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THE CONTACT BETWEEN THE HIGHER HIMALAYA CRYSTALLINES AND THE TIBETAN SEDIMENTARY SERIES: MIOCENE LARGE-SCALE DEXTRAL SHEARING

Arnaud Pêcher

Laboratoire de Géologie Alpine, Centre National de la
Recherche Scientifique, Institut Dolomieu,
Grenoble, France

Abstract. Space and time evolution of the synmetamorphic structures across the metamorphic pile have been studied in several areas along the Himalayan belt (east and central Nepal, Garhwal, Zanskar). From one area to the other the evolution is very similar: (1) At the base of the pile, in the Main Central Thrust (MCT) shear zone, the stretching lineation, penetrative and regularly oriented N0°E to N30°E, indicates the MCT transport direction, very constant all along the belt, from the Eohimalayan main metamorphic development up to the late-metamorphic movements. (2) At the top of the pile, at the contact between the crystalline unit and its sedimentary cover, gravity-driven structures are confirmed (north-vergent folds, ductile normal faulting). However, there are numerous local indications of late Miocene (syn- to late emplacement of the leucogranitic plutons) dextral shearing. (3) In between, across the medium part of the pile, the stretching lineation shows a conspicuous progressive regional clockwise rotation, clearly indicated by the strain trajectories mapped in Nepal and Garhwal. Points 1 and 2 show that the crystalline-sedimentary boundary, despite its apparent structural and metamorphic continuity, is not only a normal fault but also an important dextral shear zone, which has acted since the upper Miocene as the main southern limit of the eastward extruding Tibetan block.

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INTRODUCTION

After the continental collision between the Indian and Tibetan plates during the Eocene the large crustal shortening (today evaluated at about 3000 km [Besse and Courtillot, 1988 and references there in]) caused by convergence was asymmetrically taken up in the Asian block and in the Indian indenter. The larger amount of shortening (more than 2000 km [Achache et al., 1984]) results in the near doubling of the thickness of the Tibetan crust, which is presently around 70 km [Hirn et al., 1984a, 1984b; Molnar, 1988], but this shortening also took place through sideways extrusion of Tibet [Tapponnier et al., 1982, 1986].

Another part of the shortening, of the order of 1000 km according to palaeomagnetic data [Besse et al., 1984], occurred on the Indian side and was mainly absorbed by the stacking of the Indian crust in several slices, bounded by major thrusts. It led to the formation of the Himalayan chain (a "crustal stacking wedge" [Mattauer, 1986]), made up of parallel tectonometamorphic units, with a younging of ages from the Tibet-India collision zone lying to the north to the nonaffected peninsular India to the south.

The present geometry of the Himalaya reveals several broad units which can be regularly followed all along the belt. The Higher Himalaya Crystallines unit (also named in central Nepal the "Tibetan Slab"), which forms the backbone of the Greater Himalaya, is made up of a 5 to 12 km thick pile of migmatitic gneisses. It displays a polymetamorphic evolution, predominantly related to the Tertiary Himalayan story, with possible pre-Himalayan remnants [Baig and Lawrence, 1987; Pognante and Lombardo, 1989].

This unit is overthrusted on the Lesser Himalayan crystalline nappes along a very large Miocene thrust, usually known in a somewhat confusing way as the Main Central Thrust (MCT), or as the Vaikrita Thrust [Valdiya, 1980] in Kumaun (where the MCT was first defined by Heim and Gansser [1939], but at the base of the Lesser Himalayan nappes). The Higher Himalayan gneisses are overlain to the north, up to the suture zone (the ophiolite-bearing India-Tibet collision zone), by the folded sediments of the Indian Tethyan margin, forming a continuous Cambrian to early Eocene series which is about 15 km thick.

The geometry and kinematics of the various Himalayan thrusts are now well documented. The most important of them is the MCT/Vaikrita thrust, which is actually a several kilometer thick shearzone, affecting most of the Lesser Himalaya crystalline pile as well as the basal part of the Tibetan Slab. The shearing is responsible for the very characteristic tectonic pattern of this zone [Mattauer, 1975; Pêcher, 1977]: a "flat" cleavage, and a very remarkable penetrative stretching lineation, always oriented roughly NNE-SSW, which can been considered as the main transport (i.e., shortening) direction [Pêcher, 1977; Brunel, 1986]. The MCT/Vaikrita thrust seems also responsible for the particular "reverse" metamorphic pattern observed in the Lesser Himalaya crystallines [Le Fort, 1975], below the thrust.

Higher, in the uppermost part of the Higher Himalaya gneisses and in the basal (or southern) part of their sedimentary cover, the metamorphism decreases very abruptly, and the stretching and mineral lineations become more dispersed and tend to be parallel to the strike of the belt.

A conformable boundary between the Tethyan sediments and the underlying crystallines is usually accepted. It is supported by the apparent structural and metamorphic continuity from the gneisses to the sedimentary series: the axial slaty cleavage of the isoclinal folds visible at all scales in the sediments can be traced in the metamorphic cleavage of the gneisses, and there is no hiatus in the metamorphic isograd succession.

Despite this continuity, recent studies accept this contact as a tectonic one. According to Valdiya [1987, 1988] it could be a large thrust, the Trans-Himari thrust, running all along the belt from Zanskar to Sikkim. Actually, other studies support the existence of extensional tectonics (but they do not preclude the possible reactivation of a former thrust contact) in northeast Nepal [Burg et al., 1984; Burg and Chen, 1984; Burchfield and Royden, 1985], in central Nepal, where the major north-vergent Annapurna fold [Colchen et al., 1986] has been interpreted as a gravity collapse structure [Caby et al., 1983], in Kumaun (Martoli fault [Shah and Sinha, 1974]; Trans-Himadri thrust reinterpreted as a normal

