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Autor: Steck, Albrecht / Epard, Jean-Luc / Vannay, Jean-Claude

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Geological transect across the Tso Morari and Spiti areas: The nappe structures of the Tethys Himalaya

ALBRECHT STECK, JEAN-LUC EPARD, JEAN-CLAUDE VANNAY, JOHANNES HUNZIKER, MATTHIEU GIRARD, ALAIN MORARD & MARTIN ROBYR

Keywords: Himalayan tectonics, nappe tectonics, synorogenic extension

ABSTRACT

A new geological transect through the Tso Morari gneiss dome and the Upper Precambrian to Cretaceous sediments of the Spiti region has been used to determine the nappe structures of the Tethys Himalaya. The newly defined SW-directed Tso Morari, Tetraogal and Mata nappes have been formed by shearing off the upper crust of the north Indian continental margin during underthrusting below Asia. The NE-directed intra-continental Lagudarsi La thrust of the Spiti Valley is older than the frontal thrust of the SW-directed Mata nappe. The Mata nappe demonstrates the validity of the nappe model of Argand (1916). It is a large recumbent fold nappe in the ductile rocks of a deep tectonic level to the NE. It changes gradually towards the south-west into an imbricate structure, a stack of parallel thrust sheets, in the more brittle rocks at a higher tectonic level. The chronology of the Tertiary tectonic events has been established on the basis of structural observations: the initiation of the Mata nappe is related to the continental collision and underthrusting of the Indian continental plate below Asia. The NE-directed Lagudarsi La thrust – a frontal thrust of the Shikar Beh nappe – has been formed after the continental collision by intracontinental break off and shearing of the Indian crust. The frontal portion of this structure is older than the front of the Mata nappe. The extrusion of the high-pressure Tso Morari nappe and the later uplift of the Tso Morari gneiss dome on the high-angle Ribil fault are responsible for the exhumation of high pressure eclogite facies rocks of the Tso Morari nappe. In a later stage of compression, the internal northern part of the Mata nappe and the Tetraogal and Tso Morari nappes are overprinted by NE verging back folds. The formation of these synmetamorphic backfolds and the younger extension of the Dutung-Thaktote faults are probably related to the SE-directed extrusion of the Crystalline nappe and the Main Central Thrust farther south. At present the compression of the Himalayan chain continues as a dextral transpression between India and Asia, developing dome and basin folds at a hundred-kilometer scale, such as the Tso Morari dome and the Phirse Valley depression and creating the N-striking Tso Morari fault at the western border of a pull-apart basin.

ZUSAMMENFASSUNG

Eine neue geologische Traverse durch den Tso Morari-Gneisdom und die oberpräkambrischen bis kretazischen Sedimente der Spitiregion wurde für den Nachweis der Deckenstrukturen des Tethys-Himalaya untersucht. Die neu definierten, SW-gerichteten Tso-Morari-, Tetraogal- und Matadecken wurden durch Abscherung der oberen Kruste des nordindischen Kontinentalrandes während seiner Unterschiebung unter Asien gebildet. Die NE-gerichtete intrakontinentale Lagudarsi La -Überschiebung des Spititales ist älter als die frontale Überschiebung der SW-gerichteten Matadecke. Die Matadecke bestätigt die Gültigkeit des Deckenmodels von Argand (1916). Sie bildet eine grosse Faltendecke in den duktilen Gesteinen eines tiefen tektonischen Niveaus im Nordosten. Diese Deckfalte geht gegen SW fliessend in eine Imbrikationsstruktur, einen Stapel von parallelen Überschiebungen über, dies in den spröden Gesteinen eines hohen tektonischen Niveaus. Die Chronologie der tertiären tektonischen Phasen wurde auf Grund von strukturellen Beobachtungen ermittelt: Die Bildung der Matadecke beginnt während der Kontinentalkollision und der Unterschiebung der indischen Platte unter Asien. Die NE-gerichtete Lagudarsi La-Decke – eine frontale Überschiebung der Shikar Beh-Decke – entstand nach der Kontinentalkollision durch eine interkontinentale Zerscherung der indischen Kruste. Der frontale Teil dieser Struktur ist älter als die Front der Matadecke. Die Extrusion der Hochdruck Tso Morari-Decke und die spätere Hebung des Tso Morari-Gneisdoms am Ribilnormalbruch sind für die Exhumation der Hochdruck-Eklogitfaziesgesteine der Tso Morari-Decke verantwortlich. In einer späteren Kompressionsphase wurden der interne nördliche Teil der Matadecke und der Tetraogal- und Tso Morari-Decken von NE-vergenten Rückfalten überprägt. Die Bildung dieser synmetamorphen Rückfalten und die junge Extension an den Dutung- Thaktote-Normalbrüchen sind wahrscheinlich während der SO-gerichteten Extrusion der Kristallindecke und des Main Central Thrust (Zentrale Hauptüberschiebung des Himalaya) weiter im Süden entstanden. In der Gegenwart geht die Kompression des Himalayagebirges als dextrale Transpression zwischen Indien und Asien weiter, dies unter Bildung von Dom- und Depressionsstrukturen im Hundertkilometer-Massstab, wie der Tso Morai-Dom und die Phirsetal-Depression und gleichzeitig des N-streichenden Tso Morari-Normalbruches am Westrand eines «Pull-Apart-Basins».

Introduction

This study presents the results of a detailed geological and structural exploration of a complete transect across the northwestern Himalaya, through the Tso Morari crystalline dome and its southern sedimentary cover series of the Spiti region (Fig. 1, Plate 1). The aim of this work is to describe and characterize the change in tectonic style between the deep structures of the high grade metamorphic gneiss within the Tso Morari dome and the structures of the low grade sedimentary cover series to the south.

Instituts de Minéralogie et de Géologie, Université de Lausanne, BFSH2, CH–1015 Lausanne

