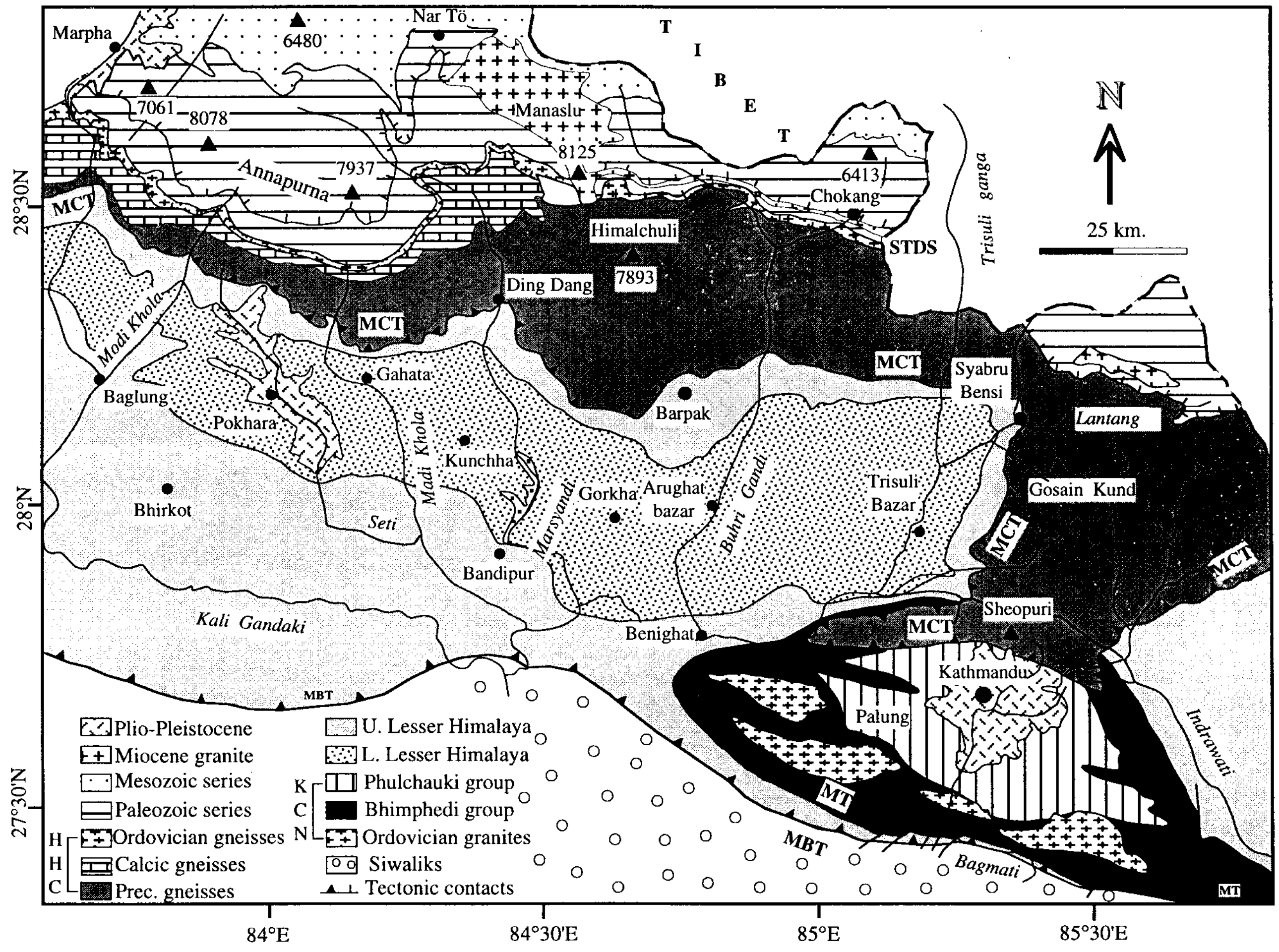

Fig. 2. Geological map of Central Nepal (modified after Stöcklin, 1980; Colchen et al., 1986; Raï, 1998). MBT: Main Boundary Thrust, MCT: Main Central Thrust, MT: Mahabharat Thrust.

2.2. The Kathmandu nappe

The Kathmandu nappe was first recognised by Hagen (1969) and mapped by Arita et al. (1973) and by Nepalese geologists at the Department of Mines and Geology (Stöcklin and Bhattarai, 1977; Stöcklin, 1980). It forms a huge N100° synclinorium divided into the lower Bhimpedi group (about 10.5 km thick Precambrian age rocks) and the overlying sedimentary Phulchauki group ($\approx$4 km thick Lower Paleozoic rocks). A number of Cambro–Ordovician granites (Le Fort et al., 1981) are recognised in the Kathmandu nappe (Fig. 2).

The frontal part of the Kathmandu nappe reaches the MBT in the south and a very narrow zone of the Lesser Himalaya separates it from the Siwaliks along the MT. This thrust was interpreted as a direct continuation of the MCT (Stöcklin, 1980; Fuchs, 1981; Pêcher and Le Fort, 1986), but recent investigations illustrate that the Kathmandu nappe has distinct lithology and stratigraphy with a separate geochronological and metamorphic evolution (Raï, 1998; Raï et al., 1998; Upreti and Le Fort, 1999), suggesting that the MT and MCT thrusts correspond to two distinct tectonic events. The northward extension of the Kathmandu nappe also reached the northern edge of the Kathmandu valley (Fig. 2).

