THE GEODYNAMIC EVOLUTION OF THE HIMALAYA- TEN YEARS OF RESEARCH IN CENTRAL NEPAL HIMALAYA AND SOME OTHER REGIONS

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Abstract. Ten years of field and laboratory studies by French teams have yielded interesting and novel views on some of the long out-standing problems of Himalayan geology. Following original observations by Heim, Gansser and others, detailed investigations of the Ladakh ophiolite zone and the Main Central Thrust (M.C.T.) in Nepal, followed by analysis of fluid inclusions, petrofabrics and metamorphism have led to descriptions of the evolution of the M.C.T., to an explanation of the famous reverse metamorphism associated with the M.C.T. and of the leucogranite intrusions. A calender of the geodynamic evolution of the Himalaya is given in conclusion.

INTRODUCTION [P.B.]

French geological research in the Himalaya started in 1950 with the climbing of Annapurna I, during which the first Spiti ammonites of Thakkhola were collected (Ichac & Pruvost, 1951). Since then, climbing expeditions with geologists as party members and entirely geologic expeditions took place regularly in Nepal. Efforts were soon concentrated on :

- Eastern Nepal : the Arun valley; the Everest, Makalu and Kangchenjunga (Janu) massifs;
- Central Nepal : the Kali Gandaki - Thakkhola, Marsyandi and Burhi Gandaki valleys; the Annapurnas, Manaslu and Ganesh Himal massifs.

The results were published mainly in memoires and as maps (Bordet, 1961; Bordet *et al.* 1971; Bordet, Colchen & Le Fort, 1975) and showed in particular :

- that there is a rather good lateral correlation along the Nepal Himalaya. However, differences exist between regions that necessitate careful field study;
- that structural units are rather easy to characterize in the fossiliferous Tibetan sedimentary zone. However, the lack of chronostratigraphic markers makes it a much more difficult task in the Midlands and the metamorphic areas and hinders correlations of Higher and Lesser Himalayan events across the M.C.T.
- that the lack of important unconformities in all the Himalayan units does not help to elucidate the tectonic, metamorphic and magmatic events.

The "Alps model", developed by the first geologists working in Nepal (e.g. T. Hagen), was soon abandoned. The main aim of research since 1970 became the finding of another model, better fitted to field observations. It was linked with the clear idea that the interpretation of the range could not be dissociated from the global tectonics theory.

A research programme was developed, which was further integrated with the ICG WG6. This programme had the following three main objectives :

1 - to delineate, as precisely as possible, the pre-orogenic history of the Himalaya :

- by determining the chronologic position of the formations engaged in the mountain building (paleontological or geochronological data),

- by analysing the old deformations, starting from the sedimentological and paleogeographic reconstructions,
- by investigating plutonic and volcanic episodes that characterize these periods;

2 - to analyse the orogenic deformation, metamorphism and magmatism, studying :

- the individual, successive phases,
- the system of constraints, the intensive parameters of thermodynamic conditions and their evolution,
- the links between these deformations, metamorphism and magmatism;

3 - to look for recent and present indications of orogenic activity in the Himalaya :

- by geomorphologic and neotectonic analyses,
- by geophysical, in particular seismic surveys presently going on.

This programme has been mainly executed in Central Nepal, but, over recent years, investigations have been extended to the innermost parts of the Himalaya in the Ladakh region.

The following lines will, after a short summary of the geological divisions adopted by our team, deal with the main results of the last ten years of our research, results that bear on the geodynamic modelling of the Himalaya.

During the course of these studies, the new information obtained, along with the maps and results of earlier authors, were compiled in map form. The "Carte géologique du haut Himalaya" (1:200 000) thus drafted was published in 1980 by the CNRS, along with an explanatory text; the map is included in the present volume (Map 2).

GEOLOGICAL DIVISIONS OF THE HIMALAYA [P.L.F.]

The Indus-Tsangpo suture zone lies north of the Himalaya and north of Nepal.

In the Nepal Himalaya, the following main lithostratigraphic and structural units are differentiated, from north to south :

- the Tibetan sedimentary series, which forms many of the highest summits, and overlies the gneisses of the Tibetan Slab,
- the Lesser Himalaya formations, also called in Nepal the Midland formations,
- the Siwalik Series, the youngest and the more external part of the belt, which have been very little studied by our team.

Two major thrusts divide the previous units :

- the Main Central Thrust (M.C.T.), between the Tibetan Slab and the Midland formations;
- the Main Boundary Thrust (M.B.T.), between the Midland formations and the Siwaliks : this thrust, still active, resembles more a large listric fault than a thrust; therefore, it is better called the Main Boundary Fault (M.B.F.).

A very brief lithostratigraphic and structural summary of these units is given below.

1) The Indus-Tsangpo suture zone of Ladakh (Andrieux *et al.* 1977b; Bassoullet *et al.* 1978a, b,c; Colchen, 1977b)

This zone is underlined by a belt of discontinuous outcrops of ophiolites, approximately aligned in NW-SE direction with the exception of a few massifs lying to the south (fig.1). The ophiolites are tectonically associated with Cretaceous to Eocene sedimentary units. In a cross section, the suture appears as an asymetric fan-shaped structure over-thrusting both India and Eurasia to the south and to the north.

2) The Tibetan sedimentary series (Colchen, 1971, 1975; Le Fort, 1975a; Bassoullet, Colchen & Mouterde, 1977)

The Tibetan sedimentary series is made of mainly marine epicontinental fossiliferous deposits from below the Lower Ordovician to Lower Cretaceous without any major break or unconformity. It is intruded by leucogranite massifs (Manaslu in Central Nepal, Makalu in Eastern Nepal). At its base, the Tibetan sedimentary series becomes more and more metamorphosed and progressively passes into the Tibetan Slab, which constitutes the infrastructure.

3) The Tibetan Slab (Le Fort, 1971b, 1975a-c; Bordet, 1977; Pêcher, 1978) (see fig.10)

The Tibetan Slab comprises various gneisses and marbles forming in Central Nepal a well-identified morphological unit at the base of the Tibetan sedimentary series. This pile of gneisses is very massive, northward dipping, without any megascopic visible folds other than large flexures. Consisting of three different formations (from bottom to top : quartz pelitic micaschists and gneisses, metamorphic limestones, augen gneisses), its thickness increases from 5 km in west to 10 km in east.

4) The Midland formations (Pêcher, 1978; Mascle, 1979) (see fig.10)

The Midland volcano-sedimentary formations can be divided into two main groups : the lower, with strong volcanic (mainly felsic) affinities includes the Ulleri augen gneisses; the upper one is much more diversified (shales, carbonaceous shales, dolomitic limestones, quartzites, mafic tufs and volcanics...). This upper group of formations outcrops on both sides (north and south) of the large Pokhra-Gorkha anticlinorium, and is variously deformed and metamorphosed. The less metamorphosed carbonaceous schists of the southern side, contain impressions of plant remains (including leaves) (Pêcher, 1978, p. 75; Mascle, 1979); they are so far the only fossils found in the Nepalese Midland formations.

THE INDUS ZONE : POSSIBLE EVIDENCE FOR EARLY TRIASSIC OCEANIZATION (Bassoullet *et al.*, 1978a, b and c) [M.C.]

Recent studies in Ladakh bring new pertinent information on the suture :

- the ophiolites are characterized by the pre-

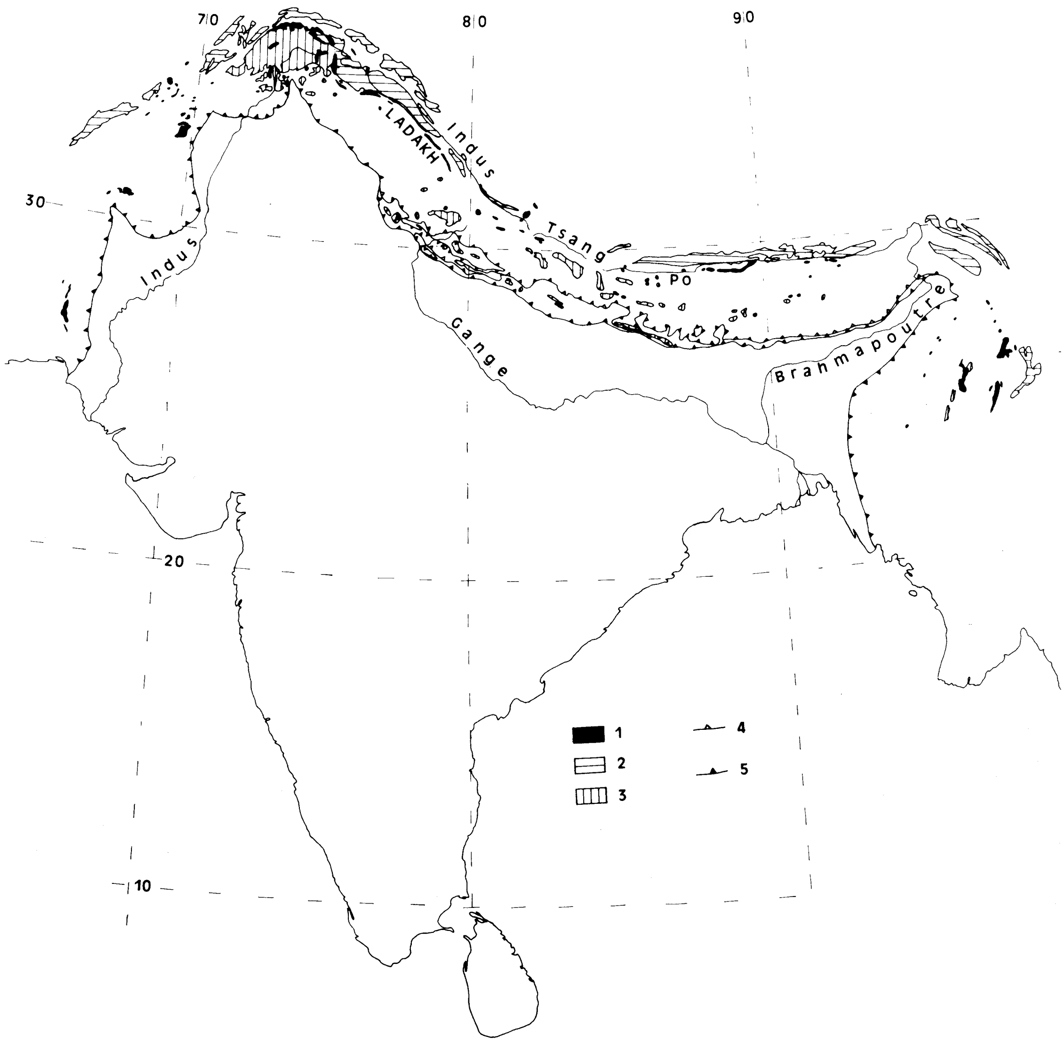

Fig. 1 - The Indus-Tsang Po suture zone, the main Himalayan structures and magmatic outcrops : (1) "ophiolites", (2) granitic bodies north of the suture zone, (3) granitic bodies south of the suture zone (Higher Himalaya leucogranites and Lesser Himalaya cordierite granites), (4) Main Central Thrust, (5) Main Boundary Thrust and equivalents.