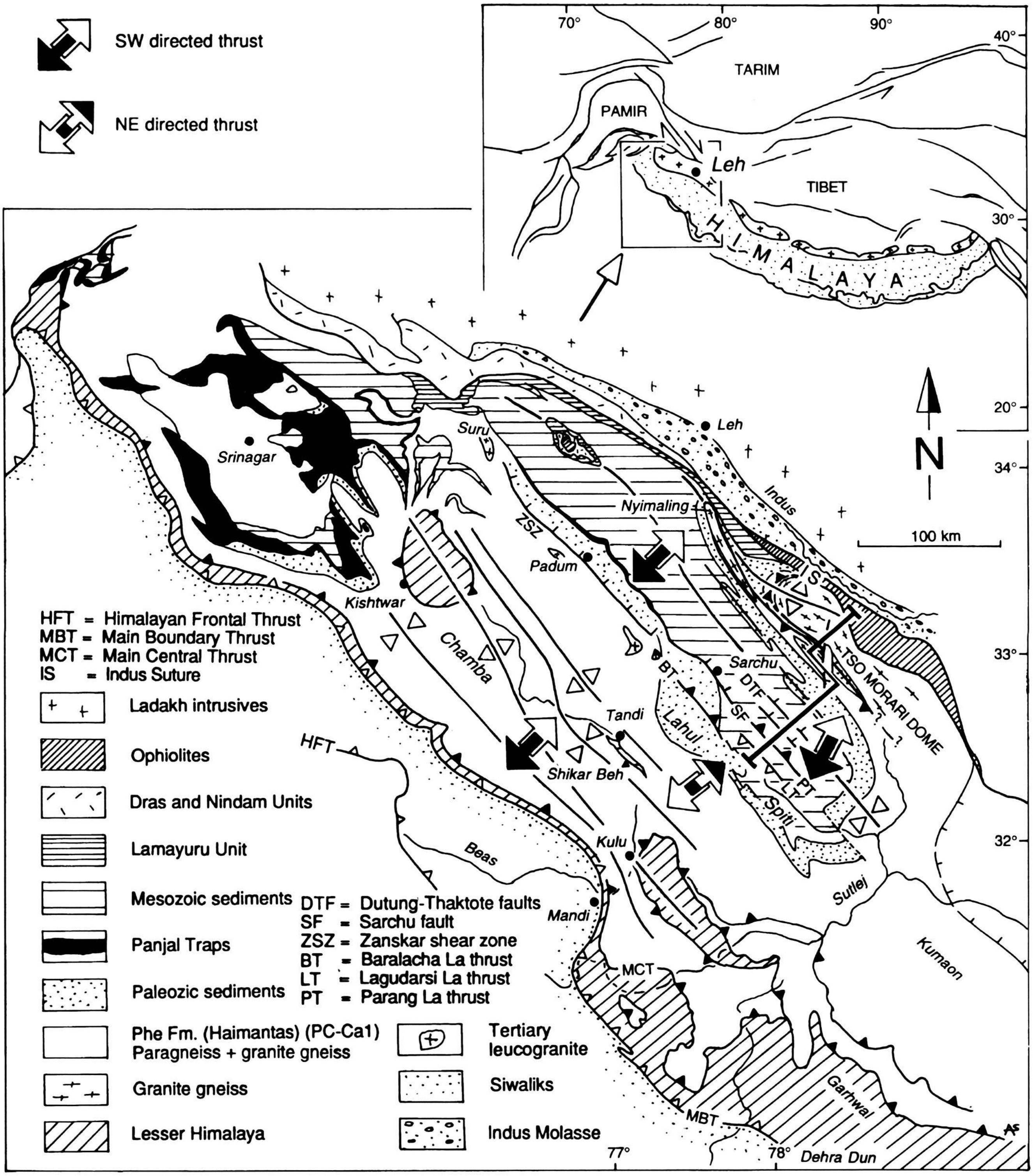

Fig 1. Generalized geological map of the studied geological transect (heavy line) through the Tso Morari crystalline dome and the Mesozoic cover series of the Tethys Himalaya.

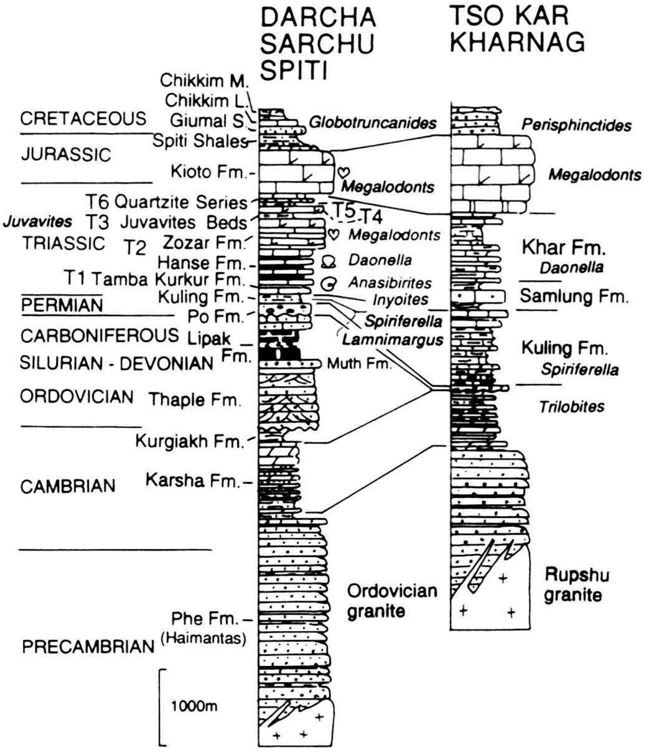

Fig. 2. Stratigraphic sections of the Himalayan Tethys Zone (North Indian margin).

In 1953, Berthelsen published a spectacular geological section through the Tso Morari gneiss dome and the sedimentary series of the Spiti region. The precise drawing depicts flat lying gneiss sheets around the Tso (Lake) Morari, similar to the recumbent gneiss folds of the Lepontine area in the Alps (Argand, 1916, Steck 1987 , Escher et al. 1993), and thin-skinned thrust structures in the Parang Valley, similar to the Jura thrust sheets (Buxtorf, 1907, Laubscher, 1980). Gansser in Heim & Gansser (1939) discovered and described the nappe structures of the Tethys zone exposed in the Kumaon region of the Central Himalaya. In spite of these observations, Berthelsen (1953) represents the «Tethys - Himalaya» as an autochtonous pile of Upper Precambrian to Tertiary sediments. An autochtonistic point of view is still maintained by Fuchs (1982, 1985, 1989) and Fuchs & Linner (1995, 1996), a view in opposition to our and other people's observations concerning the nappe tectonics of the Zanskar region (Bassoullet et al. 1980, Baud et al. 1984, Searle 1986, Stutz & Steck 1986, Stutz 1988, McElroy et al. 1990, Spring & Crespo 1992, Spring et al. 1993, Steck et al. 1993a and b). Berthelsen's (1953, Plate IX) drawing shows that he observed the thrust of the Zozar megalodont limestones onto the Juvavites beds on the left side of the Para Chu (Parang Valley) near Dutung. Berthelsen (1953) also discovered the eclogites in the Tso Morari gneiss and noticed that the degree of metamorphism changes gradually from non-metamorphic sediments in the Chikkim area in the Spiti Valley to the S, through greenschist facies rocks in the Rupshu granite and the Karzok fule ophiolites, to amphibolite facies schists with relics of an older high pressure eclogite facies metamorphism in the Tso Morari gneisses to the N. These high pressure rocks have crystallized at temperatures above 565 ± 50 °C and pressures above 20 ± 3 kbars (De Sigoyer et al. 1997). $^{40}Ar/^{39}Ar$ ages for phengite give cooling ages of ~30 ± 0.5 Ma and for biotite of ~29 ± 0.5 Ma (Mike Cosca, personal communication, De Sigoyer et al. 1997), interpreted as the time of exhumation of the Tso Morari unit. New dates on the structures and metamorphism of the Tso Morari region are reported by Thakur & Virdi (1979) and Thakur (1983a). An Upper Eocene age is postulated by Van Haver et al. (1986) and Bonhomme & Garzanti (1991) for the regional metamorphism of the Indus Molasse to the S of Leh. This could be the age of the regional greenschist and amphibolite facies metamorphism of the Nyimaling – Tso Morari region. The time of continental collision of India and Asia in the Northwestern Himalaya some 50 Ma ago is deduced as well from paleomagnetic studies (Patriat and Achache, 1984), as from sedimentary record (Garzanti et al. 1987).

The geological map (Plate 1) is based on the analysis of Spot satellite photographs and on our own geological mapping during the summers of 1996 and 1997. Our observations have been complemented by the published geological maps and descriptions by Hayden (1904), Berthelsen (1953) Thakur & Virdi (1979), Steck et al. (1993) and Fuchs & Linner (1996). Localities of this paper refer to U.S. Army Map Service (1962).

Stratigraphy

A detailed description of the classical stratigraphic section of the Spiti Valley is given by Hayden (1904). Later, Gansser (1964) characterized the stratigraphic section of the Spiti region as follows: "It is this conformable sedimentary sequence of Spiti, from Precambrian onwards, which reflects a calm epeirogenic pre-Alpine history of the "Tibetan Himalayas". Two stratigraphic sections on Plate 1 and Fig. 2 illustrate the SW – NE variation of the sedimentary deposits of the Tethyan Himalaya. The stratigraphic similarity between the different structural units exposed to the south of the Indus Suture indicate that they belong to the same North Indian crust. This is also the case for the high grade metamorphic rocks of the Tso Morari tectonic unit, which is mainly composed of Precambrian to Cambrian slates, sandstones and dolomites (Phe and Kharsha Fms.). After submission of this paper, the protoliths of the Tso Morari and Rupshu granite gneisses have been dated by the U-Pb method on zircons by M. Girard and F. Bussy, Lausanne (pers. comm.). The undeformed granite from the Polokongka La and a granite gneiss from Gyambarma Sumdo have an identical age of 479 ± 2 Ma. The Rupshu granite, with an age of 482.5 ± 1 Ma, is slightly older than the Tso Morari granite. A sequence of up to 1500 m red conglomerates

