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The metamorphism in the Central Himalaya

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ABSTRACT All along the Himalayan chain an axis of crystalline rocks has been preserved, made of the Higher Himalaya crystalline and the crystalline nappes of the Lesser Himalaya. The salient points of the metamorphism, as deduced from data collected in central Himalaya (central Nepal and Kumaun), are:

1. The Higher Himalaya crystalline, also called the Tibetan Slab, displays a polymetamorphic history with a first stage of Barrovian type overprinted by a lower pressure and/or higher temperature type metamorphism. The metamorphism is due to quick and quasi-adiabatic uplift of the Tibetan Slab by transport along an MCT ramp, accompanied by thermal refraction effects in the contact zone between the gneisses and their sedimentary cover. The resulting metamorphic pattern is an *apparent* (diachronic) inverse zonation, with the sillimanite zone above the kyanite zone.
2. Conversely, the famous inverted zonation of the Lesser Himalaya is basically a *primary* pattern, acquired during a one-stage prograde metamorphism. Its origin must be related to the thrusting along the MCT, with heat supplied from the overlying hot Tibetan Slab, as shown by synmetamorphic microstructures and the close geometrical relationships between the metamorphic isograds and the thrust.
3. Thermal equilibrium is reached between units above and below the MCT. Far behind the thrust tip there is good agreement between the maximum temperature attained in the hanging wall and the temperature of the Tibetan Slab during the second metamorphic stage; but closer to the MCT front, the thermal accordance between both sides of the thrust is due to a retrogressive metamorphic episode in the basal part of the Tibetan Slab.

Key words: Central Himalaya; Higher Himalaya; Himalayan metamorphism; Lesser Himalaya; MCT.

INTRODUCTION

After the continental collision between the Indian and Tibetan plates during the Eocene, part of the crustal shortening caused by convergence was taken up in major intra-crustal shear zones ("intracontinental subduction") which led to the formation of the Himalayan chain. The amount of shortening of the northern margin of India was at least 100 km, the minimum translation accounting for the Kathmandu tectonic klippe, and was probably much higher, of the order of 300–500 km according to palaeomagnetic data (Besse, Courtillot, Pozzi, Westphal & Zhou, 1984). This horizontal shortening was compensated for by a near doubling of the thickness of the crust, which is presently around 60 km (Molnar, 1984).

Due to these thrust movements, a composite belt of crystalline rocks, made up of different tectono-metamorphic units with variable geological histories, has been preserved all along the Himalayan chain. This paper attempts to document further its metamorphic characteristics by using data from Central Nepal, together with a review of the extensive literature devoted to the Himalayan metamorphism in Garhwal, Kumaun and Nepal. Eastern Nepal (the Everest and Makalu sections) will not be considered here, as a detailed metamorphic study of this area is in progress by M. Hubbard (see this issue, p. 17); the present knowledge on this segment of the Himalaya can be found in Brunel & Kienast (1986).

THE MAIN TECTONO-METAMORPHIC UNITS

In the central Himalaya, the metamorphic units appear as thin strips, some of which can be found on hundreds of kilometres along the strike. It is generally convenient to distinguish the Higher Himalaya crystalline from the crystalline nappes of the Lesser Himalaya, the Main Central Thrust (MCT) separating the two.

The Higher Himalaya crystalline

The Higher Himalaya crystalline (Zanskar crystalline, Vaikrita group of Kumaun, Tibetan Slab of Nepal) corresponds to the metamorphic substratum of the Palaeozoic and Mesozoic sediments of the north Indian oceanic margin, upthrusted along the MCT. It is a thick (5 to more than 10 km) pile of aluminous gneisses and schists, with intercalations of calc-silicates locally abundant.

The main metamorphic imprint (Fig. 1) corresponds to the development of a high-grade Ky–Grt–Bt (±St ± Rt/Ilm) assemblage. Sillimanite is abundant in the upper part of the pile, while cordierite is known in eastern Nepal (Brunel, 1983; Brunel & Kienast, 1986), in the Langtang area (P. Bordet, P. Le Fort, personal communication) and Marsyandi area of central Nepal, and sporadically further

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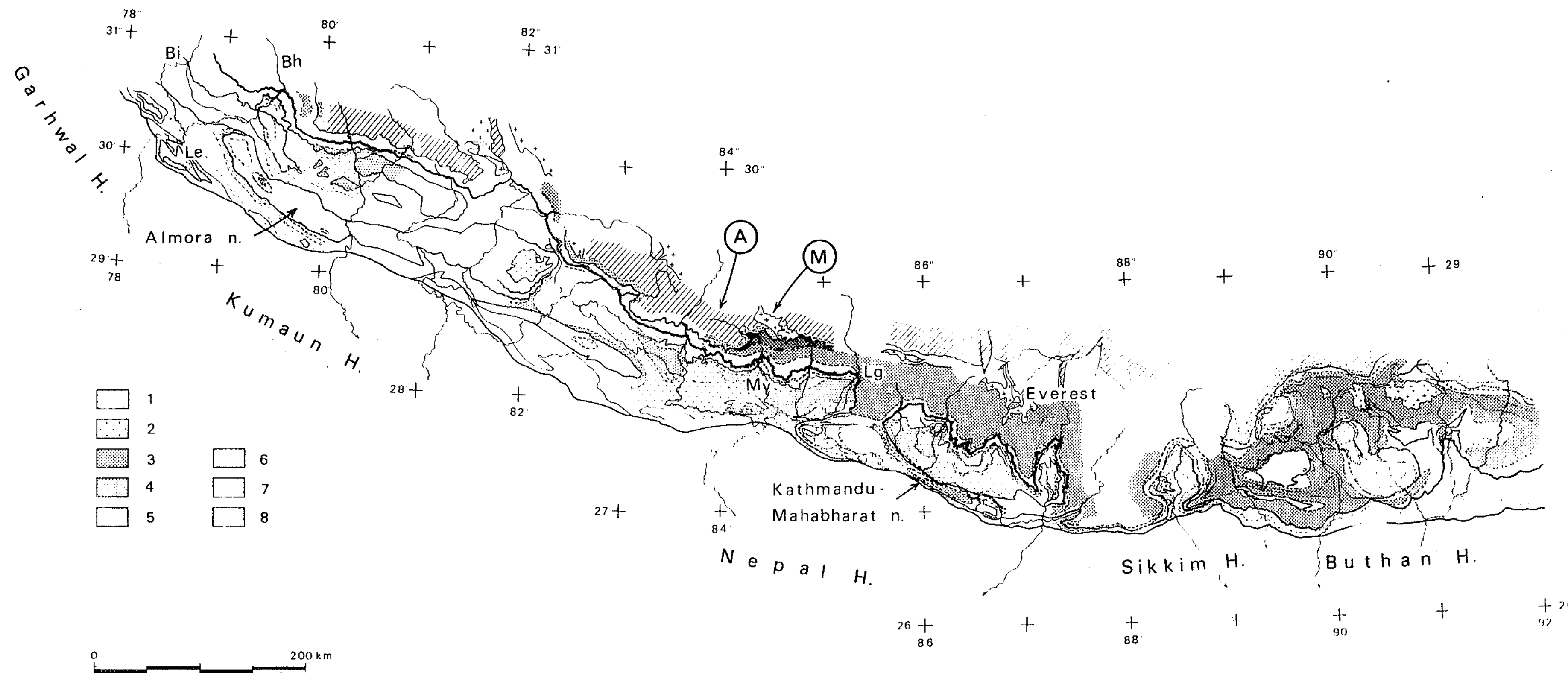