sence of several facies typical of an ophiolite assemblage : ultramafic complex (particularly harzburgites with a metamorphic tectonic fabric : blastomylonites), gabbroic complex containing cumulates and pegmatites, volcanic flows (pillow-lavas and agglomerates), tectonically associated manganiferous red radiolarites and pink limestones (Hallstadt facies);

- the ophiolites constitute in fact an ophiolitic nappe thrust southwards onto the Himalayan series. Near Photaksar, about 25 km south of the main suture line, they outcrop particularly well in a large klippe (Gansser, 1964), very similar to that of the Amlang La area (Heim & Gansser, 1939);

- within the area, two other structural units also exist. They are characterized either by a Middle Triassic-Jurassic calcareo-pelitic flysch (the Lamayuru unit) or by a Jurassic (?) to Cretaceous greywacke-pelitic flysch with some vulcanites (the Dras-Nindam unit);

- structural and microstructural studies indicate that the pseudo-fan pattern aspect of the structure is the result of several phases of tectonic evolution in which two major events can be distinguished. A first episode, occurring before the sedimentation of the Indus detritic series (Aptian-Albian to Eocene) characterizes essentially the ophiolitic and flysch nappes which were displaced southwards. The second post-Middle Eocene event resulted in the refolding and northward thrusting of the nappes onto the Indus detritic series and even locally onto the Ladakh granodiorites.

Fig. 2 - Photograph of the top of the Lamayuru exotic block (Colchen unpublished). (1) neritic Permian limestones, (2) polymetallic crust and sedimentary dykes, (3) infilling of pelagic Triassic limestones, (4) volcanic tuffs.

- a few exotic limestone blocks are associated with the ophiolites, either within the suture or within the klippes, such as the Kiogar block (Heim & Gansser, 1939; Gansser, 1964). One of them, near the monastery of Lamayuru, displays a particular succession of facies (fig.2) : a late Permian (late Djulfian) neritic limestone rich in Algae, Foraminifera, Brachiopoda and Crinoida *(Colaniella* and *Palaeofusulina* biozone according to M. Lys, Orsay), appears eroded and locally coated with polymetallic crusts.

The surface is locally infilled by pelagic limestone (rich in Ammonites of Scythian age, several species of Meekoceras similar to the fauna of the "Meekoceras beds" of the Lilang section in the Spiti area according to J. Gueix, Lausanne) mixed with a few volcanic fragments; the series ends with a succession of tuffs, volcanic agglomerates, pillow lavas and radiolarites. A similar succession, associated with Triassic red limestones, also exists within the tectonized base of the Photaksar ophiolite klippe.

In conclusion, in the internal part of the Himalayan orogen, there are evidences of :

- the presence of oceanic crust : the ophiolitic suite, regionally associated with Triassic pelagic facies;
- the occurrence of a zone, possibly related to a continental crust, with the succession in time of : neritic limestones, polymetallic crusts, pelagic sediments and volcanics. In our opinion, this succession characterizes the typical evolution of continental break-up and the associated creation of a passive margin regime.

In this case such an evolution, occurring just between the Permian and the Trias, could emphasize the activity of the Tethys Ocean.

THE TIBETAN SEDIMENTARY SERIES [M.C.]

The general stratigraphy of the Tibetan sedimentary series has been unravelled in Central Nepal (Colchen, 1971, 1975; Bordet *et al.*, 1972; Bassoullet *et al.*, 1977). Two recent discoveries may be mentioned here :

1) The Permian-Triassic boundary (Bassoullet & Colchen, 1977).

Paleontological data show the Permian-Triassic boundary to lie at the lower part of *Otoceras* sp. aff. *woodwardi* limestones of Lower Scythian. The uppermost Permian is not in evidence and is thought to be missing.

Lithostratigraphic and paleontological data strengthen this hypothesis, showing that a change of sedimentation occurred as early as Lower Triassic : low energy carbonate sedimentation (biomicrite with thin-shelled Molluscs) succeeded by heterogeneous detrital deposits was followed by further carbonate sedimentation of higher energy level. This succession is known elsewhere in the Himalaya and indicates palaeogeographical changes of sedimentation, connected to the incursion of the sea in a domain that was particularly unstable during the Carboniferous and the Permian.

2) The problem of Gondwanan and Tethyan characters of the Himalayan series (Colchen, 1977b).

Analogies of lithofacies and fauna have been described between the Carboniferous and Permian series of the Lesser and Higher Himalaya. These analogies indicate similar palaeogeographic conditions with an imbrication of the Gondwanan and Tethyan characters. Although the Higher Himalaya is a part of the epicontinental Tethyan domain, Gondwana influences appeared from time to time during the entire Mesozoic so that it can be described as a peri-Gondwana area. The opening of an oceanic Tethys (intra or extra Gondwana ?) is again suggested by Colchen (1977) who addresses the problem of the limit of the Gondwana in north India.

THE MAIN CENTRAL THRUST ZONE (M.C.T. ZONE) [A.P.]

1) Introduction

The M.C.T. Zone has been studied mainly by Pêcher since 1972 in Central Nepal (Annapurna-Manaslu and Arun valley). Several publications deal with the results of the study of deformation and metamorphism in these areas (Pêcher, 1974, 1975, 1977, 1978, 1979; Brunel, 1975; Brunel & Andrieux, 1977; Brunel *et al.*, 1979). The main metamorphic and deformational events in Central and Eastern Nepal are shown to be very similar.

The methods of study used by these authors include :

- field investigations and mapping at all scales,
- microscope study of thin sections,
- whole rock chemical analysis and microprobe mineral analysis,
- X Ray diffractometry,
- quartz C axis determinations and statistical analysis in oriented thin sections of quartzites,
- study of quartz fluid inclusions and interpretation on a heating and freezing stage.

The main results concerning the deformation and the metamorphism are summarized below.

2) The deformation

The deformation is typically un-coaxial, the rotational character increases progressively in the proximity of the thrust plane (i.e. the plane of highest deformation between the Tibetan Slab and the Midland Formations). This zone appears to be a very large shear zone, the thickness of which may reach 10 km; it gradually passes to the more superficially deformed and more intensely folded areas (the Tibetan sedimentary series, above, and the southern part of the Midland formations, below).

a) The mesoscopic geometry of the M.C.T. Zone

The mesostructure has three main aspects :

i - a flat cleavage,
ii - a conspicuous "type a" line,
iii - a scarcity of folds.

i - At the top of the Tibetan Slab, the fracture cleavage S2, axial plane of the south-vergent B2 folds soon becomes a metamorphic cleavage, and farther down a foliation plane (main structural surface of the Tibetan Slab). No structural discontinuity is observed at the base of the pile of gneisses, across the thrust : the same S2 metamorphic cleavage can be found in the Midland formations, usually parallel to the S0 boundaries, or, if not, slightly more northward dipping than S0.

ii - The existence of an omnipresent mineralogical or stretching lineation, NNE-SSW, is probably the most conspicuous feature of the M.C.T. Zone. In the higher part of the Tibetan Slab and in the Tibetan sedimentary series, the main line is an intersection line. Lower, as the metamorphic recrystallization increases, a mineralogical line (elongation of minerals) is substituted for the intersection line. Together with it, the orientation turns away from the general E-W trend of the belt : the lines scatter in the cleavage plane towards a N-S direction.

In the underlying Midland formations, the line is a stretching line, marked by the elongation of pebbles in detritic layers, by mullions in more homogeneous and competent ones, or by metamorphic striae in the schistose layers. This line, very well expressed near the M.C.T., vanishes away from it in the lower Midland formation, or in the southerly folded area; but in all the areas studied, its direction remains remarkably constant - NNE-SSW - as in the lower part of the Tibetan Slab : this direction, perpendicular to the general cartographic trace of the thrust, can be considered as the *transport direction*, and the line must be regarded as an "a" line.

The finite strain ellipsoid had been measured on the pebbles of several samples. In the Arun area (Brunel, 1975), it is typically constrictive; in Central Nepal (Pêcher, 1978), it is usually of flattening type, except in narrow (hundred of meters) bands parallel to the line, where mullion structures are particularly well expressed. So, despite the great homogeneities in orientation, these bands (kinds of "transform faults") and the differences in the shape of the strain ellipsoid, indicate strong flow heterogeneities.

iii - The scarcity of the folds : in the transition zone between the Tibetan sedimentary Series and the Tibetan Slab, the large south-vergent B2 folds flatten drastically; lower in the pile of gneisses, no large synmetamorphic folds can be clearly seen. In the part of the Midland formations within the shear zone, the still-recognizable stratigraphic polarities of the gently northward dipping metasediments exclude the presence of large recumbent folds; the only large folds are post-metamorphic concentric folds and are related to the Pokhra-Gorkha anticlinorium.