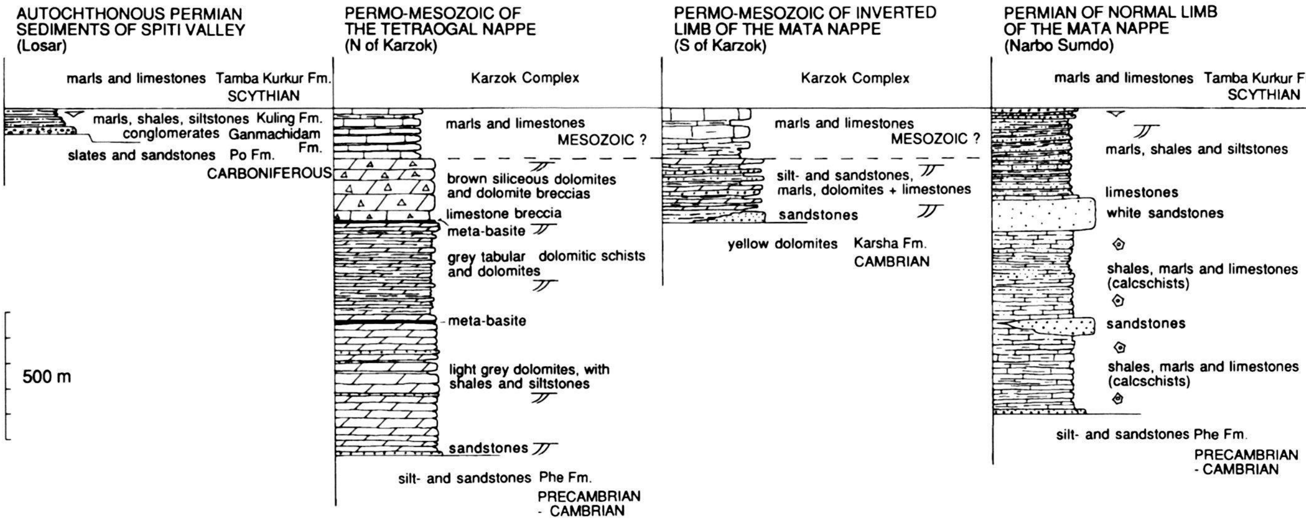

Fig. 3. Lateral variation of the stratigraphic sections of sediments of a probably Permian age between the autochthonous Kuling and Ganmachidam Fms. of the Spiti Valley to the south and the Mata nappe to the north.

and sandstones of Ordovician-Silurian age (Thaple Fm.) is covered by up to 80 m of white Devonian Muth sandstones. Both are restricted to a continental basin exposed between the Spiti Valley to the S and the Sarchu normal fault to the N. These continental detrital deposits are good stratigraphic marker horizons, but are absent in the Nyimaling and Tso Morari regions. (Fig. 3 in Steck et al. 1993). There is a large increase in the thickness of the marls, slates, sandstones and limestones of the Permian Kuling Formation from SE to NW from the internal to the external part of the Indian shelf. These detrital sediments on the N-Indian passive margin, related to the opening of the Himalayan Neotethys ocean, show a strong lateral variation of the mainly detrital deposits (Stutz, 1988 and Figs. 2 and 3). Stutz (1988) and Colchen et al. (1994) maintained the term Kuling Fm. for this Permian series, a term which was introduced by Stoliczka (1865) for a succession of calcareous sandstones and black shales of the Spiti Valley. Thakur & Virdi (1979) introduced the term Taglang La Fm. for the Permian series of the Taglang La region and Fuchs and Linner (1996) proposed the term Karzok Fm. for all the Permian deposits exposed around the Tso Morari dome, the regions of Karzok and between Jakang and the Taglang La. Characteristic deposits of this formation are black shales, marls, crinoid limestones, calcareous sandstones and quartzites. Sheets of greenschists and pillow breccias occur at different places (Fig. 3). Meta-rhyolite sheets alternating with marbles and meta-basite sheets to the north of Tso Kar are also present. The limit between the Permian and Triassic sediments is dated in the Pradong Valley, a lateral confluence of the Parang Valley, by Permian brachiopods *(Spiriferella, Lamnimargus)* and Upper Smithian ammonites *(Anasibirites* gr. *pluriformis, Inyoites)* (Plate 1, Fig. B). No determinable macro-fossils, useful for stratigraphic dating, have been found in the Permian and Mesozoic? sediments of the Tso Morari dome. Virdi et al. (1978) describe Permian conodonts *(Neogondolella biselli)* from the Taglang La region (situated 20 km to the NW of the Tso Kar). On the geological map (Plate 1) the metamorphic calcschists are designated as «Permo-Mesozoic». The stratigraphy of the Triassic to Upper Cretaceous sediments of the Spiti Valley are described by Garzanti et al. (1995). The Indus Molasse and the island arc basalts, ophiolites and associated sediments of the Indus suture zone (Sumdo complex) and the Ladakh intrusives have not been studied, with the exception of an alternation of island arc basalts and oceanic sediments which form the hanging wall of the Ribil normal fault in the upper Kalra Valley (Fuchs & Linner, 1996). Basalts with vesicular pillow lava layers, agglomeratic and pyroclastic breccias and tuffs, meta-gabbros and small slices of serpentinite alternating with carbonate sediments (recrystallised echinoderm limestones) occur in the Kalra Valley section to the north of Sumdo. The meta-basalts have been metamorphosed under low grade conditions, with albite-epidote-actinolite-chlorite-biotite as the critical greenschist facies paragenesis.

Tectonic units and structures

The following major tectonic units are distinguished on our map (plate 1 and Fig. 4). To the N, and related to the Indus suture zone, are the Ladakh intrusives, the Indus Molasse and the Sumdo complex. These units and their structures have not been studied, with exception of the island arc meta-basalts and related calcschists in the hanging wall of the young Ribil normal fault. The Tethyan Himalaya exposed to the S of the Indus

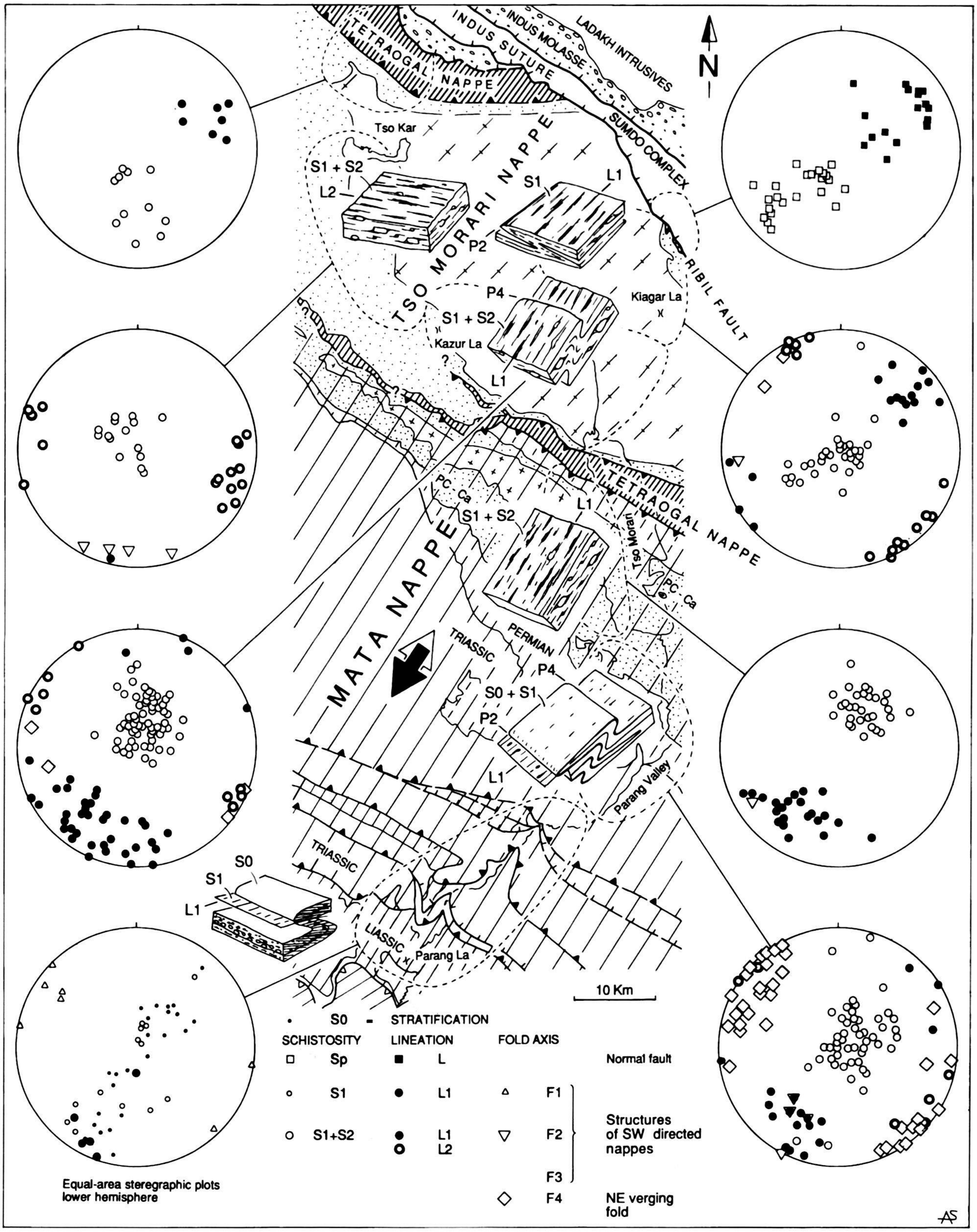

Fig. 4. Structural map of the Tso Morari, Tetraogal and Mata nappes and of the Ribil normal fault. The arrow indicates the thrust direction and the shear sense of the Mata nappe.