Colchen et al. (1980) and Stöcklin (1980) have defined a biotite zone in the upper Pulchauki group and a garnet zone in the lower Bhimpedi group. In the latter group, metapelites show an assemblage of Qtz + Grt + Bt + Pl + Ms with accessory minerals of Tr + Rt + Fe–Ti oxides and secondary Chl (Raï et al., 1998).

2.3. The MCT zone

The large scale thrusting of the HHC over the less metamorphosed sedimentary and volcanic formations has long been recognised and is called the MCT in Kumaon by Heim and Gansser (1939). Pêcher (1977, 1978) and Bouchez and Pêcher (1981) have shown that

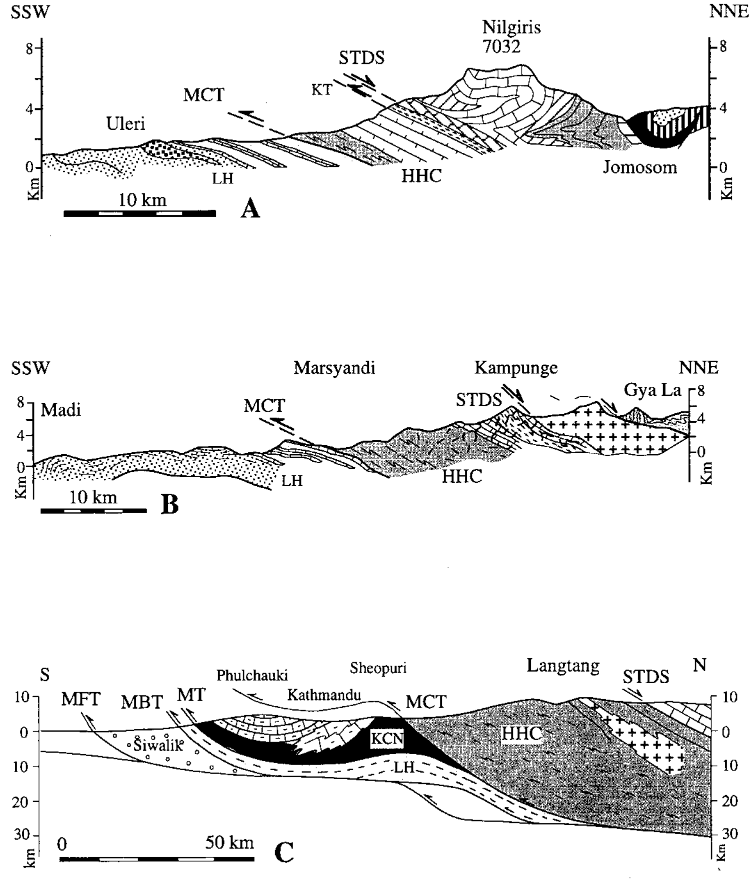

Fig. 3. Sections across the Central Nepal Nappes (after Le Fort et al., 1986 and Raï et al., 1998). A: Annapurna section, B: Manaslu section, C: Kathmandu–Langtang section. LH: Lesser Himalaya, KCN: Kathmandu Crystalline Nappe, GCN: Gosainkund Crystalline Nappe, MFT: Main Frontal Thrust, MBT: Main Boundary Thrust, MCT: Main Central Thrust, MT: Mahabharat Thrust, STDS: South Tibetan Detachment System, KT: Kalopani Thrust.

in Central Nepal this thrust is a thick ductile deformation zone (D2) affecting both sides of the thrust and is related to the thrusting at high temperature of the HHC over the Lesser Himalaya (Figs. 2 and 3). Le Fort (1975a) and Pêcher (1978) defined the MCT as (i) the lithological boundary between the migmatitic gneisses of the HHC and the upper Lesser Himalaya or Pulchauki group of the Kathmandu nappe characterised by relict sedimentary textures and (ii) the limit where the very strong L–S fabric of the Lesser Himalaya is replaced by the main planar fabric of the HHC, and where the rotational synmetamorphic deformation which increases progressively upwards reaches its maximum. North of the Kathmandu valley, along the southern slope of the Sheopuri range, the rocks of the Pulchauki group are intruded by a network of pegmatite dikes and have a tectonic contact with the schists of the HHC, which is locally called the Gosainkund Crystalline nappe. This contact corresponds to the southward extension of the MCT (Raï, 1998; Raï et al., 1998; Upreti et al., in press). In the MCT zone, the main penetrative fabrics (N100° schistosity S2, N20° mineral lineation L2 and C/S fabrics) are defined all along the Central Nepal by the mineral assemblage Qtz + Pl + Bt + Grt + Ky/St ± Rt (Le Fort, 1975a; Pêcher, 1978; Le Fort et al., 1986; Hodges et al., 1988; Macfarlane, 1995; Raï et al., 1998). Where no metamorphic break occurs between the HHC and the Lesser Himalaya or the Kathmandu nappe, thrusting along the MCT was considered synmetamorphic. This evidence suggests that the inverted metamorphism in the Lesser Himalaya is a consequence of early thrusting on the MCT (LeFort, 1975a; Pêcher and Le Fort, 1986) and that the end of the exhumation of the HHC occurred by erosion or by activation of a more frontal thrust (MBT). Nevertheless, local occurrences of late shear zones containing biotite or chlorite (Kali Gandaki, Marsyandi) and brittle thrust faults (Langtang) suggest that the MCT zone has undergone, in some places, multiple epsiodes of south-directed movement (Caby et al., 1983; Copeland et al., 1991; MacFarlane et al., 1992; Hodges et al., 1996; Harrison et al., 1997).

