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Inverse metamorphic zonation in very low-grade Tibetan zone series of SE Zanskar and its tectonic consequences (NW India, Himalaya)

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Abstract

The metamorphism of the carbonate rocks of the SE Zanskar Tibetan zone has been studied by "illite crystallinity" and calcite-dolomite thermometry. The epizonal Zangla unit overlies the anchizonal Chumik unit. This discontinuous inverse zonation demonstrates a late to post-metamorphic thrust of the first unit over the second.

The studied area underwent a complex tectonic history:

– The tectonic units were stacked from the NE to the SW, generating recumbent folds, NE dipping thrusts and the regional metamorphism. The compressive movements were active under lower temperature conditions, resulting in late thrusts that disturbed the metamorphic zonation. The discontinuous inverse metamorphic zonation dates from this phase.

– A NE vergent backfolding phase occurred at lower temperature conditions. It caused the uplift of more metamorphic levels.

– A late extensional phase is revealed by the presence of NE dipping low angle normal faults, and a major high angle fault, the Sarchu fault.

The low angle normal faults locally run along earlier thrusts (composite tectonic contacts). Their throw has been sufficient to reset a normal stratigraphic superposition (young layers overlying old ones), but insufficient to erase the inverse metamorphic relationship. However, the combined action of backfolding and normal faulting can locally lessen, or even cancel, the inverse metamorphic superposition. After deduction of the normal fault translation, the vertical component of the original thrust displacement through stratigraphy is 400 m, which is a value far too low to explain the temperature difference between the two units. The horizontal component of displacement is therefore far more important than the vertical one. The regional distribution of metamorphism within the Zangla unit points out to an anchizonal front and an epizonal inner part. This fact is in agreement with nappe tectonics.

Keywords: Metamorphism, inverse zonation, illite crystallinity, calcite-dolomite thermometry, nappe tectonics, Zanskar, Himalaya.

Résumé

Le métamorphisme des roches carbonatées de la zone tibétaine au sud-est Zanskar a été étudié par la "cristallinité" de l'illite et par thermométrie calcite-dolomie. L'unité épizonale de Zangla est superposée à l'unité anchizonale de Chumik. Cette zonation inverse discontinue démontre un chevauchement tardi à post-métamorphique de la première unité sur la seconde.

La région a subi une histoire tectonique complexe:

– Les unités tectoniques se sont empilées du NE vers le SW, engendrant des plis couchés, des chevauchements à pendage NE et le métamorphisme régional. Les mouvements compressifs ont continué à agir dans des conditions de température moindre, créant des chevauchements tardifs qui ont perturbé la zonation métamorphique. Le métamorphisme "transporté" résulte de cette phase.

– Des plis en retour à vergence NE se sont développés dans des conditions de température moindre. Ils sont responsables de la remontée de niveaux plus métamorphiques dans l'unité de Chumik.

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– Une phase d'extension tardive est révélée par la présence de failles normales de faible pendage, et par une faille normale de fort pendage et rejet important, la faille de Sarchu.

Les failles normales de faible pendage suivent souvent le tracé des chevauchements (contacts tectoniques composites). Leur rejet a été suffisant pour créer une superposition stratigraphique normale (couches jeunes sur couches vieilles), mais généralement insuffisant pour annuler la relation métamorphique inverse. Toutefois l'action combinée des plis en retour et d'une faille normale peut localement atténuer, voire annuler la superposition métamorphique inverse. En soustrayant l'effet de la faille normale, on constate que la composante verticale du chevauchement originel dans la stratigraphie est de 400 m, ce qui est insuffisant pour expliquer la différence de température entre les deux unités. La composante horizontale du déplacement est donc beaucoup plus importante que la verticale. La distribution régionale du métamorphisme dans l'unité de Zangla montre une partie interne épizonale et un front anchizonal. Ce fait est en accord avec une tectonique de nappe.

1. Introduction

In orogenic belts, the geometry of the metamorphic zonation may be deeply disturbed by syn- to post-metamorphic movements. These disturbances are exemplified by inverse zonations (FREY, 1988), such as the classical Himalayan ones (FRANK et al., 1973, 1977; THÖNI, 1977; LE FORT, 1975; ARITA, 1983; BHATTACHARYYA and DAS, 1983; BRUNEL and KIENAST, 1986; STÄUBLI, 1986). These inversions are usually continuous and are thought to result from various mechanisms such as syn- to post-metamorphic thrusting, recumbent folding or shear heating. However, these examples are all located in the high-grade series of the High Himalayan Crystalline (HHC) and of the Lesser Himalaya. In the sedimentary terranes of the Tibetan zone, inverse metamorphic zonation is poorly documented, apart from the case of the Spongtang ophiolitic klippe (Fig. 1) (FUCHS, 1977; GARZANTI and BRIGNOLI, 1989; REUBER et al., 1989), which is the most obvious nappe of this domain. Other types of disturbance of a metamorphic zonation include the tectonic folding of the isogrades and their offset by normal or transcurrent faults.

We present hereafter a case that not only provides the first evidence of discontinuous metamorphic zonation within the sedimentary series of the Tibetan zone, but also has the noteworthy characteristic that the zonation has been successively affected by different types of disturbances. The superimposition of late normal faulting on thrusting gave rise to composite tectonic contacts with a complex history (Figs 2 and 5). These processes worked in opposite senses in such a way that they nearly balanced: late extension was important enough to cancel the inverse stratigraphic superposition completely, but not the inverse metamorphic zonation. In such a case, the study of the metamorphic zonation geometry provides the best opportunity to demonstrate the existence of nappe translations.

2. Geological setting

The North Indian continental margin in Zanskar (Fig. 1) is characterized by the sedimentary series of the Tibetan zone ranging from Uppermost Precambrian to Eocene (GANSSER, 1964; KANWAR and BHANDARI, 1979; SRIKANTIA, 1981; BAUD et al., 1982, 1984; GAETANI et al., 1986; FUCHS, 1982, 1987; STUTZ, 1988).