Fig. 1. Metamorphic map of central Himalaya (Kumaun, Nepal and Bhutan). The thick line corresponds to the MCT, South of the Tibetan Slab. In central Nepal it has been traced at the base of the Kathmandu and Mahabharat nappes, considered as southern klippe of the Tibetan Slab. In Kumaun, it corresponds to the Vaikrita thrust (VT). The thin lines correspond to minor thrusts, separating the various units of the Lesser Himalaya. Metamorphism from author's data and literature (see refs in Pêcher & Le Fort, 1987, Fig. 1). 1 = Tethyan sedimentary series (anchizonal to epizonal), 2 = Higher Himalaya Miocene leucogranites, 3–8 = metamorphic zones defined by metapelitic assembages (3 = Sil ± Ky ± Ctd, 4 = Ky, 5 = Ky ± St, 6 = Bt + Grt, 7 = Bt + Chl, 8 = Chl). A and M = locations of the Annapurnas and Manaslu sections. Bi = Bhagirathi river, Bh = Badrinath, Le = Lansdowne, Lg = Langtang, My = Marsiandy river.

west in Kumaun (Badrinath area, Gupta, 1976). These gneisses are migmatitic and have been considered to be the source material for the overlying tourmaline-bearing leucogranitic bodies (e.g. the Manaslu granite). This hypothesis is strongly supported by major and trace elements (Vidal, Cocherie & Le Fort, 1982; Cuney, Le Fort & Wang, 1984; Brouand, Barbey, Cuney, Le Fort & Pêcher, 1988), and isotope geochemistry (Le Fort, 1981; Vidal *et al.*, 1982; Deniel, Vidal, Fernandes & Le Fort, 1987; France-Lanord & Le Fort, 1988.

In these gneisses, the main tectonic marker is a penetrative metamorphic foliation. The timing of this tectono-metamorphic feature is ill constrained and a partly pre-Himalayan imprint cannot be excluded. Nevertheless, the main fabric is certainly Himalayan in age as: (i) all the Rb/Sr, K/Ar or Ar^{39}/Ar^{40} isotopic ages on minerals range from 50 to 3 Ma (e.g. Saxena, 1981 for review; Maluski & Matte, 1984; Deniel *et al.*, 1987) and (ii) further west, in Garhwal and Kashmir, this foliation is the axial cleavage of large synmetamorphic recumbent folds in which Mesozoic terranes are involved (Powell & Conaghan, 1973; Honneger, Dietrich, Frank, Gansser, Thöeni & Trommsdorff, 1982).

At the top of the Higher Himalaya crystalline, neither a stratigraphical nor a metamorphic hiatus can be seen between the gneisses and the overlying Tethyan sedimentary series. Nevertheless, the transition is very sharp: the passage from the sillimanite gneisses to the Chl + Bt ± Grt Cambro-Ordovician levels is mostly achieved in a few tens or hundreds of metres. Such a crowding of the metamorphic isograds could partly reflect thermal conductivity contrasts between an already metamorphosed basement and a still unmetamorphosed cover (Fonteilles & Guitard, 1968; Jaupart & Provost, 1985). It is more likely to be due to large late-metamorphic strike-slip shearing (Pêcher, Bouchez, Cuney, Deniel, France-Lanord & Le Fort, 1984; Pêcher & Bouchez, 1987) and normal faulting (as described in Southern Tibet by Burg, 1983, and in Zanskar by Herren, 1987), disrupting the early metamorphic pattern.

Finally, higher up in the Tethyan cover, metamorphism smoothly decreases down to the anchizone, indicated by illite crystallinities in the Mesozoic (G. Dunoyer de Segonzac, personal communication in Caby, Pêcher & Le Fort, 1983).

The Lesser Himalaya crystalline

The Lesser Himalaya crystalline is made up of low (Chl, no Bt) to medium (Bt + Grt + Ky ± St) grade terranes that belong both to various autochthonous and para-autochthonous zones and to crystalline nappes such as the Almora nappe of Kumaun and Garhwal, or the Kathmandu nappe of central Nepal.

Metamorphism is most often marked by Chl + Bt or Bt + Grt assemblages. Kyanite, the typical 'marker' of the Higher Himalaya crystalline, is also found locally in the Lesser Himalaya, e.g. in the Kathmandu and Mahabharat nappes, possible southern prolongations of the Tibetan Slab, but also in the Upper Midland Formations of central Nepal or in the Almora nappe and the Landsdowne klippe, which are actual parts of the Lesser Himalaya units.