2.4. The Higher Himalayan crystallines

The HHC complex is also called the Greater Himalayan sequence or the Tibetan slab in Nepal, and consists of a 5–15 km thick continuous sequence of metapelitic and calcsilicate rocks bounded at the base by the MCT zone and at the top by the North Himalayan Normal fault (NHNF),which is also called the South Tibetan Detachment system (STDS) (Figs. 2 and 3). The protolith of the HHC is interpreted to be Late Proterozoic clastic sedimentary rocks deposited on the northern Indian margin (Vidal et al., 1982; Deniel 1985; Parrish and Hodges, 1996). These clastic sequences contain amphibolitic to granulitic metamorphic assemblage Grt + Ky + Bt + Pl + Qtz ± Ms ± Kfs ± Rt/Ilm ± relics of St. Migmatites associated with Sill and locally Crd later developed at the expense of earlier minerals in the upper part of the sequence. The migmatitic gneiss is considered to be partly the source for the overlying Tu- or Ms and Bt-bearing leucogranitic intrusions such as the Manaslu granite (LeFort, 1975b; Le Fort et al., 1987). This interpretation is supported by major and trace elements and isotope data from the granites (Le Fort, 1981; Vidal et al., 1982; Cuney et al., 1984; Deniel et al., 1987; France-Lanord and Le Fort, 1988; Guillot and Le Fort, 1995; Harris et al., 1995). Nevertheless, Rb/Sr and Sm/Nd isotopic studies suggest that a part of the migmatitic zone corresponds to the root zone of the 500 Ma granitoid and consequently the root of the HHL is essentially situated deeper, within the metapelites (Guillot and Le Fort, 1995).

In the gneisses, the main tectonic marker is a penetrative foliation dipping 10–30° to the north and is associated with a N20° stretching lineation.The linear fabric is clearly imprinted at the base of the HHC. Higher in the metamorphic sequence, the fabric associated with southward shearing progressively fades out in 1 or 2 km. The stretching lineation becomes more difficult to see, being defused by the high temperature recrystallization of Sill. Still higher, where approaching the STDS, the early southward fabric is entirely overprinted by a younger northward fabric with a dextral strike–slip component (Pêcher et al., 1992).

From west to east along a 200 km strike, the HHC are thicker, and it is possible to distinguish three metamorphic type sections which show different metamorphic paragenesis (Pêcher, 1989; Raï et al., 1998): a thin section in the Annapurna area (along the Kali Gandaki and the Madi Khola), a thick section in the Gosainkung area (from the Sheopuri summit up to the Langtang valley) and an intermediate section in the Manaslu area (along the Marsyandi and Buhri Gandi valleys) (Fig. 3).

2.4.1. The Annapurna type section

This section is characterised by a thin HHC (5 km thick) suggesting that the present-day erosion surface cuts the thrust close to its tips (Pêcher, 1989). The main metamorphic foliation is characterised in the metapelites by the following assemblage: Qtz + Bt + Pl + Grt + Ms ± Kfs ± Zo ± Rt/Ilm (Le Fort et al., 1986; Vannay and Hodges, 1996). Even, in the upper levels, Sill is very rare and the migmatization is rarely observed. Vannay and Hodges (1996) show that the earlier Ky + Ms + Bt S1 schistosity is deformed by isoclinal microfolds S2 with the secondary development of Ky along Grt–Pl contact or Pl–Pl contact near Grt and Bt suggesting the net-transfer reactions Pl = Grt + Ky + Qtz and Pl + Bt = Grt + Ms.

In the upper part, calcsilicate gneiss contains the typical amphibolitic assemblage Qtz + Pl + Kfs + Bt + Ep + Cpx + Hbl + Grt + Scp + Ms + Cal ± Scp. Finally, the upper orthogneiss is characterised by the mineral assemblage Qtz + Pl + Kfs + Ms + Bt ± Grt. Neither Ky nor Sill was found in these rocks.

2.4.2. The Manaslu type section

The relatively thick (≈8 km) metasedimentary series is characterized at its base by the same assemblage as described in the Annapurna section. Locally Qtz + Pl ± Ky ± Kfs leucosomes are also observed (Pêcher, 1989). Muscovite is abundant in the lower part whereas Kfs essentially occurs higher in the series where leucosomes become more apparent. The top part of the HHC is widely injected by granitic melts. Migmatitic layers several tens of metres thick (i.e. Tal area in the Marsyandi valley, Le Fort, 1975b) are reaffected by the synmetamorphic deformation, whereas less abundant leucosomes, which are often tourmaline-rich crosscut the Himalayan foliation. From the middle to the upper part of the HHC, Sill is abundant. Sill develops either at the expense of muscovite and kyanite or is associated with Kfs suggesting the development of the reactions:

Ms + Qtz = Kfs + Sill + H20 and Ky = Sill typical of the amphibolite to granulite facies transition (Thompson, 1976; Vielzeuf, 1984). Upward, the orthogneisses are partly mobilized and contain Sill.