Nevertheless, in outcrop, or in thin sections, some syn- to late- metamorphic folds are visible; their axial directions follow the same variations as the line : roughly E-W at the top of the Tibetan Slab, they scatter in the cleavage plane when nearing the M.C.T.; in the highly sheared zone close to the M.C.T., the axial B direction is usually parallel to the NNE-SSW flow direction.

Brunel and Andrieux (1977) are of the opinion that these folds in Eastern Nepal were probably initiated parallel to the "a" line, due to the constrictive character of the finite strain. In Central Nepal, this explanation does not fit very well with the mainly flattening type of the finite strain; but some rare outcrops, where folds are numerous enough to be statistically informative, show a dispersion of the axis directions throughout the cleavage plane, with a strong maximum near the "a" direction (sheath folds) : here, one may propose that the NNE-SSW oriented folds are due to reorientation of earlier folds by sliding in the cleavage plane, (see Pêcher, 1978, fig.91).

b) Criteria of un-coaxial (rotational) deformation

In the M.C.T. Zone, several features show the rotational character of the deformation, as well as its progressivity :

i - The rotational character is fossilized in the symmetry of the microstructures : in XZ sections (perpendicular to the cleavage, parallel to the line), they are monoclinic (i.e. "dissymmetric"); the sense of dissymmetry is then in accordance with the direction of shear, as inferred from regional considerations (the Tibetan Slab is thrust southward over the Midland formations); in YZ sections (perpendicular to both lineation and cleavage), the apparent symmetry is statistically orthorhombic;

ii - Progressive increase of shearing (increase of γ value) is revealed by the progressive changes in microstructures, and by the evolution of the dissymmetries, which become increasingly acute closer to the thrust plane.

In these aspects, the Himalaya appears as a model, where deformation on a global tectonic scale can be followed down in scale to the internal structure of the minerals. The inventory of the shear structures has been made. They concern either the geometric dissymmetries, or the preferred orientation of minerals.

i - Dissymmetries :

- almonds S-S' : in detail, the metamorphic cleavage S2 appears as a microscopic juxtaposition of almond-shaped bodies, giving a characteristic cupular aspect to the rocks. These almonds result from the association of the main cleavage plane S with an S', which must not be attributed to another deformation phase; visible in the same metamorphic assemblages, S and S' are penecontemporaneous, S' revealing sliding movements on S as soon as S was formed; the obliquity of the relation S-S' is very constant (S' more northward dipping than S) and gives the direction of sliding;
- rotation and fracturation of the porphyroclasts;
- intrafolial drag folds;
- rotated internal schistosity of porphyroblasts, associated with dissymmetric pressure shadows.

ii - Quartz microstructures and preferred orientation :

Based on microstructures in quartz-rich formations (quartzites, sandstones, quartzo-feldspathic gneisses), several main microstructural zones have been recognized of which the cartographic patterns are roughly the same as those of the metamorphic zones (see below). From bottom to top (i.e. from the Lower Midland formations to the M.C.T., and up into the Tibetan Slab), they are:

- zone of sedimentary microstructures;
- zone of porphyroclastic microstructures : the shapes of the old, flattened, detrital grains are still recognizable, surrounded by the phyllites; but most of the grains are polygonized partially recrystallized, and extended by pressure-shadows with a mosaic structure;
- mosaic microstructures are very characteristic of the upper part of the Midland formations, close to the M.C.T.; here, some samples also show characteristic mylonitic ribbon microstructure;
- exaggerated grain growth microstructures, always found in the gneisses of the Tibetan Slab, are also observed in the higher part of the Midland formations in the Burhi River area.

These various microstructures reflect the combined increase of plastic deformation and temperature when crossing the M.C.T. The influence of temperature predominates in the Tibetan Slab where the microstructures reveal a strong thermic overprint younger than the plastic deformation. Increase of the rate of deformation has been mainly demonstrated by the study of the preferred orientations of quartz C-axes (Pêcher & Bouchez, 1976; Bouchez & Pêcher, 1976; Brunel, 1979).

Using the metamorphic cleavage plane and the stretching lineation as the external geometric reference, quartz C-axes are distributed along two cross-girdles (diverging at an angle of = 2Θ), roughly symmetric in respect to the XY or YZ plane; but one of the girdles is more densely populated than the other, attesting the rotational component of the deformation. Towards the M. C.T., the dissymmetry of distribution increases, and one of the girdles even vanish completely (as in the ribbons fabrics) (see Pêcher, 1978; fig.121)

Multiplication of measurements has shown that the value of Θ (which can appear "a priori" as a good shearing rate criterion) seems to rapidly reach a minimum value (15 to 20°), and then remains constant whatever the value of the shear ratio; thus the main criterion for the γ value seems to be the rate of population density of one girdle compared to the other.

In one or two samples from the Arun area, Brunel (1979) has shown that the plastic deformation of the quartz was accompanied by a new shape fabric and the elongation of the quartz grains are oblique to the cleavage plane as defined by the phyllites. This obliquity poses the problem of the definition of the schistosity (the plane of flattening) and of the choice of the cinematic reference point, as well as the problem of the relative chronology between metamorphism (i.e. recrystallizations) and the acquisition of preferred orientations in the quartz.

3) Metamorphism

The following data on the metamorphism are based mainly on detailed petrographic investigations of Pêcher (1975-1978) in the Annapurna - Manaslu area. Brunel's observations in the Arun Valley (1975) are in good agreement with the features described here.

a) Age of the main metamorphic events in the M.C.T. Zone

The metamorphic assemblages define the S2 plane, associated to the evolution of the M.C.T.; in regard to shearing, metamorphism starts rather early (the S2 metamorphic cleavage acted as the sliding plane, chanelling the main flow deformation), and its thermal print continues throughout the movement (late-deformation figures such as in -S pegmatitic lenses, or filling of open cracks, show metamorphic assemblages similar to those of their host rock) : the main metamorphic print is therefore contemporaneous with the M.C.T. thrusting (i.e. Miocene).

Radiochronometric data on cooling ages, lead to similar conclusions : the intrusion of the Manaslu granite, related to the migmatisation of the Tibetan Slab (Le Fort, 1973), is dated as 16 to 23 m.y. by Rb/Sr measurements on muscovites (Vidal, 1978; Hamet & Allègre, 1978). Similarly, two muscovites from the front part of the M.C.T. nappe, south of Kathmandu, gave ages of 22 and 26 m. y. (Andrieux, Brunel & Hamet, 1977). A series of K-Ar ages in the Tibetan Slab of the Everest area (Krummenacher *et al.*, 1978) varies from 20.5 m. y., 9 km above the M.C.T., to 9 m.y. close to it, the decrease in age being related to the processes of erosion and cooling throughout the Miocene.

b) The possibility of an earlier metamorphism

The slight metamorphism of the Tibetan sedimentary series is not yet well correlated with the phases of deformation, and might be older than D2 - i.e. contemporaneous with D1, or, very hypothetically, a distant replica of the high pressure metamorphism of Kashmir and Pakistan (Thakur & Virdi, 1978; Bard *et al.*, 1979), dated as Upper Cretaceous (Bard, oral comm. 1979).

Within the Tibetan Slab, the syn-D2 metamorphism is strong enough to obliterate most of the previous events; nevertheless, throughout the M. C.T. Zone, structural superposition of metamorphic minerals can be seen locally : but rather than a succession of metamorphic phases (i.e. thermobarometric events separated by large lapses of time), such superpositions reflect minor discontinuities in the recrystallization-deformation processes synchronous with deformation of the M. C.T., from the initial cleavage up to the late retromorphic events, some million years later.

Thus if pre-Alpine metamorphic events had taken place in Central Nepal (some radiochronometric data might be slight indications of them), they are today masked by the Alpine, mainly Miocene metamorphism, in the structural domain of the Himalayan belt described here.

c) Main characteristics of the metamorphism in the M.C.T. Zone

Several metamorphic zones have been recognized and mapped based on the mineralogical equilibria in the KFMASH chemical system (K_2O, FeO, MgO, Al_2O_3, SiO_2, H_2O). They refer to the paragenesis of the meta-sandstones and the meta-pelites, the most abundant types of rocks in the thrust zone (fig.3 and 4).

The following minerals of the system, KFMASH, have been identified : quartz and muscovite, both very frequent; chlorite (chl; only prograde chlorites, and not retromorphic ones, are taken into account here), chloritoid (ctd), biotite (bio), garnet (grt; almandine : 60-75%, pyrope : 3-30%, spessartite : 1-25%), staurolite (sta), K-feldspar (KF), kyanite (ky) and sillimanite (sill).

Those index minerals define the following zonal succession, from the south to the north of the M. C.T. (when in brackets the mineral is scarce) :

i - chl, (ctd) zone,
ii - chl, bio, (ctd) zone,
iii - chl, bio, grt, (ctd) zone,
iv - (chl), bio, grt, sta, ky zone,
v - bio, grt, ky, (KF) zone, and
vi - bio, grt, sill, KF, (ky) zone.

In CaO rich rocks, the other main index minerals are plagioclase (scarce or detrital before zone iv), zoisite (restricted to close to the M. C.T. - that is to the limit iv-v), actinolite (zones i-iii), hornblende and diopside (zone v-vi).

The average dip of the M.C.T. Zone being northward, the succession above corresponds to an apparent increase in metamorphism from the structurally lower part of the zone (lower Midland formation outcrops in the innermost part of the Pokhra-Gorkha anticlinorium) to the higher one (upper part of the Tibetan Slab) : this succession illustrates typically the famous Himalayan "reverse metamorphism", previously described, by many authors, in the Central and Eastern Himalaya (see Le Fort, 1975a).

Higher in the Tibetan sedimentary series, where observations are too scattered to delineate precisely such mineralogical zones, the metamorphism decreases "normally", the main index minerals being sillimanite, garnet, biotite and chloritoid (plus diopside in limestone); unpublished data on illite crystallinities show that the higher epizonal or anchizonal metamorphism reaches up into the Lower Mesozoic (Dunoyer de Segonzac, Colchen & Le Fort, unpublished data).