Due to tectonism, the relationships between the various metamorphic units of the Lesser Himalaya are often debatable, but, as a rule, throughout this domain, the metamorphic grade always increases upwards, that is towards the higher structural levels of the tectono-metamorphic pile. This is the inverse metamorphic zonation, first described in Sikkim (Ray, 1947), and now a well established feature of Himalayan geology. The mechanism by which this occurs is still a very controversial point.

The Main Central Thrust (MCT)

The metamorphism in the Lesser Himalaya is clearly related to the MCT, as can be seen from the map (Fig. 1), which summarizes the rather inhomogeneous data compiled from the literature. In fact, recent work tends to relate the reverse metamorphism to overthrusting, either by frictional heating (Maruo, 1979; Arita, 1983) or by underplating of a cold slab in a way similar to that invoked for oceanic subduction (Le Fort, 1975a; Toksöz & Bird, 1977).

Despite the geodynamic importance of the MCT, its location is still debated. It was originally defined (Heim & Gansser, 1939) in Kumaun as the basal contact of the crystalline nappes. This "metamorphic" definition is relatively easy to follow in the southern part of the Lesser Himalaya, where there is a clear difference in metamorphic grade between the crystalline nappes and the sedimentary formations, separated by acute mylonitic boundaries. It becomes very ambiguous towards the North where there are no obvious breaks in metamorphic grade between the various lithological units.

Thus, it is more convenient to adopt a MCT position supported mainly by the following lithological and tectonic criteria: (i) it is the boundary between the migmatitic gneisses of the Tibetan Slab, and the Upper Midland carbonate-rich formations characterized by relict sedimentary textures; and (ii) it is the limit where the very strong L–S fabric, which is due to high temperature thrusting, and characteristic of the Lesser Himalaya, is replaced by the mainly planar fabric of the Tibetan Slab gneisses, and where the rotational synmetamorphic deformation, which increases progressively upwards in the Midland Formations, reaches its maximum.

The MCT as defined here, which appears in the field as a thick ductile shear-zone, actually corresponds to the MCT-II of Arita, Hayashü & Yoshida (1982) in central Nepal. Recent field observations (Pêcher & Scaillet, unpublished data) along the Bhagirathi valley point to the similarity between the so-defined MCT and the Vaikrita thrust of Kumaun (rather than Heim & Gansser's MCT), as already emphasized by Valdiya (1980).

METAMORPHISM IN CENTRAL NEPAL

General setting

Compared to the other parts of the Himalaya, the tectonic and metamorphic patterns in central Nepal appear rather simple, not being disrupted as much by minor thrust splays. Figure 2 shows a typical sketch section of the metamorphic pile in the Manaslu area, west of Kathmandu.

The main "nappe" of the Lesser Himalaya here is a series of pelites and sandstones (the Lower Midland Formations) and of quartz-rich pelites and carbonates (the Upper Midland Formations) more than 8 km thick. It is bounded at its base by a mylonitic zone (southward thrusting on the external sedimentary belt) and at its top by the MCT shear-zone, and is folded in a vast post-metamorphic anticlinal structure with a N110° E axis, the Kunchha–Gorkha anticlinorium (Pêcher, 1977).

The northern flank of the anticline, below the MCT, is metamorphosed and strongly deformed in the main shear-zone. Here the continuity between the Lower and Upper Midland Formations, which is clear on the relatively unmetamorphosed southern limb (Stöcklin, 1980), is more difficult to establish. As a consequence, some authors (e.g. Arita *et al.*, 1982, who places the "MCT-I" at this level) have separated them into two tectono-metamorphic units, their contact being marked by the Ulleri augen gneisses. Several pieces of evidence, stratigragphical as well as metamorphic and tectonic (see e.g. Pêcher & Le Fort, 1977) disprove this tectonic interpretation. A thrust actually exists in places between the two formations; but in contrast to the large synmetamorphic shear zone, here named the MCT, it is a minor thrust, on which the displacements are small enough to keep undisturbed the cartographic pattern of the metamorphic isograds (see the 1/200 000 scale map in Colchen, Le Fort & Pêcher, 1986).

Above the MCT, the Tibetan Slab forms a continuous sheet, dipping regularly 20°–50° northwards, and apparently lacking the large-scale internal discontinuities described further north-east in Tibet (Burg, Giraud, Chen & Li, 1984; Brun, Burg & Chen, 1985). It appears as a monoclinal pile of gneisses, the thickness of which varies along strike from more than 10 km in the Manaslu section to less than 5 km in the Annapurna section, 70 km to the west.

Early large-scale folds may have formed before or during regional metamorphism, but, if so, they have been largely obliterated by the flattening and the regular and penetrative foliation associated with metamorphic recrystallization. The only observed folds are small scale syn- to late-metamorphic folds and large post-metamorphic warps.

In the upper half of the Tibetan Slab, the synmetamorphic foliation is associated with a rather ill-defined lineation which trends parallel to the range. Lower down, the mineral lineation changes to a best imprinted stretching lineation, which becomes progressively parallel to the N20° E stretching lineation of the Midland Formations. Here, as in the Upper Midland Formations, the metamorphic fabric displays numerous criteria of rotational deformation, clearly indicating that the metamorphic recrystallization was achieved during southward-directed shearing.

The metamorphism

The metamorphic imprint varies slightly according to the thickness of the Tibetan Slab, and it is possible to distinguish schematically a Manaslu type section (thick slab) from an Annapurna type section (thin slab) (see Fig. 1 for locations):

