Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 86 (1993)

Heft: 1

Artikel: Geological transect across the Northwestern Himalaya in eastern Ladakh and Lahul : a model for the continental collision of India and Asia

Autor: Steck, Albrecht / Spring, Laurent / Vannay, Jean-Claude

DOI: https://doi.org/10.5169/seals-167241

Nutzungsbedingungen

Die ETH-Bibliothek ist die Anbieterin der digitalisierten Zeitschriften auf E-Periodica. Sie besitzt keine Urheberrechte an den Zeitschriften und ist nicht verantwortlich für deren Inhalte. Die Rechte liegen in der Regel bei den Herausgebern beziehungsweise den externen Rechteinhabern. Das Veröffentlichen von Bildern in Print- und Online-Publikationen sowie auf Social Media-Kanälen oder Webseiten ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Mehr erfahren

Conditions d'utilisation

L'ETH Library est le fournisseur des revues numérisées. Elle ne détient aucun droit d'auteur sur les revues et n'est pas responsable de leur contenu. En règle générale, les droits sont détenus par les éditeurs ou les détenteurs de droits externes. La reproduction d'images dans des publications imprimées ou en ligne ainsi que sur des canaux de médias sociaux ou des sites web n'est autorisée qu'avec l'accord préalable des détenteurs des droits. En savoir plus

Terms of use

The ETH Library is the provider of the digitised journals. It does not own any copyrights to the journals and is not responsible for their content. The rights usually lie with the publishers or the external rights holders. Publishing images in print and online publications, as well as on social media channels or websites, is only permitted with the prior consent of the rights holders. Find out more

Download PDF: 30.04.2026

ETH-Bibliothek Zürich, E-Periodica, https://www.e-periodica.ch

Eclogae geol. Helv. 86/1: 219–263 (1993)

0012-9402/93/010219-45 $ 1.50 + 0.20/0
Birkhäuser Verlag, Basel

Geological transect across the Northwestern Himalaya in eastern Ladakh and Lahul (A model for the continental collision of India and Asia)

By ALBRECHT STECK, LAURENT SPRING, JEAN-CLAUDE VANNAY, HENRI MASSON, EDGAR STUTZ, HUGO BUCHER, ROBIN MARCHANT and JEAN-CLAUDE TIÈCHE [1]

ABSTRACT

The detailed geological mapping and structural study of a complete transect across the northwestern Himalaya allow to describe the tectonic evolution of the north Indian continental margin during the Tethys ocean opening and the Himalayan Orogeny.

The Late Paleozoic Tethys rifting is associated with several tectonomagmatic events. In Upper Lahul and SE Zanskar, this extensional phase is recorded by Lower Carboniferous synsedimentary transtensional faults, a Lower Permian stratigraphic unconformity, a Lower Permian granitic intrusion and middle Permian basaltic extrusions (Panjal Traps). In eastern Ladakh, a Permian listric normal fault is also related to this phase. The scarcity of synsedimentary faults and the gradual increase of the Permian syn-rift sediment thickness towards the NE suggest a flexural type margin.

The collision of India and Asia is characterized by a succession of contrasting orogenic phases. South of the Suture Zone, the initiation of the SW vergent Nyimaling-Tsarap Nappe corresponds to an early phase of continental underthrusting. To the S, in Lahul, an opposite underthrusting within the Indian plate is recorded by the NE vergent Tandi Syncline. This structure is associated with the newly defined Shikar Beh Nappe, now partly eroded, which is responsible for the high grade (amphibolite facies) regional metamorphism of South Lahul.

The main thrusting of the Nyimaling-Tsarap Nappe followed the formation of the Shikar Beh Nappe. The Nyimaling-Tsarap Nappe developed by ductile shear of the upper part of the subducted Indian continental margin and is responsible for the progressive regional metamorphism of SE Zanskar, reaching amphibolite facies below the frontal part of the nappe, near Sarchu. In Upper Lahul, the frontal parts of the Nyimaling-Tsarap and Shikar Beh nappes are separated by a zone of low grade metamorphic rocks (pumpellyite-actinolite facies to lower greenschist facies). At high structural level, the Nyimaling-Tsarap Nappe is characterized by imbricate structures, which grade into a large ductile shear zone with depth. The related crustal shortening is about 87 km.

The root zone and the frontal part of this nappe have been subsequently affected by two zones of dextral transpression and underthrusting: the Nyimaling Shear Zone and the Sarchu Shear Zone. These shear zones are interpreted as consequences of the counterclockwise rotation of the continental underthrusting direction of India relative to Asia, which occurred some 45 and 36 Ma ago, according to plate tectonic models.

Later, a phase of NE vergent "backfolding" developed on these two zones of dextral transpression, creating isoclinal folds in SE Zanskar and more open folds in the Nyimaling Dome and in the Indus Molasse sediments.

During a late stage of the Himalayan Orogeny, the frontal part of the Nyimaling-Tsarap Nappe underwent an extension of about 15 km. This phase is represented by two types of structures, responsible for the tectonic unroofing of the amphibolite facies rocks of the Sarchu area: the Sarchu high angle Normal Fault, cutting a first set of low angle normal faults, which have been created by reactivation of older thrust planes related to the Nyimaling-Tsarap Nappe.

---

[1] Section des Sciences de la Terre, Université de Lausanne, BFSH2, CH-1015 Lausanne.

RÉSUMÉ

Le levé géologique détaillé et l'analyse structurale d'une transversale complète de l'Himalaya nord-occidental permettent de décrire l'évolution tectonique de la marge continentale nord de l'Inde au cours de l'ouverture de l'océan téthysien et de l'orogenèse himalayenne. Le rifting téthysien d'un âge paléozoique tardif est associé à divers événements tectonomagmatiques. Au Lahul supérieur et au Zanskar oriental, cette phase d'extension est enregistrée par des failles de transtension synsédimentaires du Carbonifère inférieur, une discordance stratigraphique du Permien inférieur, une intrusion granitique du Permien inférieur et des extrusions basaltiques du Permien moyen (Panjal Traps). Au Ladakh oriental, une faille listrique permienne est également liée à cette phase. La rareté de failles synsédimentaires et l'augmentation graduelle de l'épaisseur des sédiments syn-rift permiens en direction de la suture suggère une marge continentale de type flexurale.

La collision de l'Inde et de l'Asie se caractérise par une succession de phases orogéniques contrastées. Au S de la zone de suture, l'initiation de la nappe de Nyimaling-Tsarap de vergence SW correspond à une phase précoce du sous-charriage continental. Au S, au Lahul, un sous-charriage opposé, situé à l'intérieur de la plaque indienne est enregistré par le synclinal de Tandi à vergence NE. Cette structure est associée à la nappe du Shikar Beh, définie ici pour la première fois. La surcharge due à cette nappe et à d'autres nappes érodées est responsable du fort métamorphisme régional (faciès amphibolite) au S Lahul.

Le chevauchement principal de la nappe de Nyimaling-Tsarap a suivi la formation de la nappe de Shikar Beh. La nappe de Nyimaling-Tsarap s'est développée par cisaillement ductile de la partie supérieure de la marge continentale indienne subductée. Elle est responsable du métamorphisme régional progressif du Zanskar oriental, qui a atteint le faciès amphibolite sous la partie frontale de la nappe à Sarchu. Au Haut-Lahul, les parties frontales des nappes de Nyimaling-Tsarap et du Shikar Beh sont séparées par une zone de roches à faible métamorphisme (faciès à pumpellyite-actinote). A un niveau structural élevé, la nappe de Nyimaling-Tsarap est caractérisée par une structure imbriquée, passant à une large zone de cisaillement ductile en profondeur. Le raccourcissement crustal lié à la formation de cette nappe est d'environ 87 km.

La zone radicale et la partie frontale de cette nappe ont été affectées par la suite par deux zones de transpression dextre (sous-charriage oblique): la zone de cisaillement dextre de Nyimaling et la zone de cisaillement dextre de Sarchu. Ces zones de cisaillement seraient dues à la rotation antihoraire de la direction de sous-charriage continental de l'Inde par rapport à l'Asie entre 45 et 36 Ma, en accord avec les modèles de tectonique des plaques.

Plus tard, une phase de rétroplissement s'est développée dans les deux zones de transpression dextre, créant des plis isoclinaux dans le Zanskar oriental et des plis plus ouverts dans le dôme de Nyimaling et dans la molasse de l'Indus.

Au cours d'une période tardive de l'orogenèse himalayenne, la partie frontale de la nappe de Nyimaling-Tsarap a subi une extension d'environ 15 km. Cette phase s'accompagne de deux types de structures responsables de la dénudation tectonique des roches du faciès amphibolite de la région de Sarchu: la faille normale de Sarchu, coupant une première famille de failles normales à faible pendage, créées par réactivation de plans de chevauchement de la nappe de Nyimaling-Tsarap.

Introduction

The geological studies of the Himalayan chain in Lahul-Zanskar are often local or based on undetailed geological maps and vast regions are still unmapped. The aim of this work is to establish a model for the formation of the Himalaya, based on the detailed study of a complete transect from NE to SW. Since 1979, geologists from the University of Lausanne studied the region situated along the Manali-Leh road, from the High Himalayan range to the Indus Suture Zone (Fig. 1). Their investigations include a detailed 1/50000 geological mapping and a systematic study of the tectonic structures. This paper presents the synthesis of their observations. The plan of the paper is as follows: after a summary of the stratigraphy and the synsedimentary pre-Tertiary structures of the investigated area, the Tertiary Himalayan structures of the different tectonic units are presented from NE to SW and the regional metamorphism is briefly discussed. From these elements a tectonic model for the continental collision of India and Asia is proposed.

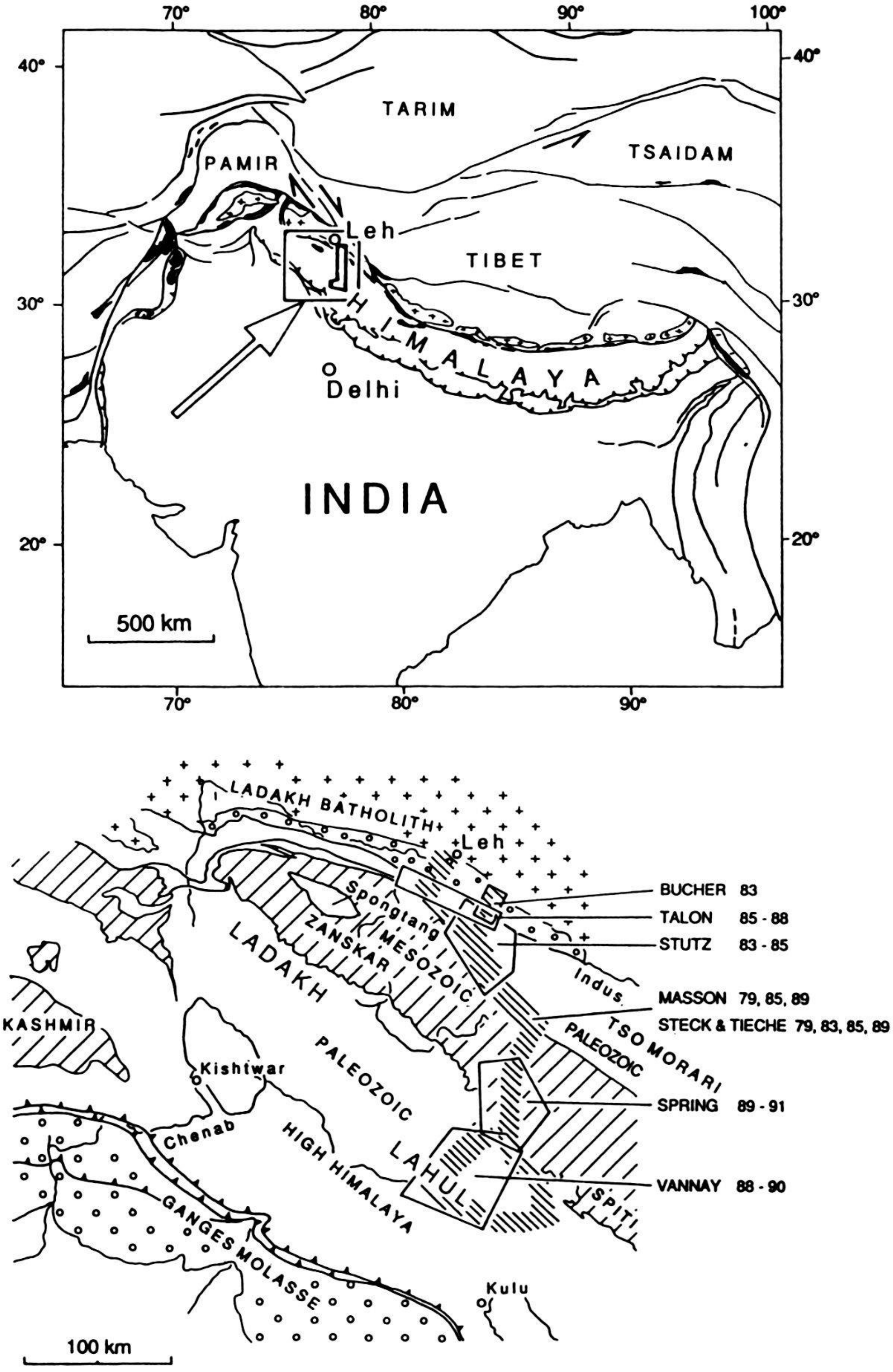


Fig. 1. Index map of the investigated area in Ladakh and Lahul.

Stratigraphy and synsedimentary tectonics

The aim of this paper is to propose a tectonic synthesis of a geological section of the western Himalaya in Ladakh and Lahul (Fig. 1 and Plate 1). For this reason the description of the stratigraphy is restricted to a summary. The stratigraphy of the Tethyan Himalaya in the investigated area is resumed in four profiles (Fig. 2), compiled after Baud et al. (1982), Fuchs (1985), Stutz (1988), Spring & Crespo (1992) and unpublished observations by J.-C. V., H. M., A. S. and J.-C. T.

A palinspastic reconstruction of the northern continental margin of India some 54 Ma ago, at the time of the collision with Asia is presented in Fig. 3. Note the scarcity of Late Paleozoic syn-sedimentary structures (Lower Carboniferous transtensional faults in Upper Lahul and a Permian listric fault in the Nyimaling Region, Plate 1) and the regular increase of the Permian syn-rift sediment thickness over a distance of more than 150 km, from the rift shoulder to the S to the first normal fault to the N. On the base of these features, this N Indian continental border is interpreted as a flexural passive margin (Wernicke 1985, Voggenreiter et al. 1988). The mechanical and rheological behavior of the N Indian margin during the Tertiary collisional processes has been influenced by several lithological and structural parameters, which are the consequences of its pre-Tertiary evolution. The following observations resume these parameters:

1) In this part of the Himalaya the oldest known rocks have been described by Frank et al. (1977) in the Berinag Series of the Larji-Kulu-Rampur Window, S of the studied area (meta-rhyolites and meta-granites: Rb/Sr whole rock isochron of 1840 ± 70 Ma).

In the investigated area, the N Indian continental margin is characterized by a continuous stratigraphic sequence, beginning with Upper Precambrian to Cambrian sandstones and slates (Phe Fm.) and ending with calcarenites, sandstones and slates of Eocene age. The different formations of this stratigraphic sequence have been described by Bassoulet et al. 1983, Baud et al. 1982, 1984, Bucher & Steck 1987, Fuchs 1982, 1985, Gaetani et al. 1986, 1987, 1990, Gaetani & Garzanti 1991, Garzanti & Van Haver, 1988, Garzanti et al. 1987, Gilbert et al. 1983, Jadoul et al. 1990, Nanda & Singh 1976, Pickett et al. 1975, Srikantia et al. 1980, Stutz 1988, Sutre 1990 and Van Haver et al. 1984. In this part of the Himalaya, no discordance between a polymetamorphic, strongly folded basement and monometamorphosed cover rocks is known, as it is typical for the European Alpine Chain. Unconformities and gaps in the stratigraphic pile and synsedimentary normal faults are related to pre-Tertiary tectonic events within the Indian continental plate and its passive margin (Fig. 2 & 3).

2) Cambro-Ordovician granites intrude the Upper Precambrian to Lower Cambrian Phe Fm. in Lahul and the Phe and Karsha Fms. of the Nyimaling Massif in eastern Ladakh. In Lahul, Rb/Sr whole rock radiometric age determinations for the intrusive granites, cropping out in the Chandra and Bhaga valleys, range from earliest Cambrian to early Ordovician: Rohtang Granite, 581 ± 9 Ma, (Mehta 1977), Kade-Jispa-Rohtang Granites 495 ± 16 Ma, (Frank et al. 1977). The Nyimaling Granite gave a Rb/Sr whole rock isochron age of 460 ± 8 Ma (Stutz & Thöni 1987). The high $^{87}Sr/^{86}Sr$ initial ratio of these intrusives indicates a crustal origin for these rocks. It is important to note that the Cambro-Ordovician granites intrude the undeformed Precambrian and Cambrian sediments of the Phe and Karsha Fm. This magmatism may be related to the same extensional tectonic event responsible for synsedimentary faults in the Ordovician Thaple Fm.

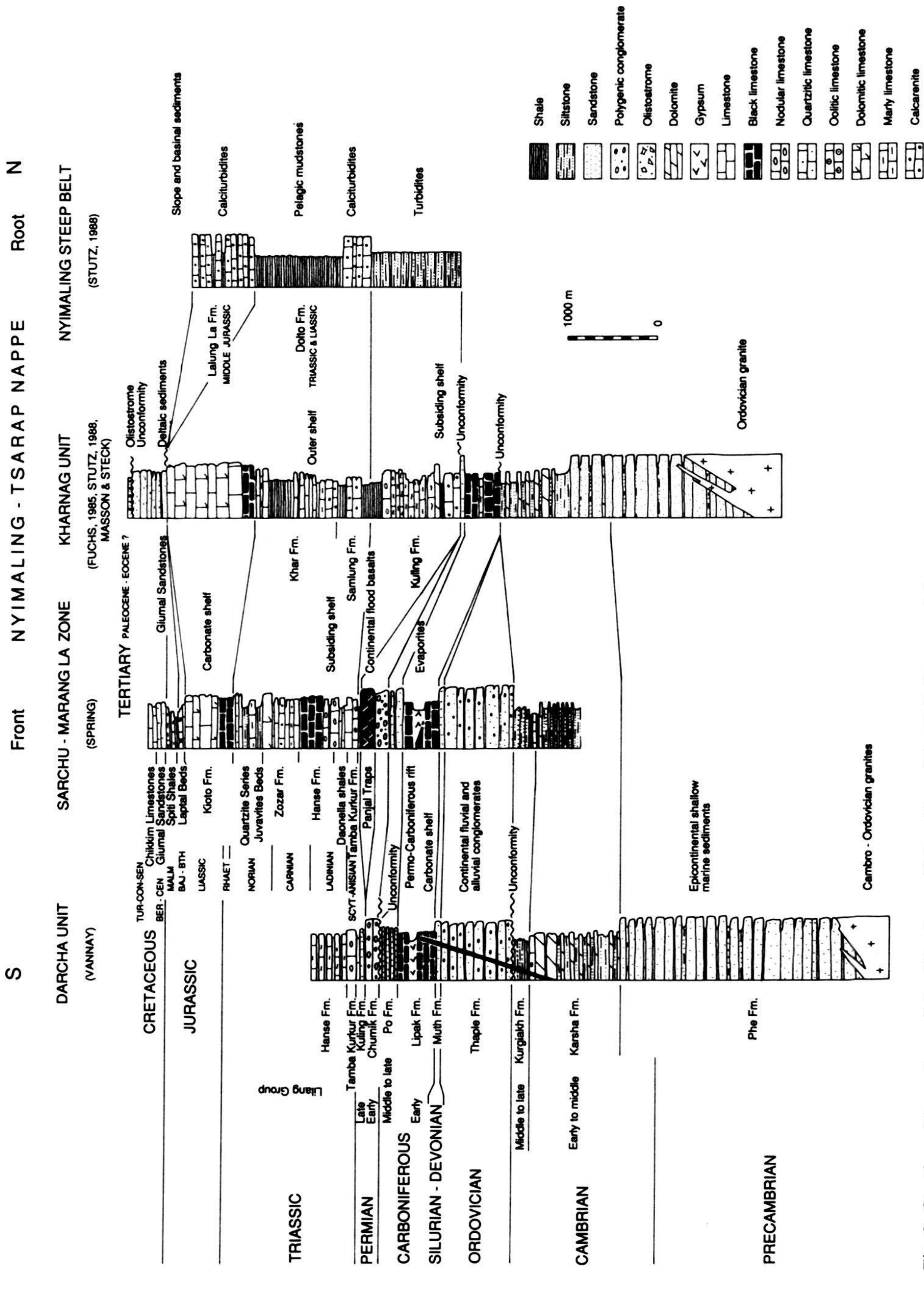


Fig. 2. Stratigraphic sections of the Himalayan Tethys Zone (North Indian margin).

3) In the Ordovician Thaple Fm. a NW–SE striking synsedimentary normal fault, sealed by the overlying Devonian Muth Quartzites, has been observed in SE Zanskar, south of the Lingti Chu (Fig. 3).

4) Synsedimentary transtensional faults, contemporaneous with deposition of the Early Carboniferous Lipak Fm., have been observed south of the Baralacha La (Pass), in Upper Lahul. These structures are intruded by basaltic dikes, grouped in a swarm called the Baralacha La Dike Swarm. A geochemical study indicates these rocks are alkalic Within Plate Basalts. Their geochemical signature differs clearly from the middle Permian tholeiitic Panjal Traps continental flood basalts (Vannay & Spring 1993). These Permo-Carboniferous tectono-magmatic events are most probably related to the initiation of the Neo-Tethys rifting. The Baralacha La Dike Swarm and the Early Carboniferous faults have been subsequently overprinted by the Tertiary Baralacha La Thrusts.

5) Stutz (1988) mapped a very important listric normal fault of Permian age in the Nyimaling Region (Plate 1 and Fig. 3). In his 1988 paper, Stutz interpreted this structure as a simple thrust fault. This structure is now reinterpreted as a Permian normal fault, related to the opening of the Permian Tethys and reactivated by thrust movements during Tertiary time.

6) The continental crust of Northern India was thinned during the Permian opening of Tethys mainly as a consequence of internal ductile deformation. The distance between the continental shelf border and the Permian rift shoulder is estimated at 200 km (Fig. 3). The opening of the oceanic domain was achieved in early Triassic time (Bassoulet et al. 1981).

7) The rheological behavior of the different formations in the stratigraphic pile depends mainly on the temperature. Deformed at low temperature, shales and marly limestones represent the most ductile rocks of the stratigraphic pile and act as "décollement zones" by simple shear processes. The Middle to Upper Cambrian Kurgiakh Fm., Lower Carboniferous Lipak Fm., Upper Permian Kuling Fm. and the Triassic Lilang Group are composed of such ductile rocks (Fig. 2). With metamorphic temperatures attained at the greenschist and amphibolite facies (Fig. 31), the rocks of the whole stratigraphic pile have a ductile behaviour.

Himalayan tectonics

The Indus Molasse

The Lower Tertiary sediments of the Indus Molasse have been deposited in an intramontane basin, developed behind the fore-arc basin of the convergent margin of Asia, south of the Ladakh Batholith (Garzanti et al. 1987). Near Upshi, 45 km SE of Leh in the upper Indus Valley, the conglomerates of the Indus Molasse overlie the intrusives of the Ladakh Batholith (Frank et al. 1979 and Fig. 4). On the southern slope of the Indus Valley, thrust planes of the Hemis Thrust indicate an overthrust of the Molasse sediments toward the NE (Fig. 4 and 5 and Frank et al. op. cit.).