- *Geometry of the isograd surfaces*

The surfaces bounding the metamorphic zones can be regarded as isograd surfaces; their geometric relation to the thrust plane throws light on the relationship between metamorphism and deformation with due regard to the uncertainty on their position - which may be precise to several 10 m or 1 km - according to the number of samples studied, (some 800 for the Annapurna-Manaslu area), and on the rock chemistry restrictions.

The salient point of the geometry of the isograds, clearly illustrated on the map or along cross-sections (cf. Pêcher, 1975, 1978, 1979; Brunel, 1975), is the conspicuous regional parallelism between the M.C.T. and the isograds (fig. 3, 4) : such a constant geometrical relationship also implies a genetic relationship, and the metamorphic distribution observed must result from the thrust-shearing events.

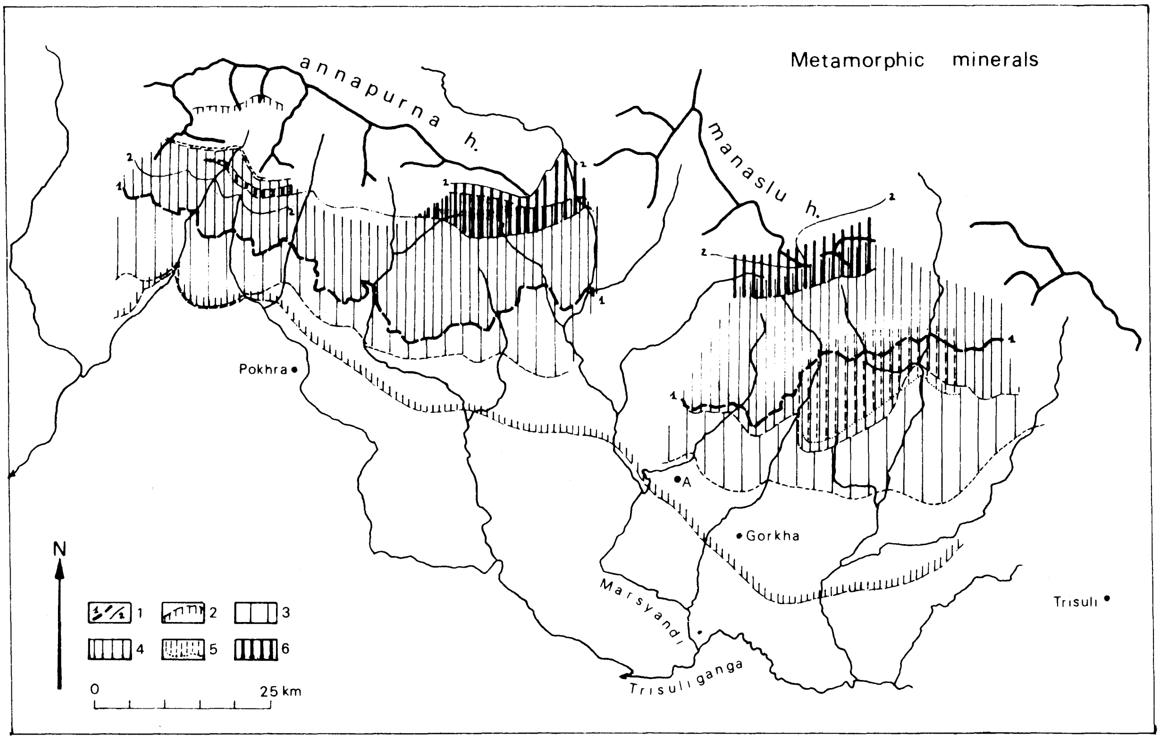

Fig. 3 - A map of the distribution of metamorphic minerals in Central Nepal (Pêcher, 1977, fig. 12). (1) lower limit of the Tibetan Slab -1- and upper limit of formation I -2-, (2) biotite appearance, (3) garnet (also present in the Tibetan Slab), (4) kyanite, (5) staurolite ; (6) sillimanite (fibrolite). A : nepheline syenite and alkaline gneisses of Ampipal.

The other following geometrical aspects must also be emphasized :

• the spacing of the isograds is closer near the front of the thrust (in the Arun Valley, where the thrust can be followed for more than 50 km from north to south, Brunel, 1975) than in areas farther back from it (in the Burhi Gandaki area, Pêcher, 1978);

• the isograds may cut lithostratigraphic boundaries: the reverse metamorphism is not due to the pile of variously metamorphozed scales or sheets, but reflects an abnormal thermobarometric distribution in the shear zone;

• no metamorphic hiatus can be clearly observed across the M.C.T. plane : the post-metamorphic displacements must be slight compared to the synmetamorphic ones. From this point of view, the western part of the area studied (Kali Gandaki-Annapurna) might be an exception : here the ky-sta zone seems to disappear against the thrust plane; it may be due to the existence of a somewhat different P.T. pattern in the frontal part of the

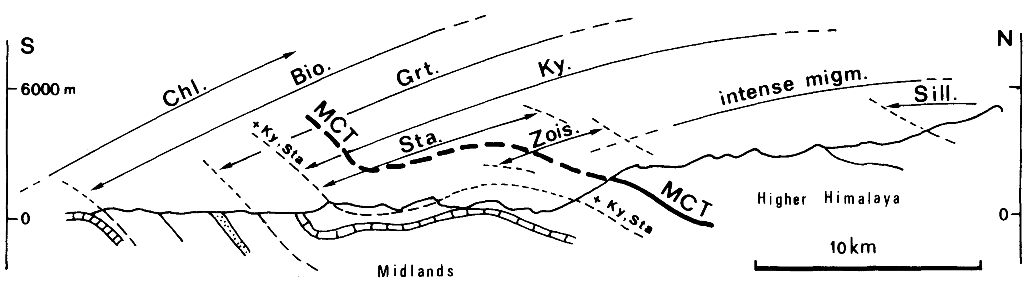

Fig. 4 - The Burhi Gandaki section and distribution of metamorphic minerals (Pêcher, 1979a). Abbreviations for minerals as in the text.

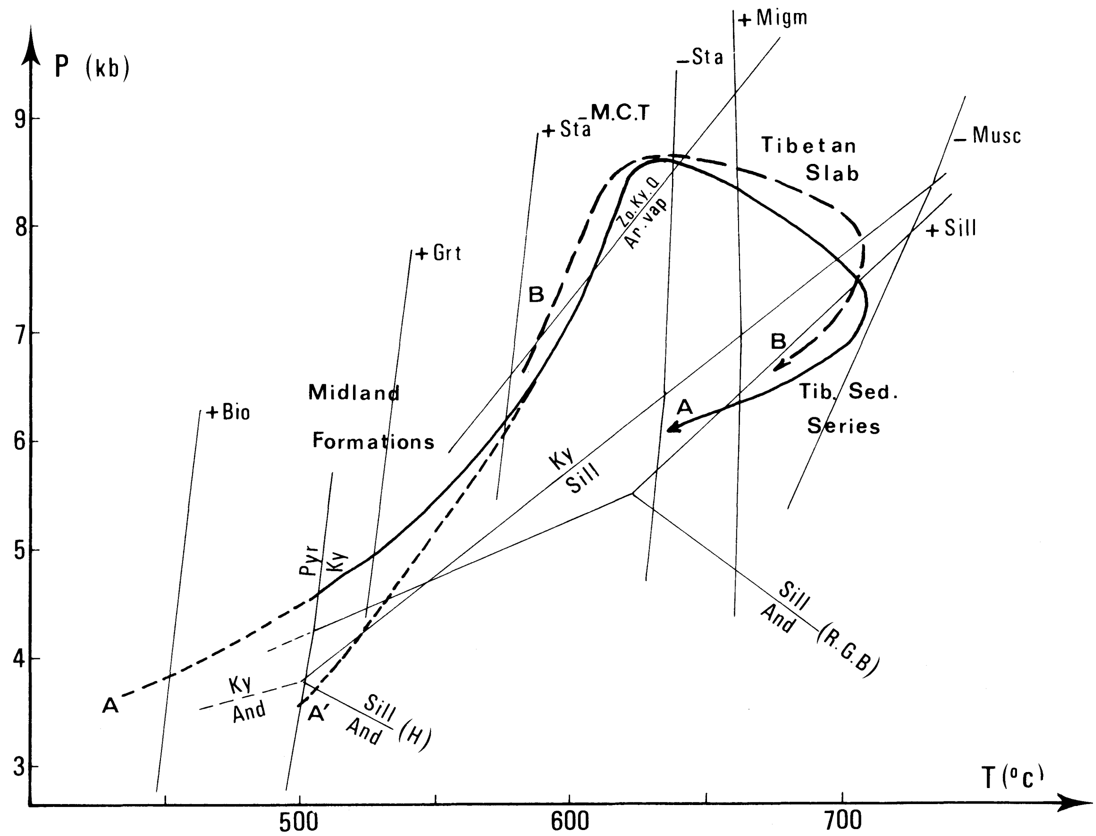

Fig. 5 - The Himalayan reverse metamorphism : pressure-temperature distribution around the M.C.T.The fluid phase composition is supposed to be either pure water (curve A) or a mixture of water and carbon dioxyde (curve B) ; curve A' takes into account the hypothetical presense of andalusite (Pêcher, 1978).
Abbreviations : see the text ; + bio..., - sta... means apparition of bio..., disappearance of sta... on the high-temperature side of the curve ; Migm = migmatization (liquidus curve), Pyr = pyrophyllite; the univariant curves for the $SiAl_2O_5$ polymorphs are from Richardson *et al.*, 1968 (R.G.B.) or Holdaway, 1971 (H.).

thrust, or it may be a precursor of the nappe system found farther west (Western Nepal or Kumaon).