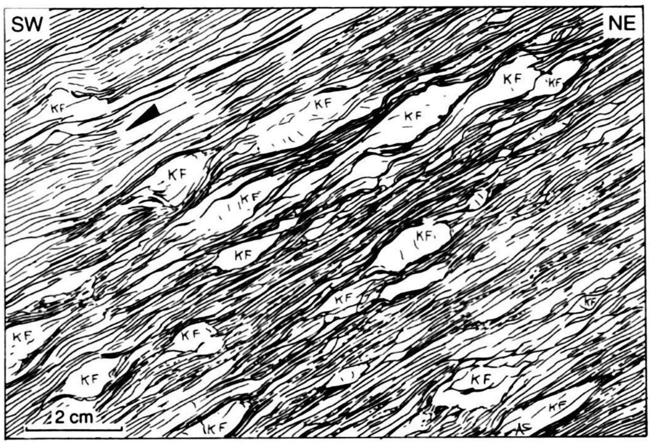

Fig. 5a. Mylonitic Tso Morari granite from Peldo. Porphyroclasts of K-feldspar are embedded in a mylonitic matrix of this high temperature mylonite. Pressure shadows on the K-feldspar clasts indicate a top-to-the SW thrusting.

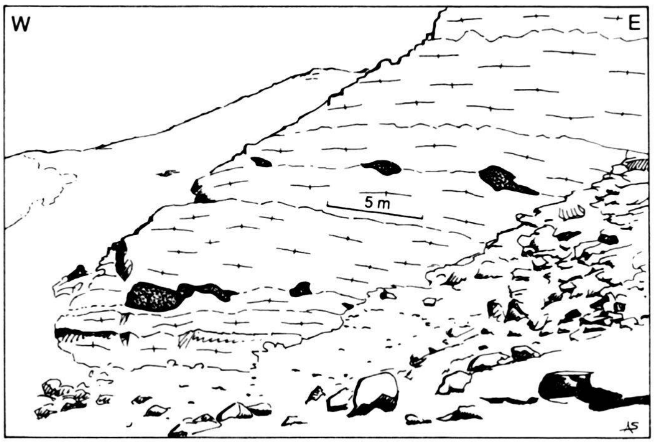

Fig. 6. Isolated eclogite boudins in the Tso Morari granitic gneiss mylonite suggest a very strong elongation of these rocks with a finite strain in excess of 3–5.

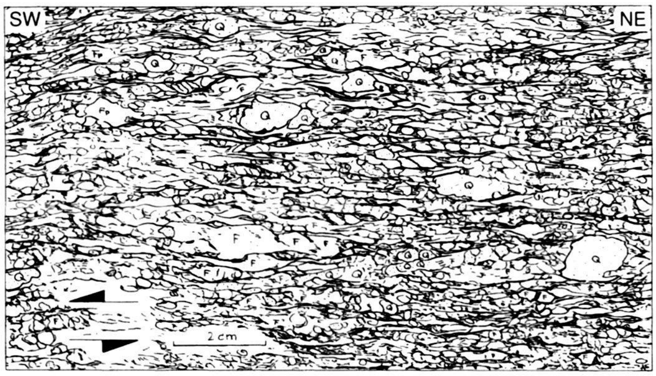

Fig. 5b. Porphyritic Rupshu granite gneiss (Mata nappe) with well preserved phenocrysts of blue quartz (Q, stippled) and Feldspar (F) from the lower contact of the intrusion. Shear criteria indicate a top-to-the SW thrusting. Pressure solution is a dominant deformation mechanism in this greenschist facies gneiss.

suture is represented by a stack of three tectonic units composed from the base to the top of the Tso Morari, the Tetraogal and Mata units. Stratigraphic, structural and metamorphic observations show that these units are nappe structures. In the Spiti Valley, there is a normal stratigraphic section of non metamorphic Permian to Upper Cretaceous sediments, which are cut by the NE directed Lagudarsi La thin-skinned thrust.

The Tso Morari nappe

The Tso Morari unit (Fig. 4 and Plate 1) consists of the Tso Morari granite gneiss and meta-sediments, Precambrian sandstones and slates of the Phe Fm. and Cambrian sandstones, slates, dolomites and marbles of the Karsha Fm, which have been overprinted by an eclogite facies metamorphism. No fossils have been found in these metamorphosed sediments (eclogite and retrograde amphibolite facies). The Tso Morari unit is strongly deformed with a main isoclinal schistosity (S2), which has transposed the former granite-sediment contacts and also the contact to the higher tectonic units to a parallel sheet structure. The Tso Morari gneiss is a strongly laminated and stretched often porphyritic granite-mylonite or -phyllonite with the oldest fabric element being NE-SW oriented stretching lineation, with top to the SW shear criteria (Fig. 5a). This mylonitic schistosity and its stretching lineation may be created during underthrusting of the Indian crust below Asia. Shear in the opposite sense occurs in some places. This gneiss also shows younger NW-SE striking stretching directions, often associated with opposite rotation of porphyroclasts. In the same outcrop shear criteria yield both top-to-the NW or top-to-the SE movement. The latter structures may indicate translation parallel to the Indus suture, mainly related to dextral transpression. The complex structures and the very strong deformation indicate a multi-phase deformation history. In these mylonites the estimated finite strain based on distance between eclogite boudins, interpreted as stretched basic dikes or sills, is generally greater than 3 and often in excess of 5 (Fig. 6). The main schistosity in the gneiss as well as in the metasediments of the Phe and Karsha Fms. folds a first generation of quartz veins and an associated S1-schistosity and therefore is the second schistosity S2. This S2-schistosity also forms the axial surface structure for ten-meter-scale isoclinal F2-folds (Fig. 7a). The coarse-grained porphyritic biotite granite of the Polokongka La region represents the undeformed protolith of the Tso Morari gneiss. All stages of transition between the undeformed granite, a granite-gneiss and a granite-mylonite are observed. Relicts of the undeformed Tso Morari granite occur not only in the Polokongka La region, but elsewhere as well, for instance, to the west of Ankun, to the east of the Kiagar La, or in the Spanglung Serpa to the east of Nuruchan. It does not form a separate intrusion and for this reason, the use of the

Fig. 7a. F2 fold in the mylonitic Tso Morari granite. At least two phases of isoclinal Folds (F1 and F2) with a mylonitic axial surface schistosity are developed in the mylonitic Tso Morari granite.

Fig. 7b. NE-verging syn-amphibolite facies crystallisation F4 folds are widespread in the Tso Morari granite gneiss. They have probably been formed during the extrusion of the Tso Morari nappe.