During the collision of India with Asia, the Tibetan zone underwent deformation, stacking and transport towards SW (BASSOULET et al., 1980; BAUD et al., 1982, 1984; GAETANI et al., 1985; STUTZ and STECK, 1986; STUTZ, 1988; SPRING and CRESPO-BLANC, 1992; STECK et al., 1993). Consequently, a regional metamorphism developed, reaching in some areas the amphibolite facies grade. In Western Zanskar, it progressively rises southward from the Indus-Tsangpo suture zone toward the HHC where several metamorphic phases have been recognised (HONEGGER et al., 1982; KÜNDIG, 1989). In Eastern Zanskar, subsequent NE vergent folding and doming caused no large scale metamorphic recrystallizations, but disturbed the zonation of the regional metamorphism. A late phase of extension generated normal faults that cut the metamorphic zonation further. As a result of these successive tectonic events, the Eastern Zanskar cross-section displays three distinct domains of high-grade metamorphism, separated by areas of low to non-metamorphic terranes (MASSON et al., 1990; STECK et al., 1993). They are, from south to north (Figs 1, 2):

– the High Himalayan Crystalline (HHC), of amphibolite facies grade (FRANK et al., 1973, 1977; POGNANTE and LOMBARDO, 1989; POGNANTE et al., 1990);

– the Kenlung Serai unit (KSU), SW of Sarchu, characterized by stau-ky-gar, qz-cc-trem and hbl-biot-olig (An 16 to 27%) bearing parageneses (RAINA and BHATTACHARYYA, 1974; SPRING and CRESPO-BLANC, 1992);

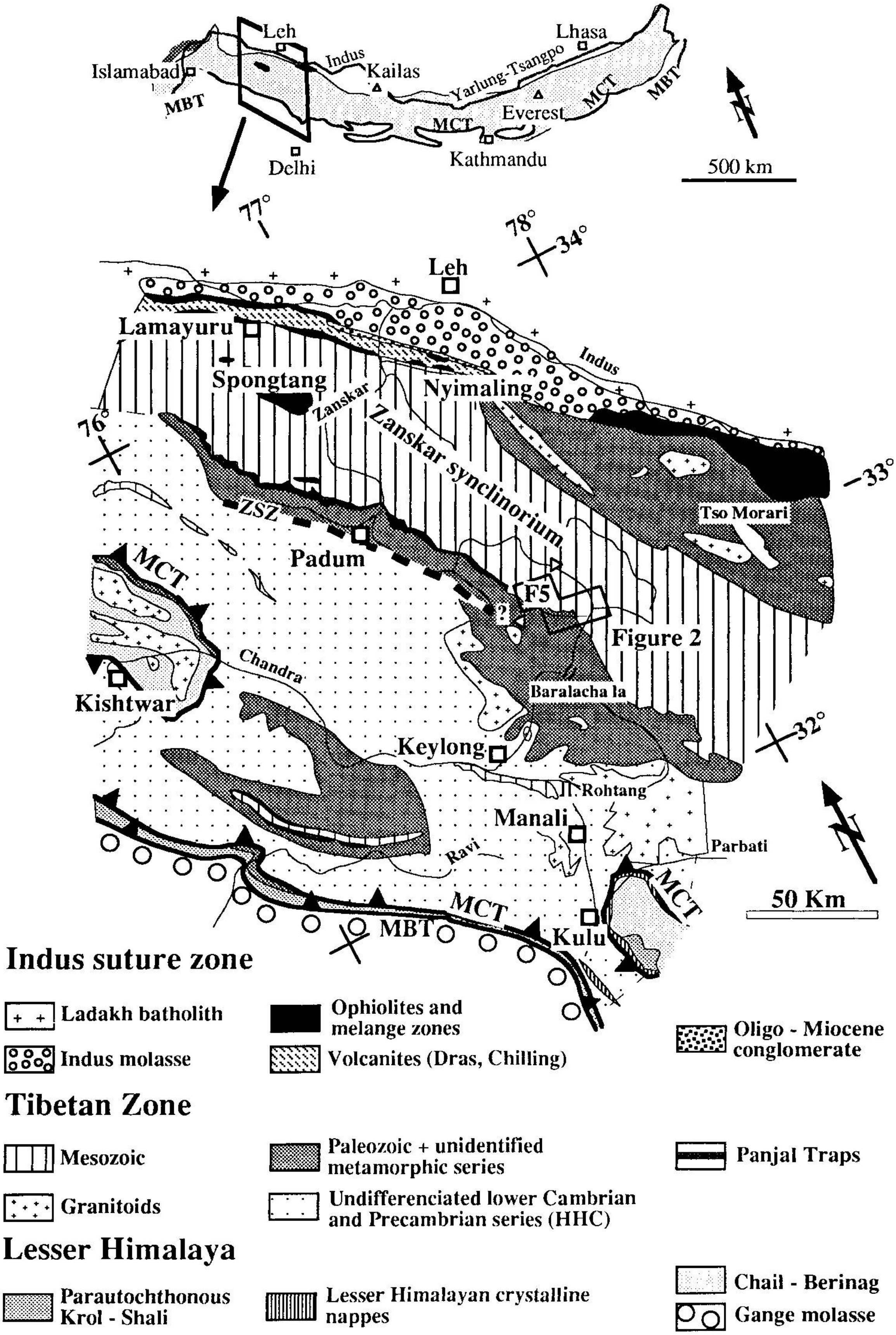

Fig. 1 Geological map of NW Himalaya completed from Spring and Crespo-Blanc (1992). MCT: Main Central Thrust, MBT: Main Boundary Thrust, ZSZ: Zanskar Shear Zone (Herren, 1987). F5: location of the cross-section (Fig. 5).