2.4.3. The Gosainkund type section

This thick section (12 km) above the MCT zone is characterised by micaschists containing Qtz + Bt + Pl ± Grt ± Ky ± Ms ± Kfs + accessory minerals (Inger and Harris, 1992; Macfarlane, 1995; Raï et al., 1998). Locally, in the lower HHC, Sill occurs with Ky, but does not overgrow it. In addition, Sill and Ky are present as magmatic phases in leucogranitic sills suggesting their coexistence (MacFarlane, 1995). Locally, just south of the Gosainkund summit, the HP granulitic assemblage (Grt + Ky/Sill + Kfs) is observed 2 km above the MCT zone (Raï et al., 1998).

Kfs and Sill appear systematically in the upper section and developed at the expense of Ms (ibid.). This recrystallization is explained in the Manalsu section by the transition from amphibolite to granulite facies. Moreover, Inger and Harris (1992) described in the upper section the development of symplectitic corona of Crd and Qtz around Grt resulting in the decompressional reaction Grt + Qtz + Sil = Crd or the Bt dehydration-melting reaction Bt + Qtz + Pl = Sill + Grt/Cd + Kfs + melt.

2.5. The Tethyan sedimentary series

The area north of the Annapurna and Manaslu ranges in Central Nepal consists of metasediments which overlie the HHC along the STDS (Fig. 2). A detailed description of these lithologies can be found in Bordet et al. (1975) and Colchen et al. (1980). The thickness of the TSS is currently presumed to be 7400 m (Fuchs et al., 1988). The thickness of already eroded sediments is difficult to estimate, but the Thakkhola graben shows at least 2400 m of Jurassic and Cretaceous sediments (Bordet et al., 1975). Schneider and Masch (1993) estimated that at the time of the Neo-Himalayan metamorphism, the total thickness of the TSS in the Manang area was approximately 10 km. All the series are affected by huge northeast-verging gravitational collapse folds, such as the Annapurna/Nilgiri fold and are associated with three northward detachments: (1) the NHNF or the STDS also called the Chame detachment in the Marsyandi valley at the boundary between the HHC and the TSS; (2) the Macchapuchare detachment also called the Kyang detachment localized within the Lower Paleozoic formations and (3) the Nar Ma detachment localized at the base of the Liassic sediments (Caby et al., 1983; Pêcher, 1991; Hodges et al., 1996; Le Fort and Guillot, 1998). In contrast, Godin et al. (1999) proposed that the huge northeast-verging folds predate ductile extensional faulting and is related to an older compressional event. Thus, the Annapurna/Nilgiri detachment represents a zone of superposed normal and thrust shearing.

The metamorphic conditions decrease upward from amphibolitic diopside ± amphibole + Kfs + Qtz assemblage in the Nilgiri limestone up to anchizonal assemblage (Ill + Chl + Qtz + Pa ± Pl ± Kfs) in the Jurassic sedimentary rocks (Schneider and Masch, 1993; Guillot et al., 1995). Contact metamorphic minerals occur around the Manaslu granite (Guillot et al., 1995). The lower contact within the Lower Paleozoic formations is characterised by a Grt + St + Bt + Qtz ± Sill assemblage whereas the upper contact in the Triassic sedimentary rocks shows a St + Bt + Ms + Pl + Qtz ± Grt ± Chl mineral association.

3. Pressure and temperature conditions

As emphasized by MacFarlane (this issue), P–T estimates are useful in elucidating the tectonic and thermal history of Central Nepal but caution must be exercised when comparing such data against an absolute scale. We review the metamorphic evolution of the K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O (KFMASH) chemical system because metapelites have been the focus of metamorphic studies and 90% of pelites are described in this system (Thompson, 1976; Spear and Cheney, 1989). Metamorphic P–T conditions are usually estimated by three different methods (e.g. Guillot et al., 1995, 1997): using a partial petrogenetic grid (in this case the KFMASH system) where the successive mineral assemblages are plotted and limited by net-transfer reaction, thermobarometry based on cation exchange reactions and computer programs such as Thermocalc of Powell and Holland (1985, 1988) and Holland and Powell (1990, 1998). For the thermobarometry based on cation exchange reaction, uncertainties on pressures and temperatures (reported at 2σ level) have been calculated by propagation of the analytical uncertainties through the geothermobarometric equations using a Monte Carlo approach (Hodges and McKenna, 1987; Hodges et al., 1993). The Thermocalc program determines the position of end-member reactions in P–T space and calculates average P at a range of T, or vice-versa, producing a curve with associated uncertainties, that is analogous to cation exchange thermobarometry. However, the curve calculated by Thermocalc is based on a range of equilibria from self-consistent thermodynamic data. With Thermocalc, errors in the calculated pressures and temperatures are the brackets (reported at 2σ level) on the respective reaction curves at the intersection of the different curves, the location of the different curves in the P–T space take also into account the uncertainties on end-member activities (Powell and Holland, 1985).