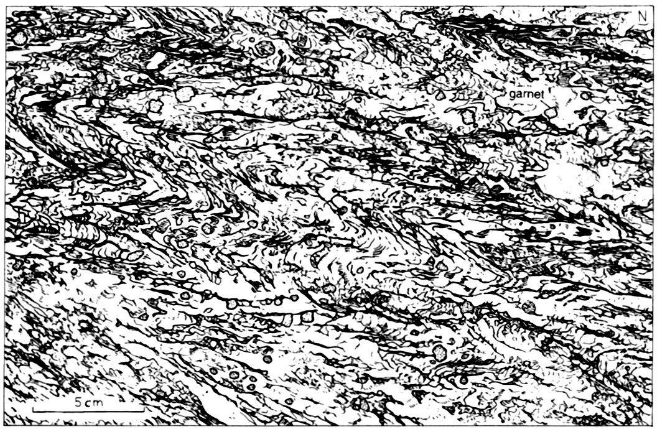

Fig. 7c. Lower greenschist facies crenulation cleavage in a mica schist with relicts of biotite, garnet and glaucophane in a metapelite (Upper Precambrian - Cambrian Phe Fm.) of the Tso Morari nappe in the footwall of the Ribil fault (Fig. 17 and 19).

term «Polokong granite» or «Polokongka La granite» (Thakur & Virdi, 1979) is rejected. After submission of this paper, two samples of zircons of the undeformed Tso Morari granite from the Polokongka La and from a Tso Morari granite gneiss from Gyambarma Sumdo have been dated. They gave the same U-Pb age of 479 ± 2 Ma (M. Girard & F. Bussy, pers. comm.). The Tso Morari granitic gneiss and its older cover of Precambrian slates and sandstones of the Phe Fm. (Haimantas) are distinguished from the overlying meta-sediments and meta-basites of the Tetraogal nappe and the Sumdo metabasites by the overall occurrence of eclogitized basaltic layers (Berthelsen, 1953). The regional distribution of eclogites and their relicts are illustrated on Fig. 8. Relics of eclogites have never been found in the higher tectonic units. This restriction of eclogites to the Tso Morari unit is well documented in the Sumdo – Kiagar La – Tso Morari transect. In the region to the SW of the line Tso Kar – Kazur La the high pressure rocks have been later retromorphosed by medium pressure staurolite – kyanite – sillimanite mineral assemblages. In the latter region we were not able to find the limit with the higher Tetraogal and Mata units. Relicts of the eclogite facies event do not exist in the Nyimaling massif to the west of the Manali – Leh road (More Plain). Thermo-barometric investigation of this eclogite and associated high pressure meta-sediments indicate that the whole tectonic unit has been metamorphosed at a minimum pressure of 20 ± 3 kbar and temperatures of 565 ± 50°C (De Sigoyer et al. 1997) and $^{40}Ar/^{39}Ar$ cooling ages for phengite of ~30 ± 0.5 Ma and for biotite of ~29 ± 0.5 Ma (Mike Cosca, pers. comm. and De Sigoyer et al. 1997). These data indicate that this tectonic unit has been subducted to a depth of 70 km before its exhumation to its present tectonic level some 30 Ma ago. The regular internal schistosity of the Tso Morari unit parallel to its upper boundary with the higher Tetraogal and Mata units indicates that the extrusion and emplacement of this allochthonous unit occurred by a normal fault relative movement parallel to its upper contact. We conclude that the Tso Morari unit is a slab of the North Indian margin, that has been subducted during underthrusting of the North Indian crust below Asia to a depth of 70 km. The formation of the mylonitic texture with two schistosities, the main NE-SW oriented stretching lineation, with top-to-the SW shear and the synkinematic high pressure mineral assemblages are related to this subduction. In a later phase this Tso Morari slab has been sheared off the Indian crust and then, as a result of buoyancy forces (Chemenda et al. 1995 and 1996), migrated parallel to the surface of underthrusting in a near surface position below the earlier accreted higher Tetraogal and Mata units. The top-to-the NE shear structures were formed during this extrusion. We conclude that the Tso Morari slab is an allochthonous nappe structure.

The Tetraogal nappe

The Tetraogal unit (Fig. 3 and 4 and Plate 1) is named after the little Tetraogal La pass (Tetraogal, Himalayan Snowcock,

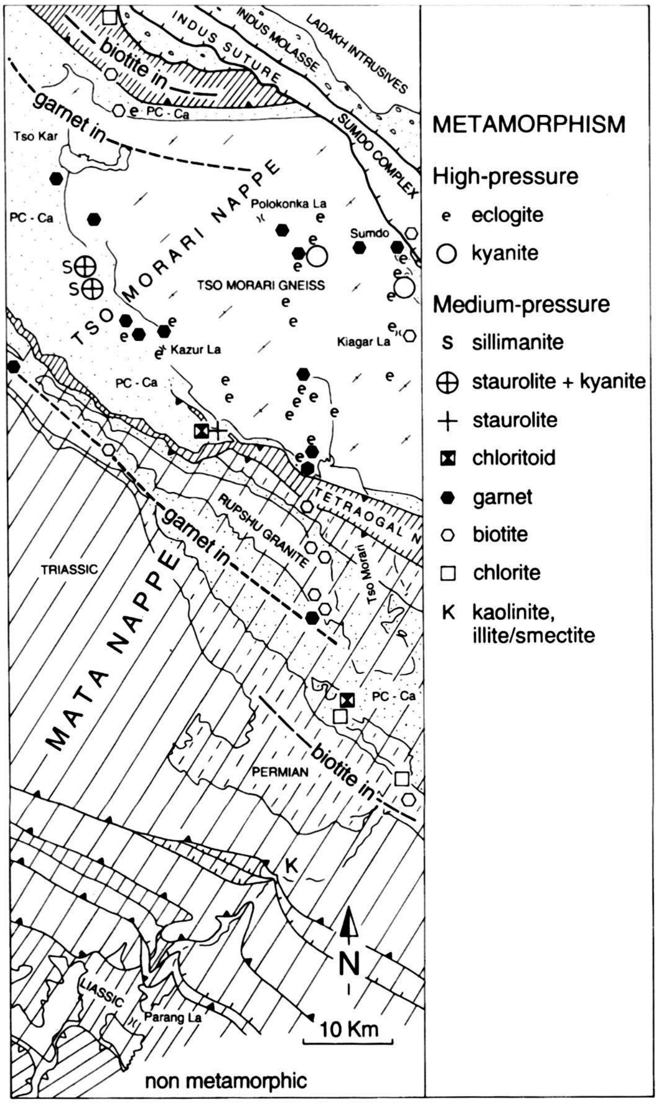

Fig. 8. Map showing the distribution of eclogites and of the index minerals of the regional medium-pressure metamorphism. Eclogites of the early high-pressure metamorphism are restricted to the Tso Morari nappe. The younger Barrovian type regional metamorphism overprints the whole nappe stack. The two outcrops of kyanite near Sumdo are from De Sigoyer (personal communication), they represent probably relicts of the early high-pressure metamorphism. The following mineral assemblages are typical for the different mineral zones in metapelites:

non metamorphic (marly limestone): kaolinite + Illite/smectite
chlorite: chlorite + white mica + albite + quartz ± calcite
chloritoid: chloritoid + chlorite + white mica + calcite + quartz
biotite: biotite + chlorite + white mica + albite + quartz ± calcite
garnet: garnet + biotite + chlorite + white mica + plagioclase + quartz
chloritoid + staurolite: chloritoid + staurolite + garnet + biotite + chlorite + white mica + plagioclase + quartz
kyanite + sillimanite + staurolite: kyanite + sillimanite + staurolite + garnet + biotite + white mica + plagioclase + quartz
kyanite: kyanite + phengite + quartz (high pressure relic).

scientific name: *Tetraogallus himalayensis*) connecting Peldo with Karzok Fule (Plate 1). This unit is made up of low grade metamorphic Permo-Mesozoic marls, limestones, dolomites, sandstones and greenschist meta-basites (with albite, epidote, chlorite, actinolite mineral assemblage, Panjal traps ?) exposed in a normal stratigraphic position (crossbeds in sandstones and dolomites, Fig. 3). It contrasts with the high pressure metamorphic rocks of the Tso Morari nappe from which it has been separated. The upper contact with the Karzok complex of meta-basalts, meta-gabbros and serpentinites is concordant and strongly deformed and is interpreted as a tectonic contact. This unit forms a sheet with parallel contacts and a parallel main schistosity S2. The stretching lineation is plunging to the SW, parallel to the main lineation in the Tso Morari and Mata units. No clear shear sense criteria have been observed in the recrystallized greenschist facies calcschists. This tectonic unit is a nappe structure, that may also be considered as a basal slice of the higher Mata nappe, as we will discuss later.