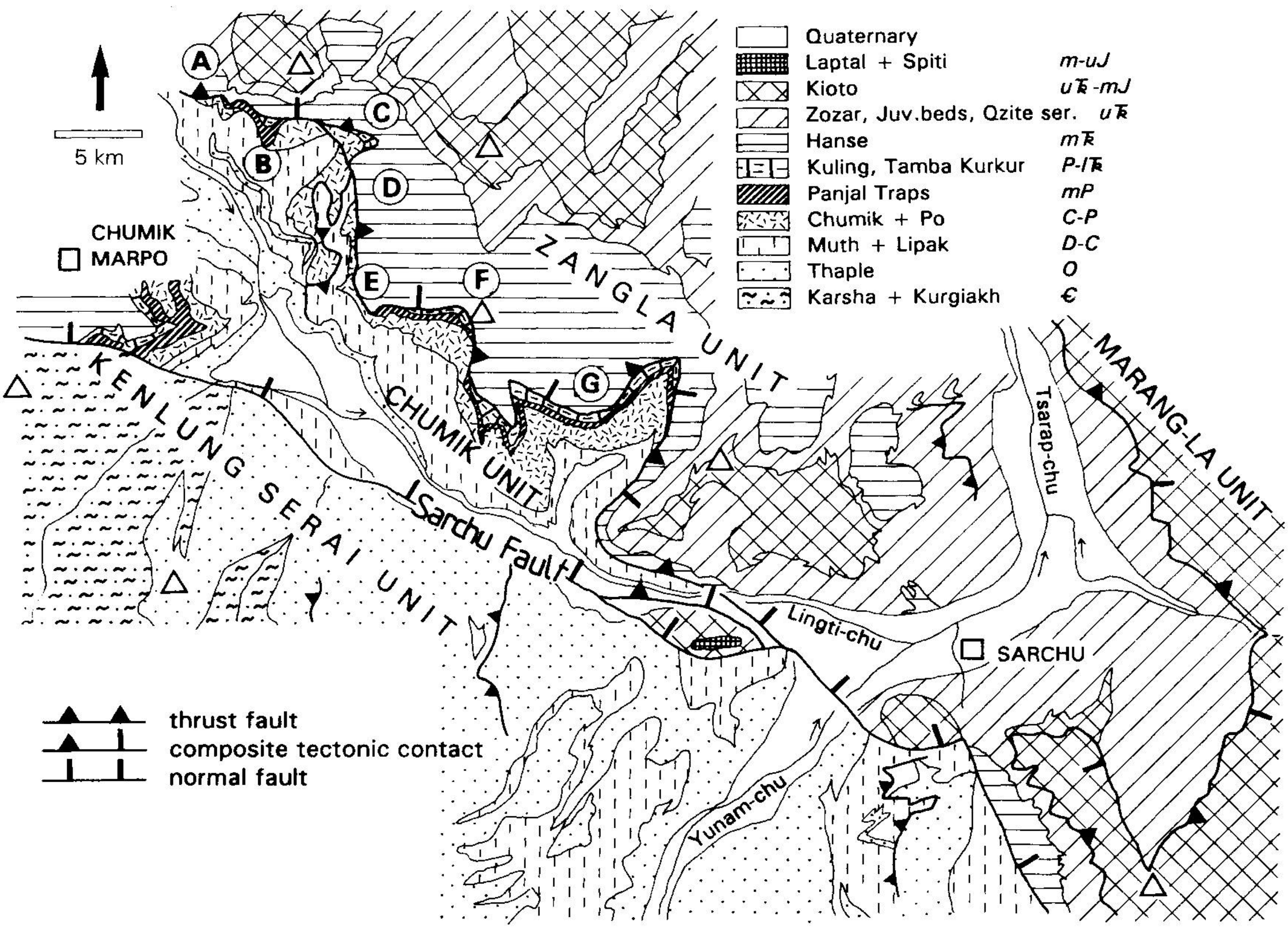

Fig. 2 Geological map of SE Zanskar (location in Fig. 1). A–G: location of stratigraphic sections (Fig. 8).

– the Nyimaling area (Fig. 1), where the series contiguous to the suture are metamorphosed in the upper greenschist facies (Stutz, 1988), grading toward SE up to the amphibolite facies in the Tso Morari region (Thakur and Virdi, 1979).

The Sarchu area (Fig. 2), in the middle of the cross-section, is critical for unravelling the relationships between metamorphism and tectonics. Several tectonic units have been recognized (Figs 1, 2 and 5) (Spring and Crespo-Blanc, 1992; Steck et al., 1993). The present paper is focused on the discontinuous inverse metamorphic superposition we have observed between two of them: the Chumik (Ordovician to middle Triassic) and Zangla (in this area Permian to upper Jurassic) units. We shall also give data on the higher grade metamorphism of the adjacent KSU.

The structural chronology in the Sarchu area is established as follows:

– the main deformation phase is characterized by large, SW vergent, recumbent folds and NE dipping thrusts. It is essentially syn-metamorphic, however thrusting lasted over a long time span and was still active during cooling. The resulting disturbances of the metamorphic zonation caused the discontinuous inverse superposition we described hereafter.

– a NE vergent backfolding phase occurred under lower metamorphic conditions. It caused the uplift of more metamorphic levels in the Chumik unit.

– the late extension took place under anchizonal to non-metamorphic conditions. It is documented by: (1) NE dipping low angle normal faults; they cut the backfolds and locally follow the thrust planes of the main deformation phase; (2) the Sarchu fault (Figs 2, 3 and 5); it is a prominent, late, steeply dipping normal fault that separates the KSU (amphibolite facies) from the Chumik (anchi to epizonal) and the Zangla (epizonal) units. The vertical displacement is apparently of the order of 10 km between the KSU and the Chumik unit, where it is only of 5 km between KSU and Zangla. This difference can be ex-