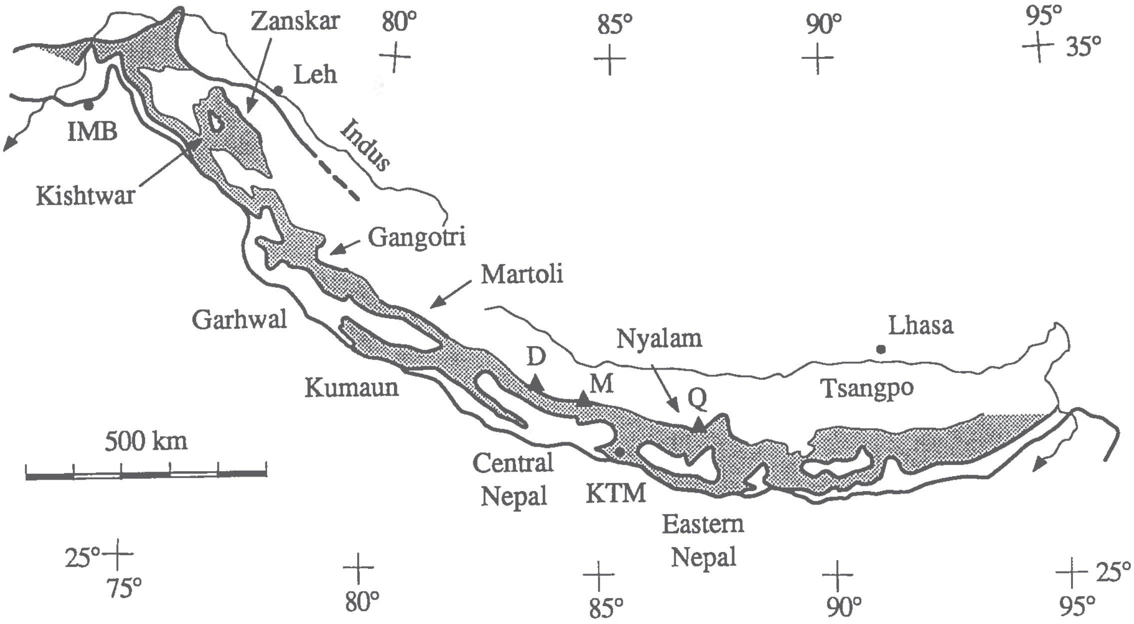


Fig. 1. Sketch map of the Higher Himalayas. The southern limit corresponds to the Main Boundary The Higher Himalayas Crystallines unit (patterned area)is bounded to the south by the Main Central Thrust and to the north by the North Himalayan normal fault (underlined where recognized in the field). Abbreviations are D, Dhaulagiri; IMB, Islamabad; KTM, Kathmandu; M, Manaslu; and Q, Qomolungma (Mount Everest).

fault [Valdiya, 1989]), in Garhwal [Pêcher and Scaillet, 1989], and, finally, in Zanskar [Herren, 1987], where it is probably the best expressed.

Ductile normal faulting can nicely explain the abrupt but continuous metamorphic decrease in between the gneisses and the sediments, as shown by Herren [1987]. But it does not account for the along-strike orientation of the lineations. In the following (Figure 1), emphasis will be put on those longitudinal structures, still much less documented than the normal "faulting" structures. Their interpretation will be supported mainly by strain trajectories maps, as given by Brun et al. [1985] for the south Tibet Nyalam section, or established from personal data (A. Pêcher, 1972 to 1989) in Nepal and Garhwal (central Himalaya) and Zanskar (western Himalaya), and completed by published structural data [Gapais et al., 1984; Herren, 1987; Brunel, 1986 and references there in](but, unfortunately, although many data on the cleavage and fold axis orientations are available, only little attention has been paid to the lineation behavior).

STRUCTURES OF THE GREATER HIMALAYA IN CENTRAL NEPAL

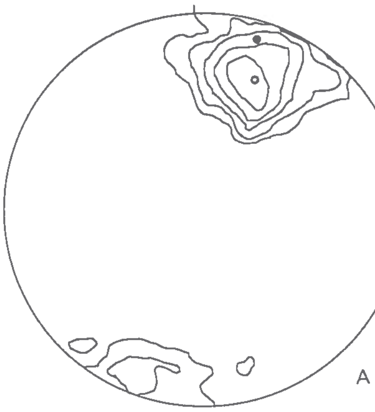
In Central Nepal the Higher Metamorphic Crystalline unit is made of a thick pile of migmatitic gneisses. Its apparent thickness varies longitudinally, from 5 km in the Annapurna section to more than 12 km in the Manaslu section, 100 km to the east. The main metamorphic imprint [Pêcher, 1977, 1989; Caby et al., 1983], corresponding to the major metamorphic foliation Sm, is characterized by kyanite (+ pyrope-rich garnet ± staurolite ± zoisite)-bearing migmatites (Barrovian-type "Eohimalayan" metamorphism). At the base of the pile the main foliation is overprinted by a strong C-S fabric, related to the MCT shearing. It was achieved either in the same high-temperature conditions (this is the case where the pile is thick, in the Manaslu section) or can be accompanied by a lower temperature retrogression (where the pile is thin, i.e. closer to the front of the thrust, in the Annapurna section).

At the top of the pile the main Barrovian metamorphism is overprinted by a low-pressure—high-temperature paragenesis. This second metamorphic episode (late Himalayan metamorphism) is especially well marked when the pile is thick, in the Manaslu section as well as eastward in Nepal, in the Everest area [Brunel and Kienast, 1986]. It is clearly evidenced by the retrogression of kyanite to sillimanite, the sporadic overgrowth of cordierite, and the accentuation of the migmatization. It is Miocene in age [Deniel et al., 1987] and synchronous to the Manaslu-type leucogranites emplacement in the base of the overlying Tethyan sediments.