The Karzok complex of meta-basalt, meta-gabbro and serpentinite

Between Karzok Gompa and Karzok Fule, a 300 m thick complex of serpentinites, meta-basalts , meta-gabbros with a lens of chromite is intercalated with marbles and marly schists of probable Permo-Mesozoic age, as already observed by Berthelsen (1953) and interpreted as ophiolitic suture. The meta-basites are recrystallized under upper greenschist or epidote – amphibolite facies conditions (albite-epidote-chlorite-actinolite-hornblende). The occurrence of hornblende may indicate a slightly higher metamorphic grade compared with the greenschist facies mineral assemblage of the lower Tetraogal and the higher Mata nappe. After Gerhard Fuchs (pers. comm.) the meta-basalts show a typical within-plate basalt geochemistry similar to the Permian Panjal traps. In the known Panjal traps, the main magmatic rocks are basalts and not serpentinites and gabbros. We suggest that this particular tectonic slice of greenstones represents the boundary between a lower Tetraogal and a higher Mata nappe. It is also possible to interprete the Tetraogal unit together with the lens of basalt, gabbro and serpentinite of Karzok as a lower tectonic flake of the Mata nappe

The Mata nappe

Stratigraphic criteria show that the Mata tectonic unit (Fig. 3, 4, 11 and Plate 1) represents, in the Tso Morari region, a recumbent fold structure characterized by a normal and an inverted fold limb. The Rupshu granitic gneiss surrounded by the Phe (Haimantas) schists and sandstones represents the gneiss core of the fold nappe. The Kioto limestones are the stratigraphically youngest sediments and the Parang La thrust represents the southwestern front of the Mata unit. The lower and upper contact of the Rupshu granite gneiss are mylonitic zones. Some observations indicate preexisting intrusive con-

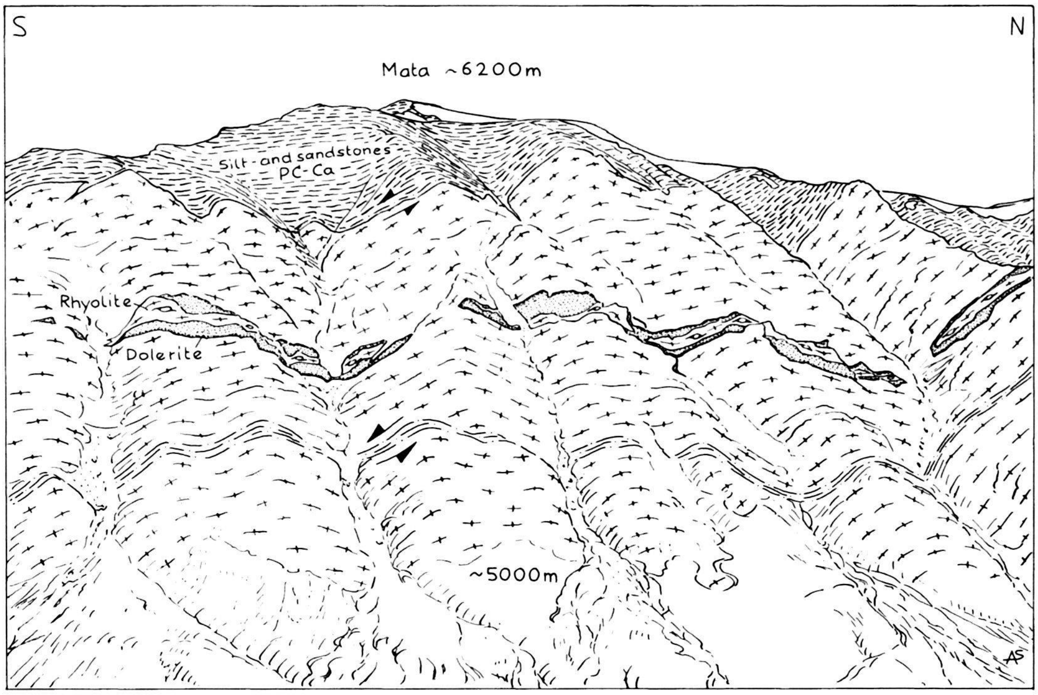

Fig. 9. View on the Mata range from Kele. The Rupshu granite and the intrusive contact with the contact metamorphosed Phe slates and sandstones on top of the Mata range are cut by a younger mixed dolerite (older) -rhyolite (younger) dike. The intensity of deformation of the Rupshu granite is very heterogeneous. A weakly deformed granite gneiss grades into ten-metre-thick granite mylonite zones, with top-to-the SW shear structures.

tacts. The lower contact of the Rupshu granite is overprinted by a mylonitic shear zone with top-to-the-SW shear criteria in a fine-grained porphyritic rim-facies of the granite (Fig. 5b). The stratigraphic section on Figure A (Plate 1) and Figure 3 illustrates the polarity criteria measured in the inverted limb of the Mata unit, exposed between the northern slope of the Mata Range and Karzok. Sedimentary structures in a carbonaceous silt and conglomerate layer at the base of the Permian sediments corroborate the inversion of the stratigraphic sequence. The upper contact of the Rupshu granite is an intrusive contact, which is also strongly deformed by a mylonitic shear zone with top-to-the-SW shear criteria. An aplitic rim, aplitic apophyses and a zone of fine-grained contact hornfels at the Mata ridge prove the magmatic contact. This intrusive contact is cut by a younger, mixed dolerite – rhyolite intrusion (Fig. 9). The coarse-grained, 20 m-thick doleritic dike developed a fine-grained chilled margin at its upper and lower contact with the Rupshu granite and is intruded in a central dike by the younger, 20m-thick porphyritic rhyolite. The sheared upper and lower contact of the Rupshu granite and discrete mylonitic zones inside the granitic sheet all show top-to-the SW shear sense criteria. No central fold hinge of the Mata unit has yet been found in the Rupshu granite gneiss. That does not mean, that such a fold structure does not exist. This relationship may be similar to the granitic gneiss cores of the Penninic recumbent fold-nappe structures of the Alps, where such folds are only documented by folded older planar structures and they are very difficult to see in homogeneous granite gneisses (Steck, 1984, Escher et al. 1993). From the Mata range to the frontal thrust of the Mata unit to the north of the Parang La, the Mata unit is mainly composed of a stratigraphic sequence of sediments from late Precambrian to Liassic age. From the Mata range to Dutung in the Parang Valley the sediments form large isoclinal folds. The stratigraphic contact between the Precambrian to Cambrian slates and schists and the Permian calcschists and a first schistosity S1 are deformed by isoclinal F2-folds (Plate 1). The Pradong recumbent fold with its core of Permian Kuling marls and slates is another spectacular SW-verging fold on the normal limb of the Mata unit. This structure can be detected on Spot-satellite color imaging. A stratigraphic section dated with brachiopods and ammonites of Permian *(Spiriferella, Lamnimargus)* and Upper Smithian *(Inyoites, Anasibirites* gr. *pluriformis)* age of the inverted F2-fold limb is shown in Figure B on Plate 1. In the frontal part of the nappe the isoclinal fold structures pass into an imbricate thrust structure of the Parang La thrust front.

Two main schistosities were developed in the Mata unit. A first schistosity (S_1) with a SW-oriented stretching lineation (L_1) parallel to the direction of overthrusting to the SW occurs throughout the structure. The first schistosity generally forms an acute angle with the stratification and is also the axial surface structure of asymmetric SW-verging folds, indicating an overthrust direction to the SW. During a progressive rotational deformation, a second schistosity (S_2) with a SW-oriented stretching lineation (L_2) parallel to the direction of overthrusting has been developed as an axial surface structure for the ductile recumbent folds in the Permian shales, marls and limestones (Fig. 4 and Plate 1). The second schistosity is restricted