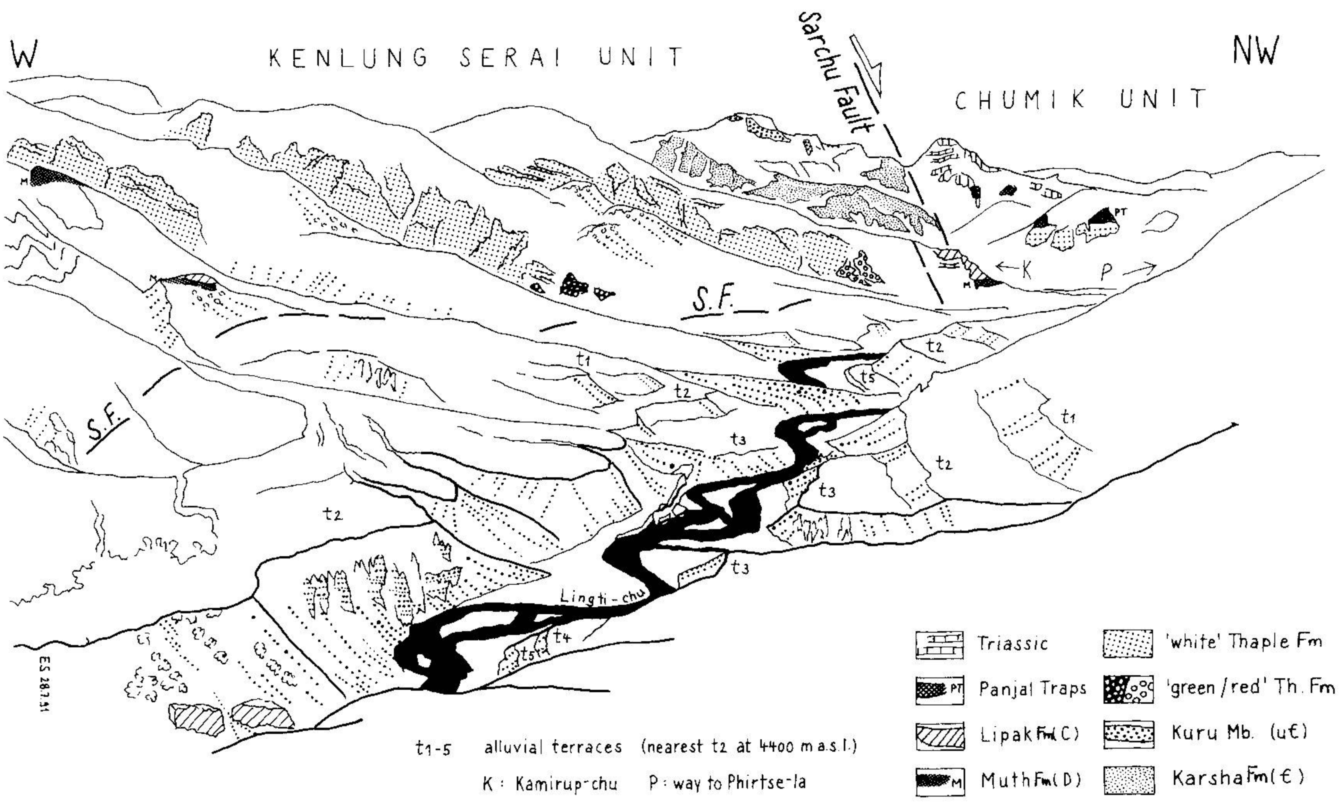

Fig. 3 View of the Kenlung Serai-Chumik normal fault contact (Sarchu Fault), 6 km WNW of Sarchu on the northern bank of the Lingti river. The ages of the formations are as in figures 2 and 8.

plained by the perturbation of the metamorphic zonation occurring between the main deformation phase and the extensional phase (backfolding and doming).

4. Methods

Since the rocks outcropping in the Zangla and Chumik units are mainly carbonates, the characterization of the metamorphism has been carried out by the "illite crystallinity" (IC) method (Kübler, 1968, 1990; Frey, 1987). Sampling has been made on fauna-free black micrites, to lessen the detrital influence. Because of the complex tectonics, we had to sample rocks of similar lithology in the different stratigraphic units. A total of 81 samples has been taken from either sides of the 15 km long tectonic contact separating the units of Zangla (31 samples) and Chumik (50 samples). Sampling has been focused on the vicinity of the contact, and some samples have been taken in deeper structural levels of the units.

The lithologies used for the thermometry in the KSU are pelites, basalts and carbonates, whereas they are exclusively dolomite bearing carbonates in the Zangla unit. No thermometry has been performed in the Chumik unit, where the metamorphic grade only reaches the lower greenschist facies.

4.1. ILLITE "CRYSTALLINITY"

The illite "crystallinity" index (IC) has been determined by measuring the width at half height of the 001 illite reflection ($\Delta°2\Theta$Cu Kα) on both air dried and glycolated slides. The limits of diagenesis-anchizone-epizone are at 0.42 and 0.25 IC index ($\Delta°2\Theta$Cu Kα). Sample preparation and experimental conditions are those of Kisch (1991).

4.2. CALCITE-DOLOMITE THERMOMETRY

Two methods have been used to quantify the temperature in the carbonate rocks: X-ray diffraction (XRD) and electron microprobe (EMP). Both work on the principle of the substitution of Ca by Mg with increasing temperature in the crystalline network of calcite. The XRD method presents the major disadvantage of not considering dolomite exsolution occurring at high temperature, thus giving apparently lower temperatures. The shift of