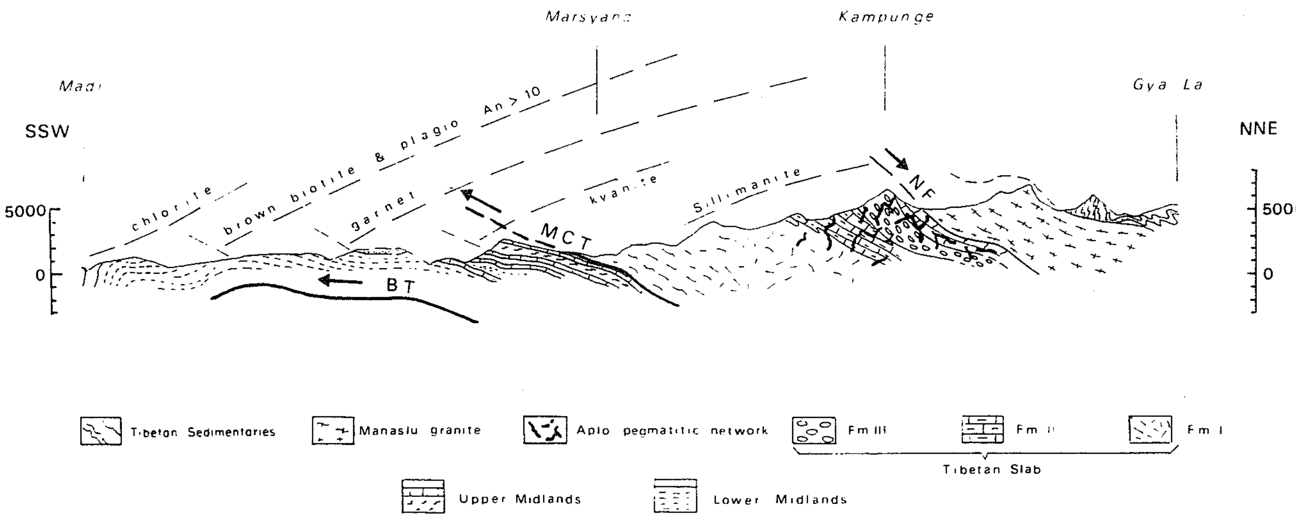

Fig. 2. Metamorphic cross-section cutting across the Manaslu massif (from Pêcher, 1978; Le Fort, 1986). This figure shows the extension of the main metamorphic index minerals. NF = normal fault + dextral strike-slip between the tibetan Slab and the Manaslu granite; BT = basal thrust, at the base of the Lower Midland Formations. The Tibetan Slab is divided into Formation I (Fm I, metapelites), Formation II (Fm II, calcsilicates) and Formation III (Fm III, orthogneisses).

Manaslu type section

In the first few kilometres above the base of the Tibetan Slab, the metamorphism is of the Barrovian type, well characterized by the assemblages of the metapelites (Caby *et al.*, 1983): Qtz + Bt + Pl + Grt + Ky + Ms ± Kfs ± Gr ± Rt ± Zo.

Zoisite and rutile are generally closely associated with biotite and kyanite, and together with staurolite, they are restricted to the lowermost portion of the Tibetan Slab. Here, Qtz + Pl ± Ky ± Kfs leucosomes are also observed, structured by the syn-MCT shearing fabric.

Muscovite is abundant particularly in the lower part of the Tibetan Slab, whereas K-feldspar essentially occurs higher in the Slab where leucosomes become more apparent. The top part of the slab is widely injected by granitic melts. It displays layers of anatectic granite up to several tens of metres thick (i.e. Tal area, in the Marsyandi valley, Le Fort, 1975b), re-affected by the main synmetamorphic deformation (early-Himalayan or pre-Himalayan injection of migmatites), whereas less abundant leucosomes, often tourmaline rich, crosscut the Himalayan foliation. In the middle and upper part of the Slab, both prismatic and fibrolitic sillimanite are abundant. The sillimanite develops either at the expense of muscovite and kyanite or as epigenetic overgrowths (fibrolite) on plagioclase feldspar. It is also found along late-stage shear planes and joints, which post-date even the late mobilizates and are related to the large ductile shear zone which separates the gneisses from the sedimentary series.

Thus the Himalayan metamorphism in the Slab is clearly a *two-stage event*. The *P–T* conditions during the first stage can be estimated according to a simplified petrogenetic grid in the system *KFMASH* using the equilibria between kyanite, biotite, chlorite, chloritoid, staurolite and garnet. Further control is provided by reactions between plagioclase, zoisite and kyanite in the Ca-bearing system and by partial melting reactions. These constraints lead to a range of temperature 600–690° C and of pressures 700–850 MPa (Pêcher, 1978), the maximum pressure values being indicated by the Pl + Ky + Zo assemblages which are confined to the base of the Slab, near the MCT. The second episode is marked in the upper part of the Slab by the appearance of sillimanite and the presence of numerous tourmaline-bearing leucosomes, emplaced after the crystallization of the muscovite, a mineral most often closely linked to the restitic assemblages. These "mobilizates", sometimes still foliated, but more often cross-cutting the main metamorphic fabric, mark a second stage of "migmatization".

Applying the *KFMASH* petrogenetic grid, discussed above, to the sillimanite-bearing lithologies gives temperatures between 650 and 710° C for a pressure of less than 700 MPa. Thus the Tibetan Slab records a *P–T* evolution towards lower pressure type metamorphism. This pressure evolution continues during the final metamorphic stages, as can be inferred from fluid inclusion microthermobarometric studies in late-metamorphic quartz-rich exudation-pods and pegmatites (Fig. 3), which indicate a pressure drop of at least 150 MPa and up to several hundred MPa.

The late thermal structure of the Tibetan Slab has been better constrained using Grt–Bt, Grt–Sil–Qtz–Pl and Alm–Grs–Ms–Pl–Bt thermomenters and barometers (Brunel & Kienast, 1986; Hodges, Le Fort & Pêcher, 1986; Le Fort, Pêcher & Upreti, 1987). Figure 4 shows the *P* and *T* evolution versus the distance above the MCT for eight samples collected in the Manaslu section. It shows an increase in pressure with depth (approx. 27 MPa/km), which fits quite well with a simple lithostatic load, and implies that the final re-equilibration of mineral rims in all the tested samples occurred at approximately the same time. It also shows a homogeneous temperature of about 600° C across the entire Slab (though the sampling does