All across the metamorphic pile the planar and linear fabric is penetrative but does not correspond everywhere to equivalent and synchronous markers:

1. In the lowermost part of the pile, close to the MCT, the MCT-related structures continue the structures observed below the thrust, in the Lesser Himalaya nappes [Pêcher, 1977; Bouchez and Pêcher, 1981]. The planar fabric is predominantly marked by the C planes of the C-S almonds. The C-S asymmetry always indicates the same sense of rotation, i.e.,the top moving southward. The linear fabric is very penetrative, as below the MCT In places it is clearly underlined by the breaking and stretching of earlier minerals such as kyanite, or by elongated pressure shadows, and then actually marks the elongation direction (LX); more often it is a mineralogical lineation (Lm), that is marked by the linear pattern of the minerals or mineral agregates. Those two lineations, Lm and LX, are always parallel and have been grouped together in the following. Their orientation, which is very constant, is typically around 20°E (Figure 2). Those orientations correspond to the main elongation direction of the finite strain ellipsoid resulting from the MCT shearing and thus can be used as the MCT transport direction markers [Pêcher, 1977; Colchen et al., 1986a; Brunel, 1986].
2. The typical shear fabric progressively fades out about 1 km above the MCT In the medium part of the pile the main planar fabric corresponds to the Eohimalayan metamorphic foliation. The stretching lineation is often more fuzzy, partly erased by late static recrystallization. Its direction first remains NNE-SSW (N10°E to N30°E), then becomes more NE-SW (N40°E to N70°E) (Figure 2), and the rotation criteria (asymmetric pressure shadows, sigmoidal inclusions, small drag folds) still indicate the same sense of shearing, i.e., top towards the south (or southwest). Thus the early metamorphic development also corresponds to a MCT-type rotational deformation, which has been probably acquired in the first steps of the crustal shearing and stacking.
3. In the upper part of the pile the southward shearing fabric almost vanishes. There are no more clear microstructural indications of shearing during the Barrovian metamorphic stage; only flattening is clearly evident, and the mineralogic/stretching lineation, often hardly visible, is then roughly E-W (N80°E to N110°E).

A new fabric is sometimes overprinted on the main foliation during the high temperature retrogression: in the Manaslu area, in the upper part of the pile (typically the sillimanite-bearing zone), the foliation is often intersected by metric shear zones, plastered with fibrous sillimanite (Figure 3). Those shears are oriented E-W and dip more steeply towards the north (45° to vertical) than the foliation of the gneisses. The sense and direction of movement, clearly marked by the sillimanite fibers and the local inflexion of the foliation, always indicate a clockwise rotation (displacement of the northern part towards the east), with often a normal fault component.



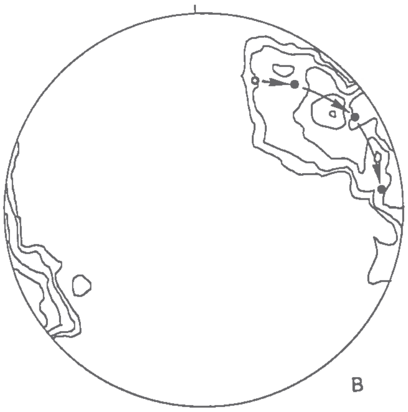


Fig. 2. Evolution of the lineation orientation in the Burhi Gandaki valley (located east of Gorka and Manaslu, see Figure 4). Equal-area projection, lower hemisphere. (a) Below the Main Central Thrust, in the Lesser Himalaya: 158 measurements, contour lines 1, 3, 5, 10, and 15 times the uniform distribution; the solid dot corresponds to the calculated best pole for the Upper Midland Formations, close to the Main Central Thrust (azimuth N24°E, dip N30°), the open dot to the best pole for the underlying Lower Midland Formations (N20°E, N11°) . (b) Above the Main Central Thrust, in the Higher Himalaya: 128 measurements, contour lines 1.5, 2.5, 4.5, and 6.5 times the uniform distribution; the open dot is the same as in Figure 2a; the solid dots account for the best poles calculated on measurements of the lower (N38°E, N23°), medium (N61°E, E12°), and uppermost (N86°E, E11°) parts respectively of the Higher Himalaya Crystallines unit and show the progressive dextral rotation of the line.

In the Burhi Gandaki section, east of the Manaslu granite [Pêcher and Bouchez, 1987], the sillimanite-bearing shears get more and more numerous near the top of the gneisses. In the last few hundred meters the old foliation is completely transposed by a new C-S fabric. It is particularly spectacular in the sills of Cambrian metagranite [Le Fort et al., 1986] intrusives in the uppermost part of the pile (Figure 3). The same shear zone, with its C-S almonds, can also be traced in the "Chokkang arm", a thin leucogranitic sill extending towards the east of the Manaslu pluton. In the less deformed zone of the sill, early tourmaline can be observed , already E-W stretched.

Thus in that section the contact between the Higher Himalaya Crystallines unit and its sedimentary cover corresponds to an important dextral shear, which occurred at the end of the emplacement of the Manaslu granite but before the temperature decrease.

West of the Manaslu granite, in the Marsyandi section, dextral shearing also exists, but is less concentrated at the gneiss-sediments boundary. Numerous sillimanite-bearing shear zones one to few tens of meters wide are observed at different levels in all the upper half of the pile (its upper 5 km), the sense of shear being clearly indicated by the deviation of the lineation trajectories: there is clearly a clockwise rotation from NE-SW in between the shears to an E-W direction where shearing is maximum.

Further west, in the Annapurna and Dhaulagiri section, where the gneissic pile is now less than 5 km thick, the late high temperature metamorphic overprint is much more tenuous, and sillimanite is scarce or absent. Here, well-defined local shear zones have been observed in place only in the upper sills of Cambrian granite. Nevertheless, there is also a progressive clockwise rotation of the stretching lineation, N20°E close to the MCT, then N70°E in the middle part of the pile, and finally E-W in its upper part, at the contact with the Sedimentary Series (Figure 4).

STRUCTURE OF THE GREATER HIMALAYA IN SOUTH TIBET (NYALAM SECTION)

The Nyalam section, along the Lhasa-Kathmandu road, about 200 km east of the previous area, is the easternmost section for which detailed structural data are available [Burg et al., 1984; Brun et al., 1985].