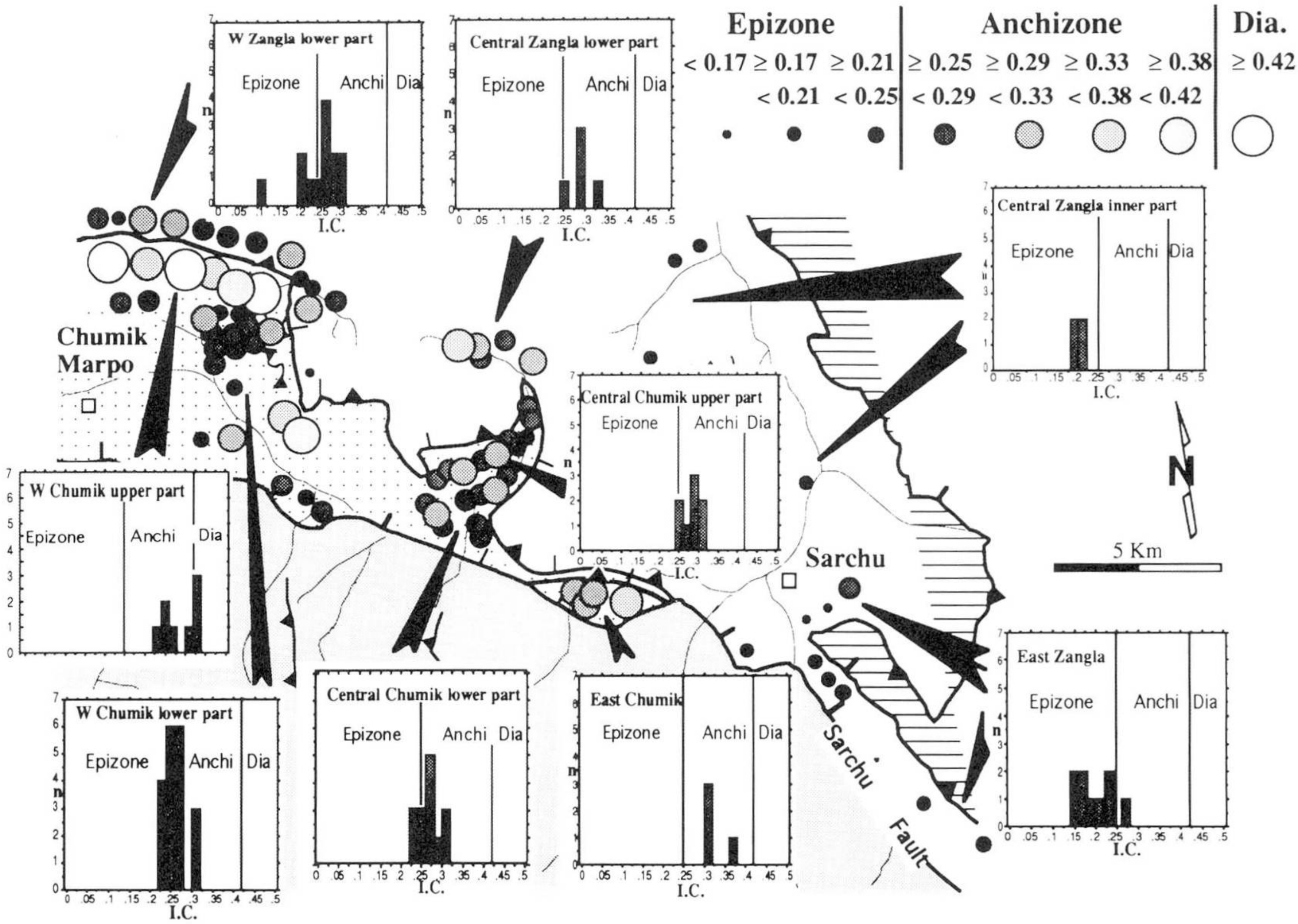

Fig. 4 Sketch map of the illite "crystallinity" values distribution and index variations. The epizonal values in W Chumik and the apparent normal metamorphic zonation in Central Chumik are a result of the backfolding phase that raised deep structural levels of the Chumik unit.

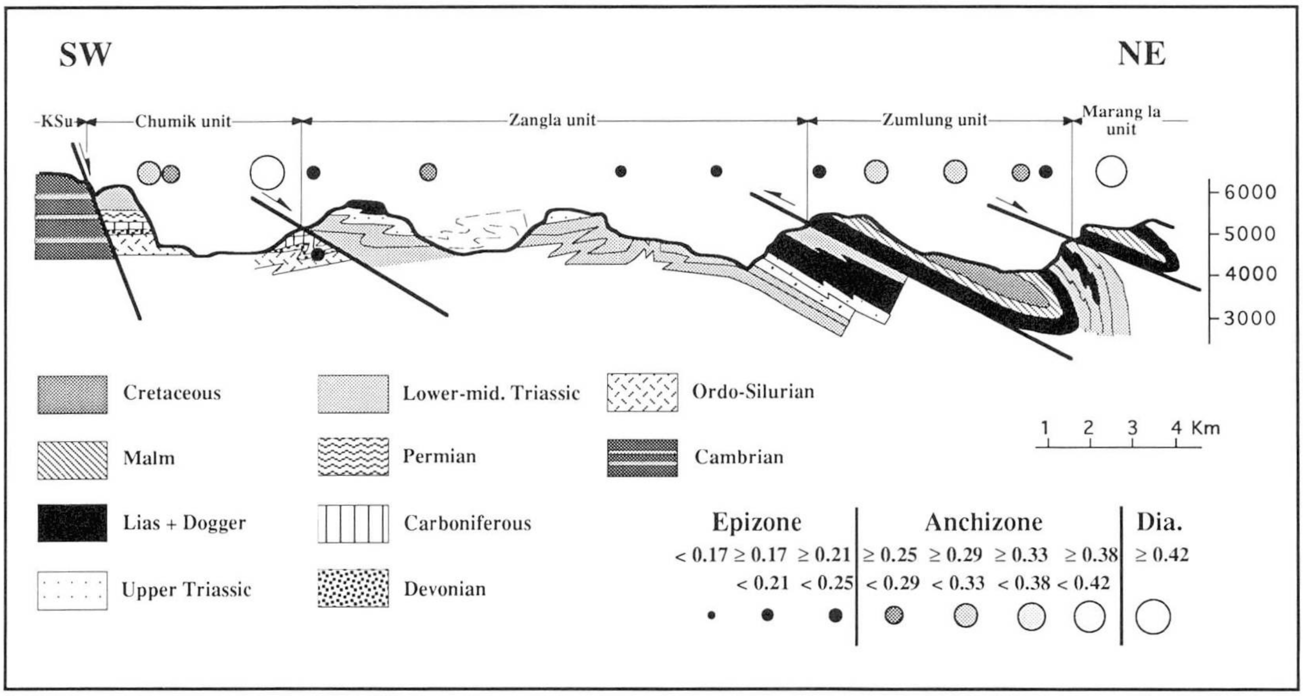

Fig. 5 Cross-section through the tectonic units of the Tibetan zone in SE Zanskar. Location in figure 1. The IC values for the Zumlung and Marang la units are own unpublished data.