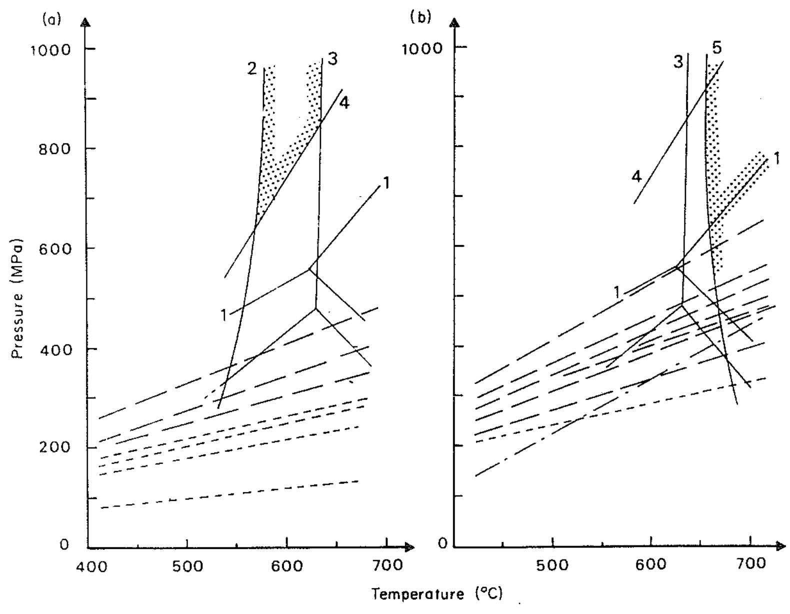

Fig. 3. *P–T* metamorphic estimates (within the shaded area) and isochores of fluid inclusions in the quartz pods, at the base of the Tibetan Slab and uppermost levels of the Midland Formations (a) and in the middle and upper part of the Tibetan Slab (b). Metamorphic equilibrium: 1 = Sil/Ky; 2 = Cld/St + Grt; 3 = Chl + St/Bt + Ky; 4 = An + H_2O/Zo + Ky + Qtz; 5 = Mus + Kfs + Ab + Q + H_2O/melt. Dashed-dotted line = (H_2O + NaCl) isochores, thin dashed lines = CO_2 isochores, long dashed lines = (H_2O + CO_2 isochores). Isochores drawn from data of Potter & Brown (1977) for the H_2O + NaCl system, Touret & Bottinga (1979) for the CO_2, and Gehrig (1980) for the H_2O + CO_2 + NaCl system.

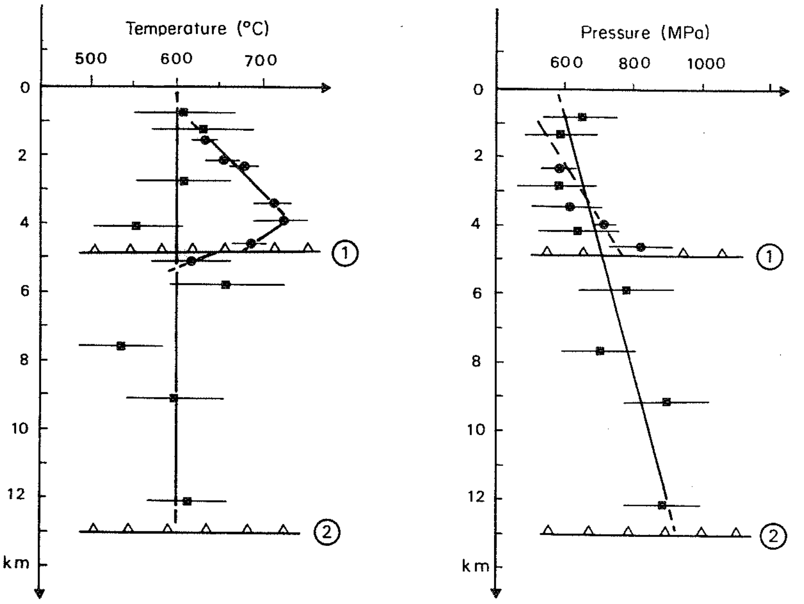

Fig. 4. Pressures and temperatures estimated by exchange thermometers in the Manaslu section (■, data from Hodges *et al.*, 1986) and in the Annapurna section (●, data from Le Fort *et al.*, 1987). Vertical axis: distance of the samples from the top of the Tibetan Slab. 1 = position of the MCT in the Annapurna section (thin Slab), 2 = position of the MCT in the Manaslu section (thick Slab).

not include the very base and very top of the unit), which, as discussed by Hodges *et al.* (1986), must be the actual thermal pattern during the second metamorphic event.

Beneath the MCT, the highermost part of the Midland Formations shows, in a zone more than 1 km thick, a paragenesis very similar to the one found at the base of the Tibetan Slab (except for the lack of any traces of migmatization), i.e.: Qtz + Pl + Ms + Bt + Grt ± Ky ± St ± Gr ± Rt ± Zo.

The persistence of high-temperature conditions after the main episode of shearing is well established by the exaggerated grain growth microstructure in quartz (Bouchez & Pêcher, 1981), by fluid inclusion data (Fig. 3) and by the post-kinematic growth of garnet and staurolite. Brown biotite is observed to crystallize as a poikiloblastic phase with inclusions of graphite and kyanite, or to recrystallize by polygonization of the biotites formed in the main cleavage and then refolded in late-metamorphic folds.

Further from the MCT, annealing is much less intense and sedimentary structures become clearly recognizable. Down to about 3 km beneath the MCT, fine-grained metasedimentary assemblages can contain staurolite and/or kyanite. This zone overlies a Bt + Grt zone, which in turn overlies a Bt + Chl zone.

The metamorphic textures observed beneath the MCT clearly indicate that the parageneses are prograde, with the exception of a few occurrences of retrogressive chlorite-bearing assemblages, mostly developed in late mylonites related to the minor thrust which locally separates the Higher and Lower Midland Formations. On the northern limb of the Gorkha anticlinorium, the prograde metamorphism increases from the core of the anticline towards the top of the succession, and reaches, immediately beneath the MCT, the same grade as observed in the lowermost part of the Tibetan Slab. There, the temperature estimated from the petrogenetic grid is about 630° C (Pêcher, 1978), i.e. of the same order as the temperatures (≈600° C) calculated from exchange thermometers for the second metamorphic event in the Slab.