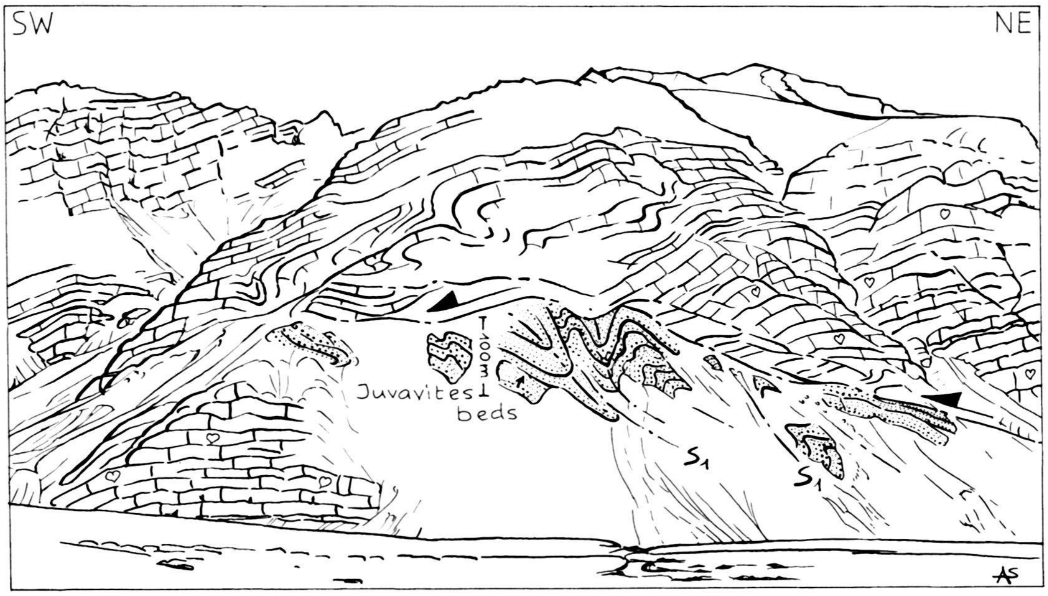

Fig. 10. A spectacular zone of detachment affects the Juvavites Beds on the left bank of the Para Chu near Dutung. The rigid Megalodont – limestones of the Zozar Formation are overthrusted on a hanging wall ramp. The Juvavites beds are deformed by drag folds characterized by a penetrative S1 – axial surface schistosity, the later is oriented perpendicularly to the main direction of compression.

to the internal part of the Mata unit north of Dutung. Only one SW-verging first schistosity overprints the quartzites and associated open folds of the Mata unit front below the Parang La (geological section on Plate 1). The ductile Monotis shale's and Juvavites beds (dated by Juvavites) are two important second order zones of detachment at the base of the more rigid Kioto and Coral limestones (Fig. 10). Third generation SW verging F3 folds are only locally developed in the Phirse Valley (Plate 1). The geometry of the Mata unit suggests that this is a nappe structure (Fig. 11) composed of a recumbent fold in the internal ductile part of the nappe, deformed under greenschist facies conditions (Fig. 8), and an imbricate thrust structure in its brittle and non-metamorphic frontal part. The Mata nappe demonstrates the validity of the nappe model of Argand (1916, Fig. 12). The Dutung-Thaktote extensional normal fault zone, which overprints the frontal imbricate structure of the Mata nappe is discussed below. The root of the Mata nappe is missing by erosion and is cut by the Ribil normal fault of the Indus suture. The displacement of the nappe between the Mata range area and the Indus suture is more than 40 km. The distance of displacement of the elements of the nappe gradually decreases from the internal north-eastern part to the external south-western part. The horizontal displacement of the frontal Parang La thrust is about some hundred to thousand meters. Finally, the thrust structure is dying out in the SW verging F1-folds with an axial surface crenulation cleavage S1 below and in front of the Mata nappe. This geometry of the Mata nappe may be explained by a mechanism of shearing off the upper part of the Indian passive margin during its underthrusting in a NE direction below Asia.

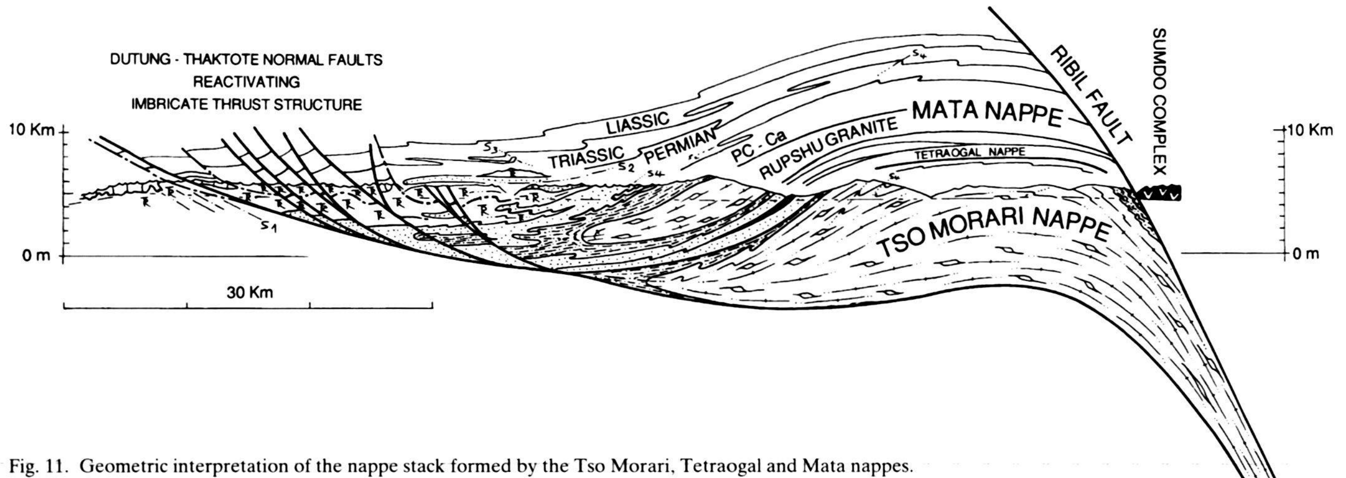

Fig. 11. Geometric interpretation of the nappe stack formed by the Tso Morari, Tetraogal and Mata nappes.

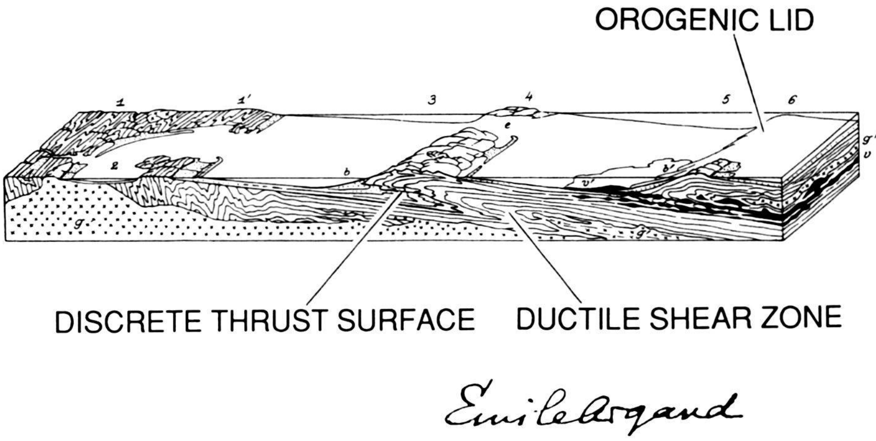

Fig. 12. Thrust model after Argand (1916).

The foreland fold belt of the Mata nappe and the correlation between the Mata nappe and the Nyimaling – Tsarap nappe

The Ordovician to Cretaceous sedimentary sequence exposed in the Spiti region in front of the Parang La thrust is affected by open folds with NW-SE striking fold axes and steep axial surfaces and an amplitude and wavelength ranging from ten to some thousand meters (Plate 1). The folds of the upper Ratang Valley (Plate 1) may be followed on the satellite photographs to the north-west, in the fold zone of the Kun Zam La region (Wyss et al. in press, Kun Zam La = Pass between the upper Spiti Valley and the Chandra Valley) and along the upper Chandra Valley in the Baralacha La thrust front of the Nyimaling-Tsarap nappe (Steck et al. 1993a & b).

The Mata nappe represents the eastern equivalent of the Nyimaling-Tsarap nappe, although the two structures are not cylindrical (Fig. 1). The geometric features of the two nappes are similar. The imbricate structure (de Margerie & Heim, 1888) of the nappe front is related to the ductile shear zone in the root of the nappe. A precise estimation of the total amount of overthrusting of the Mata nappe is not possible. The Nyimaling granite and its eastern equivalent, the Rupshu granite, form the gneiss core of a large recumbent fold with an overthrust length of more than 40 km. The ductile (up to 1000m thick) Permian shales, marls, limestones and sandstones are folded in a succession of recumbent folds with an amplitude of 10 to 15 km in the internal part of the nappe (geological section on plate 1 and figure 13 in STECK et al. 1993a & b). The folds are not cylindrical, but rather have developed as an en-echelon structure. Similarly the frontal Parang La thrust of the Mata nappe and the Baralacha La thrust of the Nyimaling-Tsarap nappe form also an en-echelon structure (Fig. 1).