- *The pressure-temperature distribution in the shear zone*

This distribution can be deduced from the chemico-mineralogical reactions at the boundaries of the metamorphic zones. Such observations will give the P-T conditions during the main recrystallization of the rock; but it does not imply that all the equilibria were reached at the same time everywhere in the shear-zone : for example, there can be still strong recrystallization synchronous with deformation in the central part of the zone, coeval with colder, "late-metamorphic", deformations in the more external parts.

With this rectriction in mind, one can deduce the pressure-temperature evolution through the shear-zone from the following equilibria (fig.5) :

- appearance of biotite, soon followed by apparition of garnet;
- disappearance of chloritoid, apparition of kyanite and staurolite;
- disappearance of staurolite soon after its apparition (due to the chemical composition of the rocks, sta forms from grt and chl, at approximately 590°C, and reacts with chl to give bio + ky at approximately 635°C : this rather narrow stability field could possibly explain the absence of the ky-sta zone in the Annapurna area for kinematic considerations, supposing that we have here a more quickly cooled frontal part of the thrust);
- stability field of coexisting kyanite and zoisite (near the M.C.T.);
- liquidus curves of ky-pl-bio-musc and sill-FK-bio-musc assemblages (migmatisation of the Tibetan Slab), and
- absence of H.P. paragenesis under the M.C.T. : no evidence of H.P. paragenesis, even as relicts, have been found here; moreover some authors (Hashimoto *et al.*, 1973; Rémy, 1974) have mentio-

ned andalusite, but its existence is not very reliably established.

Remark : The P-T distribution in fig.5 is deduced from equilibria curves established for $P_f = P_{H_2O}$. In fact, microthermometric studies of fluid inclusions in the quartz of the late-metamorphic lenses has revealed a great variability in the composition of the fluid phase being, a mixture of CO_2, H_2O and salts : the CO_2/H_2O ratio, very low away from the M.C.T., increases in the central part of the shear zone, where some samples contain nearly pure CO_2 (Pêcher, 1979). The fluid trapped in these late lenses does not reflect the fluid acting during mineralogical equilibration of the host-rock (considerations on the paragenesis stability field show that the CO_2 content in the host rock could not have been as high as in the lenses); nevertheless, a tentative P-T curve, taking into account some amount of CO_2 in the fluid phase, is given in fig.6.

These two curves differ only slightly, and both show that :

- the highest temperature values (approx. 710°) are reached in the upper part of the Tibetan Slab, 5 to 8 km above the M.C.T.;

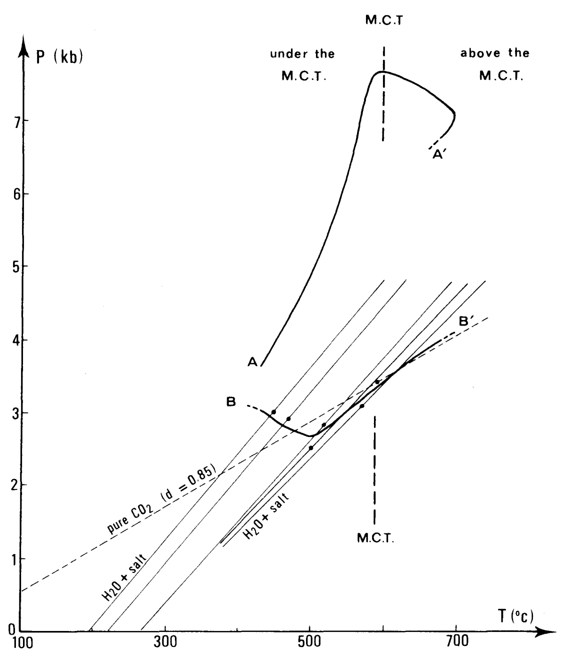

Fig. 6 - P.T. distribution around the M.C.T.,as inferred from the main metamorphic assemblages (curve AA', see fig. 5) and from the fluid inclusions in the late-metamorphic exsudation lenses (curve BB'). For the curve BB' : data from Potter and Brown (1977) (full lines, isochors for a filling by a brine) and from Kennedy (1954) (dashed line, isochor for a filling by pure CO_2). True formation temperature in the inclusion is estimated from the mineralogical paragenesis of the considered lens (Pêcher, 1978).

- the pressures increase downwards to attain a maximum near the M.C.T., (approximately 8,5 kb) and then apparently decrease lower in the underlying Midland formations.

- *Thermobarometric decrease and post-metamorphic events in the M.C.T. Zone*

The previous observations deal with the deformation-pressure-temperature pattern during the main stage of petrographic evolution of the thrust zone. Some field or laboratory results describe its variations in time :

i - the thermal influence is still evident after the major deformation. Indeed :

- the position of the veins of migmatitic mobilizates, which often cut across the gneissic structures (relaxation phenomena);
- the presence of Riedel's extension fractures (with orientations consistent with the overall shearing directions) filled with "hot" minerals : for example sillimanite, in the sillimanite zone, or even in the upper part of the kyanite zone, where it appears as a "retromorphic" mineral;
- the exaggerated grain growth microstructure, which can be interpreted as reflecting post-plastic-deformation annealing (Bouchez, 1977);
- the similarities between the paragenesis of the in-S late exsudation lenses and the paragenesis of the surrounding rocks (the paragenesis of the lenses, when rich enough, show the same index minerals as the host rock).

Thus, particularly in the Tibetan Slab, the temperature decreased little or not at all whilst conditions of deformation varied considerably (conditions of ruptural deformation, probably corresponding to a decrease of the prevailing stress).

ii - The fluid pressure (Pf) decreased faster than the temperature : a strong decrease in the fluid pressure between the main period of metamorphism and the late exsudation lenses has been demonstrated by study of the fluid inclusions in the lenses.

The Pf in these lenses has been deduced from the fluid density (in the inclusions for which it was possible to draw the isochore, i.e. inclusions of brine or pure CO_2) combined with the trapping temperature as estimated from the mineral associations.

The Pf-T curve across the M.C.T. Zone based on these data (see fig.6 : a cross-section in the Annapurna area) shows a drastic decrease of fluid pressure, of up to several kb (3 to 4 kb at the level of the M.C.T. However these values are only a first approximation, as the exact role of fluid pressure during the metamorphic processes has not as yet been clarified).

iii - Some deformation however continued in the shear-zone after the decrease in temperature :

- according to Brunel (1979), the preferred orientations of quartz C-axis would reflect mainly a late, colder, stage of the deformation;
- low grade retromorphic equilibrium are observed (for instance destabilisation of garnet and biotite to chlorite), the newly formed minerals

being then often located in Riedel's fractures ("cold" Riedels) or in open extension cracks perpendicular to the "a" rock fabric;

- slickenslide-striae occur on the older structural surfaces (the striae are usually best expressed on the steep reverse-side of the S-S' almonds, or at the surface of the exsudation lenses).

Thus there has been some cold sliding in the M.C.T. Zone, at first restricted to the old main structural discontinuity, the S2 plane. As cooling proceeded, some blocking must have occurred; new discontinuities and folding are then needed to absorb the continuing shortening. This phase may be associated with the irregular apparition of the new S3 strain slip cleavage, which is steeper than the older S2, and the formation of large B3 folds (for instance the Pokhra-Gorkha anticlinorium) in the front (south) of the previously strain-hardened (metamorphosed) wide shear-zone.

4) Origin of the reverse metamorphism, some geodynamic implications

The reverse metamorphic zonality expresses an abnormal distribution of both the pressure and the temperature, at the time of the stabilization of mineral equilibria, equilibria which could have been tempered by a rapid decrease of either temperature or pressure.

a) The pressure distribution

A very astonishing feature of the pressure distribution is its downward decrease under the M.C.T. : the total thickness of the Tibetan sedimentary series plus the Tibetan Slab is more than 20 km, and corresponds to a lithostratigraphic load which fits rather well with the 8 kb pressure proposed near the M.C.T.; in the underlying terranes, pressure should be still higher.

No really good answer to this paradox has yet been put forward. Meanwhile, one must notice that the pressures given are deduced from equilibria in rocks spaced out along several south-north cross sections following the topography, i.e. not perpendicular to the thrust plane, but quite oblique to it; the low pressure metamorphic zone of the Midland formations, although structurally the lowest, lies in fact in front of the M.C.T. trace, and not under the thrust plane; this zone might not have been covered by all the thrust pile at the time of metamorphism. Such an assertion would imply that :

- the erosion commenced very early (as shown by the strong pressure decrease printed in the late-metamorphic lenses);
- the present frontal trace of the thrust is probably not far from its maximum extension;
- the mineralogical assemblages above and below the thrust plane were not coeval.

b) The temperature distribution

Whatever the true pressure pattern, the temperature pattern can be rather easily explained (Le Fort, 1975a) by subduction type thermal models. Toksöz and Bird (1977) calculated the crustal thermic distribution in a collision belt such as the Himalaya, taking into account crustal shortening in large M.C.T. type cleavages.

These models require transitional S-shaped forms of the isotherms on both sides of large thrusts (true subduction, or "intracontinental subductions"), with the superposition of zones of normal thermal gradients above zones of reverse ones. If recrystallisation is sufficiently rapid to fossilize this particular thermal pattern, a zone of apparent reverse metamorphism (in respect to temperature) will exist.

According to the models, the zone of maximum temperature depends mainly on the relative amount of shear friction heating versus heating due to the more or less high initial temperature in the trust area. As the maximum temperature lies clearly a few km above the M.C.T. plane, the Himalayan reverse metamorphism in the lower part of the Tibetan Slab and in the Midland Formations must be essentially due to the high temperature of the Tibetan Slab prior to thrusting.

THE SOUTHERLY FOLDED AREA
(Mascle & Pêcher, 1977; Mascle, 1979; Brunel *et al.*, 1979) [A.P.]