One method is not necessarily superior to the other, and thus it appears difficult to assign absolute values to thermobarometric data. Nevertheless, this multi-method approach provides the complementary metamorphic evolution. For example, if we only consider thermobarometric information based on cation exchange rim-reactions, it would be difficult to reveal an inverted metamorphic zoning in Central Nepal as determined by Le Fort (1975a). In fact, MacFarlane (1995) discussed the P–T conditions recorded in the crystal rims as representing the closure temperature of Fe–Mg exchange of crystal pairs. This is the reason why a similar temperature of 600 ± 50°C is recorded in

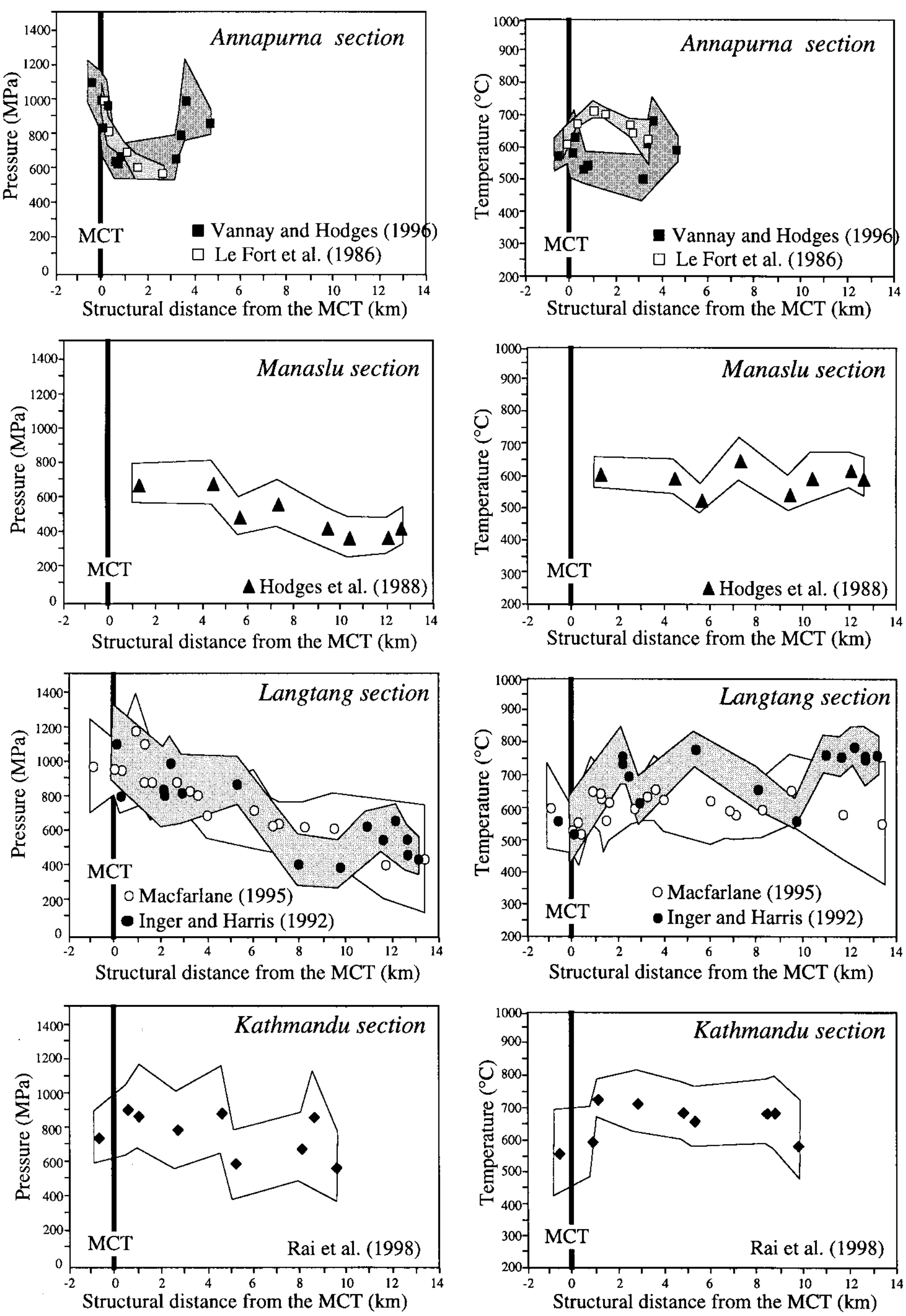

Fig. 4. Pressure and temperature calculations of M2 metamorphism with their uncertainties (at 2σ level) plotted as a function of structural distance (km) from the MCT in the different sections of Central Nepal. Vannay and Hodges (1996): rim thermobarometry; Le Fort et al. (1986): core thermobarometry; Hodges et al. (1988): rim thermobarometry; MacFarlane (1995): rim thermobarometry; Inger and Harris (1992): Thermocalc; Raï et al. (1998): Thermocalc.

two different sections of the HHC in Central Nepal, along the Buhri and Darondi valley (Hodges et al., 1988) in one hand and the Langtang valley on this other hand (Fig. 4) (MacFarlane, 1995). In these cases, such calculated temperatures are not supposed to reflect the crystallization of Kfs and Sill (minimal temperature of about 700°C at 600 MPa) rather last equilibrium conditions. In the case of the Kali–Kandaki section, the temperature evaluation is more fluctuating (Fig. 4): LeFort et al. (1986) observed a temperature increase up to 720°C above the MCT, based on mineral thermometry using the compositions of the cores of metamorphic minerals, whereas Vannay and Hodges (1996) observed metamorphic temperatures of