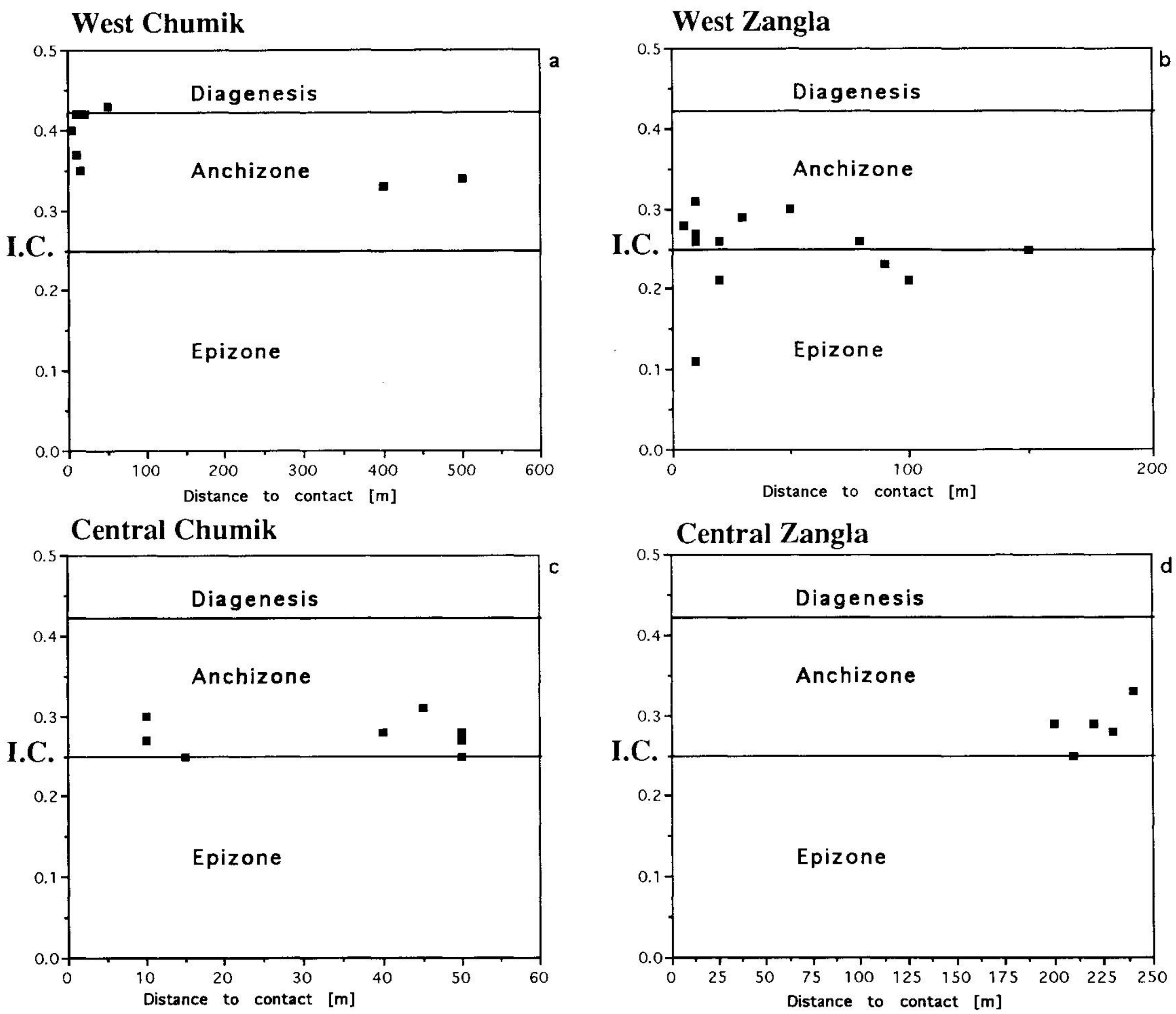

Fig. 6 a–d IC vs distance to thrust diagrams. The values of IC do not seem to be affected by the tectonic contact between Zangla and Chumik.

the Fe peak may cause a similar problem with the XRD, but this difficulty has been avoided by analyzing only samples with a very low content of iron (confirmed by carbonate coloration and EMP). Using the quantitative method by electron microprobe, only the centre of the calcite crystals was considered. Equations from HUTCHISON (1974) and ANOVITZ and ESSENE (1987) were used for XRD and EMP respectively.

4.3. THERMOMETRY IN THE KENLUNG SERAI UNIT

The metamorphic grade in the KSU is revealed by the stau-ky-gar paragenesis in a pelitic horizon. Several thermometers have been used to quantify the metamorphic climax to allow a comparison.

The biotite/garnet thermometry (equations of FERRY and SPEAR, 1978) has been performed on a pelite of the Ordovician Thaple Fm. The paragenesis is: qz-biot-musc-garn-zirc.

The quantification of the titanium percentage in the hornblende (equations of COLOMBI, 1989) has been performed on a basalt with the following paragenesis: green hbl-biot-oligocl-calc-apat-ilmenite.

Calcite-dolomite thermometry has been performed on black micrites of the Lower Carboniferous Lipak Fm.