Farther to the S, in the Martselang-Gongmaru La section, the structural style of the Indus Molasse is characterized by open synclines and anticlines, like the spectacular syncline of Hemis Gompa (Fig. 4 and Frank et al. 1977, Fig. 9). Fault structures as drawn on the sections of Baud et al. (1982), Van Haver et al. (1984), Garzanti & Van

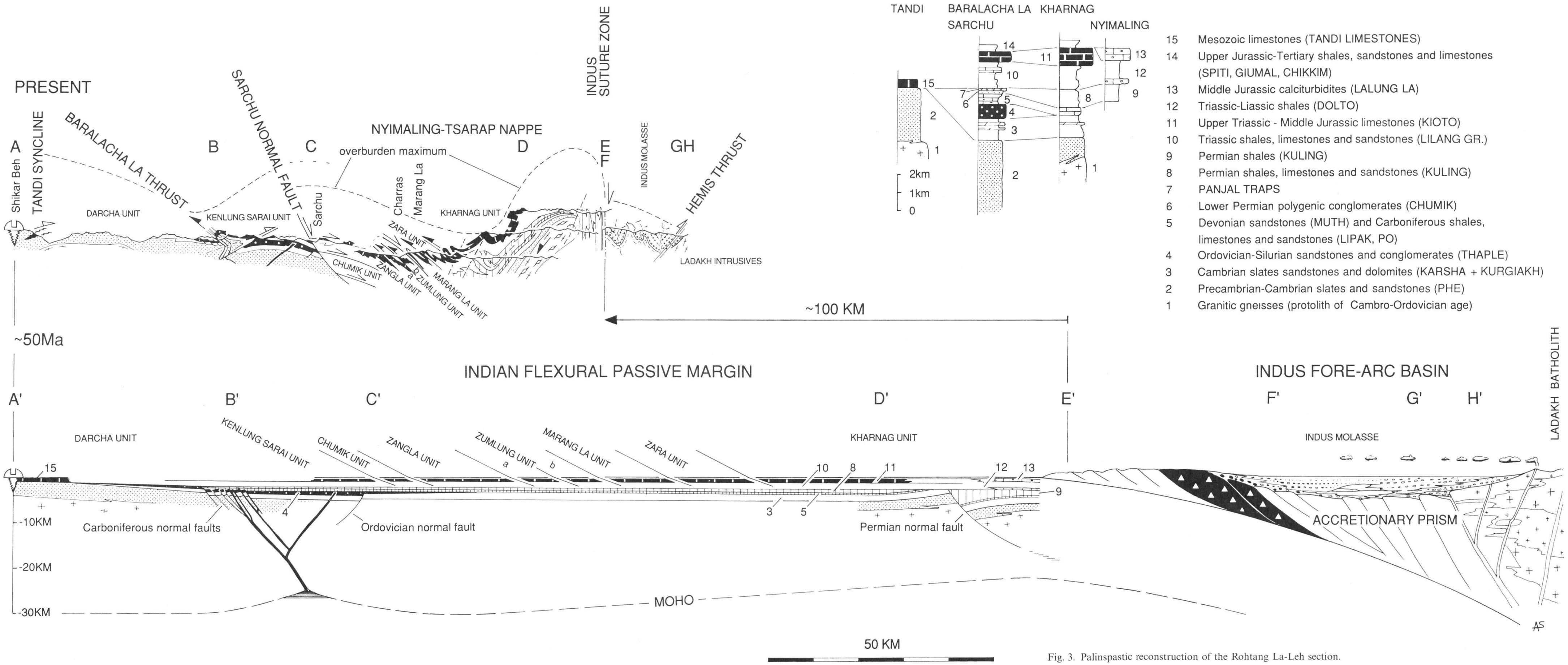


Fig. 3. Palinspastic reconstruction of the Rohtang La-Leh section.

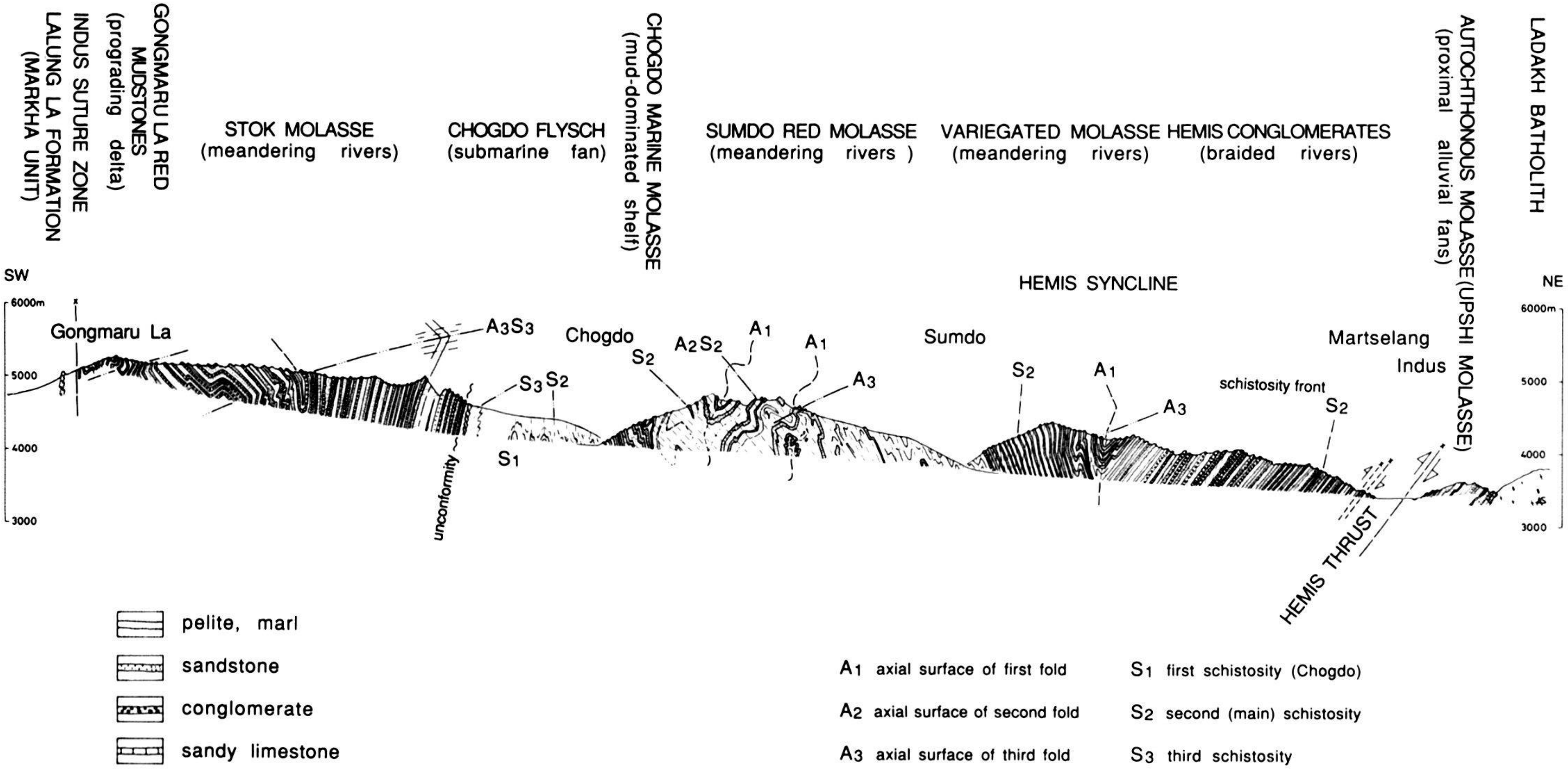


Fig. 4. Geological section of the Indus Molasse between Martselang in the Indus Valley and Gongmaru La.

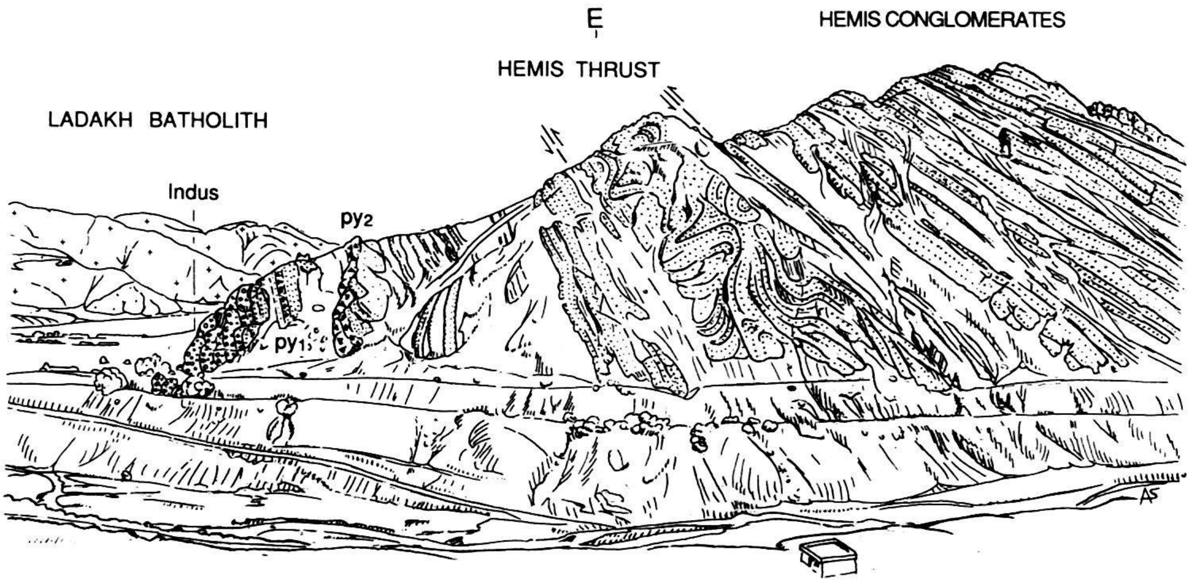


Fig. 5. View in an eastern direction on the Hemis Thrust, in the valley S of Martselang. py1 and py2 are explosive pyroclastic deposits in the Molasse conglomerates. white = sand- and siltstones, dashed = conglomerates.

Haver (1988) and Frank et al. (1987) have not been observed. Geological mapping shows that these structures rather correspond to strongly deformed zones characterized by disharmonic deformation on lithological boundaries (Bucher & Steck 1987).

A detailed structural analysis allows us to distinguish up to 3 generations of NE vergent folds and two schistosities. Fig. 6 represents a palinspastic reconstruction of the Indus Molasse section and Fig. 7a kinematic model for the post-Eocene folding and thrusting of the Indus Molasse Basin. The relations of superposed folds and schistosities show that they have been created during a rotational deformation, related to a progressive overthrust of the Molasse sediments toward the NE (Figs. 5–10). The first schistosity is restricted to the very ductile Chogdo Flysch, in the lowest part of the Molasse sequence. In the southern part of the section, between Gongmaru La and Sumdo, the second and main schistosity (S_2) is the axial surface structure (A_2) of F_2 folds. To the N, the main schistosity (S_2) becomes the axial surface structure (A_1) of the less deformed Hemis Syncline (F_1) (Figs. 4 and 7). The metamorphic grade of the Molasse sediments decreases from prehnite – pumpellyite facies between the Gongmaru La and Sumdo to very low grade in the Indus Valley. From SW to NE, the intensity of the main schistosity S_2 decreases in the same way with a "schistosity front" about 1 km south of Martselang (Figs. 4 and 7). These observations indicate that the deformation and metamorphism are related to a late NE vergent overthrust of the Tertiary Himalayan Chain onto the Molasse basin (Baud et al. 1982, Van Haver et al. 1984, Searle et al. 1990).

The Indus Suture

The Indus Suture is a major Cretaceous and Tertiary structure of the Himalaya and it had a long and complicated geological history (Plate 1 and Fig. 11). It marks the vertical contact of the Indus Molasse with the sediments of the root zone of the Nyimaling-Tsarap Nappe (Zanskar Nappes). The latest movements on the Indus Suture corre-

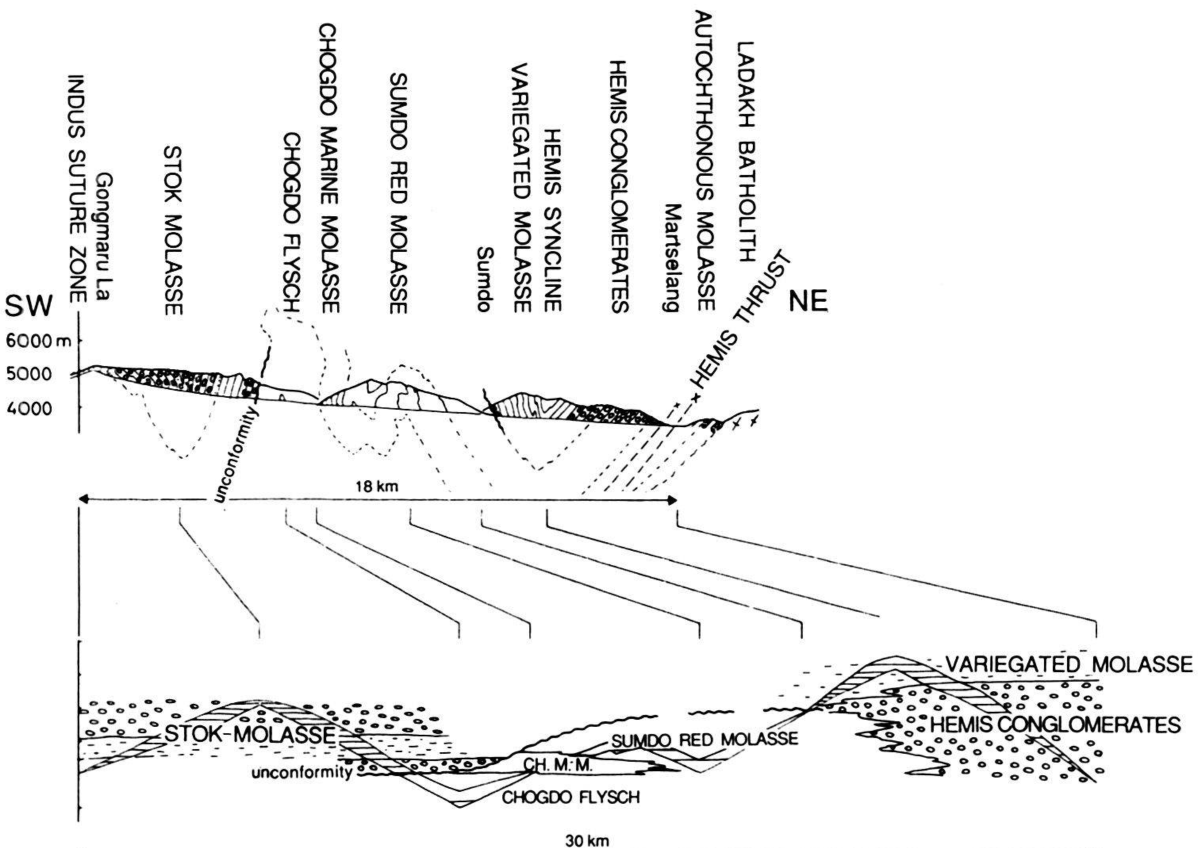


Fig. 6. Palinspastic reconstruction of the Indus Molasse section. The length balanced cross section is an approximation that does not consider ductile deformation in the slates and siltstones, responsible for change in internal deformation and disharmonic folding.

spond to an uplift of the Nyimaling Dome relative to the Molasse sediments. In this zone, root equivalents of the Spongtang Ophiolites and other nappes existing as "klippes" on top of the Zanskar nappes have been observed as tectonic slices farther to the NW, in the Markha Valley. It is beyond the aim of this paper to propose a model for the kinematics of the Indus Suture. This subject is discussed by Bassoulet et al. (1983), Gilbert et al. (1983), Honegger et al. (1982), Trommsdorff et al. (1983), Sutre (1990) and Talon (Ph.D. thesis, in preparation).

The Nyimaling Dome

The Nyimaling Dome forms the north-western end of the so called "Tso Morari Crystalline" (Berthelsen 1953, Baud et al. 1982, Thakur 1983a & b, Stutz & Steck 1986 and Stutz 1988). Figs. 11 and 12 show the structural outlines, represented on horizontal geological sections. We principally distinguish two generations of structures, related to the Himalayan Orogeny. The older group of structures was generated during the underthrusting of the Indian continental plate below Asia, and are associated with the formation of the Nyimaling-Tsarap Nappe. The younger structures are related to the creation of the Nyimaling Dome. Table 1 summarizes the chronology of the Tertiary Himalayan structures in the studied area.

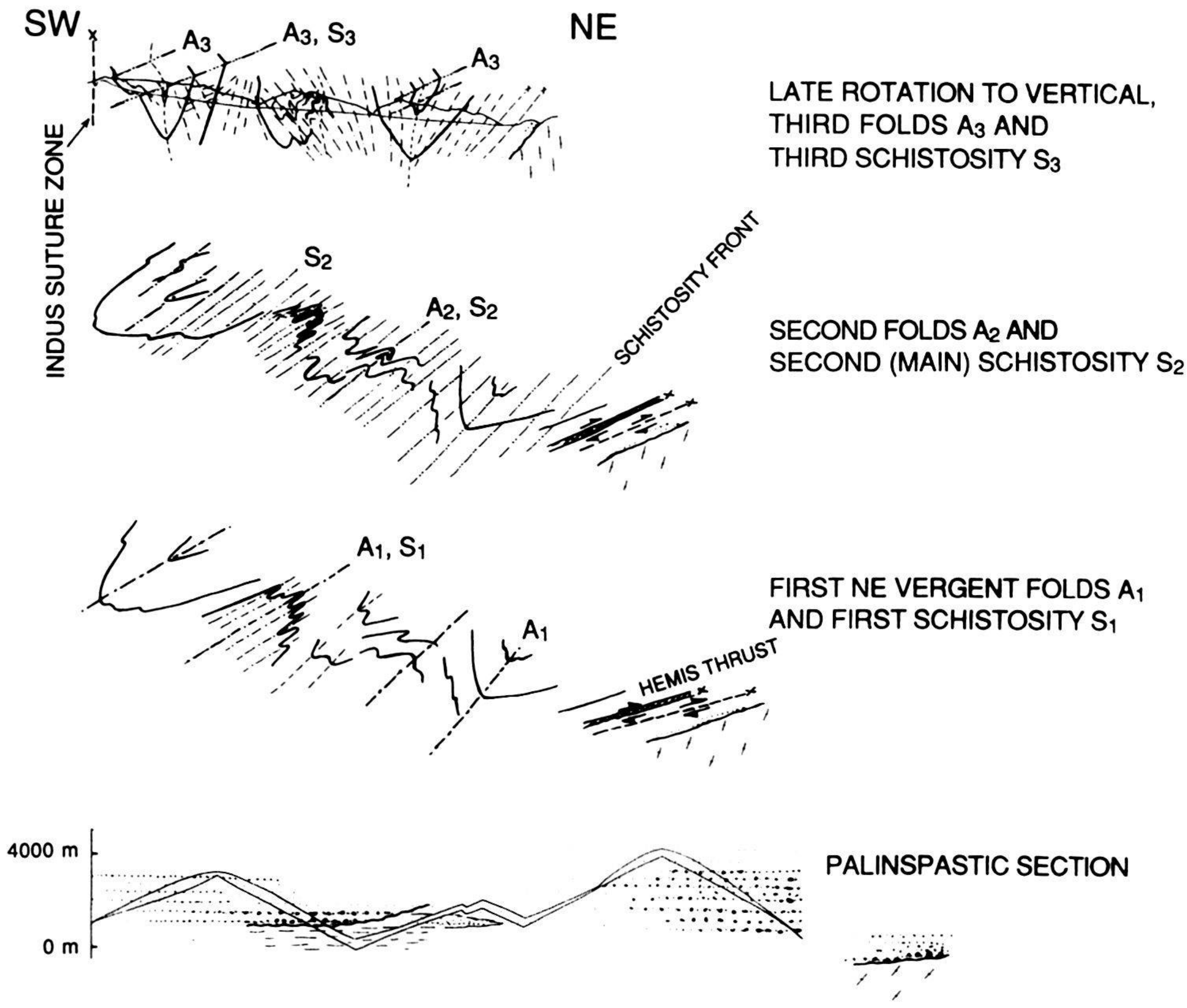


Fig. 7. Kinematic model for the NE vergent folding and thrusting of the Indus Molasse. A_1, A_2 and A_3 = axial surfaces of F_1, F_2 and F_3 folds respectively, S_1, S_2 and S_3 = related schistosities.

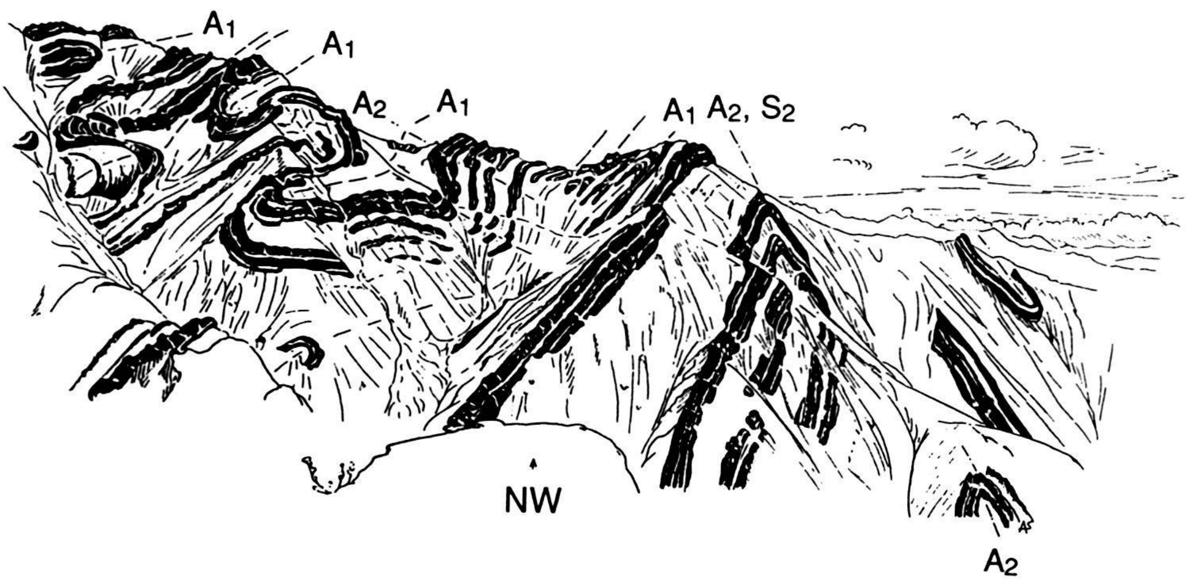


Fig. 8. NE vergent first and second generation folds in the Sumdo Red Molasse. The Sumdo Red Molasse corresponds to meandering river deposit; coarse sandy channel fills in black and red siltstones in white.

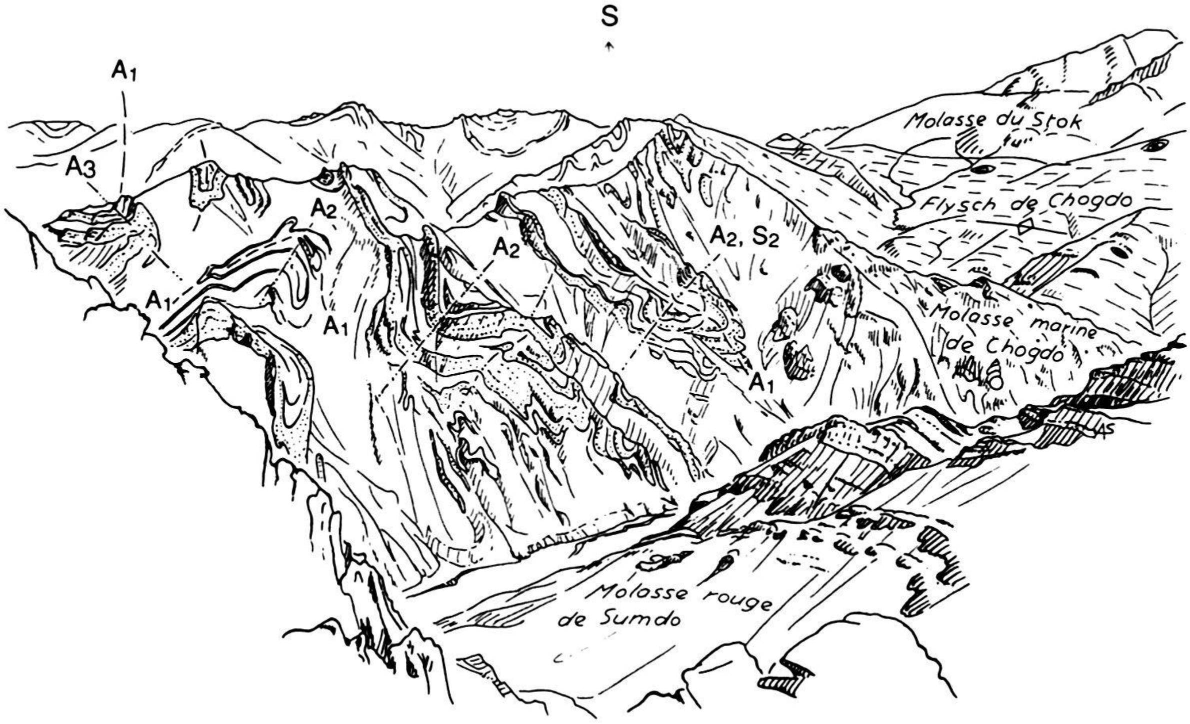


Fig. 9. Three generations of NE vergent folds in the Sumdo Red Molasse.