530°C in the same zone using the compositions of crystal rims. The former temperatures probably reflect the pre-MCT metamorphic conditions M1, and the latter reflecting MCT to post-MCT M2 conditions. The generation of the High Himalayan Leucogranites provides indirect indications on the temperature in the deepest part of the HHC. The direct correlation between the thickness and the metamorphic conditions of the HHC and the existence of abundant leucogranitic intrusions above, such as the Manaslu granite, have lead to numerous thermal models of the HHC, involving the generation of the leucogranites (Le Fort, 1975a, 1981, 1986; Le Fort et al., 1987; Vidal et al., 1982; Cuney et al., 1984; France-Lanord and Le Fort, 1988; Guillot and Le Fort, 1995; Harris and Inger, 1992; Harris and Massey, 1994; Harrison et al., 1998). The most recent studies demonstrate that the Himalayan leucogranites have been produced by decompressional partial melting of metagreywackes and metapelites from the HHC under water-undersaturated conditions at a temperature greater than 750–800°C. This suggests that thermometry based on cation exchange underestimated the metamorphic temperatures in high-grade terranes whereas a petrogenetic grid or an internally consistent thermodynamic dataset such as Thermocalc allow better evaluation of peak temperature conditions.

Concerning the pressure evaluation, the useful GASP or GMPB barometers of Ghent (1976) and Ghent and Stout (1981) rely upon the net transfer of Ca^{2+} between grossular and anorthite and thus are not easily affected by secondary diffusion. Thus, pressures estimated by this method are probably close to the lithostatic pressure recorded during the mineral crystallization and consequently, P–T estimates on the same sample do not necessarily imply that the calculated temperature is linked to the calculated pressure. Furthermore, bulk composition contributes to apparent differences in metamorphic grades. For instance, in the HCC alternating assemblages of Grt + Bt + Ms + Pl + Qtz and Ky + Grt + Bt + Ms + Pl + Qtz are commonly observed at hectometric scales.

In the case of the Lesser Himalaya, the discontinuous appearance of different index minerals such as Chl, Bt, Grt, St is directly related to a temperature increase from about 450–550 ± 100°C (uncertainties are quoted at 2σ) toward the MCT zone within Central Nepal (Pêcher, 1978, 1989; Caby et al., 1983; MacFarlane, 1995; Raï et al., 1998) for a pressure estimate from ≈500 MPa in the Annapurna (Caby et al., 1983) up to 950 MPa in the Gosainkund section (MacFarlane, 1995) with an intermediate pressure of 800 MPa in the Manaslu section (Pêcher, 1989) (Fig. 4). This pressure variation, observed along the HHC, in Central Nepal, is a consequence of the deeper level of erosion toward the east (Pêcher, 1978). With an absence of tectonic breaks between the zones of different metamorphic mineral assemblages, this metamorphic evolution is considered as an inverted metamorphic evolution during the MCT movement (M2 metamorphic event) (Le Fort, 1975a; Pêcher, 1978; Hodges et al., 1996).

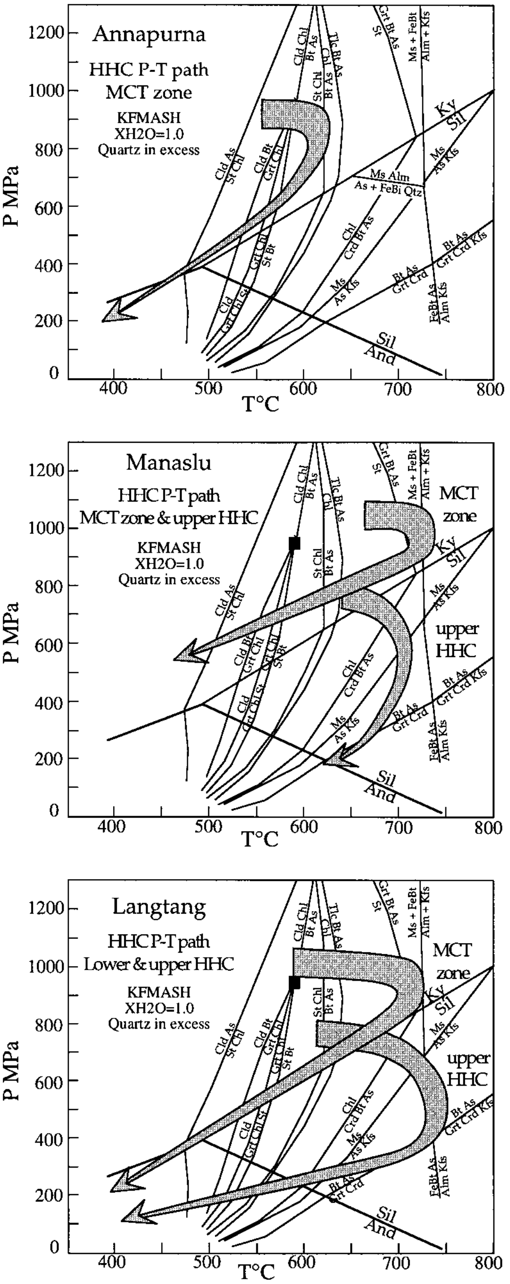

Fig. 5. P–T paths generated by metapelitic in the KFMASH multisystem grid of Spear and Cheney (1989) in lower and upper part of the HHC in the three sections described in Fig. 3. The P–T paths correspond to the history of P–T conditions followed by the MCT zone and the upper HHC during their exhumation.

In the Kathmandu nappe, the P–T evaluations by exchange thermobarometry and Thermocalc give similar results with average values of 560 ± 70°C and 780 ± 60 MPa (Raï et al., 1998) (Fig. 4).