1) The southern Lesser Himalaya

Although there is no important structural break between the northern and the southern parts of the Midlands, changes in the type and intensity of deformation give a different aspect to the southern area : tectonically, this area appears much more complex than the monoclinal and unfolded M.C.T. Zone; several phases of deformation (D2 to D5), can be recognized, on the basis of successive refolding of the cleavage; most of them were not described by previous authors (Fuchs & Frank, 1970; Rémy, 1972; Hashimoto *et al.*, 1973).

a) Structures associated to the main S1-2 cleavage :

The oldest structures are characterized by a regional cleavage which clearly affects the Midland formations up to the Eocene Tansen Formation. This cleavage, marked by very low grade metamorphic recrystallizations (sericites), appears as the prolongation of the cleavage synchronous with the shearing in the M.C.T. Zone. In relation to the tectonics of the Tibetan Slab, it can be called S1-2, although no D1 deformation has been observed.

S2 is related to isoclinal recumbent folds (nappes), of several kilometers, with large overturned limbs visible with polarity criteria such as upside-down stromatolithes and cross-bedding; the overthrusting may exceed 15 km. The D2 features visible in the field are mainly lineations; their pattern shows, in a shallower environment than in the M.C.T. Zone, that the same north-south "a" sliding is an important process of internal deformation of the rock; the sliding decreases southwards, i.e. away from the shear-zone. These lineations are :

- intersections S0 - S1-2 and microfolds axis, showing a dispersion pattern with two maxima roughly north-south and east-west, the latter becoming sharper to the South;
- mineral streching lineations, about north-south and better expressed in the northern area.

b) Post S1-2 structures

After the flow deformation, the preexisting structures of the Lesser Himalaya, shears or nappes, were refolded by concentric folds, which correspond to a deformation at higher structural level in the frontal part of the belt. These folds give the southernmost part of the Himalaya its characteristic "Jurassian" aspect, and are :

- B3 folds, frequently dissymetric to the north, and rarely so in the south, associated to a S3 cleavage of kink-band or crenulation type,
- large sub-meridian B4 folds, parallel to the Thakkhola fault zone, only exceptionally accompanied by a N-S fracture cleavage (as in the Arun valley);
- B5 large open E-W antiforms and synforms, sometimes accompanied by a S5 strain slip cleavage.

2) The Main Boundary Fault zone (M.B.F. zone)

All the previous deformations are directly related to movement along the M.C.T., and are cut by the Main Boundary Thrust, which appears in the field as a fault, plunging 60 to 70° to the north; it is accompanied by minor reverse and strike-slip faults, or by minor folds, in agreement with the direction of shortening about north-south and perfectly horizontal.

In front of the M.B.T., the Churia Hills (the Siwaliks) show very regular parallel anticlines (B5-6), with short southern and long northern limbs, which dip regularly north at some 70° near the M.B.T. to 35° a few km south of it.

QUATERNARY GEOLOGY AND GEOMORPHOLOGY [M.C.]

The team has not yet undertaken any study in the Siwaliks, but has worked on one of the major intramontane basins of the Himalaya, the Plio-Quaternary Thakkhola graben (Colchen, Fort & Freytet, 1979). This study was associated with research on the recent evolution of the Himalayan range, in particular on the Quaternary formations and the geomorphology of Ladakh and Higher Himalaya (Fort, 1977, 1978a and b).

1) Sedimentation and Plio-Quaternary tectonics in the Thakkhola basin (Colchen *et al.*, 1979)

This N-S intramontane graben lies north of the high range and cuts the Himalayan structures. The sediments, deposited on folded and faulted Triassic to Cretaceous series, show the following sequence :

- deposition of the Tetang formations (probably Pliocene) in a small basin. Sediments include polygenic conglomerates, lenses of stromatolitic limestones and an Ostracode bearing argillaceous horizon;
- phase of deformation (F2 faults);
- partial erosion of the Tetang formations and deposition of the Thakkhola formations (Plio-Quaternary) in a larger basin limited to the west by a system of F3 faults. These sediments include polygenic conglomerates, argillaceous beds and oncolithes with lenses of limestones;
- phase of deformation (F4 faults);
- erosion followed by the deposition of fluvio-glacial formations (recent Quaternary).

2) Geomorphology of the Ladakh region (Fort, 1978a)

The geomorphology of the whole region, which is a good example of arid, continental and subtropical high mountains, is controlled by the different natures of the various formations : the heterogeneous Ladakh batholith and the various Zanskar sedimentaries.

The cold Quaternary and present times gave rise to a typical morphology : regular valley-slopes and periglacial glacis (pediment), which are mainly due to the processes of gelifraction and snow-solifluxion. The Indus valley lies along a prominent structural axis of the Himalaya. Along the valley, the great extension of the Quaternary deposits (moraines and mainly fluvio-glacial deposits) and their relative positions are likely a result of both colder climates, probably wetter than at present times, and uplift, which still persists today throughout the area.

3) Quaternary deposits and periglacial aspects in the upper Burhi Gandaki

Observations of great interest have been made in the upper Burhi Gandaki valley (Fort, 1977) :

- the present glaciation is characterized by the coexistence of Himalayan and transitional Tibetan types of glaciers and by a great variety of marginal dynamics;
- the existence of a rather large unglaciated area, where the periglacial forms and the different aspects of frost-and-snow morphodynamics enable us to distinguish active and inherited cold morphologies;
- numerous remains of older glacial stages, show the relative chronology of the late Pleistocene and Holocene events;
- travertine deposits, the development of which is greatly influenced by the environment conditions.

In particular, the most original periglacial forms are the inherited and inactive ones (Fort, 1978b). The rock glaciers and the soli(geli)-fluxion lobes are indications of a colder and wetter climate than the present one. The increasing dryness of the present climate stops the formation of such typical forms and deposits, to the nearly exclusive advantage of the thermo (cryo)clastic process.

Thus, the upper Burhi Gandaki valley can be considered as an exemplary illustration of the geomorphological and sedimentological evolution suffered during the last thousands of years by the high and northern valleys of the Himalaya. It provides good observations for further comparisons with the other parts of the Himalaya and other dry, high and continental mountains of the world.

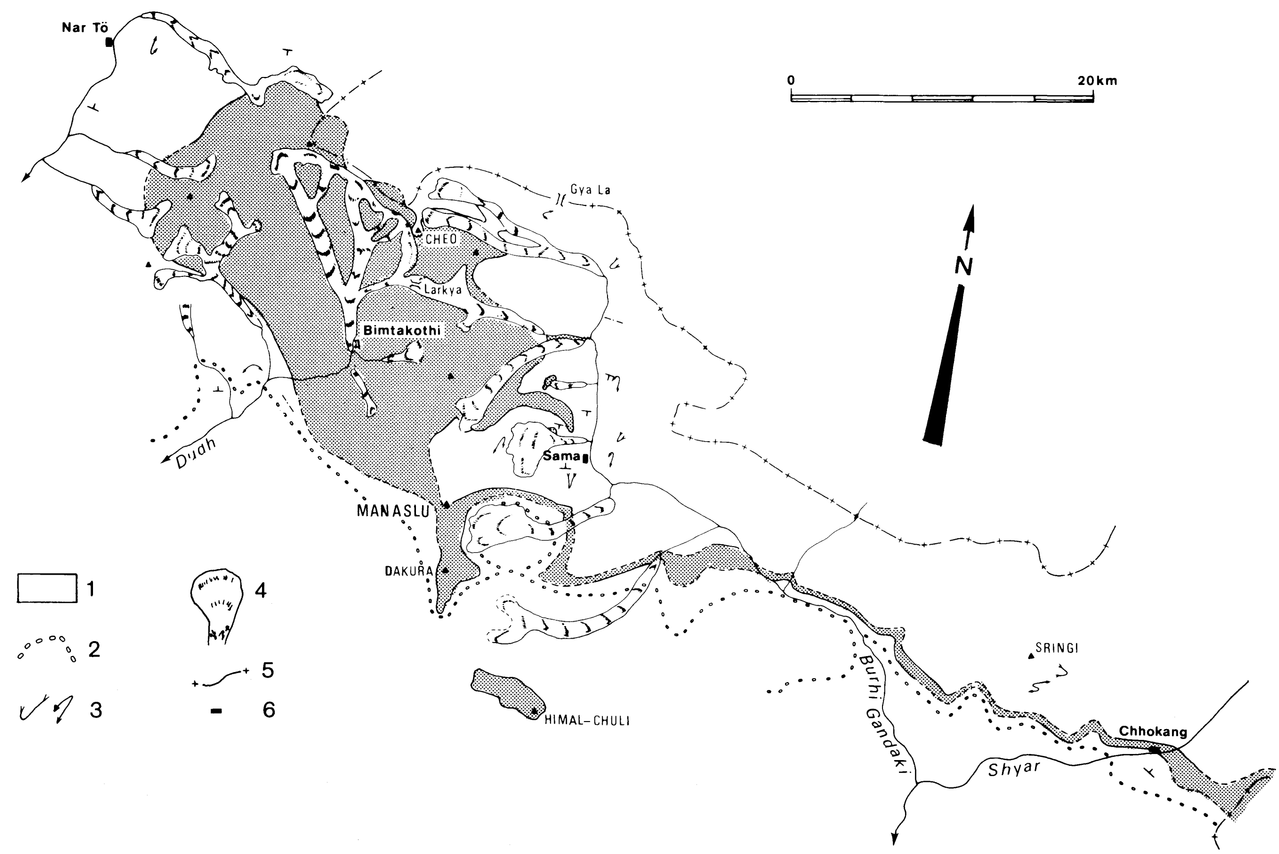

Fig. 7 - Geological sketch map of the Manaslu leucogranite (Le Fort).
(1) Manaslu leucogranite, (2) augen gneisses of the Tibetan Slab (Formation II), (3) major synclines and anticlines, (4) glaciers, (5) Nepal border, (6) main villages.

MAGMATISM. PETROLOGY AND GEOCHEMISTRY [P.L.F.]

1) The Manaslu leucogranite (Higher Himalaya)

The Higher Himalaya contains a dozen massifs of very typical leucogranites covering in all some 10.000 sq km. Difficult to reach and study, a few only have been given some attention in the past as by Misch (1949, Nanga Parbat), Bordet (1961, Makalu) and Gansser (1964, Bhutan).