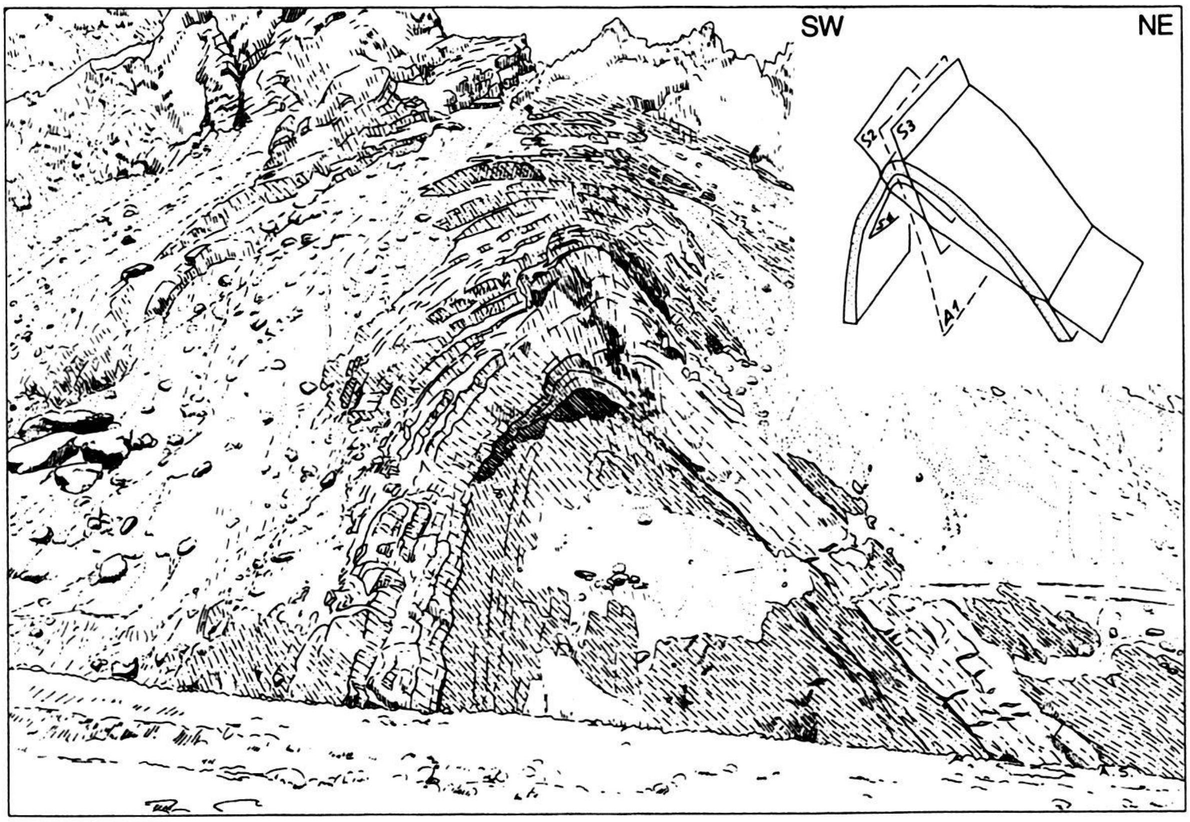


Fig. 10 A first phase fold F_1 (A_1 = axial trace) in the Sumdo Red Molasse S of Chogdo. The main schistosity S_2 cuts the anticline obliquely, indicating the NE vergence of the progressive and rotational deformation. The fold was later rotated in an anticlockwise sense into its present vertical position.

Table 1. Chronology of the Tertiary Himalayan structures in eastern Ladakh and Lahul

Continental collision and beginning of underthrusting of India below Asia (~ 54 Ma).		
A)	Early initiation of SW vergent Nyimaling-Tsarap Nappe	D1
Early NE vergent movements.		
B)	NE vergent folds F_{Ta1}, axial surface schistosity S_{Ta1} and stretching lineation L_{Ta1}: Tandi Syncline, Shikar Beh Nappe	DTa1
Main SW vergent deformations and subsequent dextral transpression and backfolding.		
C)	SW vergent folds F_{Ta2}, axial surface schistosity S_{Ta2} and an E to ENE oriented stretching lineation L_{Ta2}: SW vergent deformation of Tandi Syncline	DTa2
D)	SW vergent thrusts and folds F_2, axial schistosity S_2 and NE oriented stretching lineations $L_1 + L_2$: main development of the Nyimaling-Tsarap Nappe, Baralacha La Thrust and Chandra Tal Flexure	D2
E)	Dextral shear and underthrusting (transpression) parallel to NW-oriented stretching lineation L_3: Nyimaling and Sarchu Shear Zones	D3
F)	NE vergent "back" folds F_4, doming and dextral transpression related to the creation of the Nyimaling similar fold	D4
G)	Late dextral shear in Nyimaling-Markha Valley Steep Belt (S_5)	
Late extensional structures of Sarchu region		
H)	Low angle normal faults (reactivation of preexisting D_2 thrust planes)	D5
I)	Steep Sarchu Normal Fault	
Late compression		
J)	NE-SW compression and vertical extension: symmetric box-folds in the Nyimaling dome W vergent folds in the Kenlung Sarai Unit near Sarchu	D6

The first stretching lineation of the Nyimaling-Tsarap Nappe was labelled L_2, as this structure and the associated F_2 folds are overprinting the F_{Ta1} fold in the Chandra Valley (Fig. 29). The L_2 stretching lineation is older in the Nyimaling region than in the frontal part of the Nyimaling-Tsarap Nappe, represented by the Baralacha La Thrust and Chandra Tal Flexure. The temporal relation between L_2 in the Nyimaling region and L_{Ta1} in the Chandra Valley is not established. Two schistosities (S_1 and S_2) with the associated NE oriented L_2 stretching lineation are related to the tectonic transport of the Nyimaling-Tsarap Nappe towards the SW. The stretching lineation L_2 is still preserved in its original orientation between Jakang in the Nyimaling Massif and Charras in the Tsarap Valley (Figs. 12 and 14). Within the Nyimaling Dome the stretching lineation L_2 is generally transposed by younger deformations, mainly by the stretching lineation L_3, which is related to a later underthrusting of India below Asia in a NNW direction. This dextral transpression is oblique to the root zone of the Nyimaling-Tsarap Nappe. The intense extension associated with the younger D_3 deformation has created the spectacular kilometer-scale Bya-Ri sheath fold by overprinting a F_1/F_2 fold hinge intersection (Figs. 11 and 13). On the geological map (Plate 1 and Fig. 30), the younger stretching lineation L_3 is confined to a 30 km large dextral transpressional shear zone, limited to the NE by the Indus Suture and to the SW by a line that connects the villages of Dat and Lun. The main schistosity S_2 has been transposed by internal deformation without generating a new schistosity S_3.

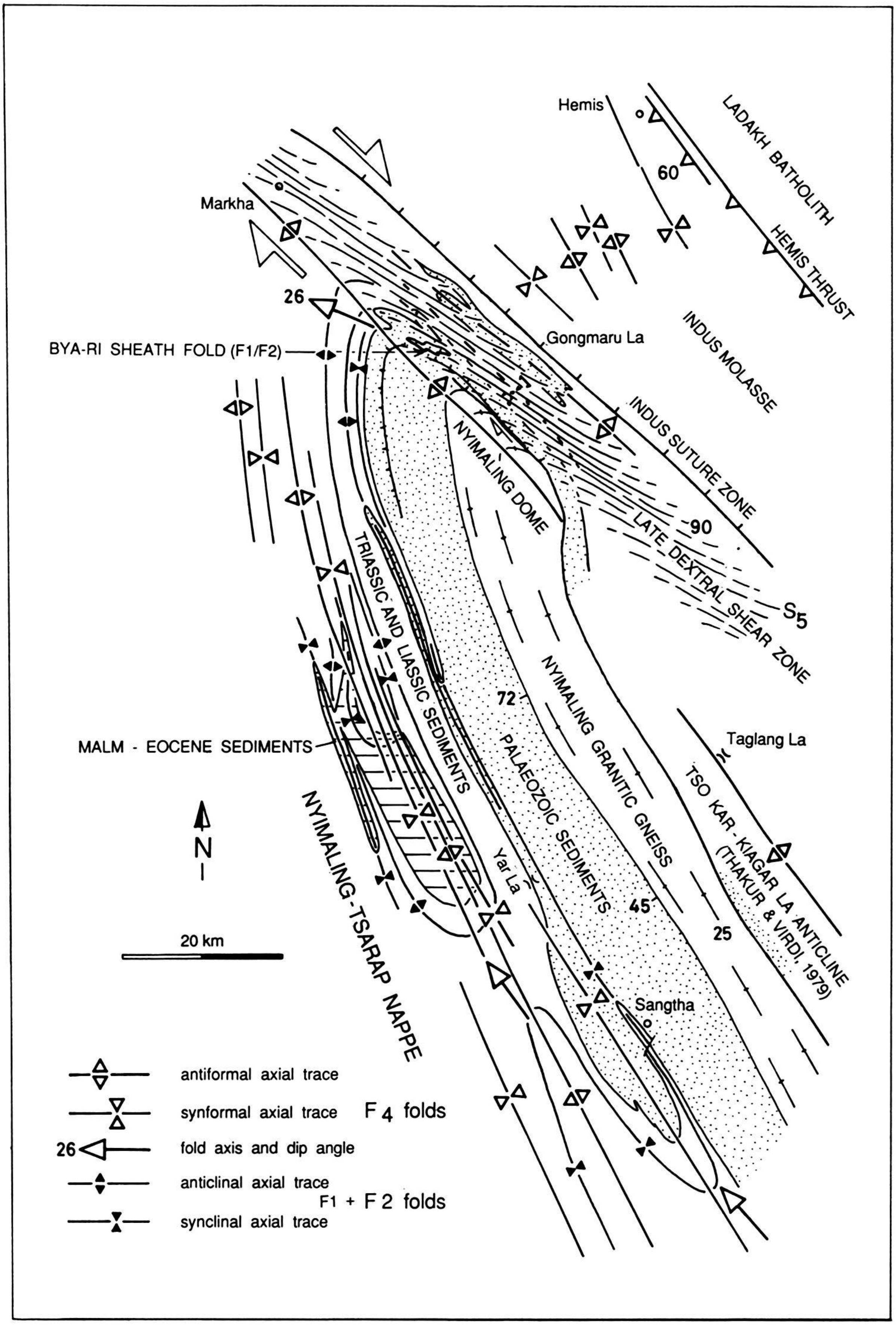


Fig. 11. Structural map of the Nyimaling Anticline (horizontal section at 5000 m). Fold structures and late dextral shear zone of the Nyimaling-Markha Valley Steep Belt.

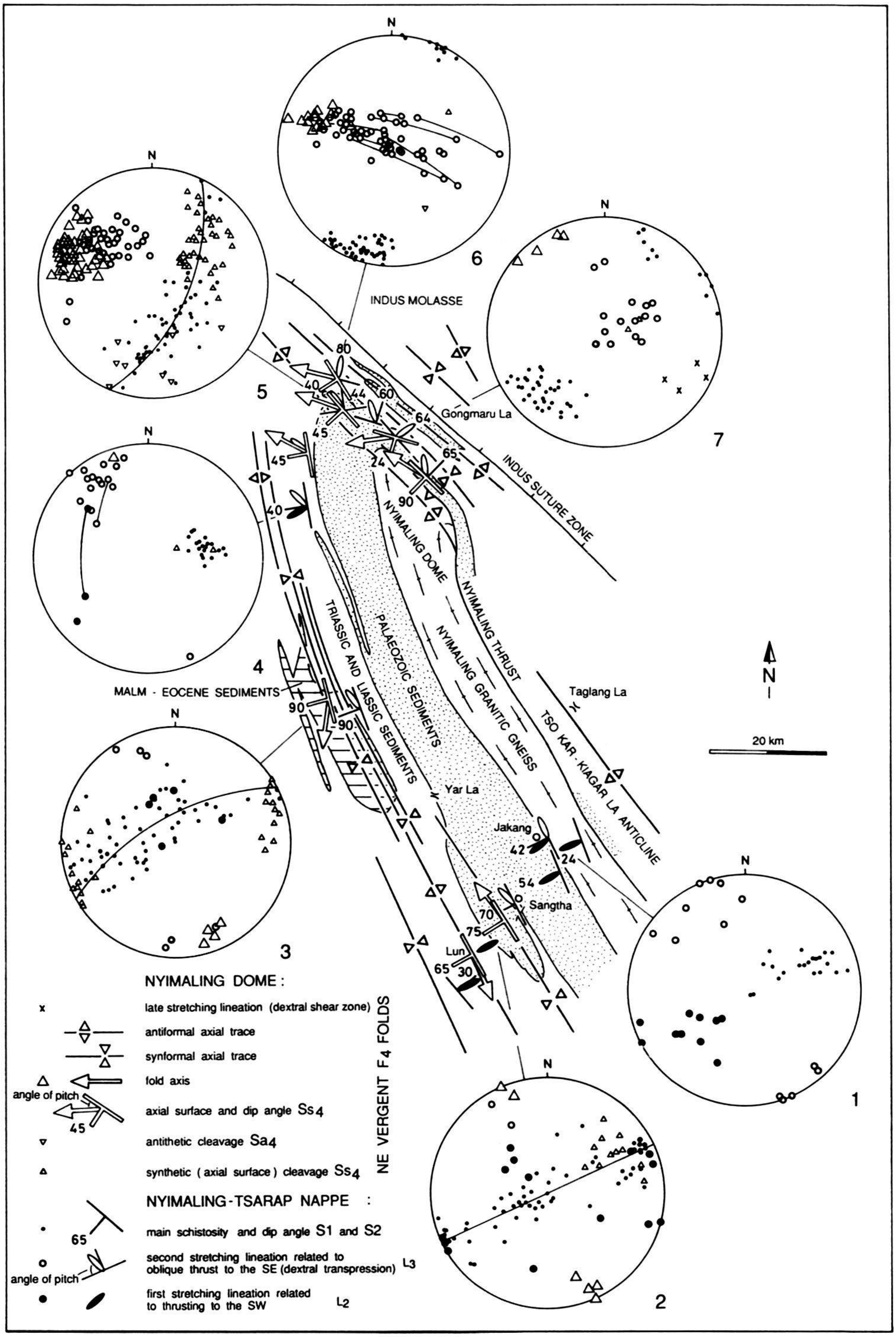
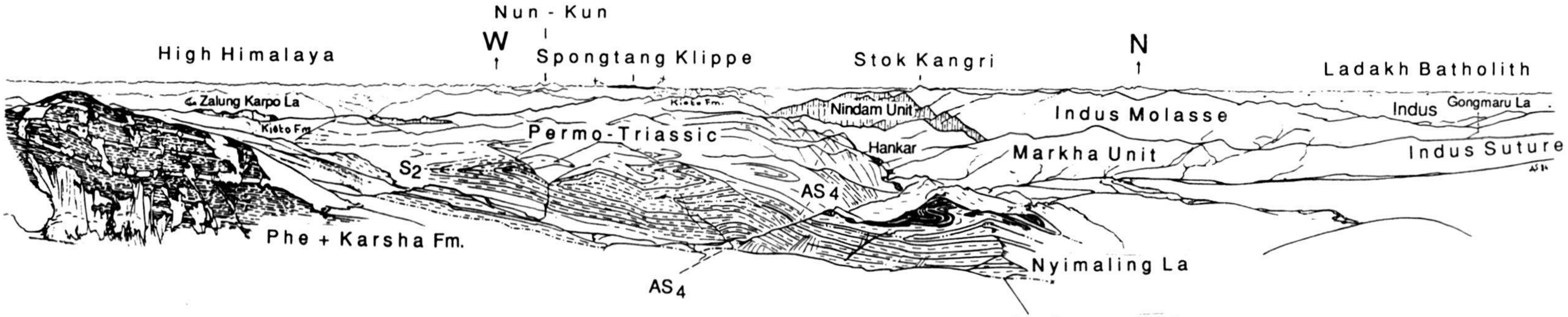
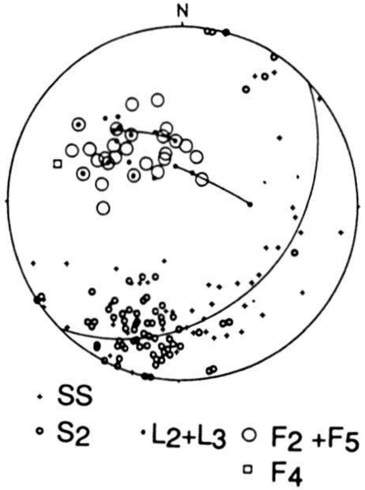


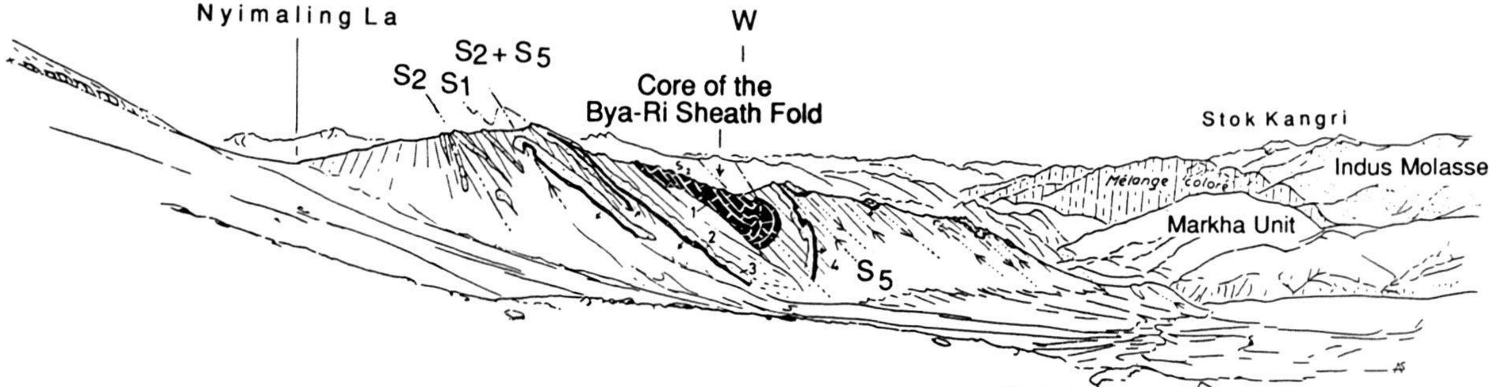
Fig. 12. Structural map of the Nyimaling Anticline. Schistosities and stretching lineations (stereograms. Schmidt projection, lower hemisphere).



Panoramic view from the Kanyatse



Structures of the Bya-Ri Sheath Fold



View of the northern ridge of the Kanyatse and the Markha Valley

Permian Kuling Formation :

4	Calcarenites
3	Quartzites
2	Black shales
1	Crinoid Limestone

The Nyimaling dome is a NE vergent "back"fold which deforms all the preexisting schistosities and the two stretching lineations L2 and L3 of the Nyimaling-Tsarap Nappe. The Nyimaling dome can be interpreted as a similar fold, with a direction of slip ***a*** (Ramsay 1967, p. 470) gently dipping to the NW and parallel to the shear direction in a zone of dextral transpression (Stutz & Steck 1986). The rotation to a vertical plane and uplift of the "root zone" of the Nyimaling-Tsarap Nappe relative to the Indus Molasse, and the reactivation as a vertical fault of the Indus Suture in a late phase, are both related to this deformation D4. In the Nyimaling-Markha Valley Steep Belt (northern limb of the antiform), dextral shear continues in the ductile shales and marls. This dextral shear generates a vertical schistosity S_4 (Stutz 1988 and Figs. 11 and 13). In the hinge zone of the Nyimaling Dome in the Langthang Valley, box folds associated with an NE–SW oriented direction of compression and a subvertical direction of extension, are related to a late compression of the dome structure.

We conclude that the Nyimaling Dome is a structure created during dextral transpression overprinting the "root zone" of the Nyimaling-Tsarap Nappe (Fig. 30).

The Nyimaling-Tsarap Nappe

In this paper, we propose the name Nyimaling-Tsarap Nappe for the whole thrusted pile of sedimentary rocks situated between the Indus Suture to the N and the Sarchu region to the S. Discordant thrust planes inside the higher and frontal part of this super-nappe allow a subdivision in different units (plate 1 and Fig. 3). In the Nyimaling-Tsarap Nappe one can follow the gradual transition through distinct deformation styles typical of different tectonic levels (Figs. 13–18). To the N, between the Gongmaru La and Dat in the Kharnag region, deformation under upper greenschist facies conditions is ductile and penetrative. In this deepest and most ductile part of the nappe, simple shear is the main mechanism of deformation. In the Nyimaling region, discrete thrust planes are generally missing, with the exception of a thrust structure, which has been developed by reactivation of a pre-existing Permian normal fault. On this originally NE dipping fault, younger Permian sediments are overlying, from N to S, sediments of upper Precambrian to Permian age, proving that this structure was first a normal fault. A slice of Cambrian dolomites in the Permian sediments indicates a later (Tertiary) overthrust of about 4 km along the Permian normal fault (Stutz 1988). In the Nyimaling Region, the deformation is more intense in ductile members, especially in the 3000 m thick Triassic and Permian marly sediments and Carboniferous limestones, but also in the Nyimaling Granitic Gneiss (Fig. 14). It is generally less intense in the Upper Precambrian and Cambrian sandstones of the Phe and Karsha Fms. Some lenses in the Nyimaling Granite and the rigid black colored pelitic sandstones (hornfels) of the contact aureole of the granite, escaped the penetrative deformation. It is probable that the Nyimaling Gneiss, which overlies north of Jakang the younger Karsha Fm., represents a Tertiary

---

Fig. 13. Panoramic views of the isoclinal recumbent folds and sheath folds of the "root zone" of the Nyimaling-Tsarap Nappe. The fault on the Nyimaling La is a Permian normal fault, that has been reactivated as a thrust fault in Tertiary time. In black: yellow crinoid limestone forming the core of the kilometric Bya-Ri Sheath Fold (F_1/F_2). This figure represents a new interpretation of Fig. 5 in Stutz & Steck (1986).