In the HHC, the combination of the different thermobarometrical methods discussed above allow a proposed P–T evolution at the base of the metamorphic sequence (MCT zone) and at the upper part of it (Fig. 5). In the MCT zone and the lower part of the HHC, almost two successive metamorphic events are recognised. The M1 phase (Eo–Himalayan) corresponds to a progressive temperature increase, before the MCT motion, from about 550°C to locally greater than 700°C corresponding to the transition from St bearing amphibolite to Ky bearing granulite for a pressure range between 1100 and 800 MPa (Pêcher, 1989) (Fig. 5). It is noticed that the lowest pressures and temperatures are recorded in the western section (900 ± 90 MPa and 610 ± 40°C) compatible with the higher level of erosion (Fig. 5). The Himalayan metamorphic event M2 associated with the MCT motion shows a west to east pressure increase from 650 ± 30 MPa to 865 ± 100 MPa whereas the temperatures slightly increase from 540 ± 650°C to 605 ± 100°C (Fig. 5). In the Gosainkund section, the good preservation of Ky + Kfs assemblages 2 km above the MCT zone suggests a metamorphic condition of about 700°C and 800 ± 100 MPa with Thermocalc (Inger and Harris, 1992; Raï et al., 1998) whereas Grt–Bt thermometry suggest lower temperature conditions of 600 ± 50°C (MacFarlane, 1995) (Fig. 4).

The P–T evolution of the Tethyan Sedimentary Series is evaluated by Garzanti et al., (1994) and Schneider and Masch (1993) based on the field evidence, mineral stability, carbonate thermometry and illite crystallinity and extrapolation of the pressure data observed below the STDS. Estimated pressure decreases from 300 MPa to approximately 100 MPa at the top, and the temperature decreases from 510–530°C at the base to 370–390°C in the Carboniferous formations. Guillot et al. (1995) evaluated the pressures of the TTS in the metamorphic aureole of the Manaslu granite and obtained 540 ± 100 MPa at the base of the series and 330 ± 100 MPa in the Triassic formation. The consistent temperatures of about 550 ± 80°C along the contact reflect the local thermal reequilibration during the granite emplacement. The low pressure estimates in the TSS compared to the higher pressure records in the HHC is related to the extensional juxtaposition of the higher-level TSS with the deeper-lever HHC (Schneider and Masch, 1993; Guillot et al., 1995).

4. Timing of metamorphism

Most of the thermochronologic data from Central Nepal record cooling after intense Neo-Himalayan metamorphism M2 and anatexis during the Miocene, thus relatively little is know about the metamorphic history of the region prior to 30 Ma. There is petrologic evidence for Eo–Himalayan metamorphism (Caby et al., 1983; Pêcher, 1989; Vannay and Hodges, 1996) but it has remained unclear whether there was significant crustal thickening within Central Nepal prior to the Miocene (Coleman and Hodges, 1998; Aldsorf et al., 1998; Guillot et al., 1999). In the Kali Gandaki and Marsyandi valleys, orthogneiss horizons of the HHC gives monazite U–Pb ages of 35–36 Ma (with closure temperature > 650°C; Mezger et al., 1992). This suggests that there was either Oligocene M1 metamorphism or magmatism within the upper HHC (Parrish and Hodges, 1992; Hodges et al., 1996; Coleman and Hodges, 1998). In addition, an Ar/Ar hornblende age of 37 Ma (with a closure temperature of 500°C; Harrison, 1981), and a Rb/Sr muscovite age of 34 Ma (with a closure temperature of 550°C; Jäger et al., 1967) are obtained in the Kali Gandaki valley and in the upper Langtang valley, respectively (Vannay and Hodges, 1996; Inger and Harris, 1992). Coleman and Hodges (1998) also obtained 27–30 Ma Ar/Ar cooling ages (300–400°C; Pÿrdy and Jäger, 1976) on micas in the upper part of the HHC, above the NHNF in the upper Marsyandi valley.

The Neo-Himalayan metamorphism is well documented directly and indirectly. The indirect approach gives older ages which consists of dating the crystallisation age of the leucogranite intrusions. Ar/Ar dating on hornblendes from the contact aureole of the Manaslu granite indicate an age of about 23 ± 0.5 Ma (Guillot et al., 1994) and U–Pb monazite ages from the same intrusion give similar ages ranging from 23 to 25 Ma (Deniel et al., 1987; Harrison et al., 1998, 1999). A monazite age of 25 Ma has also been obtained on a pegmatite just below the MCT, north of the Kathmandu nappe (Parrish in Raï, 1998). A second group of crystallization and cooling ages at ≈18–19 Ma is also obtained on the Manaslu granite (Copeland et al., 1990; Guillot et al., 1994; Harrison et al., 1998, 1999) suggesting secondary tectonic and magmatic activity.

Numerous Ar/Ar mica ages and U–Pb monazite ages obtained on metamorphic rocks of the HHC (Copeland et al., 1991; Inger and Harris, 1992; Vannay and Hodges, 1996; Hodges et al., 1996; Coleman and Hodges, 1998; Harrison et al., 1998) and on the Kathmandu Nappe (Johnson and Rogers, 1997; Raï, 1998) also show that the high temperature (> 500°C) movement along the MCT occurred principally between 22 and 18 Ma. The older Ar/Ar and Rb/Sr cooling ages of about 22 Ma obtained on the southern part of the Kathmandu nappe, however, suggest that this nappe was emplaced in the Lesser Himalaya earlier than the HHC and corresponds to an out-of-sequence unit (Andrieux et al., 1977; Raï, 1998; Raï et al., 1998; Upreti and Le Fort, 1999).