In Central Nepal, a detailed study has been made of the Manaslu leucogranite. Previous results and unpublished data are summarized below.

a) Petrologic characteristics of the Manaslu leucogranite

Several preliminary reports have been published on the Manaslu granite (Le Fort, 1973, 1974b, 1975a and c). Geological mapping of the eastern part (fig.7) enables a more thorough description of this typical Higher Himalaya leucogranite. The massif covers an area of some 450 sq km in the shape of a lenticular slab, and shows three main parts :

i - *the core* is made of a very homogeneous two mica, medium grained granite, completely devoid of enclaves and thoroughly foliated. Dykes and patches of tourmaline aplopegmatites criss-cross the granite with variable abundance. The granite is composed of quartz (30 %), euhedral zoned plagioclase (33 %, rim An 3 to 8, center An 12 to 20), K feldspar (27 %, mixing of orthoclase and microcline), muscovite (8 %) sometimes associated with a little fibrolitic sillimanite, biotite (2 %), rare accessories (apatite, zircon, opaques). Table 1 gives the average chemical analysis of this very homogeneous granite.

ii - *the lower* part of the slab of granite shows an increasing abundance of the tourmaline aplopegmatites. They invade the thinly banded gneisses on which rests the slab, leaving metasedimentary enclaves of various size (micaschists and marbles). A few hundred meters thick, this part is concordant with the upper part of the Tibetan Slab. Towards *the roof* of the granite, masses of tourmaline, muscovite, amazonite and beryl-bearing pegmatites appear.

iii - the eastern part of the massif narrows abruptly, east of Manaslu, into a very long sheet some 300 m thick, concordant with the country rocks at the top of the Tibetan Slab. This *eastern "arm"* has been followed for over 50 km until

TABLE 1. Chemical analysis, mean values for 36 samples of the core and 23 samples of the Eastern sheet ("arm") of the Manaslu leucogranite (CRPG, Nancy, quantometric analysis by K. Govindaraju, wet chemistry by M. Vernet, U by C. Kosztolanyi). P.F. stands for loss of ignition.

	Core	Arm		Core	Arm
SiO_2	74.04	73.94	F(1)	1110	940
Al_2O_3	14.67	14.72	Cl(1)	15	22
$Fe_2O_3t.$	0.84	0.81	B(1)	from < 50 to 820	
MnO	0.02	0.02	Ba(2)	192	128
MgO	0.19	0.14	Co(2)	49	50
CaO	0.50	0.46	Cr(2)	<10	<10
Na_2O	4.06	4.14	Cu(2)	<10	<10
K_2O	4.49	4.48	Ni(2)	<10	<10
TiO_2	0.07	0.07	V(2)	<10	<10
P_2O_5(1)	0.14	0.13	U(3)	10.8	7.1
P.F.	0.76	0.72	Sr(2)	76	41
Total	99.78	99.63	Rb(4)	385	-

(1) wet chemistry on 10 samples of the core and 2 of the arm
(2) mass spectrometry (quantometer)
(3) wet chemistry on 7 samples of the core and 2 of the arm
(4) isotope-dilution analysis on 4 samples (Vidal, 1978)

it enters China, north of the Ganesh Himal. The granite is similar to the granite of the core (table 1) although with a more pronounced foliation. This "arm" does not exist in the west. Here a huge network of aplopegmatitic dykes with two mica or two mica and tourmaline invade the lower Tibetan sedimentary series for several kilometers beyond the granite.

The bottom of the slab of Manaslu granite shows no contact metamorphism with the surrounding country rocks of amphibolite facies regional metamorphism, other than a few occurrences of wollastonite within a few meters of the contact. However, as the Manaslu granite intrudes higher and higher levels of the Tibetan sedimentary series, a more and more pronounced contact halo appears. Near the top, where the granite intrudes the thin interbedded Upper Triassic shales, sandstones and lumachelles, the contact metamorphism has converted these rocks into staurolite garnet micaschists, muscovite quartzites and pyroxene marbles over some 50 m.

The general foliation of the granite corresponds to the main schistosity of the country rocks (S2). The granite is syn- to late metamorphic.

A few kilometers below the Manaslu lenticular slab, anatexis spreads out on a regional scale in the kyanite and sillimanite gneisses of Formation I of the Tibetan Slab. This anatectic zone is particularly well developed underneath the Manaslu granite and reduced where the granite does not appear. This zone is considered as constituting the place where the leucogranitic magma was formed, in other words the *roots* of the Manaslu leucogranite. The aplopegmatitic network between this zone and the bottom of the granite would partly correspond to the feeders of the granite.

In a general thermodynamic model of the M.C.T. (Le Fort, 1975a), anatexis and the production of close to eutectic magma is directly linked with the intracontinental subduction. Thus this granite is thought to be typical of crustal origin with no interference of activity of the mantle. Le Fort (1973, 1974b, 1975a) suggests that all the other Higher Himalaya leucogranites have similar characteristics and origin.

b) Rb-Sr isotopic geochemistry of the Manaslu leucogranite

Higher Himalaya leucogranites are syntectonic (Le Fort, 1973); they are nearly contemporaneous with the main phase of deformation and metamorphism of the Tibetan sedimentary series. Radiometric dating would thus date the main phase of the Himalayan orogeny. Two different laboratories have tried the Rb/Sr isotopic dating on Manaslu granite samples taken by Le Fort.

Hamet and Allègre (1976) published a whole rock isochron (9 points) of 28 m.y. with an initial ratio of 0,7408. A whole rock - muscovite measurement of one of the samples gave an age of 23 m.y. Vidal (Rennes) measured anew three of the same samples analyzed by Hamet and Allègre as well as four new samples. The previous isochron was not met again (Vidal in the Himalaya International Colloquium of the C.N.R.S., 1977, pp. 539-540; Vidal, 1978), and a scattering of points was found; the new muscovite - whole rock data gave an age of 16 m.y.

Although Hamet and Allègre (1978) acknowledged their faulty dating but tried to maintain their isochron, actually this isochron does not exist (fig.8). The high value of the initial Sr ratio is confirmed within the possible range of age (Eocene to Pliocene).

Several explanations have been put forward for the scattering of the points :

- non representative sampling : however the major elements geochemistry shows the homogeneity of the different samples collected by only one geologist accustomed to such problems;
- the smallness of the samples : due to the difficulties of sampling and transport, the samples barely exceed 1 kg. However an "adequate" weight is not known;
- isotopic homogeneity has not been attained during melting of the sialic parent rocks.

This last explanation seems to be the most realistic one. In fact, leucogranites quite frequently present such a scattering, as shown for the Lesser Himalayan leucogranite of Palung by

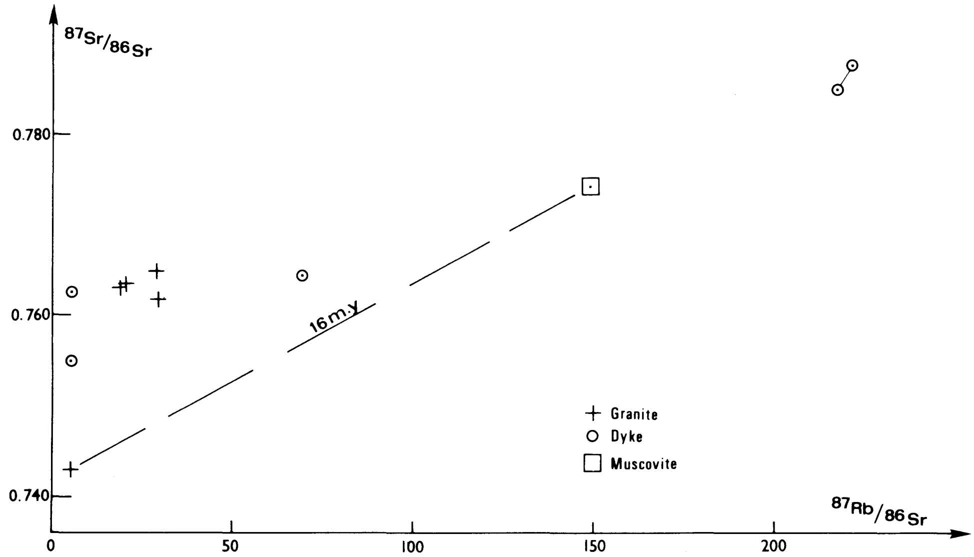

Fig. 8 - Rb-Sr diagram for the Manaslu leucogranite : samples from the core (D14, D22, D37, D65, U464, U476), the border zones (D8, D45, U303), the arm (U277) and aplitic dykes in the country rocks (B6, B7, N67). The important scattering of the whole set as within each category far exceeds analytical error.

Andrieux *et al.* (1977a). The role of intense fluid circulation remains unknown.

c) Geochemistry of Rare Earth Elements

The geochemistry of Rare Earth Elements has been studied (Cocherie, 1977 and 1978; Cocherie *et al.*, 1977) in order to evaluate of its compatibility with the proposed origin of the Higher Himalaya leucogranites through partial melting of the crustal material of the Tibetan Slab.

In this respect, seven samples of leucogranite, two of gneisses and two of anatexites from the Tibetan Slab have been analysed by radiochemical neutron activation (granites) or mass spectrometry (gneisses and anatexites).

The results for the leucogranites (fig.9) show :

- a general low REE content (10 to 25 chondrites) compared to granitic rocks;
- a regular enrichment of the light REE against the heavy REE (La/Yb > 10), in other words a regular fractionation from La to Lu;
- a conspicuous negative anomaly in Eu;
- a REE content even lower than that of the gneisses and anatexites from which they would have originated.

This last point raises a problem, as in partial melting, the incompatible elements (the light REE and to a lesser degree the heavy REE) should concentrate in the melt. However to produce granite melts with the observed REE pattern, one would need a parent gneiss with very low REE content. Such gneisses are not known. In explanation, Cocherie (1978) suggests either that these elements may not have an incompatible behaviour and/or that the fluid phases that were certainly very abundant may have driven out the REE by forming carbonate complexes.