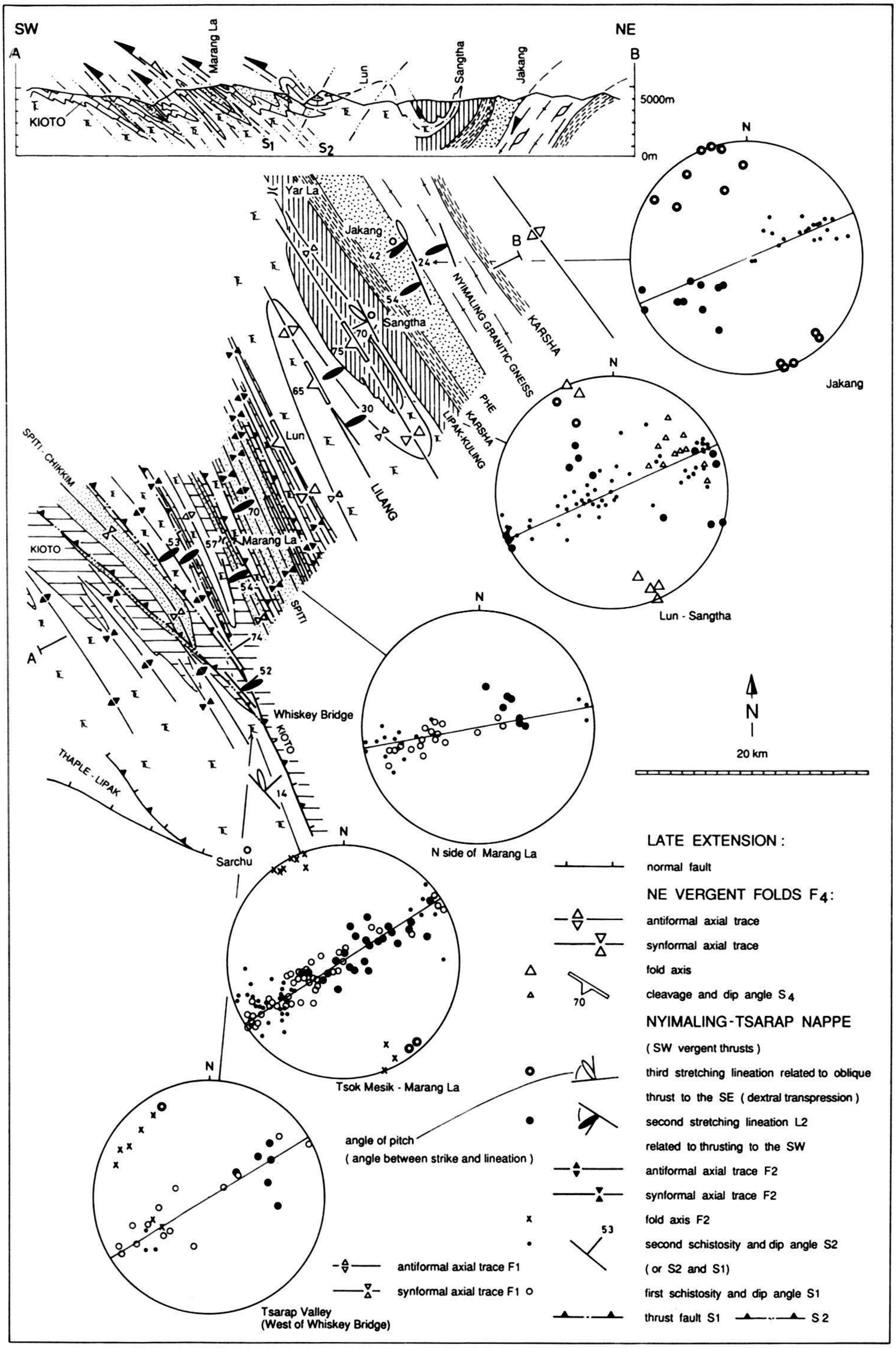


Fig. 14. Structural map of the Nyimaling-Tsarap Nappe (horizontal section at 5000 m, stereograms. Schmidt projection, lower hemisphere).

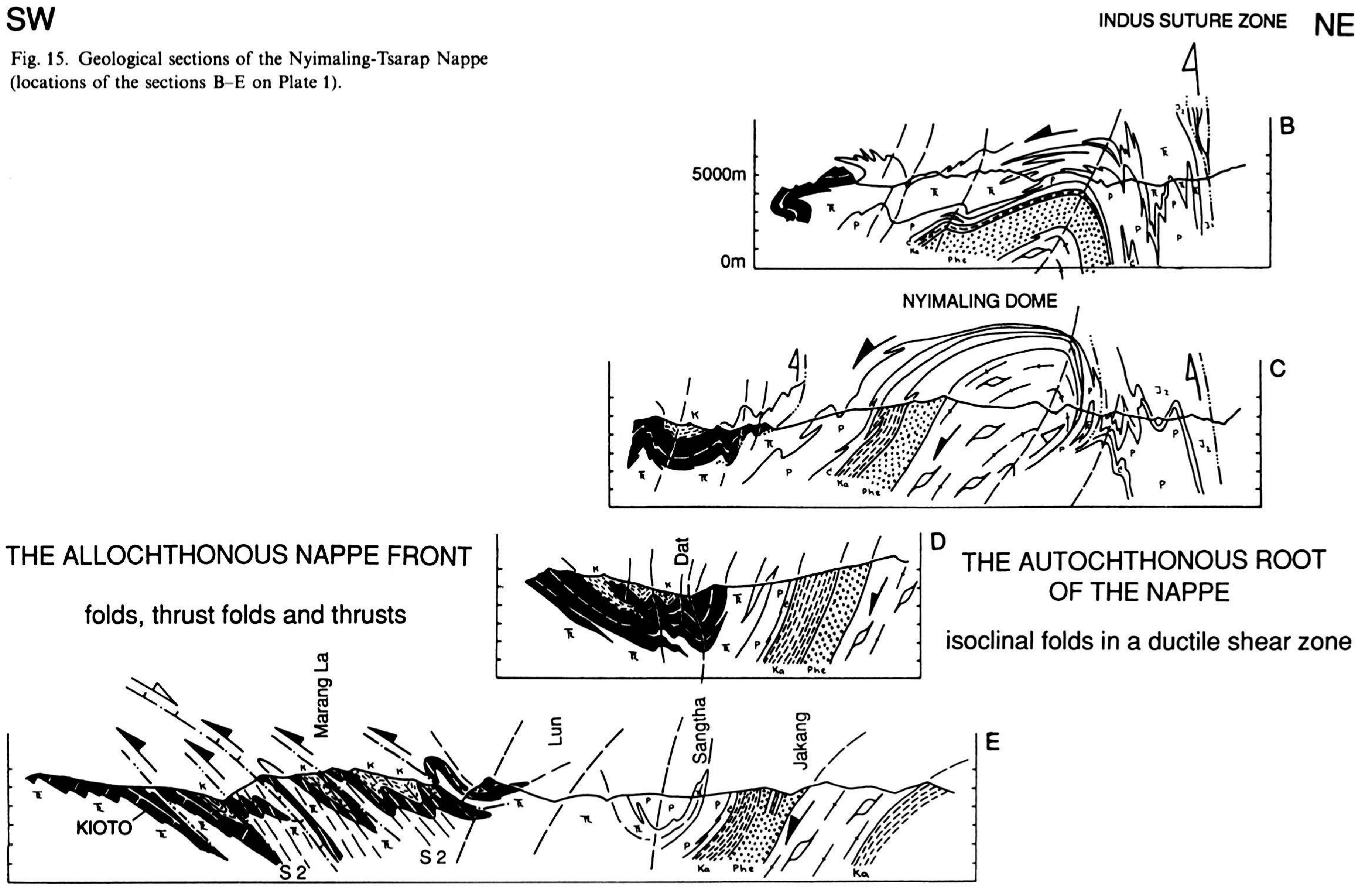


Fig. 15. Geological sections of the Nyimaling-Tsarap Nappe (locations of the sections B–E on Plate 1).

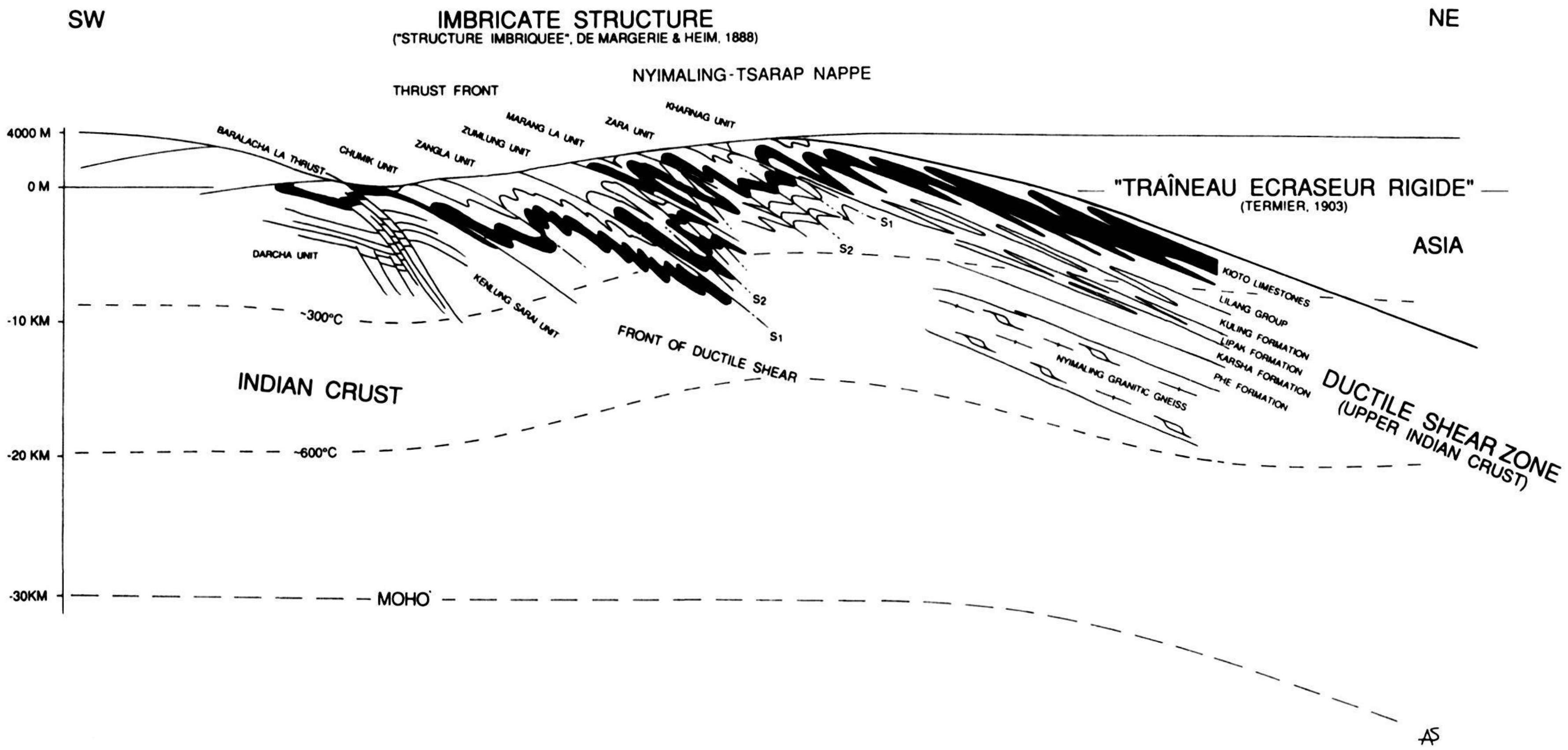


Fig. 16. Structural model for the Nyimaling-Tsarap Nappe (situation before backfolding, extension, uplift and erosion). An imbricate structure with discrete thrust surfaces characterizes the upper tectonic level. This structure grades into a large ductile shear zone with depth, and is associated with large recumbent folds. This nappe structure has been developed by ductile shear of the upper Indian crust during underthrusting below the Asian Plate.

recumbent gneiss fold (Fig. 14). Farther to the SE, the profiles of Berthelsen (1953) suggest similar structures in the Tso Morari region, where deeper structural levels crop out. The structure of the Nyimaling Granitic Gneiss unit is comparable to the recumbent gneiss fold nappes of the Alps (Steck 1987, Escher & al. 1988, Steck et al. 1989, Escher et al. 1992).

To the S, the region between Lun and Sarchu corresponds to a higher tectonic level in the Nyimaling-Tsarap Nappe. The deformation concentrates on discrete thrust planes, responsible for a "ramp-and-flat" tectonic style. These thrust planes are located in the frontal part of the Nyimaling-Tsarap Nappe, where they define the limits of different tectonic units, as in an imbricate structure ("structure imbriquée", De Margerie & Heim 1888). Towards the internal parts of the nappe, these thrusts gradually disappear in the ductile Triassic and Permian marls and shales and in the ductile "root zone" (Figs. 3, 15 and Plate 1). This relationship between discrete, more brittle shear zones in a high tectonic level and a large ductile shear zone in a structural deeper level, is schematically shown in Fig. 16. The sense of overthrust is shown by the vergence of asymmetric folds. The precise direction of movement of the Nyimaling-Tsarap Nappe is indicated by the NE-SW oriented stretching lineation L_2, corresponding to the great X axis of the strain ellipsoid and developed on the two schistosities S_1 and S_2 (Fig. 14). The thrust planes and first generation folds F_1 have been formed simultaneously with the development of the first schistosity S_1. The second schistosity, which is the axial surface schistosity of the second generation folds F_2, generally shows a steeper dip towards the NE and often makes an angle of about 20° with S_1. With the progressive development of S_2, the overthrusting movements on the preexisting discrete main thrust planes S_1 continued. This relationship between these different structures of a progressive rotational deformation is clearly visible in the thrust zones between the Tsarap River and the Marang La (Figs. 17 and 18). The southern front of the Nyimaling-Tsarap Nappe is affected by the very complex structures of the Sarchu Zone (Spring & Crespo 1992). The length balanced cross section of Fig. 3 shows a shortening of about 90 km related to the thrusting of the Nyimaling-Tsarap Nappe. This approximate palinspastic reconstruction does not take into account the amount of internal ductile deformation of the rocks. The Nyimaling-Tsarap Nappe has been developed by ductile shear of the upper Indian crust during underthrusting of the Indian continental margin below the accretionary prism and the rigid margin of the Asian Plate (Fig. 3). The lower and frontal limit of the ductile shear zone has propagated progressively through the Indian upper crust towards the SW. The incorporation of different tectonic units in the Nyimaling-Tsarap Nappe occurred gradually in time and space. From N to S, we distinguish the following succession of tectonic units: Kharnagh, Zara, Marang La, Zumlung b, Zumlung a, Zangla and Chumik Units. The amount of deformation and translation is decreasing in the frontal Kenlung Sarai Unit and in the Baralacha La Thrusts (Figs. 3 and 16). The Nyimaling-Tsarap Nappe represents in *imbricated structure* ("structure imbriquée") such as defined and drawn by De Margerie & Heim (1888, Fig. 105), more than 100 years ago. This imbricate structure differs from the "imbricate fan" defined by Boyer & Elliott (1982) by the fact that the frontal thrust silces are not related to a unique "sole thrust" but to a large ductile shear zone, characterized by fold structures and situated in the upper crust. The model of Boyer & Elliott is only applicable to thrust systems developed at shallow tectonic levels, as for instance the Jura Thrust system in the Alps (Buxtorf 1907, Laubscher 1965). There is a

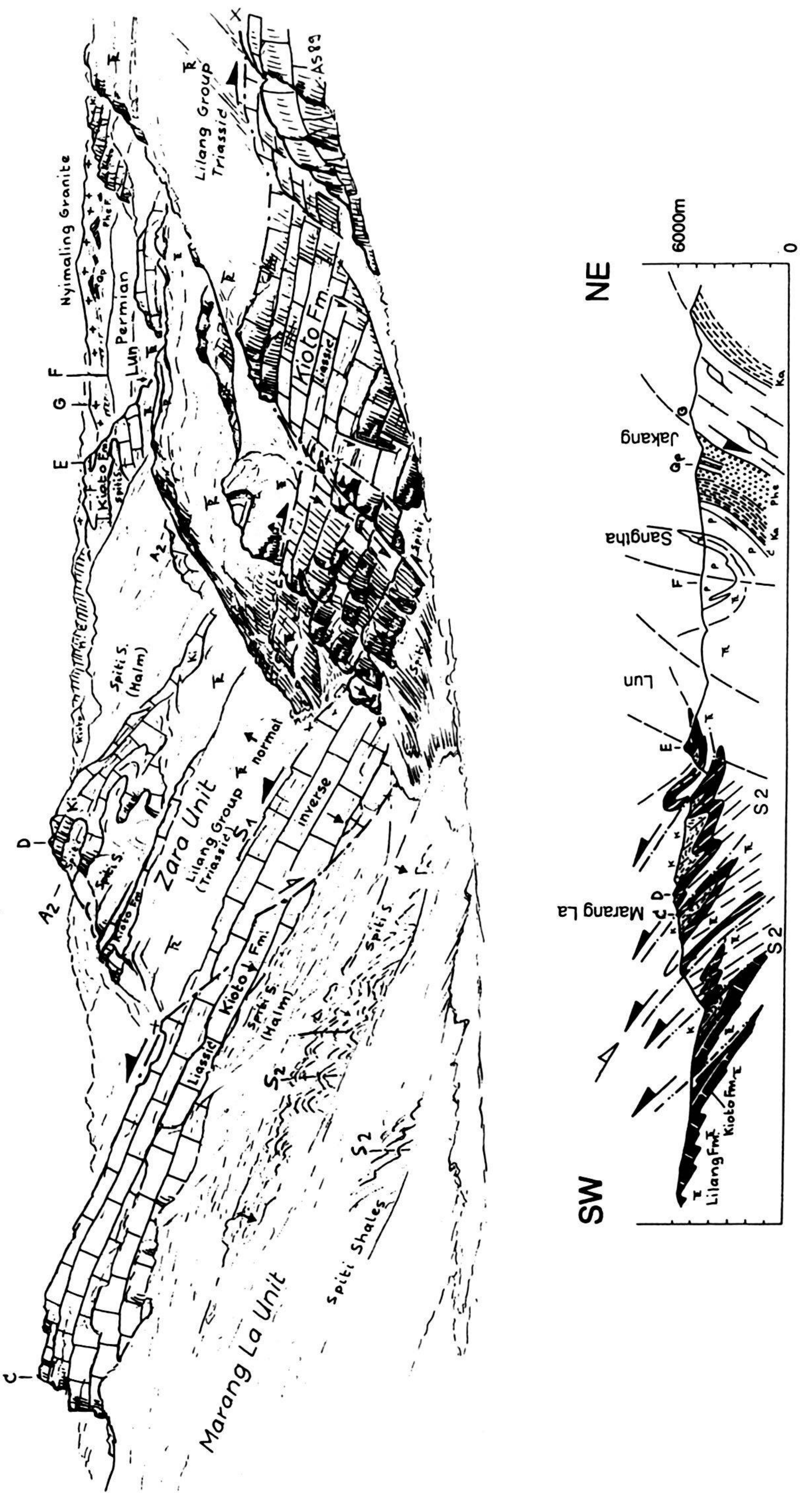


Fig. 17. View from Marang La (5300 m) to the N of the frontal thrusts and folds of the Nyimaling-Tsarap Nappe.

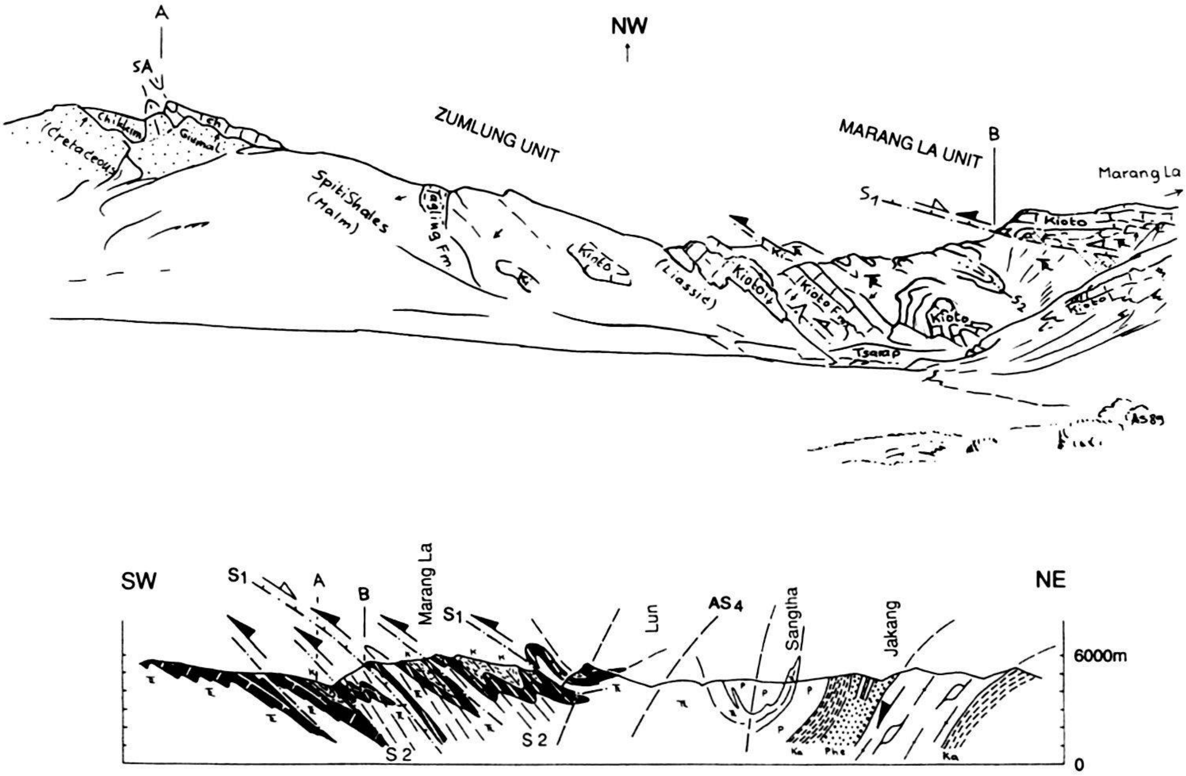
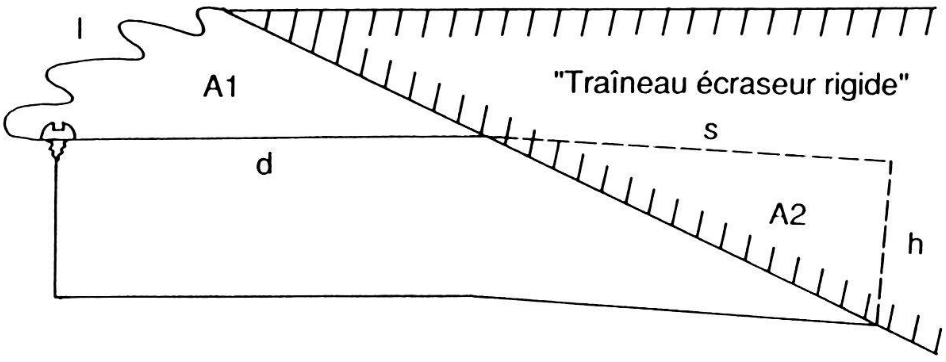


Fig. 18. View of the Tsarap Valley above Charras Bridge: frontal thrusts and folds of the Nyimaling-Tsarap Nappe. The thrust of the Marang La Unit on the Zumlung Unit has been reactivated as a low angle normal fault, during a late phase of extension.

controversy about the autochthony (Fuchs 1989) or allochthony (Baud 1989) of the Tethyan Zone of the Himalaya. Fuchs' (1989) main argument is the following: "In Zanskar the alleged pile of nappes consists of formations of Paleozoic to Eocene age in normal stratigraphic order." This is what our geological sections actually show (Figs. 3, 15 and 16); the normal stratigraphic succession is generally preserved and is only locally disturbed by recumbent folds in the ductile northern part of the section (deep tectonic level) and by overthrusts in the nappe front to the S (high tectonic level). We interpret these facts as consequences of a nappe translation mechanism by *simple shear*. This transport mechanism has two characteristics: the normal stratigraphic sequence and the continuity between the thrust front and the autochthonous root of the nappe are maintained.