Annapurna type section

This section differs from the previous one mainly in the lesser thickness of the Tibetan Slab, here only about 5 km, suggesting that the present-day erosion surface cuts the thrust closer to its tip. A much clearer tectonometamorphic boundary appears between the kyanite-bearing gneisses of the Tibetan Slab and the underlying Midland Formations with well preserved sedimentary structures.

In the Slab, the most characteristic paragenesis associated with the main metamorphic foliation is similar to that found in the Manaslu section: Qtz + Bt + Pl + Grt + Ms ± Kfs + Ky ± Zo ± Gr ± Rt/Ilm. But, even in the upper levels, sillimanite is very rare and the migmatization less well developed.

Moreover, a petrographical study systematically reveals retrogressive metamorphism at the base of the Tibetan Slab (Caby *et al.*, 1983). It is visible in a 150-m thick phyllonite zone which is often poorly exposed. These phyllonites contain large relict porphyroclasts of muscovite and kyanite, surrounded by a fine-grained phyllitic matrix. Primary rutile is pseudomorphosed by titanite and ilmenite. The early garnet porphyroblasts are fractured and associated with elongated pressure shadows containing recrystallized fine-grained biotite. Thus, the retrogressive metamorphism recorded in these phyllonites has a dynamic character and is, at least at the beginning, associated with fairly high temperatures (~500° C, according to the stable white mica + Bt + Grt assemblages); later on, it has decreased down to low-grade greenschist facies (Chl + sericite + Cal).

The thermal and barometric structure of the Slab has been specified more precisely using the Bt–Grt thermometer and the Pl–Grt barometer (Le Fort *et al.*, 1987) in 17 samples. Figure 4 shows the *P* and *T* evolution versus distance above the MCT.

The temperatures inferred are not constant across the whole Slab, but increase with a rather high gradient of about 34° C/km from the top of the Slab down to the beginning of the basal mylonitic zone, where it abruptly reverses. The pressure is poorly constrained, as only four kyanite-bearing samples offer suitable equilibria for pressure measurement. They lead to an average increase in pressure with depth of about 100 MPa/km, i.e. far too high. In fact, this is due to the two lower samples, close to the MCT, which record abnormally high pressure compared with the two higher ones. They could record an early cooling of the lowermost part of the crystalline sheet during its thrusting along the MCT, before the tectonic denudation marked by the gravity folding of the sedimentary cover, whereas the two higher samples could record the later "normal" cooling history of the Higher Himalaya.

In the uppermost part of the Midland Formations the retrograde metamorphism observed in the phyllonites does not extend beneath the MCT. In the first 100–200 m, micaschists occur, which though resembling the phyllonites, show parageneses with Bt + Ms + Grt + Pl + Rt + Ep that are clearly prograde and synkinematic. Ductile mylonitic textures are developed with quartz ribbons where *c*-axis fabrics indicate shearing towards the south (Bouchez & Pêcher, 1981).

Further below the MCT, the mica schists become finer grained, with the foliation marked by prograde white mica, biotite and/or chlorite, associated with Ab + Ep (Zo cores) + Rt ± Cld ± Grt. Here again the rotational growth of garnet and chloritoid indicates southward shearing. At depths of 2–3 km beneath the MCT, the low-grade phyllites (sericite + Chl ± Cld) retain some clearly identifiable sedimentary structures.

The study of compositional zoning in garnet porphyroblasts of the Annapurna section (Arita, 1983; Le Fort *et al.*, 1987) confirms the very different metamorphic history of the rocks above and below the MCT (Fig. 5). In the Tibetan Slab, garnets are pyrope-rich (13–40 mol. %) and poor in CaO + MnO (usually less than 2%), and display a "reverse" type of zonation with the pyrope/almandine ratio decreasing from the core to the rim. In contrast, in the Upper Midland Formations ("Main Central Thrust Zone" of Arita), garnets are almandine-rich and have a "normal" zoning pattern with spessartine-rich cores and almandine-rich rims. The composition of white micas indicates that most of the muscovites of the kyanite-bearing gneisses of the Tibetan Slab are too Fe-rich and too Al-poor to be in equilibrium with the initial Barrovian assemblages (Arita, 1983), and must have crystallized or re-equilibrated at lower temperature conditions. This fits with the garnet story, indicating a medium-temperature phase of retromorphosis.

DISCUSSION

The preceding sections help to draw out the salient features of metamorphism in the central segment of the Himalayan chain. These are (i) a multi-stage metamorphic history, general and clearly recorded in the Tibetan Slab

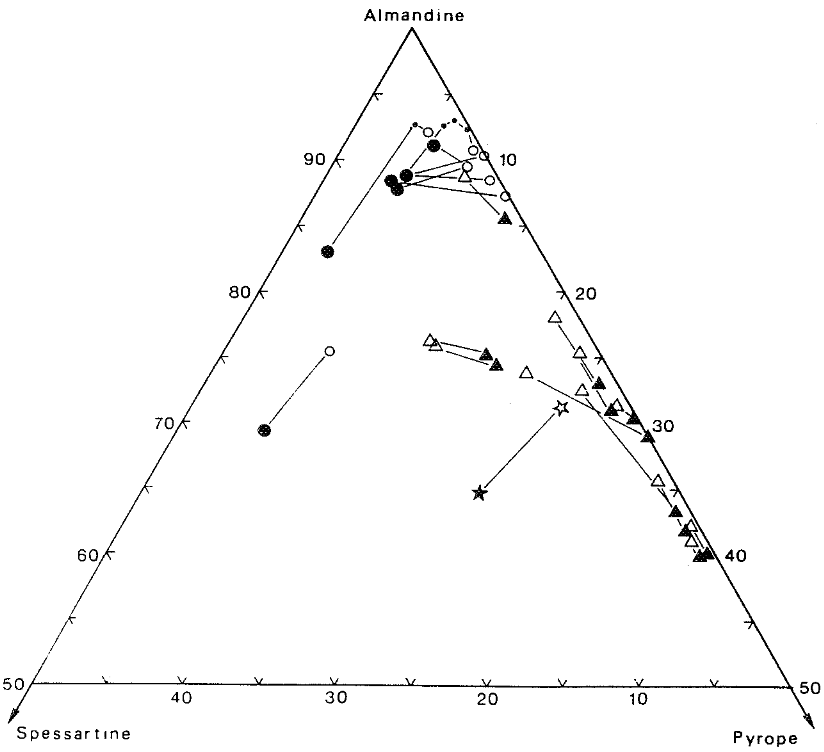

Fig. 5. Garnet composition in the Annapurna section. Data from Arita (1983) and Le Fort *et al.* (1987). Tie-lines join the core compositions (filled symbols) to the rim compositions (open symbols). Circles refer to samples from the Midland Formations, below the MCT, and triangles to samples from the Tibetan Slab. The stars correspond to the sample 84 of Le Fort *et al.* (1987), very close to the base of the Tibetan Slab, in the syn-MCT retromorphic zone.