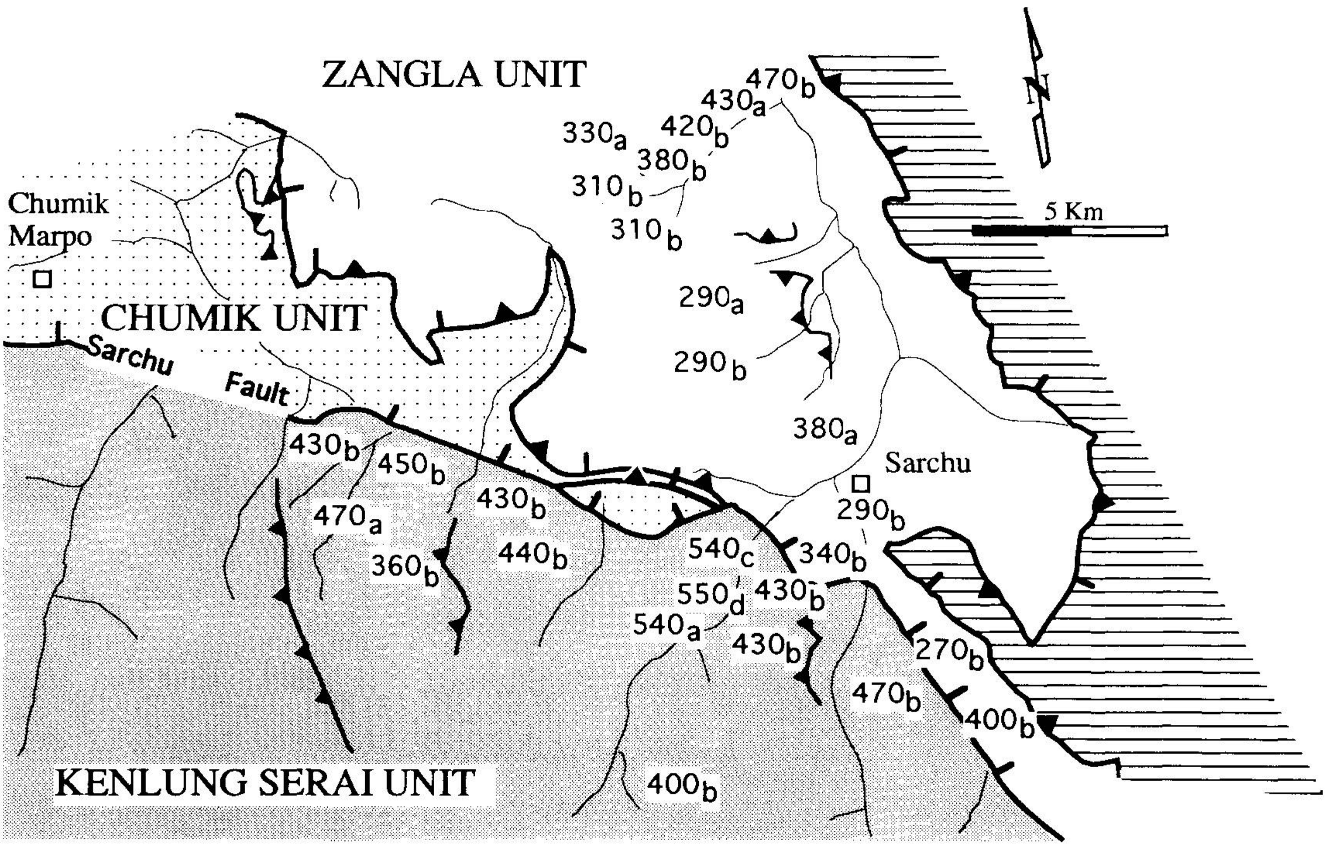

Fig. 7 Temperatures obtained by thermometry (all the values are ± 50 °C):
- 540a: quantitative equations (Anovitz and Essene, 1987).
- 310b: semi-quantitative equations (Hutchison, 1974).
- 540c: equations for the biotite-garnet pair (Ferry and Spear, 1978).
- 550d: Ti-hornblende thermometer (Colombi, 1989).

The low values obtained by the XRD method (b) in the KSU could be explained by dolomite exsolution processes.

5. Results

The study of the distribution of the "illite crystallinity" index and the calcite-dolomite thermometry values displays the following results:

– On either sides of the tectonic contact between Zangla and Chumik, a metamorphic leap has been observed, of 0.25 over 0.38 west, and 0.19 over 0.32 east (mean values) (Fig. 4). At the centre, the leap is not significant: 0.29 over 0.28. In this zone, huge backfolding structures have been observed, bringing up deep, more metamorphic levels of the Chumik unit. This can explain the apparent normal metamorphic zonation in Central Chumik, and the presence of epizonal values in the lower part of west Chumik (Figs 4 and 5).

– No variation of the "illite crystallinity" index value has been detected near the contact separating Chumik from Zangla (Figs 6 a–d).

– A vertical gradient can be pointed out in the Chumik unit, where the lower part of this unit is more metamorphic than the upper part (Figs 4 and 5).

– A horizontal gradient prevails in the Zangla unit, since its inner part is more metamorphic than its frontal part (Figs 4 and 5).

– The orientation of "isocrysts" of IC is NNW–SSE in both Chumik and Zangla units, roughly perpendicular to the stacking direction of the units. These "isocrysts" lines are cut by the Sarchu fault, as displayed by the increasing IC values toward the E in the Zangla unit (Fig. 4).

– The calcite-dolomite thermometry by electron microprobe in the KSU displays remarkable concordance with the other thermometry methods (Fig. 7), allowing confidence for the results obtained by this method in the Zangla unit. The biotite-garnet thermometer indicates conditions of 540 ± 50 °C; the titanium percentage in the hornblende, 550 ± 50 °C, and the calcite-dolomite thermometry,540 ± 50 °C. Nevertheless, the XRD method yields temperatures of about 100 °C below those obtained with other thermometers in