The Higher Himalaya Crystallines unit consists here, as in central Nepal, of a pile of various gneisses and migmatites, about 10 km thick. Metamorphism is still characterized by Barrovian assemblages in the base of the pile (kyanite+ garnet ± staurolite ± sillimanite), and low-pressure type assemblages (K feldspar + sillimanite ± cordierite) in its upper part. The pile is separated into several slices by mylonitic zones, in which the lineation trend is E-W. In these zones, noncoaxial deformation criteria indicate westward shearing. Nevertheless, it can be noticed that the stretching lineations draw a clockwise rotation in between the mylonitic zones [Brun et al., 1985, Figure 2].

A few hundred meters above the top of the Higher Himalaya metamorphic crystallines the base of the Tethyan sedimentaries is intruded by several Miocene Manaslu-type leucogranitic lenses, which are affected

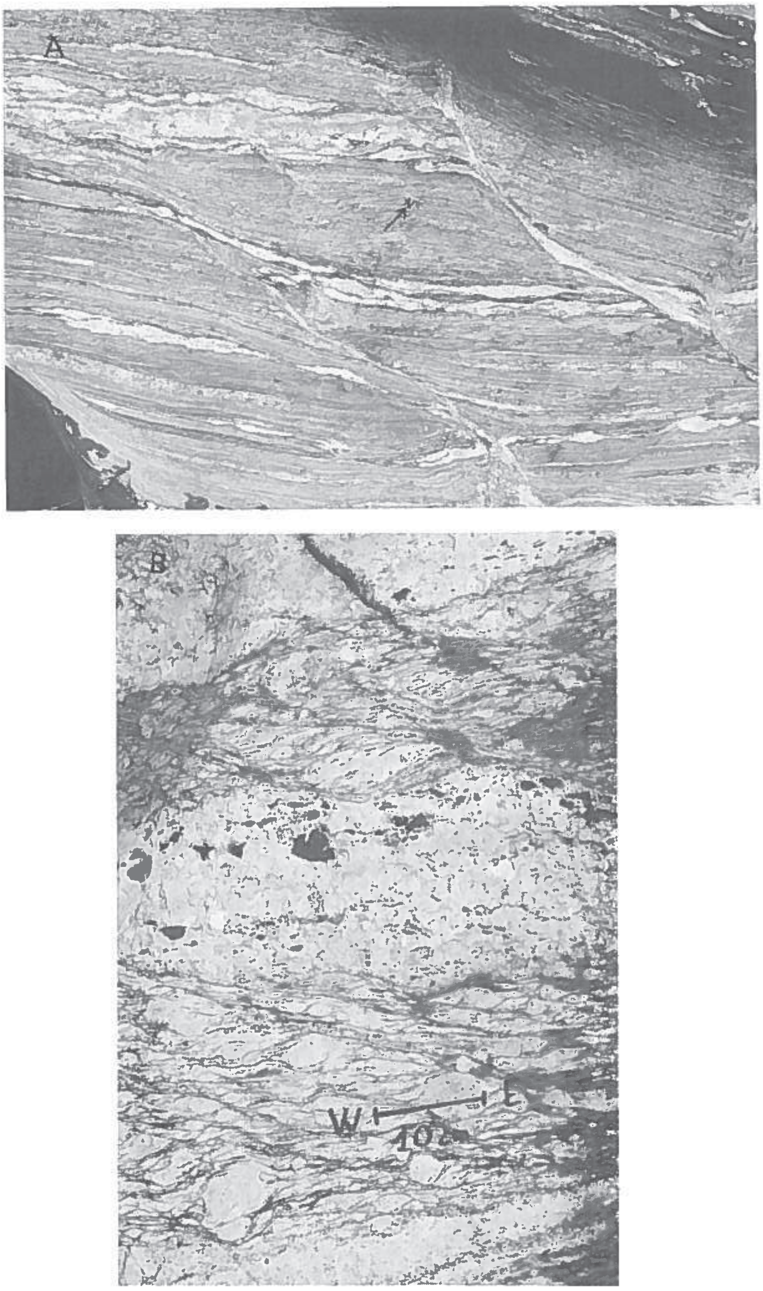


Fig. 3. Dextral shear zones observed in the field. (a) Local shear, plastered with sillimanite, observed in the medium part of the Tibetan Slab, Burhi Gandaki valley, east of the Manaslu (see Figure 4). (b) C-S structure indicating more penetrative shearing in the ≈ 500 Ma old metagranites (orthogneisses) and in the Miocene tourmaline-rich leucogranitic lenses of the "Chokkang arm", uppermost levels of the Higher Himalayas Crystallines unit, east of the Manaslu granite.

by a strong planar and linear (N20°E to N50°E) fabric. The microstructures (penetrative C-S structures, lattice preferred orientation of quartz) [Burg et al., 1984] indicate that the fabric results from progressive shearing during and after the emplacement of the granites, corresponding to normal plus dextral shearing (the stretching lineation pitch related to the shear foliation, estimated from the published data [Burg et al., 1984], appears to be approximately 45° towards the east).