(late stage evolution towards lower pressures), local and restricted to the vicinity of late minor thrusts in the Lesser Himalaya and (ii) an "inverse" metamorphic zonation, which results from superimposing two different-type stages of metamorphism in the Tibetan Slab, but which is recorded in the primary prograde assemblages throughout the Lesser Himalaya, where it is apparently closely linked to the thrusting history (close geographical relationship with the MCT, and syntectonic growth of the metamorphic minerals during southward-directed MCT shearing).

The metamorphic P–T-time pattern is sketched in Fig. 6.

The Tibetan Slab

The first metamorphic stage (time t_1, Fig. 6), which is rather poorly documented, corresponds to the major tectono-metamorphic event which produced the regional

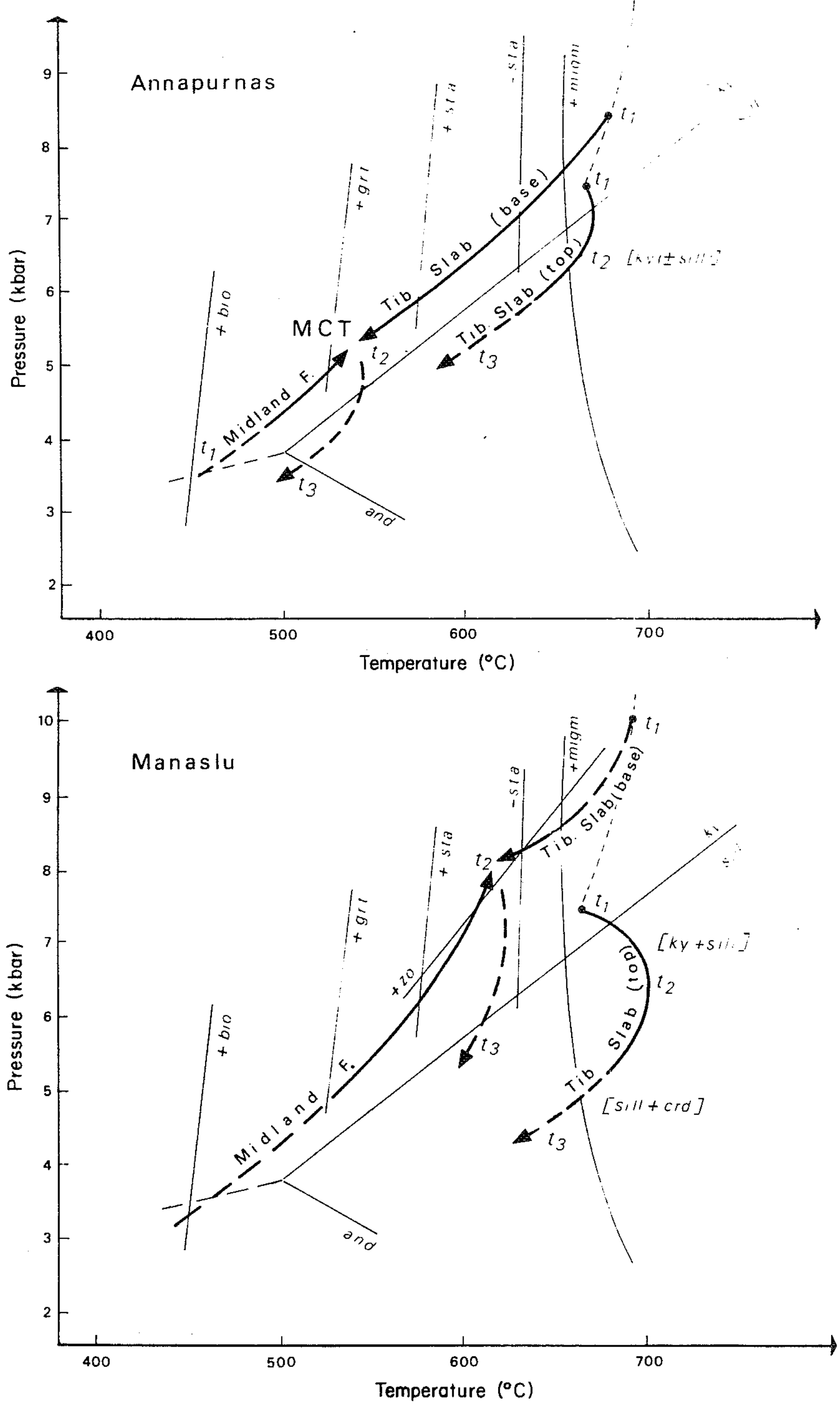

Fig. 6. Schematic pressure–temperature diagrams for an Annapurnas-type section and a Manaslu-type section. In both diagrams evolution starts at t_1 eo-Himalayan times with medium-pressure metamorphism in the Tibetan Slab. Thrusting along the MCT develops prograde metamorphism in the Midland Formations and cooling at the base of the Tibetan Slab until time t_2. As the Slab overthrusts the Midlands, erosion and tectonic denudation of the sedimentary cover of the Slab produce heating of its upper part (maximum around time t_2). Cooling down of the system follows dotted lines and is recorded mainly along cold thrust movements.

fabric in the medium and upper part of the Tibetan Slab. It is the eo-Himalayan (or rather "eo-MCT") phase of Caby *et al.* (1983), which possibly can be equated to the eo-Himalayan piling of nappes of the north-Himalayan domain. The metamorphism was of moderately high pressure, reaching maximum temperatures of about 650–700° C and pressures of more than 800 MPa. Considering the thickness of the pile overlying the gneisses (there are still about 15 km of Tethyan sediments, but the pile was certainly much thicker at the time, i.e. before its basal part had been strongly thinned in the shear-zone separating the gneisses from their sedimentary cover), these conditions would imply a rather low geothermal gradient.