Late Pliocene reactivation of the MCT zone is recognised in different valleys of Central Nepal. Copeland et al. (1991) first reported young Ar/Ar ages from the MCT zone in the Buhri Gandaki valley at circa 5–4 Ma and interpreted this resetting as infiltration of hot fluids through the MCT zone, related to MBT activity. MacFarlane (1993) reported from the Langtang valley, younger cooling ages of 2–3 Ma on the brittle part of the MCT zone, directly related to reactivation of the MCT zone during ramping on the structurally lower MBT. The same evolution is observed in the Marsyandi valley by Edwards (1995) with Ar/Ar cooling ages ranging from 2.6 to 9.4 Ma within the MCT zone. New monazite ages from the ductile MCT zone in the Buhri Gandaki valley confirm a ductile reactivation of the MCT at about 6 Ma (Harrison et al., 1997).

A similar evolution is observed in the Kathmandu nappe area. On its northwestern part Johnson and Rogers (1997) reported a Rb/Sr biotite age at 7.5 ± 0.1 Ma whereas Raï (1998) reports Ar/Ar ages north of the Kathmandu nappe, up to 6 Ma and interpreted it as a Pliocene to Present-day flexuration of the MCT and MBT zone above a fixed ramp.

5. Inverted metamorphism or thermal inversion in Central Nepal

The existence of an inverted metamorphism or a thermal inversion throughout the MCT zone and along the Himalayan belt has been in debate for the past 25 years. Le Fort (1975a) and Pêcher (1977, 1978) have shown that the low-metamorphic-grade terranes of the Lesser Himalaya in Central Nepal are overlained by the higher-grade terranes of the HHC along the MCT. This inverted metamorphic zonation is also recorded in fluid inclusions (Pêcher, 1979). The first proposed interpretation for these unusual characteristics given by Le Fort (1975a) involves large-scale intracontinental underthrusting of the cold Lesser Himalaya slab under the hotter HHC. This model suggests that the inverted metamorphism can be understood in terms of a paleo-thermal inversion. Recent explanations have been proposed considering new thermobarometrical and geochronological data. Arita (1981), England et al. (1992) and Harrison et al. (1997, 1998, 1999) pointed out that heat dissipation accompanied by shear stresses in the MCT zone is necessary to maintain high temperatures and that the heat may have resulted in the generation of the leucogranitic magmas. In the latter paper, the authors take into account the effect of episodic reactivation of the MCT zone on the decompression of the HHC and consequently on the successive formation of the High Himalayan leucogranites between 23 and 18 Ma and of the North Himalayan leucogranites between 17 and 8 Ma.

Another explanation for high temperatures in the MCT zone is an accretion of crustal material from the subducting plate to the upper plate and surface erosion of the upper plate (Royden, 1993; Huerta et al., 1996). Recent works by the Harris team in Central Nepal (Harris and Inger, 1992; Harris et al., 1993, 1995; Harris and Massey, 1994), however, show that the generation of the high Himalayan leucogranites do not imply heat or fluid additions but corresponds to decompressional melting of the HHC during the M2 metamorphic event. Furthermore, as discussed above, the recently documented evidence of episodic reactivating of the MCT zone during the Pliocene after the main Miocene ductile motion suggested that the observed metamorphic inversion cannot be accounted for by a single thermal inversion. Numerous authors, such as Ruppel and Hodges (1994) or MacFarlane (1995) interpreted the observed inverted metamorphism as reflecting diachronous attainment of equilibrium temperature conditions. This suggestion is supported by the numerical model of Guillot and Allemand (1997) showing that the competition between advection and conduction of heat throughout the MCT zone can be explained by a continuous cooling of the MCT zone during the exhumation of the HHC, while the upper part of the HHC advected the heat and remained hotter. This model explains the preservation of two contrasting P–T paths at the base and at the top of the HHC (Fig. 4).

Finally, it has also been considered that the inverted metamorphism locally corresponds to a geometrical inversion of the pre-existing metamorphic sequence M1, (1) by a low-temperature reactivation of the MCT zone (Brunel and Kienast, 1986; Mohan et al., 1989), (2) by folding of the metamorphic sequence (Searle and Rex, 1989), (3) by shear displacement along millimetre spaced shear bands (Jain and Manickavasagam, 1993) or (4) by ductile shear of the entire 5–10 km MCT zone during M2 (Hubbard, 1996; Grujic et al., 1996).

6. Conclusion: Uniform theory and internally consistent theory

Twenty five years ago, Patrick Le Fort described modern concepts of the metamorphic evolution of the Himalaya, based on the observations from Central Nepal; he developed a theory linking the metamorphic, tectonic and anatectic evolutions. By the 90 s, many geological investigations added complicated data to this uniform theory and demonstrated that metamorphism and related tectonic and anatectic processes are more or less episodic at the scale of the million years. This new view of mountain belts will be more and more applied in the future and will allow the geologists to have a better understanding of orogenic processes. In this global scheme, the Himalaya in general and the Central Nepal in particular will remain an ideal natural laboratory to test models of mountain building.

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