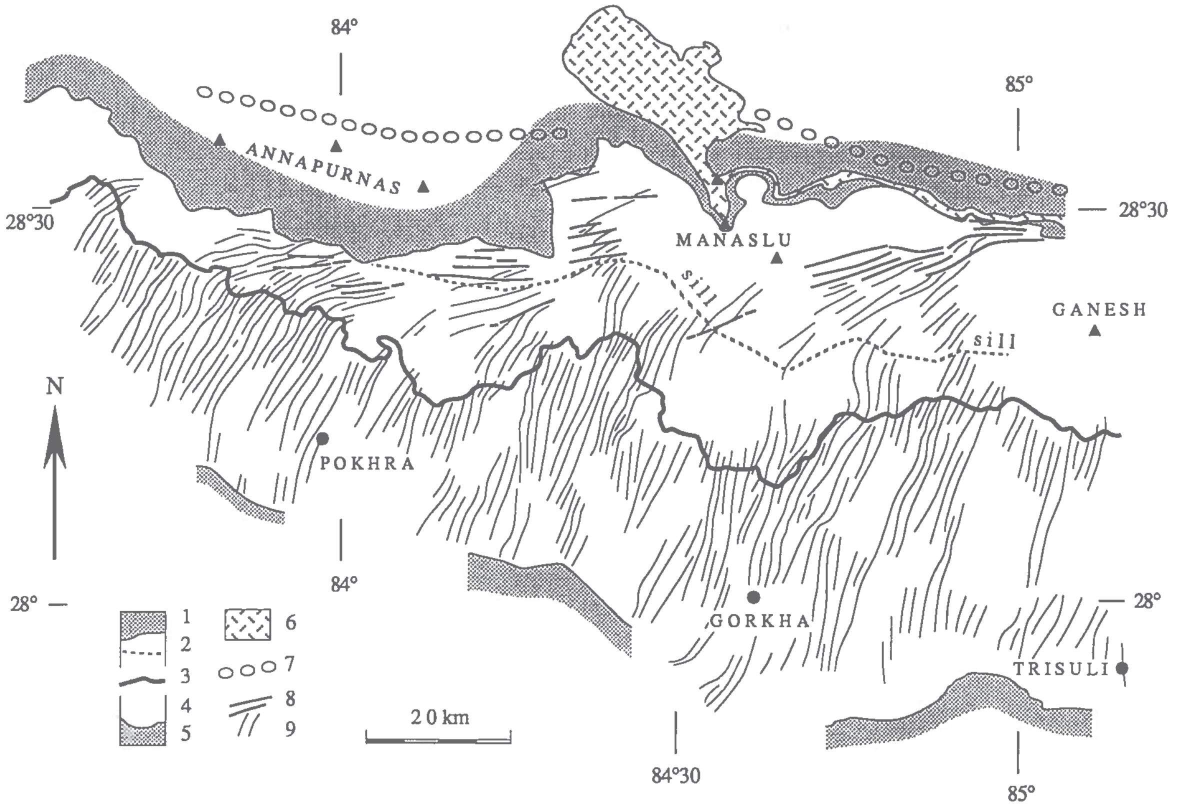


Fig. 4. Stretching lineation trajectories in Central Nepal (P. Le Fort and A. Pêcher unpublished data, 1972-1989, more than 2000 measurements). Legend numbers are 1, Sedimentary cover; 2, Higher Himalaya Crystallines unit and sillimanite isograd; 3, Main Central Thrust; 4, Midland Formations; 5, Sedimentary Series of the Southern Himalaya; 6, Miocene Manaslu leucogranite and its eastern prolongation, the "Chokkang arm"; 7, axial trace of the north-vergent Annapurna fold; 8, lineation in the sillimanite-bearing shears; and 9, Eohimalayan and Main Central Thrust-related lineation.

STRUCTURES OF THE GREATER HIMALAYA IN GARHWAL

In Garhwal, in the Bhagirati and Bhillangana river sections [Pêcher and Scaillet, 1989], the Higher Himalayan gneiss pile is also about 10 km thick. Its lithology and metamorphic story are similar to those in Nepal, but the sillimanite is only present in the uppermost levels.

Just below the MCT (the Vaikrita thrust) the first crystalline unit of the Lesser Himalaya (Munsiari zone) is mainly made of amphibolite and Precambrian [Bhanot et al., 1980] porphyritic granites. In that material the MCT shear fabric is spectacularly expressed by C-S structures and the stretching lineation, particularly penetrative in the metagranites. Its orientation is still approximately N20°E.

Above the MCT, at the base of the Higher Himalayan gneisses, the MCT shear zone corresponds to a 2 km thick band of phyllonites: they are garnet-green biotite retrogressed schists, which mark late (postmain Barrovian metamorphism and postcooling) movements of the thrust. In that band the transport direction is roughly the same as lower down (N20°E to N45°E).

Above the phyllonitic zone, in the gneisses, the stretching direction is no longer parallel to the transport direction of the Himalayan thrusts. As in Nepal, a progressive clockwise rotation is observed (Figure 5) and in the upper gneissic levels as well as in the base of the sedimentary cover the stretching lineation is oriented parallel to the belt, N90°E to N110°E. In this zone the finite strain ellipsoid is actually of flattening type, as indicated by boudinage on all scales. Two types of pinch and swell structures are observed. The first type is asymmetric E-W elongated boudins, often associated with asymetric north-vergent folds; together they mark the northward collapse of the top of the pile (the Sedimentary Series), a phenomenon equivalent to that of the ductile normal fault observed elsewhere in the

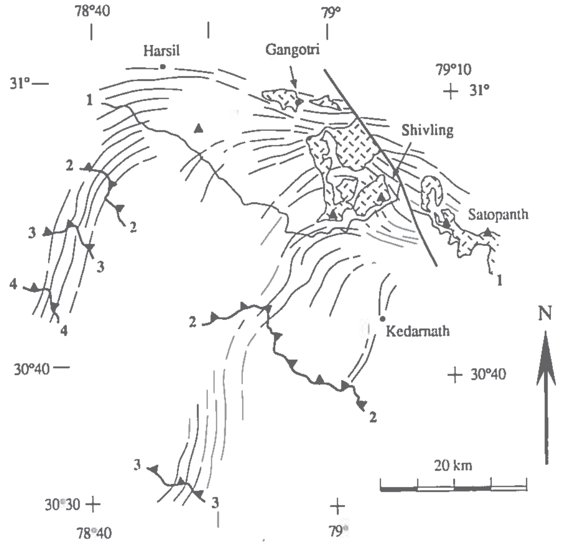


Fig. 5. Stretching lineation trajectories (continuous lines) in Garhwal Himalaya (adapted from Pêcher and Scaillet [1989]). Main geological and structural limits: 1, Upper boundary of the Higher Himalaya Crystallines unit; 2, Main Central Thrust/Vaikrita thrust; 3, thrust separating the Munsiari and Ramgarh Formations in Lesser Himalaya; and 4, Main Central Thrust as defined by Heim and Gansser [1939]. The patterned area corresponds to the Gangotri leucogranite.

Himalaya. The second type of structure observed is N-S elongated boudins, which emphasize the along-strike E-W elongation.