A satisfactory explanation has not yet been reached, though the same problems appear to characterize all the leucogranites (Cocherie, 1978).

2) The Midland augen gneiss and Lesser Himalayan granites

a) Midland augen gneiss (Ulleri formation) (Le Fort & Pêcher, 1974; Le Fort, 1975a; Pêcher & Le Fort, 1977; Pêcher, 1978).

Characteristic horizons of feldspathic augen gneiss have been recognized and mapped within the Midland Nepal formations (fig.10). They appear at the same lithostratigraphic level, towards the top of the Lower Midland group, with a highly variable thickness ranging from zero to 1500 m in the region of Ulleri; they constitute the *Ulleri formation* of which the main characteristics can be summarized as follows :

- lithostratigraphic control;
- tectonic and metamorphic characters similar to those of the surrounding rocks;
- intercalations of schists and quartzites similar to those of the surrounding rocks;
- transitional contacts when visible;
- lateral variations with conglomeratic beds in the same lithostratigraphic position;
- heterogeneity of the augen gneisses;
- variability of the alkaline ratio;
- occurrence of bluish rounded quartz;
- presence in their vicinity of metamorphosed tholeiïtic volcanics (amphibolites), (Lasserre, 1977).

These field and geochemical characteristics all fit in well with a felsic volcano-sedimentary origin, with subordinate mafic layers.

No fossil or radiometric dating evidence is available to assert the age of the Ulleri formation. However, it took part in the Himalayan oro-

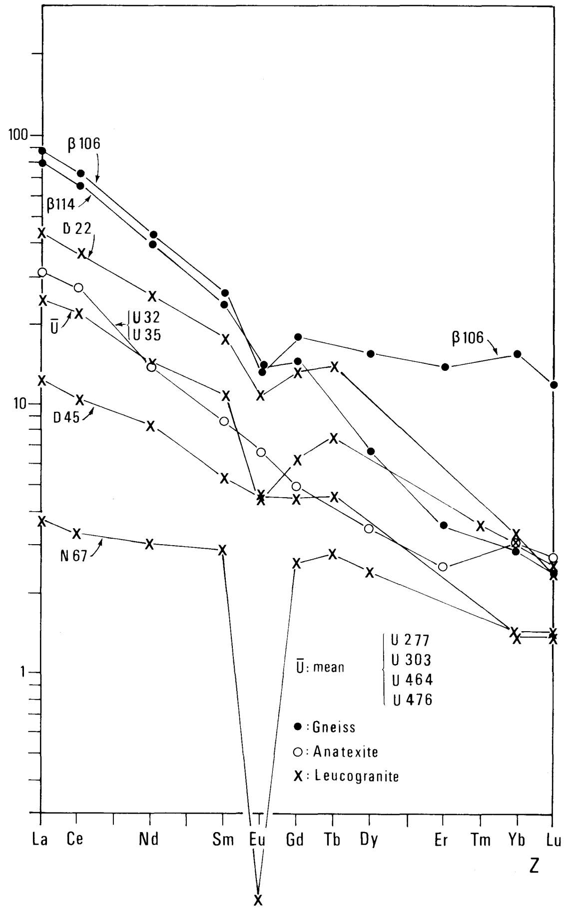

Fig. 9 - Chondrite normalized rare-earth patterns (logarithmic) for the Manaslu leucogranite, two samples of anatexites and two samples of non migmatized schists from Formation I of the Tibetan Slab (Cocherie, 1978, fig. 11).

geny (K/Ar ages on minerals) and a Lower, or Middle, Palaeozoic age is suggested.

Similar augen gneisses occur widely in the Himalaya, always in the same lithostratigraphic context, although they have been described under various names as a result of the different hypotheses concerning their origin.

The wide occurrence of this volcano-sedimentary episode leads to several important geodynamic implications :

- it should eliminate a certain number of tectonic nappes and injected scales which were inferred when the augen gneiss were supposed to be part of an old crystalline basement;
- it eliminates the need of a Palaeozoic orogeny, as claimed by several workers, on the basis of pre-Himalayan granites and radiometric dating;
- it implies a peculiar pre-Himalayan geodynamic pattern, little of which is known at present.

b) Lesser Himalayan granites (Le Fort, Debon & Stebbins, 1978)

In the south of Nepal, eight to ten granite massifs form the core of the Mahabharat range. Poorly studied, they recently have been partly mapped by Stöcklin *et al.* (1977) and one of them was sampled for Rb/Sr dating (Andrieux *et al.*, 1977a). Debon and Le Fort started their field study in 1977 on four of them, south of Kathmandu and only preliminary results have been published (Le Fort *et al.*, 1978).

They can be described as follows :

- the elongated massifs show sharp contacts; generally structurally concordant with the country rocks, which are regionally metamorphosed micaschists with two micas and garnet. Hardly any contact metamorphism is visible. The concordant foliation increases near their boundary. In certain cases, this foliation is a metamorphic one, supporting a two mica-garnet paragenesis;
- the granite is in general a porphyritic monzogranite of medium grain, with two micas and *cordierite* (altered). Varieties with varyingly abundant tourmaline, are associated with it. Garnet and andalusite may occur. Chemical analyses of the two mica-cordierite monzogranite show its hypofeldspathic, hypo-alcaline (hyposodic) aluminous and relatively quartz-rich character;
- in addition to the metasedimentary enclaves, these granites contain numerous closely spaced microgranular mafic enclaves, that are more common in granodiorites than in granites;
- they always intrude the formations of the M.C.T. overthrust just north of the M.B.T. (cf. Mahabharat nappe of Brunel, 1976), and remain as elongated klippes. They were emplaced before overthrusting took place and no trace of feeders is visible beneath the klippes in the Midland formations. They were followed, not only in Nepal, but also along two thirds of the Himalaya (1600 km from 73 to 87° E) and with the same characteristics.

The fact that the Lesser Himalayan granites have very similar petrological and geochemical characteristics, and a very constant structural position along most of the entire length of the Himalaya, speak in favour of their major geodynamic significance.

Highly foliated and transformed to orthogneiss near their contacts, and at their ends (the "Outer Band" of the Dalhousie granite; Mac Mahon, 1882) they were tectonized and metamorphosed during their Himalayan nappe transport.

3) Geochemistry of amphibolites and alkaline gneisses from the Midland formations of Nepal (J.L. Lasserre, 1977)

Amphibolites occur at several levels in the Midland formations of Nepal. They are mainly developed in the upper part of these formations, where four main horizons have been studied (Lasserre, 1977). Their mineralogy is constant : actinolite, quartz, biotite, clinozoisite, albite, ilmenite, apatite and sphene. Results of chemical analysis (17 elements) of some fifty samples form a fairly homogeneous group showing that they have been derived from more or less differentiated tholeiitic basalts, of island-arc tholeiite type. Spilitisation does not seem to occur.

Lasserre also suggests that a part of the Midland formations, including the Ulleri augen gneisses (Le Fort & Pêcher, 1974; Pêcher & Le Fort, 1977), are result of associated felsic and mafic volcanism, that could be the consequence of the interaction of an old island-arc with a continental margin.

Independently, a massif of nepheline syenite and alkaline gneisses has been discovered for the first time in the Himalaya, at Ampipal, north of Gorkha (Lasserre, Pêcher & Le Fort, 1976). Of moderate extension (8 x 2 km) (fig.3), this massif comports miaskitic nepheline syenites cut by a few mafic and ultramafic alkaline dykes (melteigite, jacupirangite), both more or less foliated. Chemical analyses (19 elements) show that these rocks are of igneous origin and that they are probably a result of fractional crystallization of an initial olivine alkaline basalt magma. Lasserre (1977) also related their genesis to the rifting of the Indian continent at the time of the Himalayan collision. However, Rb/Sr dating (Le Fort & Sonet unpublished) seems to give a much older age to these rocks.

CONCLUSION [M.C., P.L.F.]

This paper has summarized facts of geodynamic significance observed by our team. In conclusion, we would give the main ten successive steps of the geodynamic evolution of the Himalaya (see also Le Fort, 1971a, 1975a; Bassoullet *et al.*, 1977) :

1 - Upper Precambrian to Devonian : epicontinental sedimentation in the Higher (and Lesser ?) Himalaya. Widespread felsic volcanic activity in the Lesser Himalaya;

2 - Carboniferous to Permian : epicontinental sedimentation, basaltic volcanism and epirogenesis throughout the Himalaya; overlap of Gondwan and Tethyan realms;

3 - Triassic to Middle Jurassic (Dogger) : platform sedimentation in the (Lesser and) Higher Himalaya; fragmentation of the Northern "edge" of the Indian craton, oceanization : opening of the Tethys Ocean (within Gondwana ?);

4 - Upper Jurassic (Malm) to Neocomian : platform sedimentation in the Higher Himalaya, northward subduction of oceanic crust with possible birth of an island arc, first emplacement of ophiolitic nappes towards the south;

5 - Aptian to Upper Cretaceous : mafic volcanism and platform sedimentation at the beginning in the Higher Himalaya, subduction continues, deposition of the Indus molasse following the erosion of the first Transhimalayan reliefs;

6 - Eocene : important slowing of the spreading rate of the Indian ocean, marine transgression, closure of the oceanic crust and collision of Indian and Eurasian plates, second emplacement of ophiolitic nappes towards the south;

7 - Oligocene : no marine deposit, M.C.T. starts functioning as a intracontinental zone of subduction, the first Himalayan reliefs rise;

8 - Miocene : metamorphism (normal and reverse) and deformation linked to the M.C.T. reach their maximum, emplacement of the Higher Himalaya leucogranites, erosion of the Himalayan range and consequent sedimentation in the Siwalik basin;

9 - Pliocene : movement on M.C.T. stops and is relayed by M.B.T., sedimentation continues in Siwaliks and starts in intramontane basins;

10 - Pleistocene : M.B.T. continues and overthrusts the Siwaliks, erosion fills the Ganga Basin, widespread epirogenic movements.

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