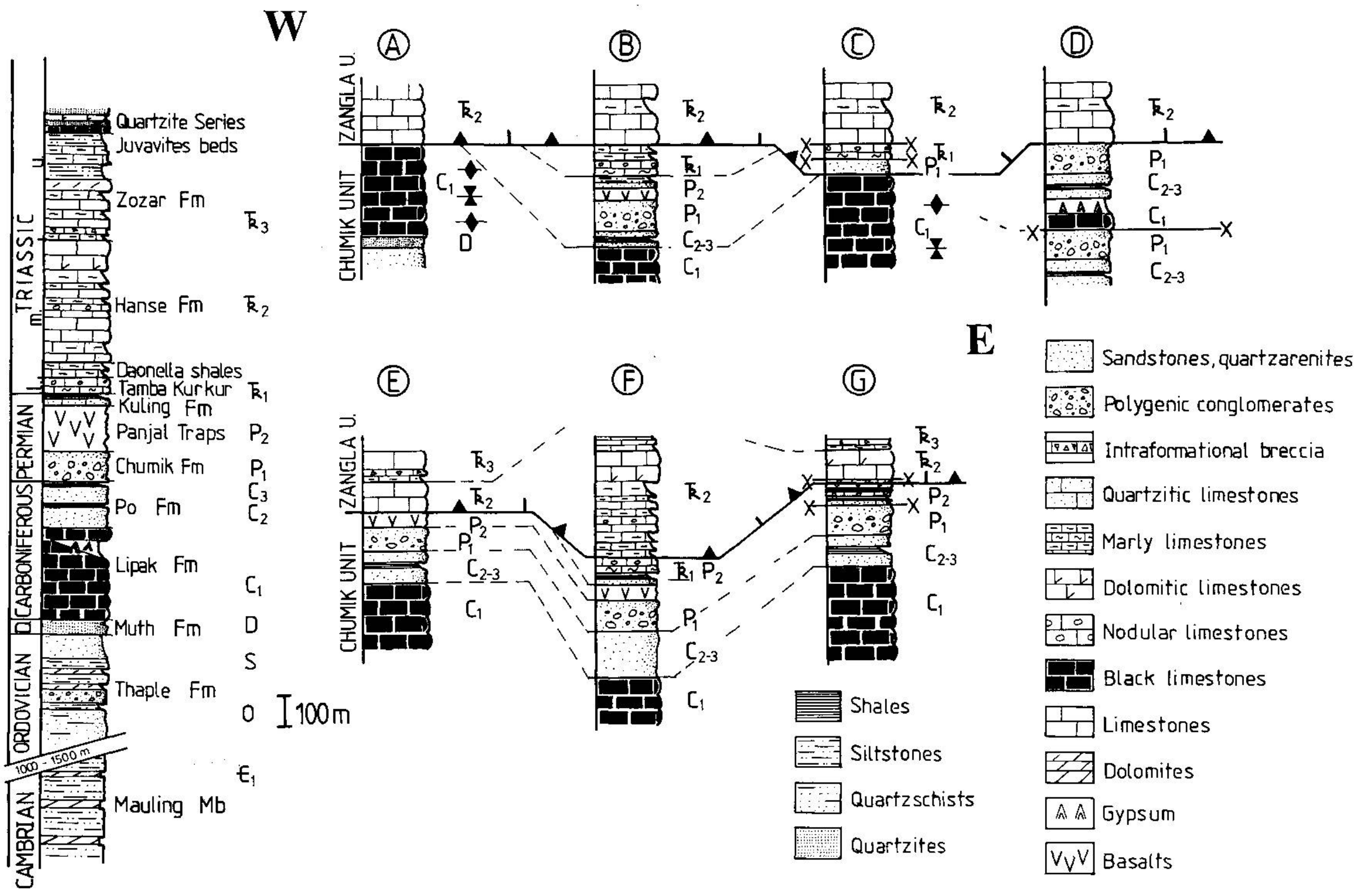

Fig. 8 Sections along the Zangla-Chumik complex tectonic contact. To the left is the synthetic stratigraphic column of the SE Zanskar Tibetan zone (after SPRING and CRESPO-BLANC, 1992 and own unpubl. observations). Location of the profiles in figure 2. The sections show the influence of the low-angle normal faults.

the KSU (Fig. 7). This can be explained by the dolomite exsolution at high temperature.

– The calcite-dolomite thermometry by XRD in the Zangla unit confirms the regional metamorphic trend observed with the IC and electron microprobe methods.

– The Sarchu fault is a major discontinuity (Figs 2 and 3). It is a normal fault since it puts the younger and weakly metamorphosed rocks of the Chumik and Zangla units in contact with the more metamorphosed rocks of the KSU (Fig. 5). The vertical displacement between the amphibolite facies KSU and the zeolite facies (paragenesis on a basalt) Chumik unit is of about 10 km (300 °C difference, assuming a 30 °C/km gradient), whereas it is much lesser between the KSU and the epizonal Zangla unit.

– The displacement of Zangla over Chumik is difficult to estimate. The "décollement" level of Zangla is presumably in the evaporite layers of the lower Carboniferous Lipak Fm. In the Sarchu area, the base of Zangla reaches downwards only the lower Permian (Fig. 8C). The topmost layers of Chumik are of Middle Triassic age (Fig. 8B). Therefore, the initial thrust related to the main deformation phase cuts an observable stratigraphic thickness of about 400 m (assuming an approximately constant thickness of the layers in the two units considered). This is not sufficient to explain a temperature difference on both sides of the thrust, that may be in the order of 50 to 100 °C in the western sector. The thrust must be rooted in a more internal, higher temperature zone, and its horizontal component of displacement must be more important than the vertical one.

6. Discussion and conclusions

In the sedimentary series of the Tibetan zone, a discontinuous inverse metamorphic zonation has been ascertained by systematically measuring the "illite crystallinity". It bears evidence of the late tectonic transport of the epizonal Zangla unit over the anchizonal Chumik unit. The upper unit (Zangla) displays a metamorphic zonation frequent in nappes, with an inner part more metamorphic than its front (Fig. 5).

The complex nature of the tectonic contact between the two units has been established by stratigraphic and structural analyses; the initial thrust of Zangla over Chumik has been reworked first by the backfolding phase, then by a NE dipping low angle normal fault. The throw of this fault has been sufficient to reset a normal stratigraphic superposition (younger rocks over older ones), but insufficient to cancel the reverse metamorphic relation. The combination of post metamorphic deformations can, here and there, obliterate the metamorphic leap, by uplifting deep levels (backfolding phase) of the lower unit and putting them in normal fault contact with layers of similar metamorphic grade of the upper unit.

The Zanskar belt displays a good example of a situation where crucial information on a partly obliterated nappe structure is preserved in the geometry of the metamorphic zonation. Our study not only provides such an example of "transported metamorphism", but also gives a possible explanation of the scarcity of direct stratigraphic evidence for nappe tectonics in the Tibetan zone of the Himalayas. Detailed mapping has revealed complex structures where the classical clues allowing the identification of nappes are completely occulted. The effects of a late extensional phase were important enough to cancel the inverse stratigraphic relationship caused by the thrust, but not the inverse metamorphic zonation. Therefore, the information on the main orogenic translation movements is best preserved in the geometry of the metamorphic zonation.

By analogy with the Alps and other mountain belts where "discontinuous inverse metamorphic zonation seems to be a rather common feature in low-grade external zones" (FREY, 1988), one can suspect that this feature could be more common in Zanskar than seems from the present documentation, and that other examples will probably be discovered.

Acknowledgements

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