The Himalayan Gangotri tourmaline-bearing leucogranite is emplaced like the Manaslu granite in the base of the sedimentary cover. It is separated into several kilometer-size lenses, actually producing a spectacular "en tablettes de chocolat" pattern [Pêcher and Scaillet, 1989; Scaillet et al., 1989], due to predominant flattening during or just after the granite emplacement. The internal petrographic fabric (magmatic fluidal lineation) and magnetic fabric (magnetic susceptibility anisotropy) of the granitic lenses [Scaillet et al., 1989], although rather fuzzy, display a preferential E-W elongation, showing that the extension parallel to the belt was already initiated at the time of the granitic pluton emplacement.

STRUCTURES OF THE GREATER HIMALAYA IN ZANSKAR-LADAKH

The structural and metamorphic pattern of the Zanskar Higher Himalayan Crystalline unit has been extensively studied in recent years [Honegger et al., 1982; Gapais et al., 1984; Searle, 1986; Herren, 1987; Kundig, 1989; Searle and Rex, 1989; Staübli, 1989], and will be only briefly reported here, supplemented by unpublished data [Brouand and Pêcher, 1983].

In Zanskar the Higher Himalaya Crystallines consist of a very thick (nearly 20 km) sequence of polymetamorphic migmatitic gneisses, widely intruded by granitoid intrusions, approximately 500 Ma in age [Frank et al., 1977; Honnegger et al., 1982]. As in Central Himalaya, two main episodes of metamorphism can be distinguished: an Eohimalayan Barrovian episode, with possibly some remnents of a pre-Himalayan story [Pognante and Lombardo, 1989], overprinted by a general-low pressure—high-temperature episode, marked by Kfeldspar + sillimanite and incipient migmatization. This second episode postdates the formation of nappes and large-scale folds in the Tethyan cover [Honegger et al., 1982] and is related to the MCT thrusting event by Searle and Rex [1989].

The basal contact of the crystallines has not been observed at the front of the MCT thrust, which in this section is more or less confused with the Main Boundary Thrust (MBT), but in the Kishtwar window. Here one can see the same tectono-metamorphic pattern as everywhere else along the MCT: a reverse metamorphic zonation, with closely spaced isograds in the underlying Lesser Himalaya series [Staübli, 1989], and the typical MCT shear zone C-S and LX fabrics. The stretching lineation is still oriented N-S to N20°E (Figure 6), i.e., it conforms to the average Himalayan convergence direction, and is no longer perpendicular to the belt (western Himalaya is oriented NW-SE).

Above the MCT, up to the top of the crystallines, the tectonic pattern is more complicated than in central Himalaya. In place of the regularly northward dipping pile, investigations of Honnegger et al. [1982] and Kündig [1989] reveal complex domal structures, well marked by the metamorphic foliation trajectories. Incomplete investigations with M. Brouand [1983] around the Cishoti dome (about 20 km North of Atholi) would indicate a radial pattern around the domes (reorientation of the lineation, or overprinting by a new one, during the doming?).

The contact between the Higher Himalayan Crystalline and the base of the overlying Sedimentary Series (the Cambrian Phe formation) has been studied in detail by Herren [1987] in the Zanskar valley, from Rangdom to Padum, for about 100 km from NW to SE. It appears as a 2 to 7 km thick shear zone, dipping 45° towards the NE. The microstructural criteria (C-S almonds, rotated minerals) clearly indicate a normal shearing (normal fault). The transport direction, marked by the stretching lineation, varies from 40°E to 70°E [Herren, 1987; A. Pêcher, unpublished data, 1983]. As the shear zone dips more steeply than the isograds, those are stacked together, and, consequently, there is an apparent very sharp but continuous metamorphic decrease from the migmatites to the anchizonal sediments. The shear zone also crosscuts the sills of Himalayan, Manaslu-type, tourmaline-bearing leucogranites.

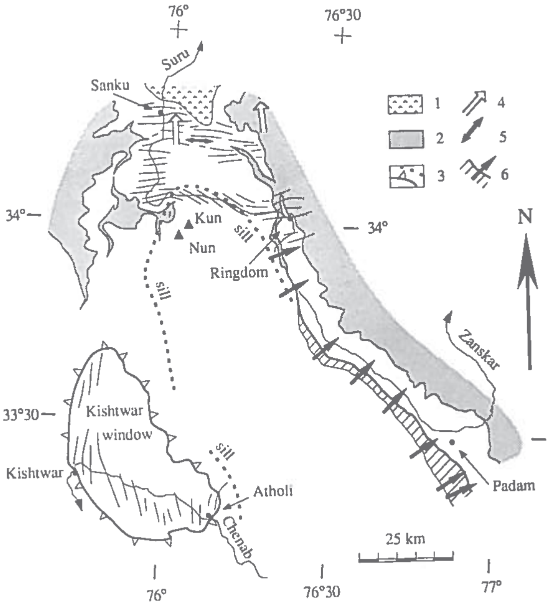


Fig. 6. Stretching lineation trajectories in Zanskar-Ladakh. Data from Gapais et al. [1984], Herren [1987], Staübli [1989] and A. Pêcher (unpublished data, 1984). Legend numbers are: 1, Dras volcanics, remnants of the island arc; 2, sedimentary cover; 3, Higher Himalaya Crystallines unit (with the sillimanite isograd), bound at its base by the Main Central Thrust, and Kishtwar window (Lesser Himalaya); 4, vergence direction of the late metamorphic folds, north of the Kun-Nun (Suru) dome; 5, main stretching direction in the same area; and 6, Zanskar normal shear zone and related lineation. The stretching lineations trajectories correspond to the set of continuous lines oriented roughly E-W in the Sanku-Ringdom area and N-S in the Kishtwar window.

West of Rangdom, in the Suru valley, the shear zone vanishes. The Higher Himalayan Crystalline form the great Suru dome (Nun and Kun area), evidenced by the metamorphic foliation trajectories [Gapais et al., 1984; Kündig, 1989] in which remnants of the cover (Triassic limestones and Permian volcanites) are still recognizable down to the sillimanite zone, pinched in south-vergent synclinal cores.