This first stage is clearly overprinted by a comparatively low-pressure stage. Its age, Miocene, is constrained by: (i) the geochemical data, which strongly support a genetic relationship between the tardi-metamorphic tourmaline-rich leucosomes and the overlying Manaslu granite, which was emplaced in several pulses between approximately 25 Ma and 15 Ma (Deneil *et al.*, 1987); and (ii) the tectonic position of the sillimanite, which usually plasters the *c*-planes of the numerous ductile shear–zones which affect the gneisses as well as the base of the Manaslu granite (Pêcher *et al.*, 1984). During this Miocene stage, the *P–T* pattern varied from one section to another, apparently depending on the thickness of the gneissic pile, that is the truncation level of the MCT.

In the Manaslu section (thick slab), abundant development of sillimanite is observed in the upper part, together with injection of mobilizates. Temperatures would then have risen to more than 700° C. Later on, a surprisingly homogeneous temperature pattern was achieved, with an equilibration of the exchange thermometers at 600° C. In the Annapurna section (thin slab), the increase in temperature is less obvious (no sillimanite), the late mobilizates much less well developed, and the temperature normally increases with depth.

The raising of the geothermal gradient during the second stage could be due to the combination of two phenomena acting together.

1. The quasi-adiabatic uplift of the Slab during the thrust movement along a large-scale MCT ramp is considered to be responsible for the pressure drop through rapid erosion and/or tectonic denudation (see Caby *et al.*, 1983; Burg *et al.*, 1984). The large north-facing recumbent overfold of the Annapurna, with a lateral extent of more than 200 km and an inverted limb of up to 25 km (Colchen *et al.* 1986), is a good marker of the gravitational instability induced by the MCT. The longitudinal shearing at the top of the Slab, which could reflect large-scale thinning of the crust by eastward extrusion of Tibet (Pêcher & Bouchez, 1987), would have acted towards the same result.

2. Once the unmetamorphosed sedimentary cover and the migmatitic gneisses were rapidly brought close together by the tectonic movements, thermal refraction at the contact zone, due to a thermal conductivity contrast (Jaupart & Provost, 1985) could have resulted in a local increase in temperature at this boundary and the crowding together of the isotherms.

At least in the area where widespread migmatization occurred, the large-scale percolation of granitic melts would have buffered the temperature. This suggestion has been made by Hodges *et al.* (1986) to explain the homogenization of the temperature all across the Slab in the Manaslu section, and is supported by the different thermal distribution in the Annapurna section, where the granitic injections are much less abundant.

Whatever causes the increase in thermal gradient, the high temperature pulse in the Tibetan Slab leads to an apparent inverse metamorphic pattern (sillimanite-bearing zone overlying the sillimanite-free zone). However, it cannot be considered as the continuation of the "true" inverted metamorphic succession observed beneath the MCT.

The MCT shear-zone and the Midland Formations

In the Midland Formations, the outstanding feature is the reverse metamorphism, which is recorded in prograde recrystallization. Any explanation for it must take into account the following.

1. The isogradic surfaces appear to be roughly parallel to the MCT plane, as can be deduced from mapping or direct observations along the deeply eroded valleys. All the microstructural criteria support metamorphic equilibrium being achieved during the southward directed shearing.

2. Far away from the tip of the MCT (Manaslu section), the metamorphic zones are wide and there is, at the MCT level, a close agreement in maximum metamorphic temperatures attained on both sides of the thrust (about 600° C). The conditions of the subsequent decrease in temperature, recorded for instance by mineral textures and neo-crystallization or fluid-inclusion data, appear to be rather static and of low-pressure type.

3. Closer to the thrust tip (Annapurna section), the metamorphic zones in the Midland Formations are much thinner. The highest temperature (550–600° C) is still recorded just beneath the MCT, but it is somewhat lower than those indicated for prograde parageneses in the Tibetan Slab. Nevertheless, thermal equilibrium is achieved between terranes above and below the MCT, but this is due to retrogressive metamorphism at the base of the Slab.

These data strongly support the hypothesis that the metamorphic pattern beneath the MCT, in contrast to the pseudo-reverse metamorphic zonation of the Tibetan Slab, is a primary prograde pattern developed during the MCT shearing. At present, there are still not enough geochronological and mineralogical data to constrain the time–dependant evolution of *P*, *T* and tectonic displacement, and to build up precise models explaining such a pattern. Data suggest that heat was supplied mainly to the Midland footwall by the Tibetan Slab hanging wall during the MCT thrusting, leading to a transient thermal regime during which the isotherms assumed an elongage sigmoidal geometry (model proposed by Le Fort, 1975a, 1981). In areas far behind the thrust tip, the quantity of heat supplied was sufficient to metamorphose a relatively thick (several km) slice of underlying terranes. Nearer the thrust tip, the heat supplied from above is greatly diminished, as (i) the Tibetan Slab is thinner; (ii) it lost a large part of its heat budget during tectonic transport; and (iii) the cold thermal upper boundary (topographic surface) is lowered, erosion being more accentuated. Thus the underlying formations are relatively less metamorphosed. Still closer to the thrust tip (e.g. at the Kathmandu or Mahabharat nappe fronts), the hot shear belt is replaced by a cold thrust which places high-grade gneisses directly upon almost unmetamorphosed formations (see Fig. 1).

Finally, it should be stressed that the absence of true low temperature/high pressure parageneses in the Lesser Himalaya is rather surprising in view of the 'hot iron' effect produced by the overriding Tibetan Slab. The simplest hypothesis to explain this anomaly would be a coupling between the operation of the MCT and tectonic denudation of the Tibetan Slab. If such is the case, it is possible that the late-stage thermal pulse at the top of the Tibetan Slab was more or less synchronous with the lesser Himalaya prograde metamorphism.

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