In Fig. 19, we propose a two dimensional model for the calculation of the extension and the depth of the shear zone. For the boundary conditions, we assume that there is no change of the rock volume (= surface in two dimension) and no change of the length of the competent Liassic Kioto Fm. strata during nappe formation. The result of this approximation is represented in Fig. 20. The translation path is about 87 km and the calculated depth of the shear zone is about 7 km. The depth of 7 km seems to be reasonable as it corresponds to the thickness of the strongly deformed shaly sandstones, shales, marls and marly limestones between the Phe and Kioto Formations. Nevertheless, the most questionable assumption in this model is the preservation of the original length of the measured strata. It is quite possible that the Kioto limestones have been elongated in the deeper, more ductile root zone of the nappe. Consequently the calculated



BOUNDARY CONDITIONS

Constant area: $A1 = A2$

Constant length of strata: $s = l - d$

Simple shear: $h = \frac{A2 \times 2}{s} = \frac{A1 \times 2}{l - d}$

Fig. 19. Shear model.

s represents a maximum length and *h* a minimum depth of the shear zone. The approximation could be improved by a quantitative determination of the internal deformation of the Kioto limestones.

On the base of our map and structural observations, we conclude that the geometry and the kinematic of the Nyimaling-Tsarap Nappe is comparable with the tectonic style of alpine nappes, as described by Argand (1916). This conclusion contrasts with the models proposed by Searle (1986) and McElroy et al. (1990) for the Zanskar Nappes, some 50 km farther to the W. According to these authors, the Zanskar Nappes are characterized by imbricate thrust-duplexes and imbricate fans, related to a main basal detachment thrust.

The Sarchu Zone

The Sarchu Normal Fault, separating Paleozoic sediments to the S from Triassic carbonates of the Lilang Group to the N, was first observed by Srikantia & Bhargava (1982) (Plate 1 and Fig. 21). Near Sarchu, the NW–SE striking and NE dipping Sarchu Normal Fault separates highly metamorphosed sediments of Ordovician to Carboniferous age to the SW (critical paragenesis: staurolite-kyanite-biotite-garnet) from low grade Triassic sediments to the NE. In the last few years this region has been mapped in great detail, measurements of Illite "Crystallinity" have been carried out and a tectonic model has been proposed by Spring & Crespo (1992). Based on a structural map (Fig. 21), a geological section (Fig. 24) and a metamorphic map (Fig. 31), a model for the structural evolution of this region is proposed (Fig. 21 and Table 1).

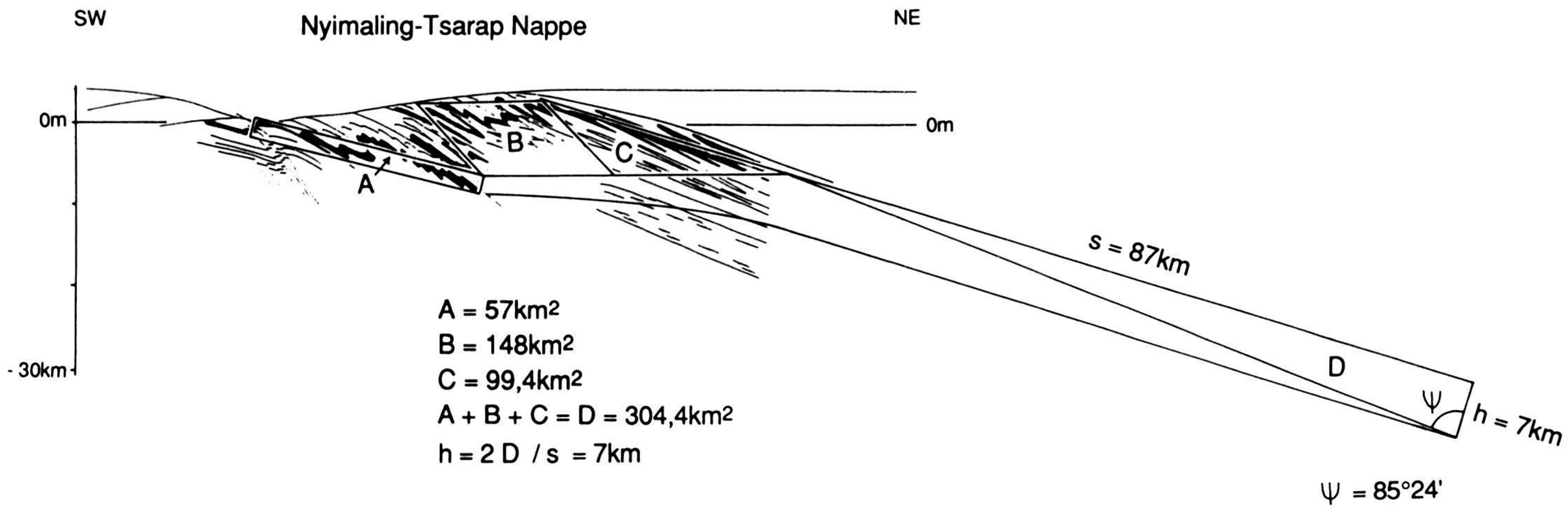


Fig. 20. Application of the shear model (Fig. 19) to the Nyimaling-Tsarap Nappe.

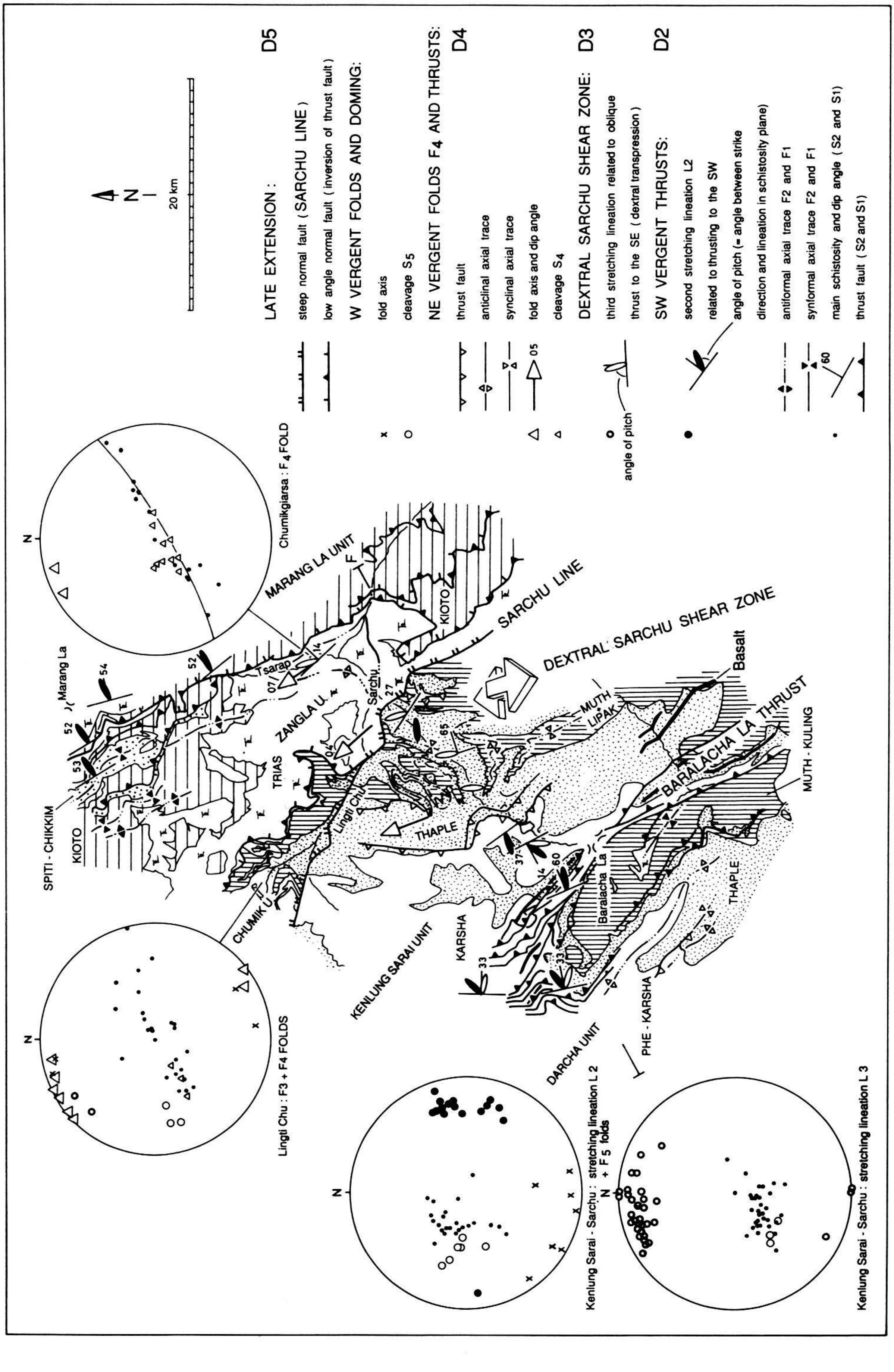


Fig. 21. Structural map of the Sarchu region.

In the Sarchu region, we observed a concentration of many kinds of deformational structures of different ages. We interprete this fact as a consequence of a repeated reactivation of older large scale structures or of the initiation of younger structures on preexisting ones. The oldest structure observed in this region is a synsedimentary normal fault in the Ordovician Thaple Fm., S of the Lingti Chu. This normal fault has almost the same NW direction of strike as the Tertiary Sarchu Normal Fault, 3 km farther to the N, but it shows an opposite inclination. S and N of the fault, the Thaple sandstone reaches a thickness of 1300 m and 500 m respectively proving a vertical displacement of 800 m. The structure is sealed by the undisturbed Devonian Muth Fm. quartzites. A subvertical and N striking Carboniferous (?) gabbroic and a Lower Permian granitic dike cut the Yunam Valley about 6 km south of Sarchu (Spring et al. 1992 and Plate 1). This composite intrusion is most probably associated with an extensional structure, related to the initiation of the Tethys rifting. The middle Permian Panjal Traps basalts are limited to the Chumik and Kenlung Serai Units, but no feeder dikes have been observed (Plate 1).

In this region, the Tertiary deformation started with a SW vergent underthrusting as indicated by the stretching lineation L_2, below the frontal part of the Nyimaling-Tsarap Nappe. The associated crustal thickening is responsible for the regional metamorphism in the Kenlung Sarai Unit. We observe a strong metamorphic gradient from a chlorite-stilpnomelane-pumpellyite zone, SW of Baralacha La, to a kyanite-staurolite zone, S of Sarchu. These rocks were metamorphosed at temperatures of 540 °C (biotite-garnet geothermometer, Spring et al. 1993). Assuming a maximum geothermal gradient of 30 °C/km this indicates a minimum depth of about 18 km. Therefore, above the amphibolite facies metapelites (staurolite – kyanite) S of Sarchu, a nappe stacking of about 18 km has been removed by tectonic unroofing (extension, uplift and erosion). This nappe pile corresponds to the SW front of the Nyimaling-Tsarap Nappe, as shown in the schematic model of Figs. 31, 32 and 33. Amphibolite facies grade rock samples near Sarchu give K/Ar cooling ages of 22.8 ± 0.5 Ma for muscovite and 20.8 ± 0.4 Ma for biotite and $^{40}Ar/^{39}Ar$ cooling ages of 33.5 Ma for amphibole (total gas age) and of 19.3 ± 0.2 Ma for biotite (plateau). These ages are interpreted as cooling ages of these metamorphic rocks, from about 500 °C to 300 °C (Spring et al. 1993).

During a later synmetamorphic stage, the nappe front was affected by oblique underthrusting of the Kenlung Serai Unit parallel to a N to NNW oriented stretching lineation L_3 as indicated by sample-scale shear criteria. This ductile dextral Sarchu Shear Zone represents a transpression structure, similar to the dextral transpression zone in the Nyimaling Massif (Fig. 30). These structures are synmetamorphic and associated with amphibolite facies conditions in the Kenlung Serai Unit, anchizone in the Chumik Unit and epizone in the Zangla Unit (map of metamorphic zones, Fig. 31). The dextral underthrusting is followed by a NE vergent backfolding F_4, with isoclinal recumbent folds in the ductile Kenlung Serai Unit and open folds in the more rigid Zangla Unit (Figs. 21, 22 and 23). The zone of NE vergent folds coincides with the zone of dextral underthrusting and the F_4 fold axes have the same N to NNW orientation as the stretching lineation L_3. The backfolding followed the first dextral shear during a rotational deformation in a zone of dextral transpression, situated in the frontal part of the Nyimaling-Tsarap Nappe pile. A similar situation is observed farther to the N, in the Nyimaling Region, along the Indus Suture.

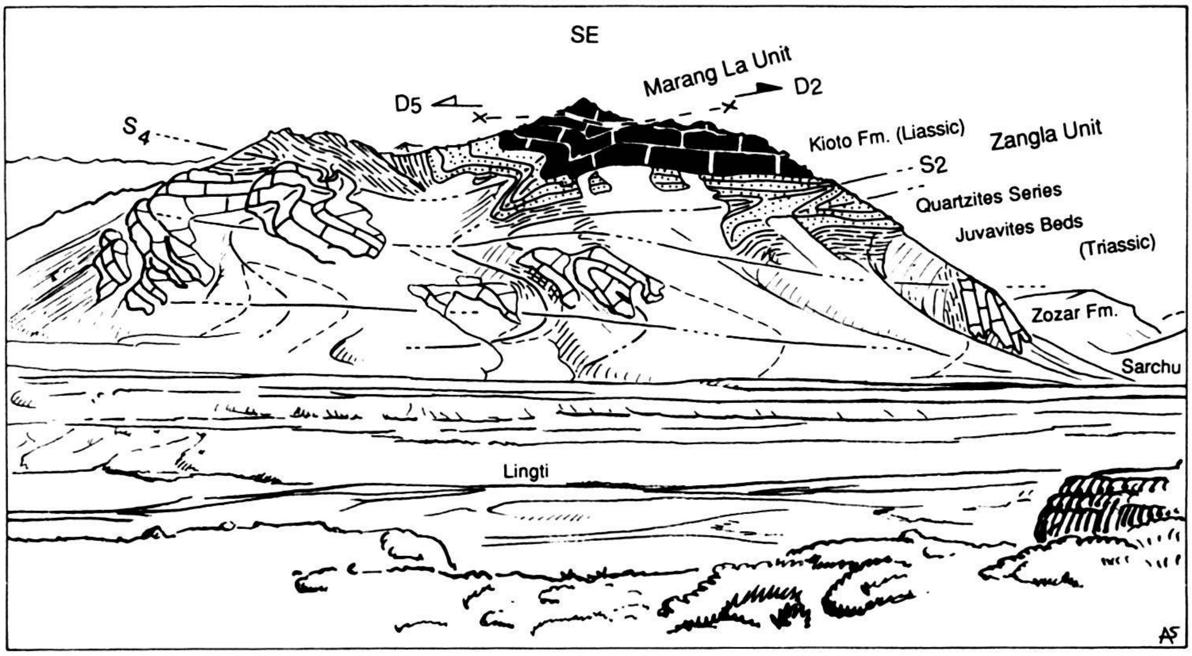


Fig. 22. View of the mountain slope dominating the plain NE of Sarchu. In the lower Zangla Unit we distinguish second generation folds associated with an axial surface schistosity S_2 and related to the SW vergent thrusting of the Nyimaling-Tsarap Nappe. These structures are refolded by NE vergent backfolds (S_4). The geological map shows that all these structures and the Triassic sediments (Zozar Fm., Juvavites Beds and Quartzites Series) are cut by a low angle normal fault at the base of the Liassic Kioto Limestones of the Marang La Unit. The low angle normal fault (D_5) represents an reactivated older thrust plane (D_2).

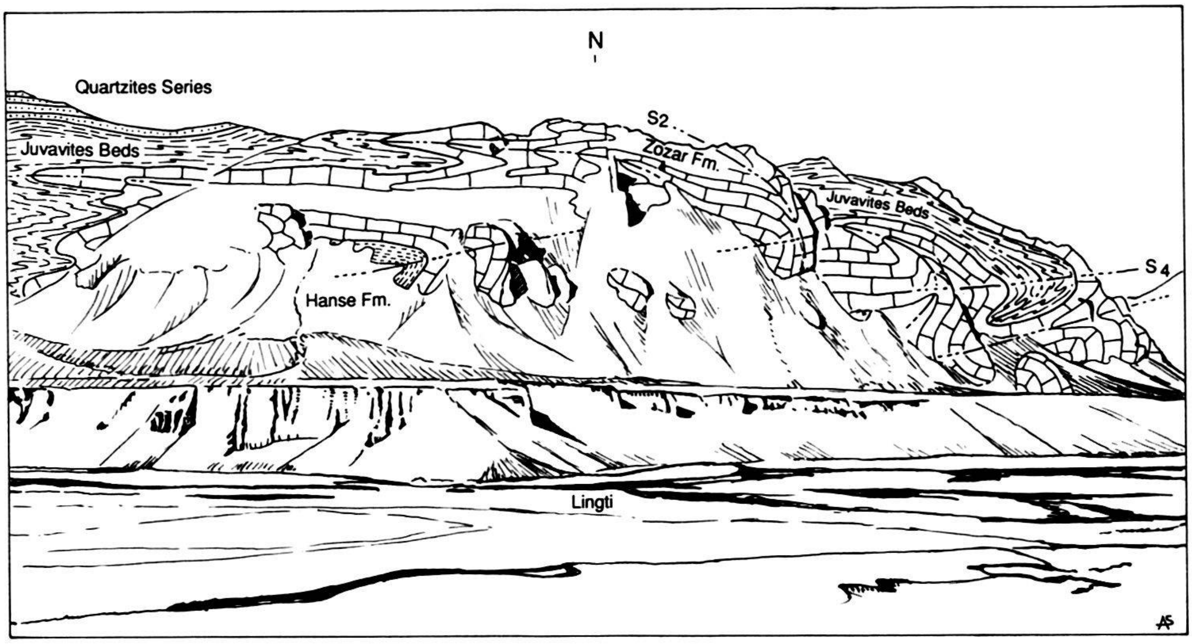


Fig. 23. View of the mountain side N of the Sarchu Plain. The SW vergent folds S_2 of the Nyimaling-Tsarap Nappe (Zangla Unit) are deformed by NE vergent back folds S_4.

The zone of dextral transpression and the NE vergent folds F_4 are cut by two generations of normal faults. Spring & Crespo (1992) suggest a very important late extension, initiated by reactivation of pre-existing gently dipping thrust surfaces, and later cut by the steep Sarchu Normal Fault. These extensional structures, together with uplift and erosion, are to a large extent responsible for the unroofing of the high metamorphic rocks S of Sarchu (Figs. 31, 32 and 33). The precise direction of relative movement on these late extensional structures is not known, as no small scale structures related to this extension have been observed, these late faults being usually covered by Quaternary screes. In other parts of the Himalaya, several models interprete these structures of late extension by normal faulting and the backfolding as related to the so-called phenomenon of "gravitational collapse" (Burg & Cheng 1984, Burchfiel & Royden 1985, Herren 1987, Searle et al. 1987, Pêcher 1991 and others). For the following reasons we doubt this model could explain the structures of the Sarchu region:

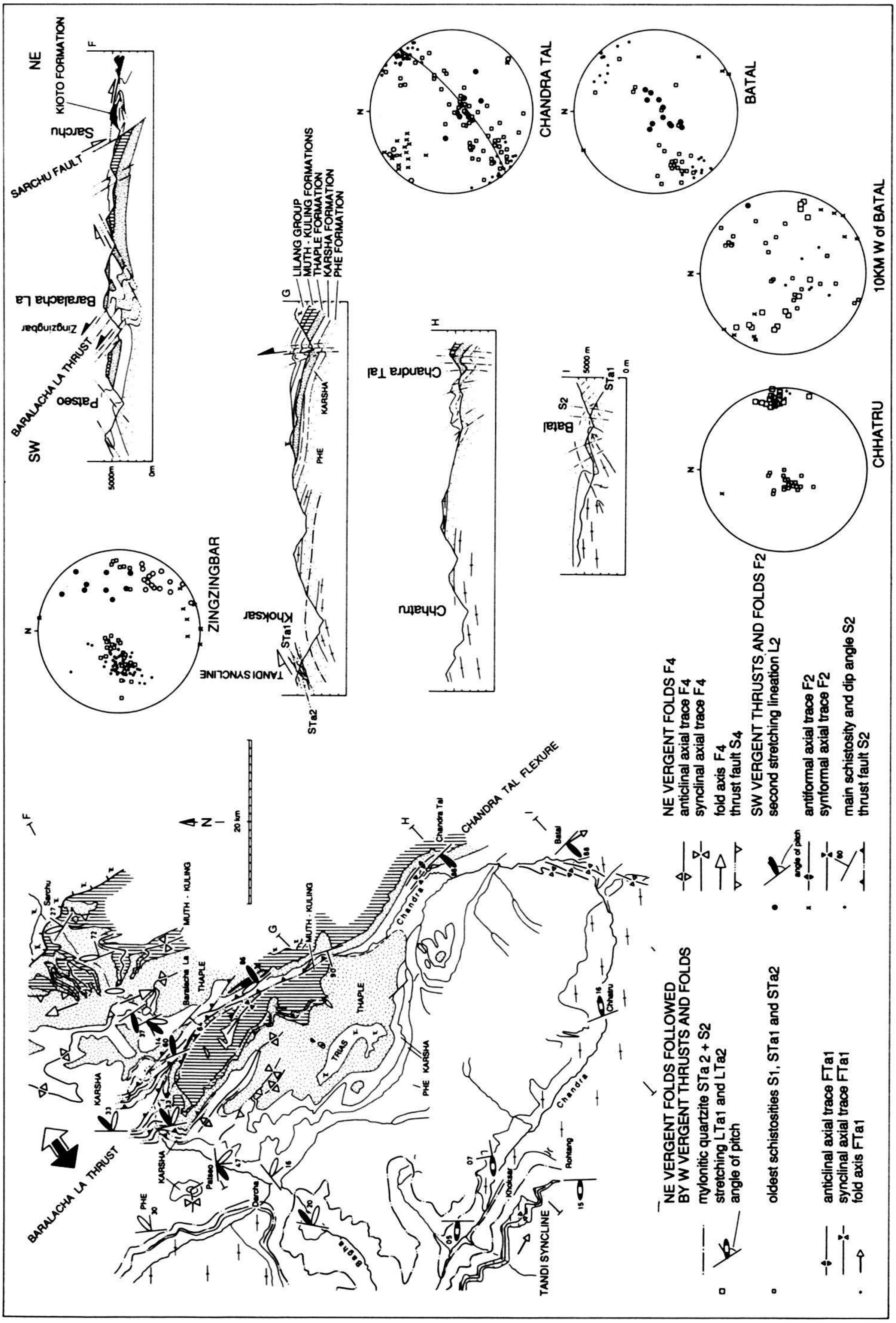
1. Normal faulting and backfolding are related to two distinct phases of deformation. The backfolding is older and related to structures of compression. These backfolds are cut by the younger extensional faults.
2. The total extension on low angle normal faults in the frontal part of the Nyimaling-Tsarap Nappe is about 15 km. The gravitational force related to the topographic relief of the Himalaya seems much too small to produce this type of deep-seated structures. Consequently, we propose the occurrence of an extensional phase between India and Asia during the late stage of the Himalayan Orogeny. On the Tibetan slope of the Himalaya in Nepal, Pêcher & Le Fort (1989) and Pêcher (1991) propose a phase of transtension to explain similar structures.

The Baralacha La Thrust and the Chandra Tal Flexure

The Baralacha La represents the watershed of 3 rivers: the Yunam flows down to the NNE, crossing perpendicularly the main Himalayan structures, and joining the Lingti and Tsarap Rivers in the Sarchu Plain. The direction of the two other rivers, the Bhaga to the W and the Chandra to the SE of the pass, is controlled by a concentration of Himalayan folds and thrusts. The geological map and profiles (Fig. 24) show a great number of SW vergent thrusts and folds near the Baralacha La (Fig. 25). Descending the Chandra Valley to the SE, the Baralacha La Thrusts are gradually replaced by SW vergent folds of the Chandra Tal Flexure (Fig. 26). The SW direction of thrusting and folding is indicated by the stretching lineation L_2 (Fig. 24). Between the Baralacha La, the Chandra Tal (Chandra lake) and Batal the axial surface schistosity S_2 of the SW vergent folds has been rotated to its present vertical position by late NE vergent backfolding F_4.