North of the Suru dome the contact beetween the migmatites and their cover is oriented E-W. Here, the deformation is predominantly of flattening type (as indicated by "en tablettes de chocolat" boudinage or by the shape of the finite strain markers), and the main elongation axis is approximately E-W (Figure 6), i.e., along the strike (low LX pitch). North-vergent small folds, locally associated with a S3 strain slip cleavage formed in lower temperature conditions, marks a late collapsing of the overlying sedimentary nappes [Gilbert and Merle, 1987].

East of the Suru dome, in Ringdom area, the contact zone is NW-SE, parallel to the metamorphic cleavage. The stretching lineation is still E-W. However, the finite deformation, although still of predominant flattening type, also shows a shearing component, the top of the pile moving eastward. In fact, there is a continuous gradation from the normal faulting in the Zanskar valley (where the contact is NE-SW) to E-W stretching north of the Suru dome, the type of deformation apparently depending upon the orientation of the gneissic contact, inherited from the doming event (or accentuated by it).

The Higher Himalaya Crystallines unit reappears about 50 km northeast of the Zanskar fault, in the Tso-Morari dome. Here, detailed structural studies by Stutz and Steck [1986] indicate that the existence of this domal structure is due to late dextral simple shear in a direction NW-SE.

DISCUSSION

The above data, restricted to the sections of the Himalaya where enough mesostructural and micro-structural data are available, confirm the existence of an important tectonic boundary north of the Greater Himalaya, at the contact between the Higher Himalaya crystallines and the Tethyan Sedimentary Series. Rather than a sharp and easily located boundary, it corresponds to a thick corridor of ductile deformation, mainly indicated by small-scale tectonic markers and stacking of the metamorphic isograds. The apparent lithological, structural, and metamorphic continuities are maintained across this contact, which explains why it has been only recently recognized. Two types of movements actually occurred at the contact: normal faulting (or, in a more general way northward extension tectonics) and also dextral shearing.

Northward extension is expressed in several ways. In the Nyalam and Zanskar sections it is marked by a steep shear zone. However, in other sections it is more diffuse and best evidenced by north-vergent folds. Then the geometry of the section implies also a normal fault type decollement level at the base of the sedimentary pile, which has not yet always been found (in the Annapurna and Dhaulagiri section it should be located in the thick and homogeneous lower Cambrian limestones, in which no shear criteria can be easily found in the field).

The timing of the normal faulting is not sharply constrained. In Everest area, Eastern Nepal, early normal fault structures are crosscut by the Miocene leucogranite [Burchfield and Royden, 1985]. In the others sections, faulting is bracketed between the end of the emplacement of the leucogranites (around 15 Ma) and the end of the thermal decrease (around 5 Ma [Copeland et al., 1990]): it is contempo-raneous with the MCT movement, and could account for the strong pressure decrease between the Eohimalayan

Barrovian metamorphism and the Miocene high-temperature sillimanite-bearing retrogression.

This northward collapse structure can be most easily interpreted as a gravity-driven décollement, as suggested by Caby et al. [1983], Burg et al. [1984], or Burchfield and Royden [1985]. An interdependance between the collapsing and the diapirism of the North Himalayan leucogranites was suggested by Mattauer and Brunel [1989]; but if so, it can be only a second-order effect, as collapsing occurred in the part of the belt where the belt of North Himalayan plutons exists (central and eastern Himalayas) as well as in the part where it does not (Garhwal and Zanskar Himalaya).

Besides normal faulting, another outstanding aspect of the structure of the upper High Himalayan Crystallines is the progressive clockwise rotation of the stretching lineation, from N20°E close to the MCT to N90°E to N110°E at the tectonic contact at the summit of the pile, a geometry which cannot be related to the collapse structures. To explain it, some key features are given by the central Himalaya Manaslu section:

1. Longitudinal lineations are mainly marked by the late sillimanite, which plasters medium- to small-scale steep dextral shears.
2. In the contact zone, at the top of the gneisses, shearing contemporaneous with the sillimanite growing progressively increases and concentrates in a single thick shear zone, in which all the tectonic markers indicate a clockwise rotation. The E-W sillimanite lineation then clearly marks the shear transport direction (eastward displacement of the northern compartment, i.e., of the Tethyan Sedimentary Series).
3. Between the sillimanite-bearing shears the Eohimalayan LX lineation remains NE-SW; where it trends E-W, this can be related to the passive rotation of the foliation at the vicinity of the shears.
4. The clockwise shearing took place during the high-temperature sillimanite metamorphism, during and/or immediately after the Manaslu granite emplacement: As the normal faulting, it can be approximately bracketed between 20 and 5 Ma. The penecontemporeneity of normal faulting and dextral shearing is also indicated by the continuous variations in the pitch values of the transport lineation in the contact zone, from more than E70° (normal faulting component predominant) to usually less than 10° (dextral strike slip shearing predominant).

Thus the Manaslu section actually indicates that the tectonic contact bordering the northern flank of the Greater Himalaya has acted in Central Nepal as a large clockwise shear zone, in competition with normal faulting. It also shows that the longitudinal shearing affects all the upper part of the gneiss pile, inducing a passive clockwise rotation of the earlier formed structures (Eohimalayan stretching lineation).

If we consider the data of Brun et al. [1985] in the Nyalam section, the situation is more complicated: the mylonitic zones observed in the gneisses correspond to sinistral (and not dextral) shearing; on the other hand, rotation of the stretching line between the mylonitic zones corresponds to dextral rotation. This pattern possibly is due to the anticlockwise reactivation of initially clockwise shears or, possibly, to competition between relative movements between the slices of gneisses (induced by local mechanical heterogeneities, as suggested by Brun et al. [1985]) in a regional-scale flattening strain regime.

In all others parts of the belt where enough direction data are available the Eohimalayan stretching lineation pattern systematically displays a clockwise rotation. But where the high-temperature metamorphic imprint is less marked, and where the small- to medium-size indications of shearing are scarce, the significance of this rotation is more debatable.