The Baralacha La Thrust has probably been initiated by reactivation of normal faults of Early Carboniferous age. Fortunately some of these Carboniferous faults have not been overprinted by the later Tertiary deformation and their original geometry is still preserved. Some of these faults are intruded by basaltic dikes, which never cut sediments younger than the Lower Carboniferous Lipak Fm. The dikes are overprinted by the

Fig. 24. Structural map of the Baralacha La-Chandra Valley region. The oldest structure of the region is the NE vergent Tandi Syncline and similar structures in the Darcha Unit. The SW vergent Baralacha La Thrust – Chandra Tal Flexure structure is younger.


BARALACHA LA THRUST
TANDI SYNCLINE
CHANDRA TAL FLEXURE
KARSHA
PHE
THAPLE
MUTH - KULING
TRIAS
Sarchu
Baralacha La
Patseo
Darcha
Khoksar
Rohtang
Chhatru
Chandra Tal
Batal
Chandra
Bagha
N
20 km
F
G
H
SW
NE
5000m
0m
SARCHU FAULT
KIOTO FORMATION
Zingzingbar
LILANG GROUP
MUTH - KULING FORMATIONS
THAPLE FORMATION
KARSHA FORMATION
PHE FORMATION
STa1
STa2
S2
ZINGZINGBAR
CHANDRA TAL
BATAL
10KM W of BATAL
CHHATRU
NE VERGENT FOLDS FOLLOWED BY W VERGENT THRUSTS AND FOLDS
mylonitic quartzite STa 2 + S2
stretching LTa1 and LTa2
angle of pitch
oldest schistosities S1, STa1 and STa2
anticlinal axial trace FTa1
synclinal axial trace FTa1
fold axis FTa1
NE VERGENT FOLDS F4
anticlinal axial trace F4
synclinal axial trace F4
fold axis F4
thrust fault S4
SW VERGENT THRUSTS AND FOLDS F2
second stretching lineation L2
antiformal axial trace F2
synformal axial trace F2
main schistosity and dip angle S2
thrust fault S2

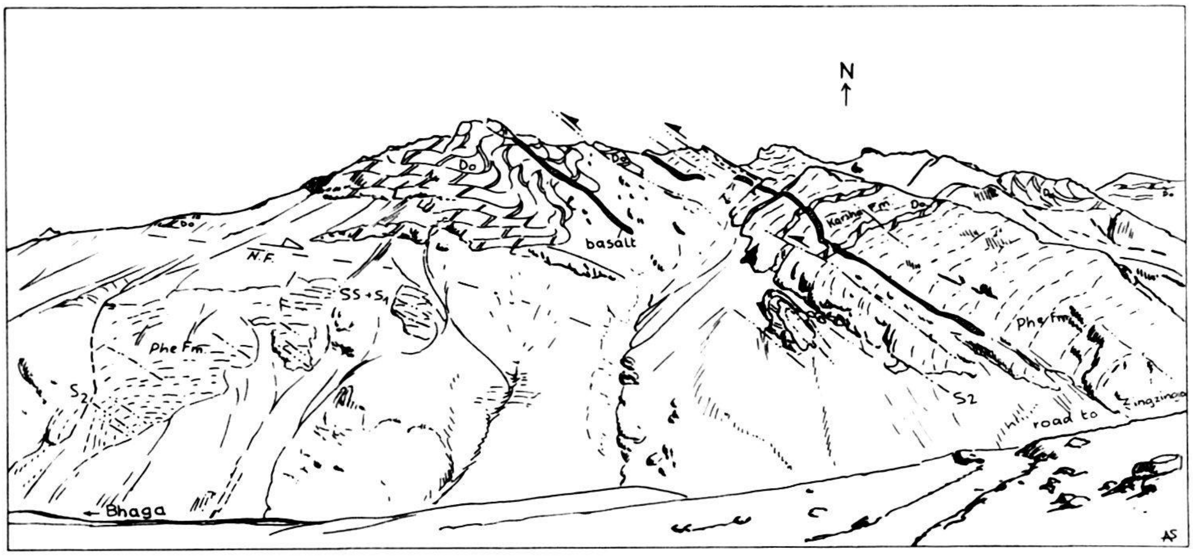


Fig. 25. Thrusts and folds of the Baralacha La Thrust, between Zingzingbar and Patseo on the right side of the Bhaga River. Basaltic dikes of probable Carboniferous age are transposed parallel to the dominant second Tertiary schistosity S_2. Do = dolomites of the Mauling and Thidsi Mb. of the Karsha Fm. N.F. = normal fault.

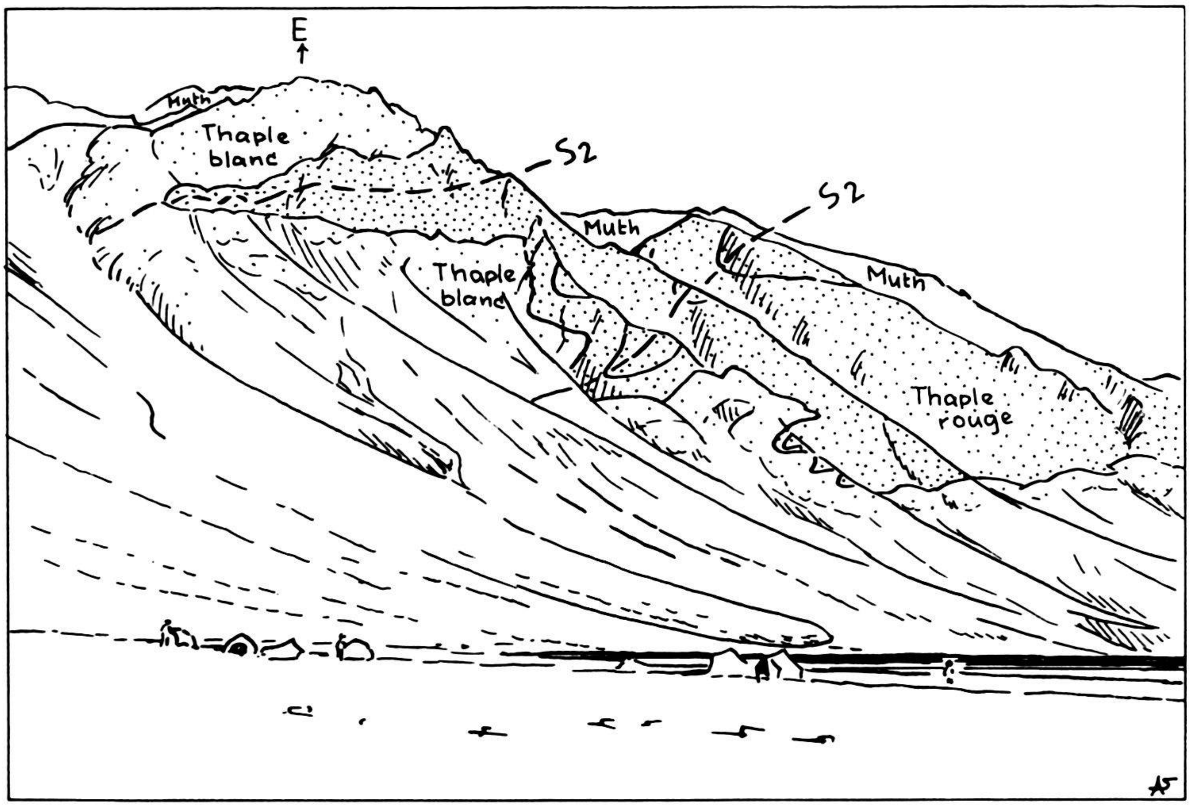


Fig. 26. Near the lake of Chandra Tal, in the upper Chandra Valley, the Baralacha Thrusts grade into SW vergent fold structures of the Chandra Tal Flexure, associated with a subvertical axial surface schistosity S_2.

Tertiary regional metamorphism and deformation structures. In the Baralacha La region, the basaltic dikes are apparently never deformed by F_2 folds (Fig. 25). This could be explained by the fact that their orientations are quite similar to the later Tertiary axial surface schistosity S_2, which in some cases cut the dikes at a very low angle. All the dikes are metamorphosed and often have a schistose texture. A geochemical and geological study shows that these dikes are not the feeder dikes or hypabyssal equivalents of the middle Permian Panjal Traps basalts. These dikes could be associated with the Lower Carboniferous transtensional phase responsible for the synsedimentary faults (Vannay & Spring 1993). Apart from the spectacular discordant reverse faults, we mapped an older décollement thrust, often following the black shales of the Middle Cambrian Surichun Mb. of the Kurgiakh Fm. The palinspastic reconstruction (Fig. 3) indicates that the Baralacha La Thrust represents a minor reverse fault structure probably developed on a preexisting Lower Carboniferous rift structure (Vannay & Spring 1993). The Baralacha La Thrust and the Chandra Tal Flexure correspond to an attenuation of the deformation in the front of the Nyimaling-Tsarap Nappe. We interprete these structures as the SE limit of the Nyimaling-Tsarap Nappe.

The Tandi Syncline and the lower part of the Chandra and Bhaga Valleys

The Tandi Syncline is an enigmatic structure in the Himalaya. It consists of Mesozoic limestones folded in the gneisses and micaschists of the High Himalayan chain, which correspond to the metamorphosed Upper Precambrian to Lower Cambrian Phe Fm. sediments (Figs. 27 and 28). The Tandi Syncline has been the subject of few studies which generally provided controversial and unsatisfying interpretations (Frank et al. 1973, Powell & Conaghan 1973, Pickett et al. 1975, Srikantia & Bhargava 1979 and 1982). According to Raina & Prashra (1974) and Srikantia & Bhargava (1979), the Tandi Syncline represents a Permian to probably Jurassic sequence. New paleontological discoveries by Vannay (Gymnitinae and Ceratitida ammonites) confirm these ages. The structure of the Tandi Syncline has important implications on the Himalayan tectonics and there is a controversy about the vergence of this large scale fold. According to Powell & Conaghan (1973), the Tandi Syncline is related to the first phase of deformation recognizable in the studied area. In order to make this structure compatible with the general Himalayan tectonic movements towards the SW, these authors interprete it as an antiform closing to the NE. This interpretation contrasts with the works of Frank et al. (1973) and Srikantia & Bhargava (1979 and 1982) who represent this unit as a synform closing to the SW, in their geological sections. According to the two later authors, the unusual vergence of this structure is related to a discrete NE vergent thrust, antithetic and syngenetic to the SW vergent Main Central Thrust (MCT) and cutting the upper part of the Tandi Syncline. Our detailed mapping and structural study proved that the Tandi Syncline is an isoclinal synform closing to the SW and that it is not associated with a discrete NE vergent thrust. Moreover, the stratigraphic nature of the contact and the presence of basal conglomerates at some places suggest that the Tandi unit is autochthonous. Only locally is the contact subsequently deformed by mylonitic shear zones of the D_{Ta2} tectonic phase. The Tandi Syncline represents a large scale expression of the oldest Tertiary deformation recognizable in the lower parts of the Chandra and Bhaga

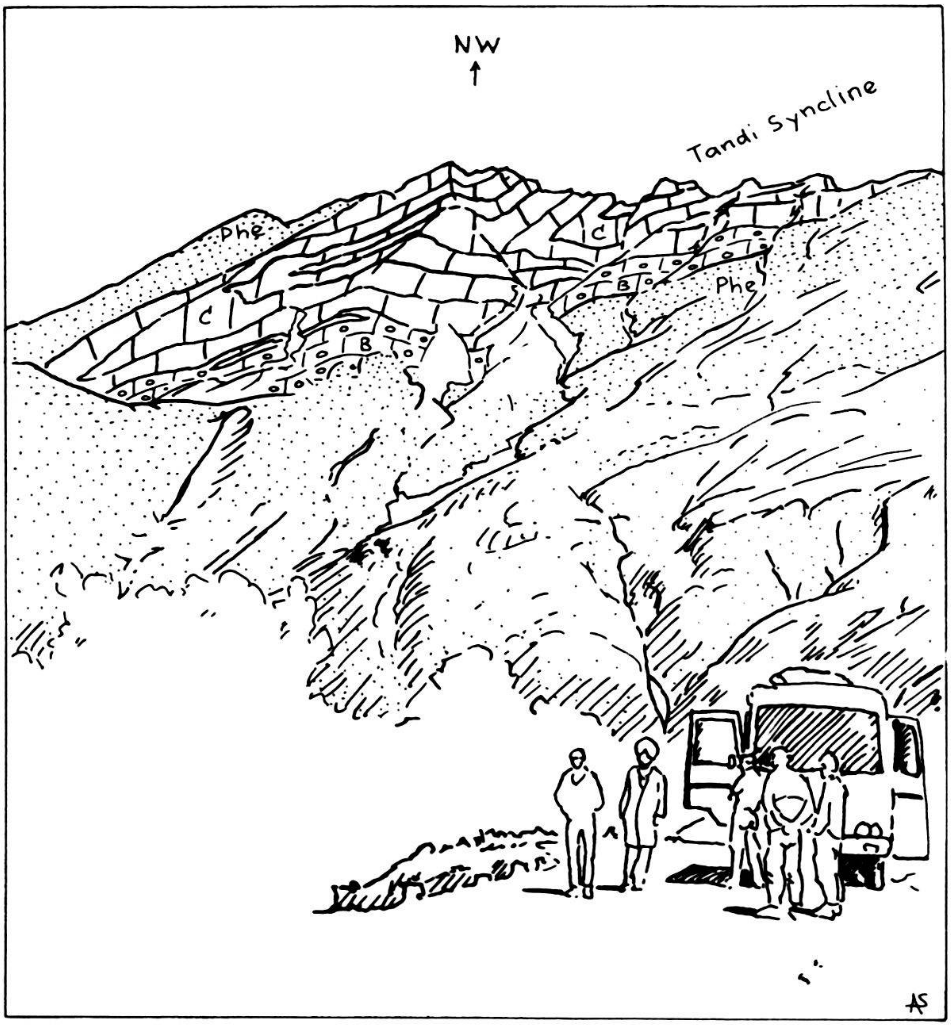


Fig. 27. The closure of the Tandi Syncline seen from the road S of Rohtang La. B = white and brown limestones and sandstones. C = blue limestones and marls.

Valleys. This deformation, labelled D_{Ta1}, has not been observed farther to the NE. The first schistosity S_{Ta1} is parallel to the stratigraphic bedding and to the axial surface of the isoclinal F_{Ta1} folds. The first stretching lineation L_{Ta1} has been transposed in an E–W to ENE-WSW orientation by the subsequent D_{Ta2} deformation. Therefore the precise direction of movement of the early D_{Ta1} phase is not known. The Tandi Syncline is overprinted by SW vergent F_{Ta2} folds and by the second S_{Ta2} schistosity. The L_{Ta2} stretching lineation indicates a direction of underthrusting towards the E to ENE (Fig. 30). Near Batal, the kilometer-scale NE vergent F_{Ta1} anticlines in ortho- and paragneisses and the S_{Ta2} main schistosity are overprinted by the younger F_2 folds and S_2 schistosity of the Baralacha La Thrust and Chandra Tal Flexure (Fig. 29). Finally, the whole region between Tandi and Chandra Tal is affected by a late doming phase and NE vergent open fold F4.

The main consequence of the Tandi Syncline structural characteristics is that the earliest Tertiary deformation in the studied area has a vergence toward the NE. This vergence contrast with the general tectonic movements to the SW, in concordance with

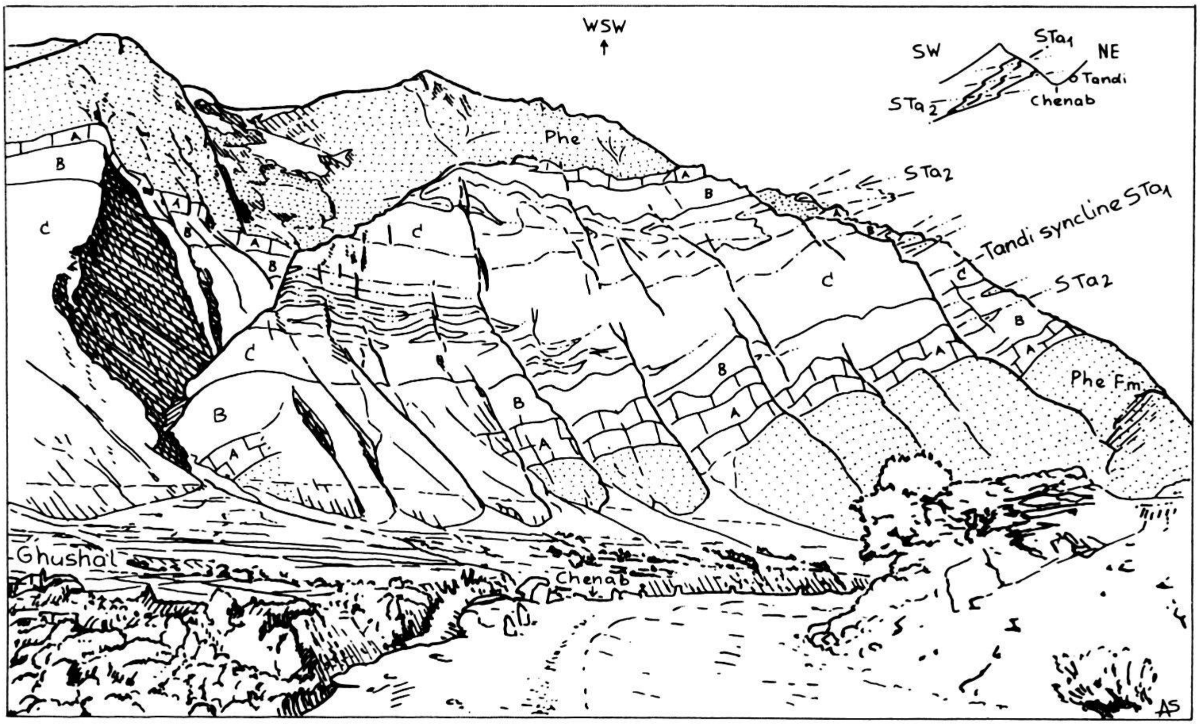


Fig. 28. View of the Tandi Syncline south of Ghushal village in the upper Chenab Valley. The NE vergent Tandi Syncline F_{Ta1} and first axial surface schistosity S_{Ta1} are overprinted by SW vergent second folds F_{Ta2} and their axial surface schistosity S_{Ta2}. A = blue limestones, B = white and brown limestones, dolomites and sandstones, C = blue limestones and marls.

the classical models for the Himalayan tectonics. Our observations do not confirm the hypothesis of a NE vergent thrust associated with the Tandi Syncline, as proposed by Srikantia & Bhargava (1982). In our interpretation we consider the unusual vergence of the Tandi Syncline together with the regional metamorphism. This metamorphism, which reached amphibolite facies conditions in the lower part of Chandra Valley (kyanite-staurolite zone near Chhatru and Khoksar) decreases towards the NE to lower greenschist and pumpellyite-actinolite facies just to the SW of the frontal part of the Nyimaling-Tsarap Nappe (chlorite-stipnomelane-pumpellyite south of the Baralacha La Thrust, Fig. 31). To the N, the metamorphic conditions increase again as a consequence of the Nyimaling-Tsarap Nappe formation (staurolite-kyanite-garnet in the Sarchu area). Therefore the high grade regional metamorphism of the lower part of the Chandra Valley is not related to the Nyimaling-Tsarap Nappe and it can only be explained by a pile of nappes overthrusted from the SW toward the NE (Figs. 32 and 33). On the basis of our observations, we conclude that, in the Chandra and Bhaga Valleys, the Tertiary deformation has started with an intracontinental underthrusting of a northeastern block below a southwestern one. This crustal thickening is responsible for the regional metamorphism in the Chandra Valley – Rohtang La region (Fig. 31). We name the lowest element of this NE vergent nappe stacking the "Shikar Beh Nappe". The higher parts of these nappes are now eroded. The underthrusting of India towards the NE, creating the Baralacha La-Chandra Tal structure and the main Central Thrust (MCT) farther to the S, is younger.

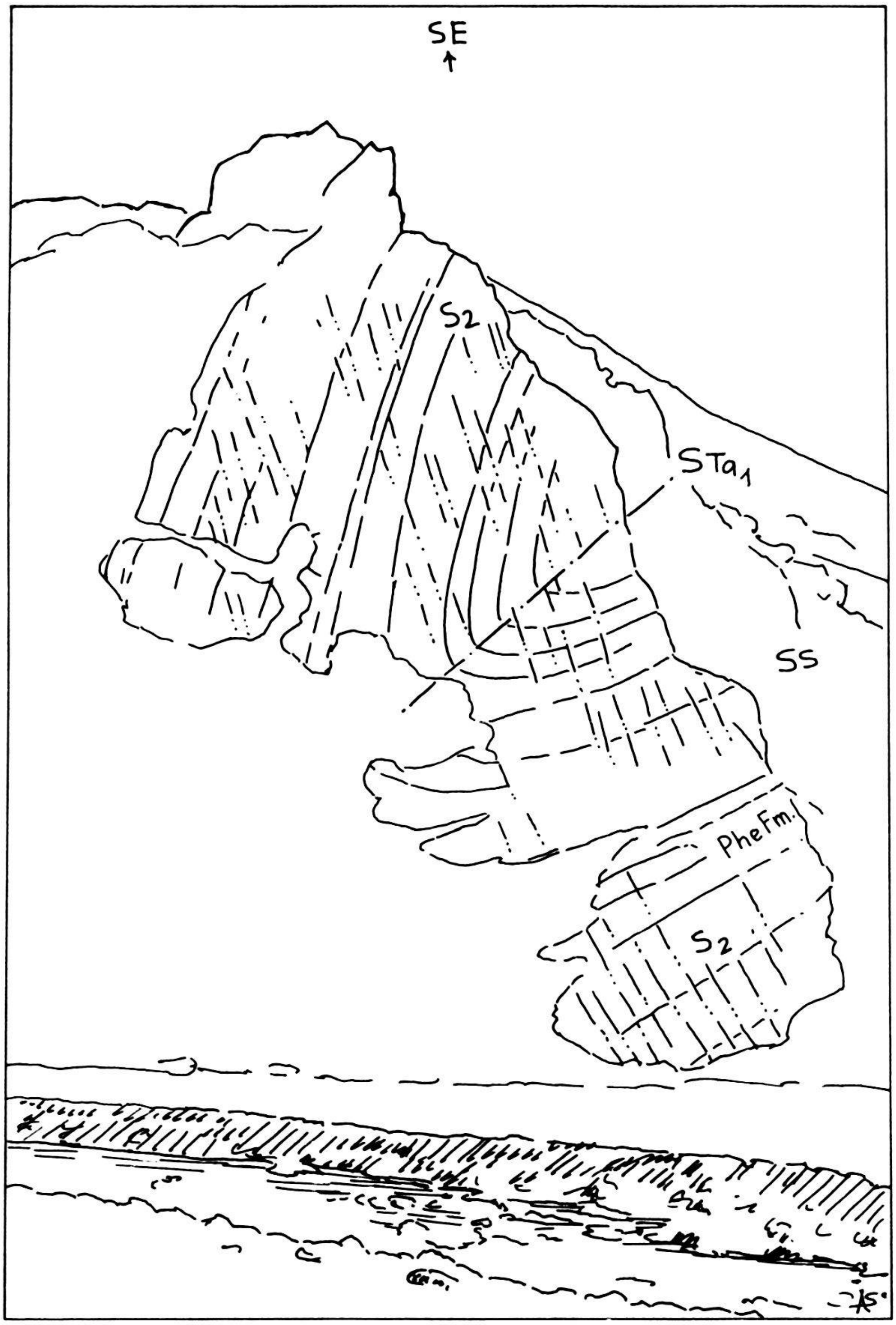


Fig. 29. NE vergent F_{Ta1} fold in the metamorphic sandstones of the lower Chandra Valley (Phe Fm. South of Batal), obliquely cut by the main schistosity S_2, related to the Baralacha La Thrust-Chandra Tal Flexure phase of deformation.

According to Hirn et al. (1984a & b), seismic profiles indicate a decoupling and a recurrence of the Moho discontinuity below the High Himalaya of Nepal. This recurrence suggests a S dipping zone of intracontinental underthrusting in the Indian plate. The NE vergent Shikar Beh nappe stacking could be related to a similar deep structure.

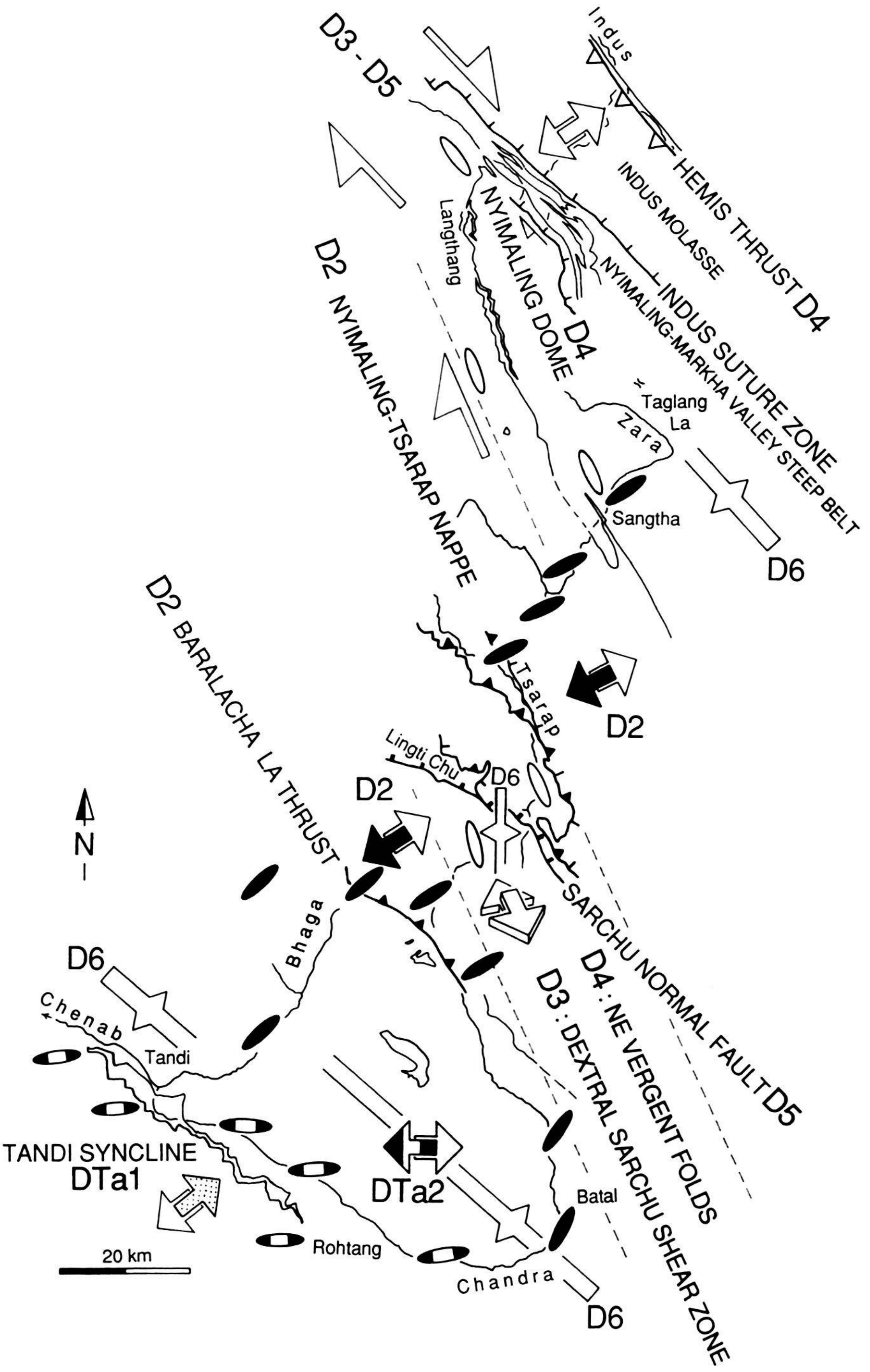


Fig. 30. Schematic structural map of the region between Rohtang La and Leh.

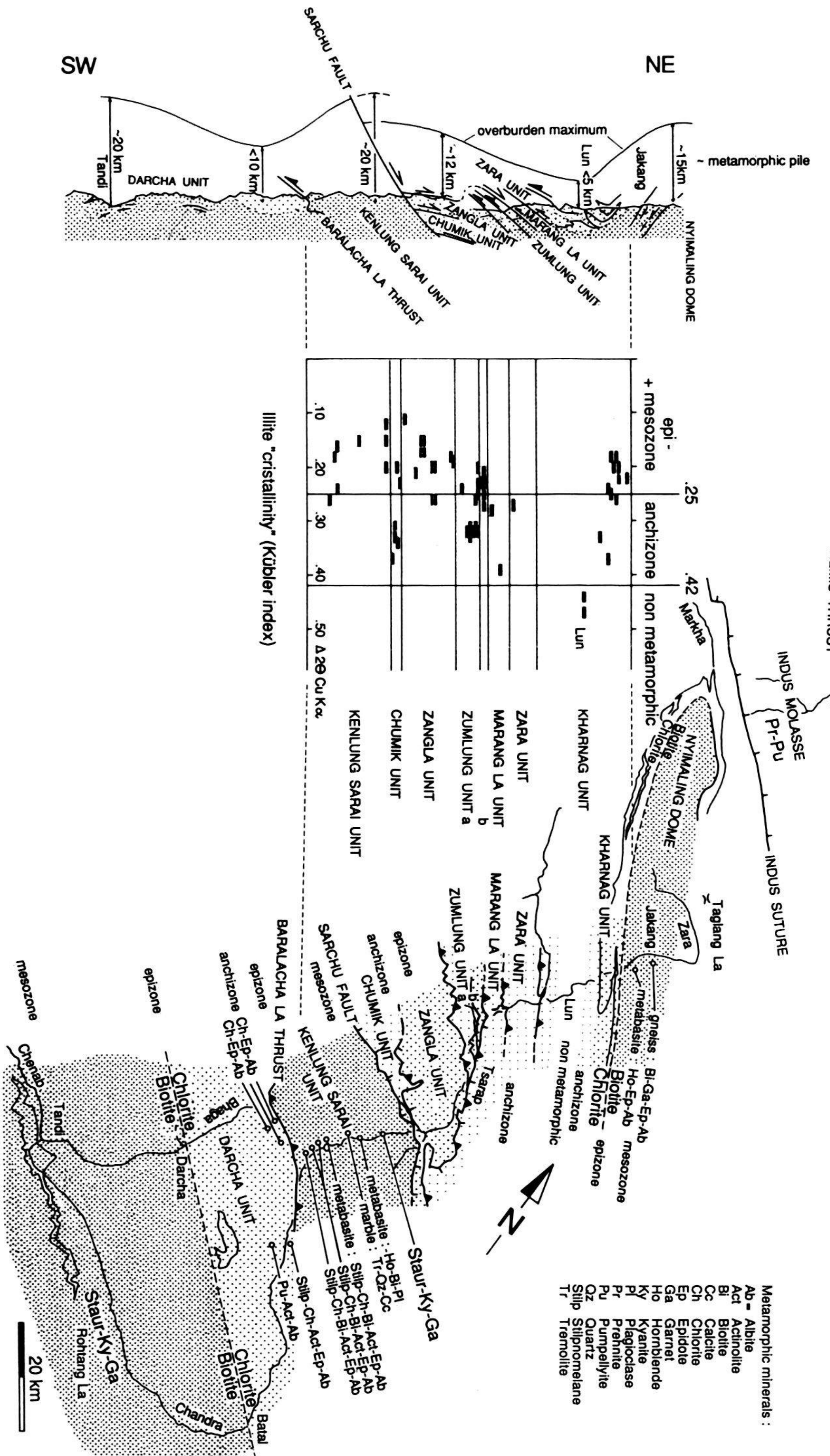


Fig. 31. Map of Tertiary metamorphic zones..

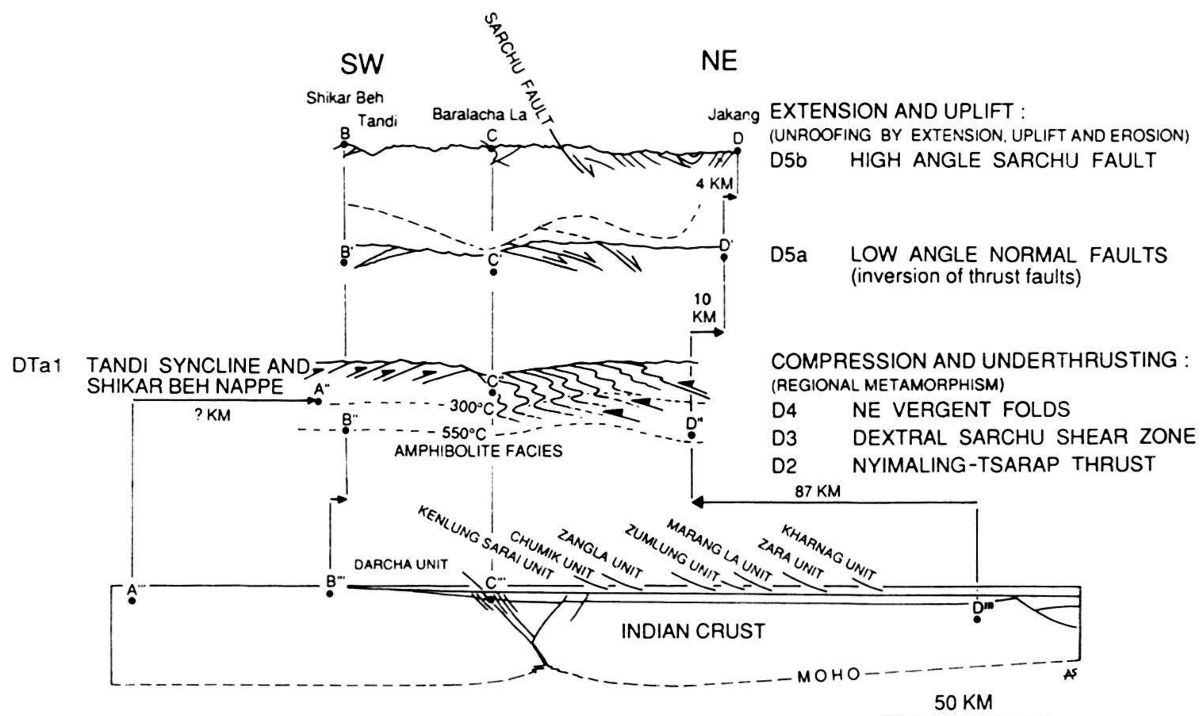


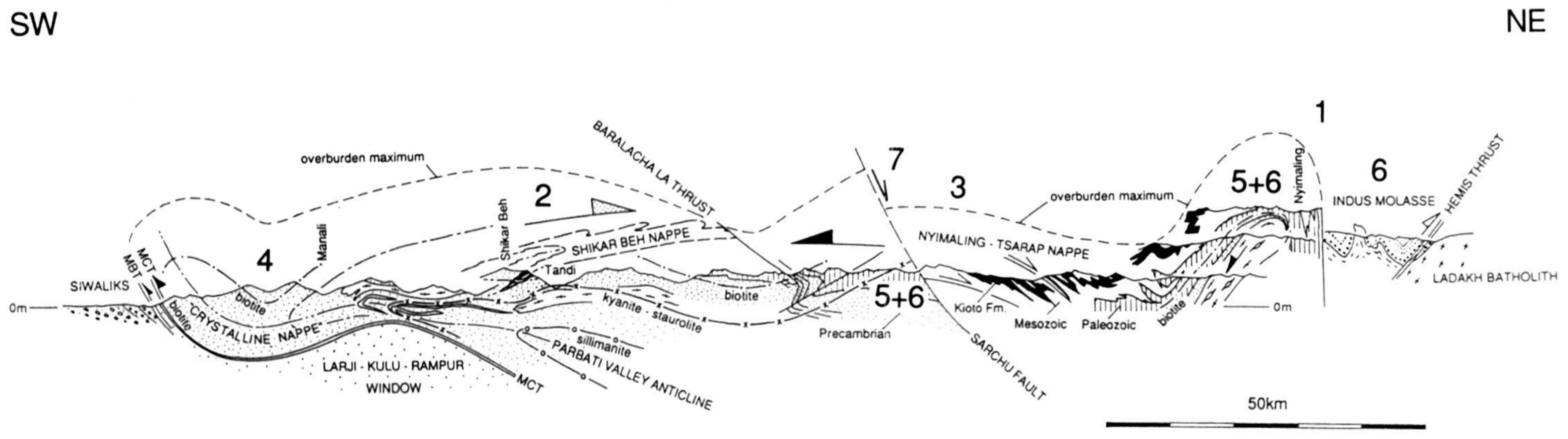
Fig. 32. Tectonic model for the Rohtang La-Leh section.

Regional metamorphism

The map of the Tertiary metamorphic zones (Fig. 31) has been compiled after Frank et al. (1977), J.-C. V. for the region S of Baralacha La, Spring & Crespo (1992) for the Sarchu region, Stutz (1988) for the Nyimaling massif and unpublished observations by H.M. and A.S. Illite crystallinity (Kübler index, Kübler 1990, Frey 1987) measurements are used to indicate the metamorphic grade in the low grade and non metamorphic rocks (all samples containing paragonite have been removed). We distinguish three zones of high grade metamorphism:

- amphibolite facies rocks of the High Himalaya, in Upper Lahul (Chandra Valley),
- staurolite-kyanite-garnet rocks in the Kenlung Serai Unit, in SE Zanskar (Sarchu),
- upper greenschist facies to epidote-amphibolite facies rocks in eastern Ladakh (Nyimaling Massif).

The complex distribution of rocks of various metamorphic grades in the tectonic units around Sarchu has been studied and a model of the metamorphic history has been proposed by Spring & Crespo (1992). More data on the regional metamorphism of the Sarchu region are given by Spring et al. (1993). Rb/Sr age determinations on metamorphic micas of the Tertiary metamorphic zones of the Manali-Tandi region (Frank et al. 1977) allow some conclusions about the thermal history of this region. The very constant Rb/Sr age of metamorphic biotites at ~ 16,5 ± 2 Ma between Manali and the Chandra Valley is interpreted as the age of cooling below 300 °C, during the late regional uplift and erosion of this metamorphic zone. The amphibolite facies rocks of the Kenlung Serai



Chronology of the Tertiary Himalayan structures

1-	Continental collision, underthrusting of India below Asia and initiation of the Nyimaling-Tsarap Nappe	(Eocene)
2 -	NE vergent Shikar Beh Nappe	(Eocene)
3 -	SW vergent Nyimaling-Tsarap Nappe	(Eocene)
4 -	SW vergent "Crystalline Nappe" (MCT and MBT)	(Oligocene-Miocene)
5 -	Dextral transpression	(Oligocene)
6 -	NE vergent folding	(Miocene)
7 -	Late extension	(Miocene)

Fig. 33. Geological cross section of the Himalaya in Ladakh and Lahul. The geology of the region situated south of the Rohtang La-Shikar Beh area has been compiled after FRANK et al. (1977b).

Unit near Sarchu have been the subject of a radiochronological study. An $^{40}Ar/^{39}Ar$ age of 33.5 Ma for amphiboles (total gas age), K/Ar ages of 22.8 ± 0.5 Ma for muscovites and 20.8 ± 0.4 Ma for biotites and an $^{40}Ar/^{39}Ar$ age of 19.3 ± 0.2 Ma for biotites (plateau), are interpreted as the cooling ages of these rocks from about 500 °C to 300 °C (Spring et al. 1992a).

Tectonic history and conclusions

Based on geological mapping and observations and on plate tectonic models, we propose in this chapter a model for the Tertiary tectonic evolution of the Himalaya in eastern Ladakh and Lahul.

The Mesozoic ocean floor of the Himalayan Tethys was subducted in a NE and N direction below the Asian Plate. The voluminous 100 to 40 Ma old plutonic rocks of the Ladakh Batholith, are explained as the product of the partial melting of the subducted oceanic crust (Honegger et al. 1982, Schärer et al. 1984). The Ladakh Batholith, 70 km wide, formed a stable block in the Asian plate margin during the Tertiary continental collision.

The motion of India relative to Asia has been independently computed by several workers (McKenzie & Sclater, 1971, Molnar & Tapponnier 1975, Pierce 1978, Patriat & Achache, 1984, Scotese et al. 1988, Dewey et al. 1989). All models display a rapid decrease in the plate motion rate of India in the time interval between 54 and 35 Ma and a drastic anticlockwise rotation of India some 45 and 35 Ma ago. According to classical

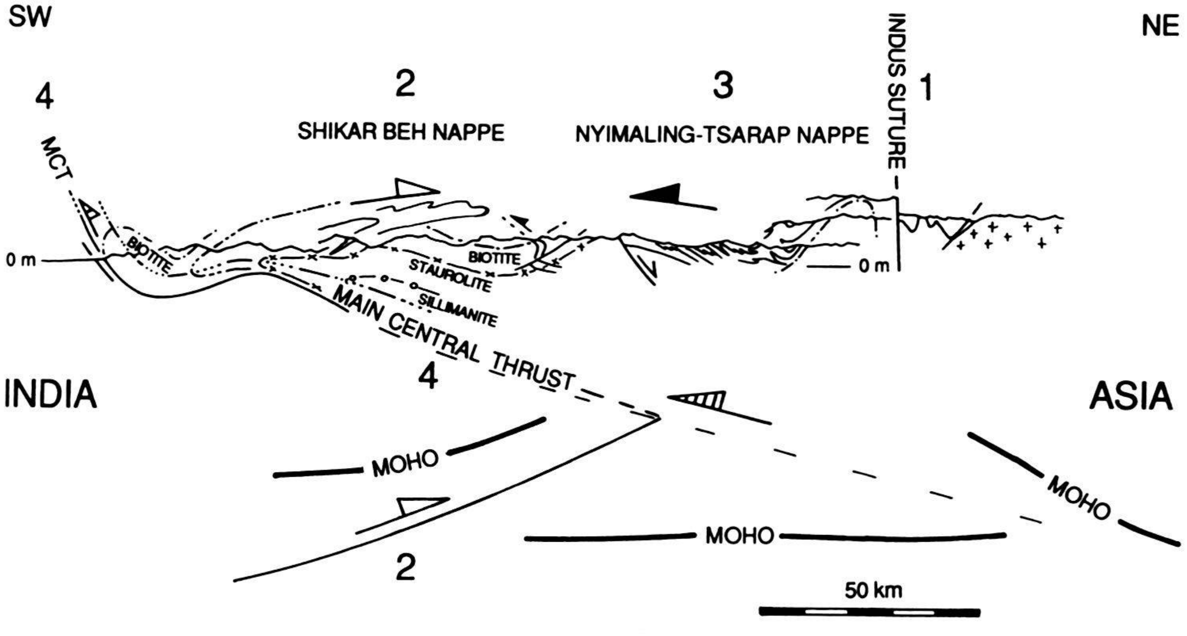


Fig. 34. Model for the chronological relationship between shallow and deep structures in the NW Himalaya. After creation of the Indus Suture (1), the early NE vergent Shikar Beh Nappe (2) could be associated with a deep-seated thrust as suggested by the decoupling and reccurrence of the Moho below the Nepal Himalaya (Hirn et al.1984a & b). These structures are subsequently superposed by the SW-vergent Nyimaling-Tsarap Nappe (3) and Main Central Thrust (4).

interpretations, these data indicate that the continental collision of India and Asia occurred during this time. This period coincides with the deposition of the youngest sediments of the Noetethys and also of the oldest sediments of the Indus Molasse.

The youngest sediments of the North Indian shelf involved in the nappe structures are marls and limestones (shelf carbonates) containing reworked Paleocene nummulites of probably Early Eocene age. These sediments crop out in the Lingshed and Zangla Nappes and in the basal slice of the Spongtang ophiolite Klippe (Garzanti et al. 1987). A Tertiary olistostrome with reworked Paleocene nummulites has been observed by H.M. in the Nyimaling-Tsarap Nappe, in the Kharnag Region S of the village of Dat.

The early thrusting of the Nyimaling-Tsarap Nappe from the North Indian continental border toward the SW, corresponds to a first record of crustal thickening related to the continental collision. The progressive underthrusting of India below Asia and the related crustal constraints caused a mechanical destabilisation in the Indian continental crust, which led to the creation of a NE vergent "crustal flake" or "flakes" (Oxburgh 1972) south of the Manali and Rohtang La region. The NE vergent Shikar Beh Nappe and the Tandi Syncline belong to this intracontinental nappe stacking (Fig. 33). The zone of high grade amphibolite facies regional metamorphism of the lower Chandra Valley, gradually passing towards the N to lower greenschist facies in the Baralacha La region, is a consequence of this southern zone of crustal thickening (Fig. 31). This conclusion, based on unequivocal field observations, contrasts with the classical model for the Himalayan tectonics, which postulates that the high grade metamorphism of the "High Himalayan Crystalline" is due exclusively to crustal thickening associated with SW vergent structures.

The NE vergent Shikar Beh Nappe has been subsequently overprinted by SW vergent structures associated with the Nyimaling-Tsarap Nappe, such as the Baralacha La Thrust-Chandra Tal Flexure. Structural observations compiled after Frank et al. (1977 b) for the tectonic unit S of the studied area have been integrated into our profile (Fig. 33). The structural relations along the complete transect suggest that the SW vergent "Crystalline Nappes" and the Main Central Thrust (MCT) developed after the creation of the NE vergent Shikar Beh Nappe and Tandi Syncline. It is possible that the MCT represents a shear zone developed in the ductile metamorphic crustal rocks generated on the base of the older NE vergent nappe stacking.

In the Nyimaling-Tsarap Nappe, the NE dipping underthrust is followed by an oblique underthrusting (dextral transpression), parallel to a N to NW oriented stretching lineation L_3. We distinguish two shear zones, the dextral Sarchu Shear Zone below the frontal part of the Nyimaling-Tsarap Nappe pile, and the dextral Nyimaling Shear Zone, near the root zone of the nappe (Fig. 30). This dextral shear indicates an anticlockwise change of underthrusting direction of the North Indian continental border relative to Asia. We correlate this tectonic phase with the anticlockwise rotation of the Indian Plate drift direction, which occurred some 45 and 36 Ma ago, according to plate tectonic models (Molnar & Tapponnier 1975, Pierce 1978, Patriat & Achache, 1984, Scotese et al. 1988, Dewey et al. 1986). According to Klootwijk et al. (1985) this rotation can be subdivided into two stages: a first slight counterclockwise rotation at about 50 Ma (Middle Eocene) and a more substantial counterclockwise rotation from 36 Ma (Early Oligocene) onwards.

If the proposed correlation between plate movement and deformation structures is correct, we conclude that the emplacement of the Nyimaling-Tsarap Nappe was completed during the Eocene or at latest in Early Oligocene time (about 35 Ma).

In the Sarchu and Nyimaling regions, the zones of dextral transpression gradually pass to zones of NE-vergent folds, associated with an opposite sense of underthrusting. In the Nyimaling region, these "backfolds" are accompanied and followed by movements of dextral shear. NE vergent folding and associated dextral transpression are probably responsible for the tectonic unroofing of the Nyimaling-Tso Morari Crystalline by uplift and erosion. The NE vergent folds and thrusts of the Indus Molasse do not seem to be affected by dextral shear. Fig. 1 illustrates the major dextral and sinistral strike slip faults affecting the Asian continent to the N of the Himalaya and related to the continental collision (Tapponnier et al. 1982, 1986). The movement of the Sarchu and Nyimaling Shear Zones coincides with the dextral movements of the major strike slip faults occurring just to the N of the Himalayan chain.

Finally, in a late period of the Himalayan Orogeny, the frontal part of the Nyimaling-Tsarap Nappe was overprinted by extensional movements. In the Sarchu Region, we distinguish a first set of old, low angle normal faults, developed parallel to preexisting thrust surfaces of the Nyimaling-Tsarap Nappe. These faults have been subsequently cut by the Sarchu high angle normal fault, which put in contact amphibolite facies metamorphic rocks to the S and lower greenschist facies rocks to the N. The precise sense of extensional movements is still not known. The strong cooling and exposure of the amphibolite facies metamorphic rocks of the Sarchu region is probably caused by different processes such as erosion associated with backfolding, doming and tectonic unroofing related to late extension.