It can be interpreted as the trace of a progressive change in the orientation of the main deformation axis from the early episode of stacking (Eohimalayan episode, just postdating the collision) to the N20°E transport direction later overprinted in the MCT shear zone. But neither the global story of the Indian Ocean opening nor the Eocene shortening direction (already NNE-SSW) recognized in the field in the Indus suture zone [see Burg and Chen, 1984; Colchen et al., 1986b] show any indications of such a change. On the contrary, the global shortening direction appears to be remarkably constant from the 52 Ma collision up to the Pliocene-Quaternary formation of the Siwalik prism.

Thus the clockwise rotation of the lineation, clearly indicated by the strain trajectory maps, can better be interpreted in the same way as in the Manaslu section, i.e., as a the passive rotation of a preexisting marker in large-scale progressive dextral shearing, with a complete parallelization to the shear direction in the zone of maximum shearing (i.e., at the gneisses-sediments contact). According to the thickness of the affected zone (around 5 km, that is, of the same order as the thickness of the affected zone in the Manaslu sections) the minimum amount of shearing could have been of the order of several tens of kilometers.

This Miocene clockwise motion of Tibet relative to the Greater Himalaya (Figure 7) can be interpreted in the light of the recent geology of the Tibetan plateau: all across the Tibetan plateau, there is a strong neotectonic activity, with large strike-slip faults and numerous N-S oriented Quaternary grabens. They indicate an WNW-ESE extension of Tibet [Armijo et al., 1986], with eastward extrusion at the Pacific margin of the Asian continent (indenter model of Tapponnier and Molnar [1977], Molnar and Tapponnier [1978], and Tapponnier et al. [1982]). Two main Quaternary tectonic patterns can be distinguished in Tibet:

1. Northern Tibet, with only few N-S grabens, limited to the north by the sinistral Altyn Tagh fault and to the south by the dextral en échelon system of the Karakorum Jiali fault zone, 250 km north of the Great Himalaya, appears to be a "rigid" block

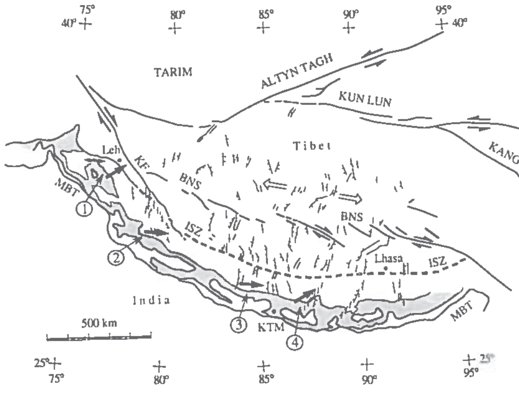


Fig. 7. Sketch map of the Himalaya (Higher Himalaya Crystallines is patterned area) and Tibetan plateau, showing the main Quaternary faults. Movement on the North Himalayan shear zone is marked by the large solid arrows. Abbreviations are BNS, late Jurassic Banggong - Nujiang suture zone (reactivated in the Jali fault system); IZS, Middle Eocene Indus-Zangbo suture (open dots); KF, Karakorum fault; and KTM, Kathmandu. Numbers 1 to 4 refer to the North Himalayan shear zone in Zanskar, Garhwal, central Nepal, and Nyalam sections, respectively.

extruding eastward in accordance with the indenter model.

2. Southern Tibet, limited by the Karakorum Jiali fault zone to the north and the Greater Himalaya to the south, displays most of the N-S grabens. They mark an important E-W extension, possibly due to gravitational thinning of the previously thickened Tibetan crust [England and Houseman, 1988].

The juxtaposition of the E-W stretched southern Tibet and the Greater Himalaya, apparently unstretched longitudinally in the Quaternary, implies differential longitudinal movements at their contact. Considering that Tibet has a free boundary to the west but that its eastward extrusion is enhanced by the Pamir-Karakorum crustal thickness and mountain height, those differential movements can only correspond to clockwise shearing, with the shear amount increasing from west to east. But no sharp longitudinal Quaternary fault is observed in southern Tibet, and the limit where this accommodation takes place remains obscure. It does not appear to be the Indus-Tsangpo line, but must be farther to the south, just north of the Greater Himalaya: the graben-rich domain extends up to here (for instance, the Thakkola graben, between Dhaulagiri and Annapurna, progressively vanishes across the upper part of the metamorphic pile, where the amount of dextral shearing decreases), and the deep structure of the area extending between the Great Himalaya and the Indus-Tsangpo suture is the same as the one below Tibet [Molnar, 1988].

The dextral shear zone described here looks like a possible Miocene equivalent of the Quaternary southern border of the Tibetan plateau, of course seen in lower erosion levels. The timing of the uplift of Tibet is still debated, but it seems that it has mainly occurred since the early Pliocene [Dewey et al., 1988], and that the Tibetan plateau elevation was probably no more than 1 km at the Miocene [Zhao and Morgan, 1985]. Thus it would preclude gravitational extension as the main driving effect for the formation of the north Himalayan shear zone. It can be better considered in the indenter model as the southern mechanical boundary of a relatively rigid Tibetan block already extruding eastward; that is, it would be a Miocene analogue (or duplicate) of the Karakorum-Jiali fault zone. In such an hypothesis the variations of the type of deformation observed along the Greater Himalaya—Tibetan block contact could reflect differences in the relative orientation of the boundaries of the blocks and the average main N20°E continental shortening direction:

1. From Zanskar to central Himalaya, where there is a marked obliquity between the shortening directions and the perpendicular to the boundary, the situation is such that the deformation in the boundary zone must have an important dextral rotational component. In Zanskar-Ladak, where the obliquity is maximum, eastward extrusion corresponds either to true dextral shearing (Tso-Morari dome) or to predominant normal faulting (Zanskar fault).

2. However flattening could be predominant when the shortening is perpendicular to the boundary: this is the case north of the Suru dome and may also be the case in the Nyalam section, where a divergent sense of shearing could correspond to crustal-scale flattening.

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A. Pêcher, Laboratoire de Géologie Alpine CNRS (URA 69), Institut Dolomieu, 15 rue Maurice Gignoux, F-38031, Grenoble Cedex, France.

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