We conclude that the structural record in the Tibetan zone of the Himalayan chain allows a kinematic reconstruction of its progressive deformation during the Himalayan Orogeny. It corroborates the relative sense of displacement of India relative to Asia, proposed by recent plate tectonic models. A kinematic model of the continental collision of India and Asia is proposed in Fig. 32. Fig. 33 presents an updated geological cross section of the NW Himalaya, including the observations by Frank et al. (1977b and 1987) for the region S of the Rohtang La. In this model we suggest the following succession of orogenic phases:

1 The first stage of continental collision corresponds to an early underthrusting of India below Asia, which marks the initiation of the SW vergent Nyimaling-Tsarap Nappe (Eocene).
2 The NE vergent Shikar Beh Nappe (and the now eroded higher nappes) record an opposite underthrusting within the Indian plate (Eocene).
3 The main thrusting of the SW vergent Nyimaling-Tsarap Nappe (Eocene) follows the development of the Shikar Beh Nappe. The related crustal shortening is about 87 km.
4 The thrusting of the "Crystalline Nappe" is associated with the Main Central Thrust, which developed as a shear zone in the regional metamorphic ductile crustal rocks below the Himalayan nappe stacking (Oligocene-Miocene, Le Fort, 1975, Frank et al. 1977b, to present, Seeber et al. 1981).
5 The root zone and the frontal part of the Nyimaling-Tsarap Nappe have been subsequently affected by two zones of dextral transpression and underthrusting: the Nyima-

ling Shear Zone and the Sarchu Shear Zone. These shear zones are interpreted as consequences of the counterclockwise change in the underthrusting direction of India relative to Asia, which occured some 45 or 36 Ma ago, according to plate tectonic models.

6 NE vergent folding.

7 Late extension of about 20 km in the Sarchu region (Early Miocene, Spring et al. 1993).

Acknowledgments

We wish to thank all the people who helped in this study. Particularly Mike Cosca, Aymon Baud, Maurizio Gaetani and Jean Marcoux for the critical review of the manuscript, Philippe Thélin for the X-ray laboratory supply and G. Mascle for discussion and his great help in organizing the transport of our rock samples. Financial support from the Herbette Foundation (Lausanne University) for our field work in 1979, 1983, 1985 and 1989 and for the publication of the coloured map are gratefully acknowledged.

REFERENCES

ARGAND, E. 1916: Sur l'Arc des Alpes Occidentales. Eclogae geol. Helv. 14, 145-204.

BASSOULET, J. P., BELLIER, J. P., COLCHEN, M. MARCOUX, J. & MASCLE, G. 1978: Découverte de Crétacé supérieur calcaire pélagique dans le Zanskar (Himalaya du Ladakh). Bull. Soc. géol. France, 7/20, 961-964.

–, COLCHEN, M., JUTEAU, T., MARCOUX, J., MASCLE, G. & REIBEL, G. 1983: Geological studies in the Indus Suture Zone of Ladakh (Himalayas). In: Stratigraphy and Structure of Kashmir and Ladakh, Himalaya (Ed. by GUPTA, V. J.) Hindustan. Publ. Corp., Delhi 96-124.

BAUD, A. 1989: L'autochtonie en pays de nappes: réponse à G. Fuchs. Eclogae geol. Helv. 82, 693-697.

BAUD, A., ARN, R., BUGNON, P., CRISINEL, A., DOLIVO, E., ESCHER, A., HAMMERSCHLAG, J. G., MARTHALER, M., MASSON, H., STECK, A. & TIECHE, J. C. 1982: Le contact Gondwana-péri-Gondwana dans le Zanskar oriental (Ladakh, Himalaya). Bull. Soc. géol. France 24, 341-361.

–, GAETANI, M., GARZANTI, E., FOIS, E., NICORA, A. & TINTORI, A. 1984: Geological observations in southeastern Zanskar and adjacent Lahul area (northwestern Himalaya). Eclogae geol. Helv. 77, 171-197.

BERTHELSEN, A. 1953: On the geology of the Rupshu district, N.W. Himalaya. Meddel. Dansk geol. forening, København 12, 351-414.

BONHOMME, M. & GARZANTI, E. 1991: Age of metamorphism in the Zanskar Tethys Himalaya (India). Géol. alp. (Grenoble), Mém. H.S. 16, 15-16.

BOYER, S. E. & ELLIOTT, D. 1982: Thrust Systems. Bull. amer. Assoc. Petroleum Geol. 66, 1196-1230.

BUCHER, H. & STECK, A. 1987: Stratigraphy and tectonics of the Indus basin: the Martselang-Gongmaru La section (Ladakh). Terra Cognita 7, 112.

BURCHFIEL, B. C., CHEN ZHILIANG, HODGES, K. V., LIU YUPING, ROYDEN, L. H., DENG CHANGRONG & XU JIENE 1992: The south Tibetan detachment system, Himalayan Orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt. Spec. Pap. geol. Soc. Amer. 269, 1-41.

BURCHFIEL, B. C. & ROYDEN, L. H. 1985: North-south extension within the convergent Himalayan region. Geology 13, 679-682.

BURG, J. P. & CHENG, G. M. 1984: Tectonics and structural zonation of southern Tibet, China. Nature (London) 311, 219-223.

BUXTORF, A. 1907: Zur Tektonik des Kettenjura. Bericht über die 40. Vers. Oberrheinischen geol. Vereins Lindau, 1-10.

DIETRICH, V. J., FRANK, W. & HONEGGER, K. 1983: A Jurassic-Cretaceous island arc in the Ladakh-Himalaya. J. Volc. and Geotherm. Res. 18, 405-433.

DEWEY, J. F., CANDE, S. & PITMAN III, W. C. 1989: Tectonic evolution of the India/Eurasia Collision Zone. Eclogae geol. Helv. 82, 717-734.

ESCHER, A., MASSON, H. & STECK, A. 1988: Coupes géologiques des Alpes occidentales suisses. Mém de Géol. Lausanne, 2.

Favre, P. & Stampfli, G. M. 1992: From rifting to passive margin: The example of the Red Sea, central Atlantic and Alpine Tethys. In: Proceedings geodynamic of rifting symposium, Glion, Switzerland (Ed. by Ziegler, P.) Tectonophysics 215, 69-97.

Frank, W., Baud, A., Honegger, K. & Trommsdorff, V. 1987: Comparative studies on profiles across the northwest Himalayas. In: The anatomy of mountain ranges (Ed. by Schaer, J.-P. & Rodgers), J. Princeton Univ. Press, Princeton New Jersey, 261-275.

–, Gansser, A. & Trommsdorff, V. 1977a: Geological observations in the Ladakh area (Himalayas). A preliminary report. Schweiz. mineral. petrogr. Mitt. 57, 89-113.

–, Hoinkes, G., Miller, C., Purtscheller, F., Richter, W. & Thöni, M. 1973: Relations between metamorphism and orogeny in a typical section of the Indian Himalayas. Tscherm. mineral. petrogr. Mitt. 20, 303-332.

–, Thöni & Purtscheller, F. 1977b: Geology and Petrography of Kulu-South Lahul area. Colloq. int. C.N.R.S. 268, 147-172.

Frey, M. 1987: Low Temperature Metamorphism. Blackie, Glasgow and London.

Fuchs, G. 1982: The geology of western Zanskar. Jb. geol. Bundesanstalt (Wien) 125, 1-50.

– 1985: The geology of the Markha - Khurnak region in Ladakh (India). Jahrb. Geol. Bundesanstalt Wien 128, 403-437.

– 1989: Arguments for the autochthony of the Tibetan Zone. Eclogae geol. Helv. 82, 685-692.

Gaetani, M., Casnedi, R., Fois, E., Garzanti, E., Jadoul, F., Nicora, A. & Tintori, A. 1986: Stratigraphy on the Tethys Himalaya in Zanskar, Ladakh. Riv. ital. Paleont. (Stratigr.) 91, 443-478.

– & Garzanti, E. 1991: Multicyclic history of the northern India continental margin (Northwestern Himalaya). Bull. amer. Assoc. Petroleum. Geol. 75, 1427-1446.

–, Garzanti, E. & Tintori, A. 1990: Permo-Carboniferous stratigraphy in SE Zanskar and NW Lahul (NW Himalaya, India). Eclogae geol. Helv. 83, 143-161.

Garzanti, E., Baud, E. & Mascle, G. 1987: Sedimentary record of the northward flight of India and its collision with Eurasia (Ladakh Himalaya, India). Geodynamica Acta 1, 297-312.

– & Van Havert, T. 1988: The Indus clastics: fore-arc basin sedimentation in the Ladakh Himalaya (India). Sediment. Geology 59, 237-249.

Gilbert, E., Colchen, M., Mascle, G., Reibel, G., Reuber, I. & Van Haver, T. 1983: Multiphased tectonics in the Indus Suture Zone, Ladakh Himalaya. Terra Cognita 3, 266.

Herren, E. 1987: Northeast-southwest extension within the Higher Himalayas (Ladakh, India). Geology 15, 409-413.

Hirn, A. et al. (12 authors) 1984a: Crustal structure and variability of the Himalayan border of Tibet. Nature (London) 307, 25-27.

– et al. (12 authors) 1984b: Lhasa block and bordering sutures - a continuation of 500 km Moho traverse through Tibet. Nature (London) 307, 23-25.

Honegger, K., Dietrich, V., Frank, W., Gansser, A., Thöni, M. & Trommsdorff, V. 1982. Magmatism and metamorphism in the Ladakh Himalayas (the Indus-Tsangpo suture zone). Earth and planet. Sci. Lett. 60, 253-292.

Jadoul, F., Garzanti, E. & Fois, E. 1990: Upper Triassic- lower Jurassic stratigraphy and paleogeographic evolution of the Zanskar Tethys Himalaya (Zangla Unit). Riv. ital. Paleont. (Stratigr.) 95, 351-396.

Klootwijk, C. T., Conaghan, P. J. & Powell, C. McA 1985: The Himalayan Arc, large-scale continental subduction, oroclinal bending and back-arc spreading. Earth and planet. Sci. Lett. 75, 167-183.

Kübler, B. 1990: "Cristallinité" de l'illite et mixed-layers: brève révision. Schweiz. mineral. petrogr. Mitt. 70, 89-93.

Laubscher, H. 1965: Ein kinematisches Modell der Jurafaltung. Eclogae geol. Helv. 58, 232-318.

Le Fort, P. 1975: Himalayas: the collided range. Present knowledge of the continental arc. Amer. J. Sci. 275A, 1-44.

Margerie, de E. & Heim Albert, 1888: Les dislocations de l'écorce terrestre. J. Wurster, Zürich.

McElroy, R., Cater, J., Roberts, I., Peckham, A. & Bond, M. 1990: The structure and stratigraphy of SE Zanskar, Ladakh Himalaya. J. geol. Soc. (London) 147, 989-997.

Mc Kenzie, D. P. & Sclater, J. C. 1971: The evolution of the Indian Ocean since the Late Cretaceous. Geophys. J. r. astron. Soc. 24, 437-528.

Molnar, P. & Tapponnier, P. 1975: Cenozoic tectonics of Asia: effects of a continental collision. Science 189, 419-426.

Oxburgh, E. R. 1972: Flake tectonics and continental collision. Nature (London) 239, 202-204.

PATRIAT, P. & ACHACHE, J. 1984: India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. Nature (London) 311, 615–621.

PÊCHER, A. 1977: Geology of the Nepal Himalaya: deformation and petrography in the Main Central Thrust zone. Colloq. int. CNRS n° 268, 301–318.

– 1991: The contact between the higher Himalaya Crystallines and the Tibetan sedimentary series: Miocene large-scale dextral shearing. Tectonics 10, 587–598.

– & LE FORT, P. 1989: Stretching lineation trajectories in the crystalline pile of central Nepal. 5th Himalaya-Tibet-Karakorum Workshop, Milano, Abstr. vol. p. 39.

PIERCE, J. 1978: The northward motion of India since the Late Cretaceous. Geophys. J. r. Astron. Soc. 52, 277–311.

PICKETT, J. W., JELL, J. S., CONAGHAN, P. J. & POWELL, C. MCA. 1975: Jurassic Invertebrates from the Himalayan Central Gneiss. Alcheringa 1, 71–85.

POWELL, C. MCA. & CONAGHAN, P. J. 1973: Polyphase deformation in Phanerozoic rocks of the Central Himalayan gneiss, Northwest India. J. Geol. 81, 127–143.

RAINA, V. K. & PRASHRA, K. C. 1974: A new fossil find in the metamorphic rocks of the Patan Valley, Himachal Pradesh. Indian Minerals 28, 124–125.

RAMSAY, J. G.: Shear zone geometry: a review. J. Struct. Geol. 2, 83–99.

SCHÄRER, U., HAMET, J. & ALLEGRE, C. J. 1984: The Transhimalaya (Gangdes) plutonic belt in the Ladakh region: a U-Pb and Rb-Sr study. Earth and planet. Sci. Lett. 67, 327–339.

SEARLE, M. P. 1986: Structural evolution and sequence of thrusting in the High Himalayan, Tibetan-Tethys and Indus suture zones of Zanskar and Ladakh, Western Himalaya. J. Struct. Geol. 8, 923–936.

–, WINDLEY, B. F., COWARD, M. P., COOPER, D. J. W., REX, A. J., REX, D., TINDONG, L., XUCHANG, X., JAN, M. Q., THAKUR, V. C. & KUMAR, S. 1987: The closing of Tethys and the tectonics of the Himalaya. Bull. geol. Soc. Amer. 98, 678–701.

SEEBER, L., ARMBRUSTER, J. & QUITTMEYER, R. C. 1981: Seismicity and continental subduction in the Himalayan Arc. In: Zagros Hindu Kush Himalaya, Geodynamic Evolution (Ed. by GUPTA, H. K. & DELANY, F. M.). Amer. geophys. Union, Washington, Geodynamics Series 3, 215–242.

SCOTESE, C. R., GAHAGAN, L. M. & LARSON, R. L. 1988: Plate tectonic reconstructions of the Cretaceous and Cenozoic ocean basins. Tectonophysics 155, 27–48.

SPRING, L. & CRESPO, A. 1992: Nappe tectonics, extension and metamorphic evolution in the Indian Tethys Himalaya. Tectonophysics 11, 978–989.

–, VANNAY, J. C., BUSSY, F., COSCA, M. & HUON, S. 1992: Permo-Carboniferous "alkaline" granitic magmatism in the Indian High Himalaya (Upper Lahul – SE Zanskar): geochimical characterization and geotectonic implications. Spec. Publ. geol. Soc. London (in press).

–, STUTZ, E., THELIN, P., MARCHANT, R., MASSON, H. & STECK, A. 1993: Inverse métamorphic zonation in very low-grade Tibetan series of SE Zanskar and its tectonic consequences (Himalaya, NW India). Schweiz. mineral. petrogr. Mitt. 72, (in press).

SRIKANTIA, S. V. & BHARGAVA, O. N. 1982: An outline of the structure of the area between the Rohtang pass in Lahaul an the Indus Valley in Ladakh. Geol. Surv. India, misc. Publ. 41, 193–204, Calcutta.

STECK, A. 1987: Le massif du Simplon – Réflexion sur la cinématique des nappes de gneiss. Schweiz. mineral. petrogr. Mitt. 67, 27–45.

STECK, A., EPARD, J. L., ESCHER, A., MARCHANT, R., MASSON, H. & SPRING, L. 1989: Coupe tectonique horizontale des Alpes centrales. Mém. Géol. (Lausanne) 5.

–, SPRING, L., VANNAY, J. C., MASSON, H., BUCHER, H., STUTZ, E., MARCHANT, R. & TIÈCHE, J.-C. 1993: The tectonic evolution of the Northwestern Himalaya in eastern Ladakh and Lahul. In: Himalayan Tectonics (Ed. by SEARLE, M. & TRELOAR, P. J.). Spec. Publ. geol. Soc. London (in press).

STUTZ, E. 1988: Géologie de la chaîne de Nyimaling aux confins du Ladakh et du Rupshu (NW-Himalaya, Inde). Mém. Géol. (Lausanne) 3.

– & STECK, A. 1986: La terminaison occidentale du Cristallin du Tso Morari (Haut-Himalaya; Ladakh méridional, Inde). Eclog. geol. Helv. 79, 253–269.

– & THÖNI, M. 1987: The Lower Paleozoic Nyimaling granite in the Indian Himalaya (Ladakh): new Rb/Sr data versus zircon typology. Geol. Rdsch. 76, 307–317.

SUTRE, E. 1990: Les formations de la marge Nord-Neotethysienne et les mélanges ophiolitiques de la zone de suture de l'Indus en Himalaya du Ladakh, Inde. Thèse de doctorat Univ. Poitiers, (inédit.).

TAPPONNIER, P., PELTZER, G., LE DAIN, A. Y., ARMIJO, R. & COBBOLD, P. 1982: Propagation extrusion tectonics in Asia: New insights from simple experiments with plasticine. Geology 10, 611–616.

–, PELTZER, G., & ARMIJO, R. 1986: On the mechanics of the collision between India and Asia. Spec. Publ. geol. Soc. London 19, 115–157.

TERMIER, P. 1903: Quatre coupes à travers les Alpes franco-italiennes. Bull. Soc. géol. France 28, 411–433.

THAKUR, V. C. 1983a: Deformation and metamorphism of the Tso Morari crystalline complex. In: Geology of the Indus Suture Zone of Ladakh (Ed. by THAKUR V. C. & SHARMA, K. K.) Wadia Inst. of Himalayan Geol. (Dehra Dun), 1–8.

– 1983b: Paleotectonic evolution of Indus-Tsangpo Suture Zone in Ladakh and southern Tibet.: Geology of the Indus Suture Zone of Ladakh (Ed. by THAKUR V. C. & SHARMA, K. K.) Wadia Inst. of Himalayan Geol. (Dehra Dun), 195–204.

– & VIRDI, N. S. 1979: Lithostratigraphy, structural framework, deformation and metamorphism of the southeastern region of Ladakh, Kashmir Himalaya, India. Himalayan Geol. 9, 63–78.

TROMMSDORFF, V., DIETRICH, V. & HONEGGER, K. 1983: The Indus suture zone: Paleotectonic and igneous evolution in the Ladakh-Himalaya. In: Mountain Building Processes (Ed. by HSÜ, K. J.) Academic Press, London, 213–219.

VAN HAVER, T. 1984: Etude stratigraphique, sédimentologique et structurale d'un bassin d'avant arc: exemple du bassin de l'Indus, Ladakh, Himalaya. Ph.D. Thesis, University of Grenoble.

–, BASSOULET, J. P., BLONDEAU, A. & MASCLE, 1984: Les séries détritiques du bassin de l'Indus au Ladakh: nouvelles données stratigraphiques et structurales. Riv. ital. Paleont. (Stratigr). 90, 87–102.

–, BONHOMME, M. G. MASCLE, G. & APRAHAMIAN, J. 1986: Analyse K/Ar de phyllites fines des formations détritiques de l'Indus aud Ladakh (Inde). Mise en évidence de l'âge Eocène supérieur du metamorphisme. C. R. Acad. Sci. (Paris) Serie II, 302(6), 325–330.

VANNAY; J. C. & SPRING, L. 1993: The geochemistry of the continental basalts within the Tethyan Himalaya of Lahul-Spiti and SE Zanskar (NW India). Spec. Publ. geol. Soc. London (in press).

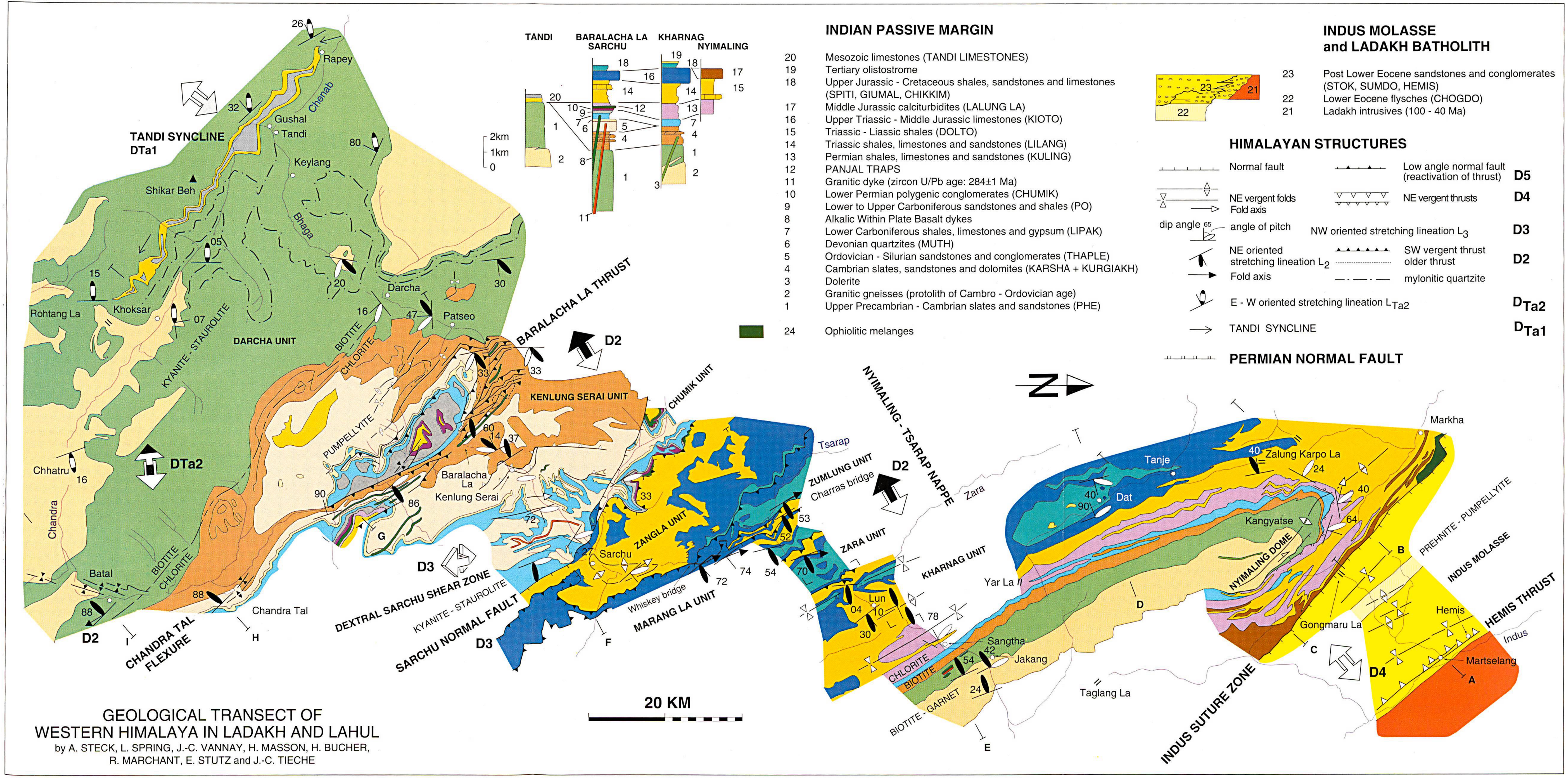
VOGGENREITER, W., HÖTZEL, H. & MECHIE, J. 1988: Low-angle detachment origin for the Red Sea Rift System? Tectonophysics 150, 51–75.

WERNICKE, B. 1985: Uniform-sens normal simple shear of the continental lithosphere. Canad. J. Earth Sci. 22, 108–125.

Manuscript received 4 may 1992
Revision accepted 23 November 1992

Plate 1. Geological transect of Western Himalaya in Ladakh and Lahul.

Plate 1



GEOLOGICAL TRANSECT OF WESTERN HIMALAYA IN LADAKH AND LAHUL

by A. STECK, L. SPRING, J.-C. VANNAY, H. MASSON, H. BUCHER, R. MARCHANT, E. STUTZ and J.-C. TIECHE