The Lagudarsi La thrust

A spectacular NE-directed thin-skinned thrust structure is exposed in the steep wall of Liassic Kioto limestones, on the Lagudarsi La trail, which connects the pass with the village of Kiato (Kioto, Fig. 13). A steep SW-plunging stretching lin-

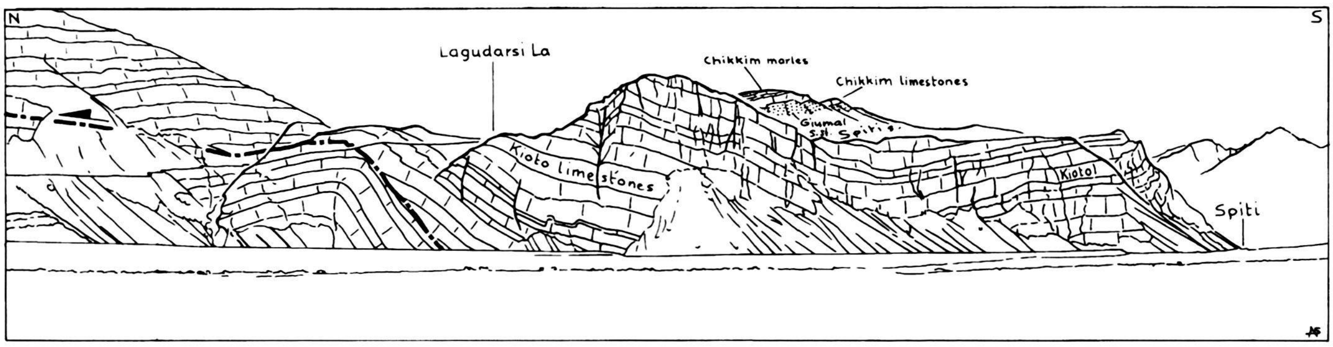

Fig. 13. The NE-directed Lagudarsi La thrust on the trail linking the Lagudarsi La with Kiato (Kioto) in the Spiti Valley. The thrust plane is folded by a younger SW-vergent fold in front of the SW-directed Parang La thrust.

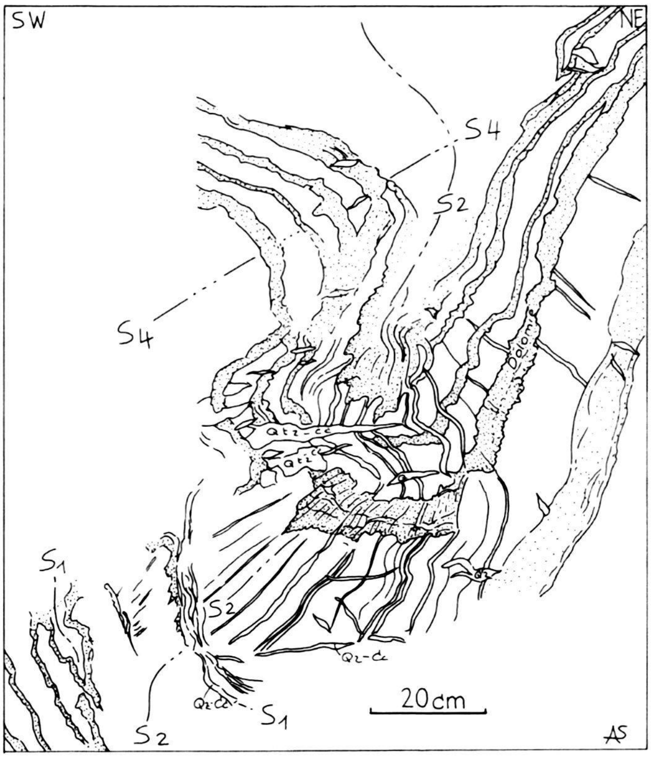

Fig. 14. Near Umdung, the axial surface schistosity of the Pradong recumbent fold structures is a second schistosity, which folds quartz – calcite fiber (L1) veins that are parallel to the S1 – schistosity and rare F1 – folds. The SW – vergent recumbent folds are affected by NE-oriented F4 – back folds.

eation and calcite fibers are parallel to the NE-oriented overthrust direction. Interference structures of this NE-vergent nappe front and the opposite SW-directed Parang La thrust are exposed in the 300m deep gorge of the Parilungbi River (Plate 1). In general the SW-vergent folds and associated schistosity of the Parang La thrust are younger than similar NE-directed structures of the Lagudarsi La thrust. In the Spiti Valley the age relation between the two nappe fronts is the same as observed farther west between the older NE-vergent Shikar Beh nappe front and the younger SW-vergent Baralacha La thrust, representing the southern front of the Nyimaling - Tsarap nappe (Steck et al. 1993 a & b, Vannay & Steck, 1995, Wyss et al. submitted). We consider the Lagudarsi La thrust as the northeastern front of the Shikar Beh nappe. Another NE-directed thrust with SW-oriented stretching fibers, has been observed farther to the east in the Parilungbi Valley, about 5 km below the Parang La, in the Upper Triassic Quartzite Series. This thrust is interpreted as the eastern continuation of the Lagudarsi La thrust (Plate 1).

Late NE-vergent "backfolding"

From Umdung in the Parang Valley to the north, the SW-directed and SW-verging nappe structures are overprinted by NE-vergent "backfolds" (F4) (Fig. 14). These folds are younger than the SW-verging F3-folds in the Phirse Valley and therefore F4-folds. In the Permian strata near Kiangdom, chloritoid porphyroblasts crystallized synkinematically with the formation of the NE-verging crenulation cleavage of the back folds, and therefore represent temperature conditions of the medium pressure regional metamorphism. These structures are cut by the younger Dutung – Thaktote normal faults in the Mata nappe and the Ribil normal fault at the Indus suture (Plate 1 & Fig. 11) and folded by the younger Quaternary dome and basin structures (F5).

The same type of NE-vergent folds occur in the Tso Morari nappe, where they were created under amphibolite facies conditions (Fig 7b and 15). That probably means that the whole nappe-stack has been in a same late D4-phase overprinted by NE-verging folds.

The Dutung – Thaktote normal faults

The imbricate structure of the Parang La thrust was overprinted by the Dutung – Thaktote normal faults, a sequence of mainly steep NE-dipping high-angle faults (Plate 1, Figs. 11 & 16). Some of the faults cross cut each other, or are reactivating older low-angle thrust faults of the Mata nappe (Fig. 16). The Dutung-Thaktote normal faults correspond to the south-eastern expression of the Sarchu (Spring, 1993) and Zanskar (Herren, 1987) normal faults. All these extensional structures overprint preexisting inverse faults and have been developed in an en-echelon position, which may be related to dextral transtension (Fig. 1). For the Zanskar shear zone Herren (1987) calculate an extension of about 25 km and Dèzes et al. (submitted) calculate an extension of at least 35 km. Spring (1993) suggests an extension of at least 20 km for the Sarchu region. The cumulative offset on the Dutung-Thaktote normal faults has not been measured. The normal faults have probably formed during extrusion of the Crystalline nappe to the south. At the scale of the Himalaya range, these extensional structures belong to the North Himalayan shear zone (Pêcher, 1991) or the South Tibetan detachment system (Burchfiel et al. 1992).

The Ribil normal fault

At Ribil, a NW-striking and steep (68°) NE - dipping normal fault, the Ribil fault, separates the isoclinal NE-dipping stratification and schistosity of the metabasite and calcschist layers of the Sumdo complex to the North from Mesozoic or Permian calcschists of the Tetraogal nappe to the south (Fig. 17, 18, 19). To the west of Sumdo, the Ribil fault follows the Zildat Phu and forms the contact between the Tso Morari nappe and the Sumdo Complex (Plate 1). The steep normal fault crosscuts the planar NE-dipping stratification as well as a gently dipping crenulation cleavage, associated with small chevron type folding developed only in the footwall, formed by the Permo-Mesozoic sediments of the Tetraogal nappe and the Upper Precambrian slates and sandstones of the Phe Fm. (Haiman-

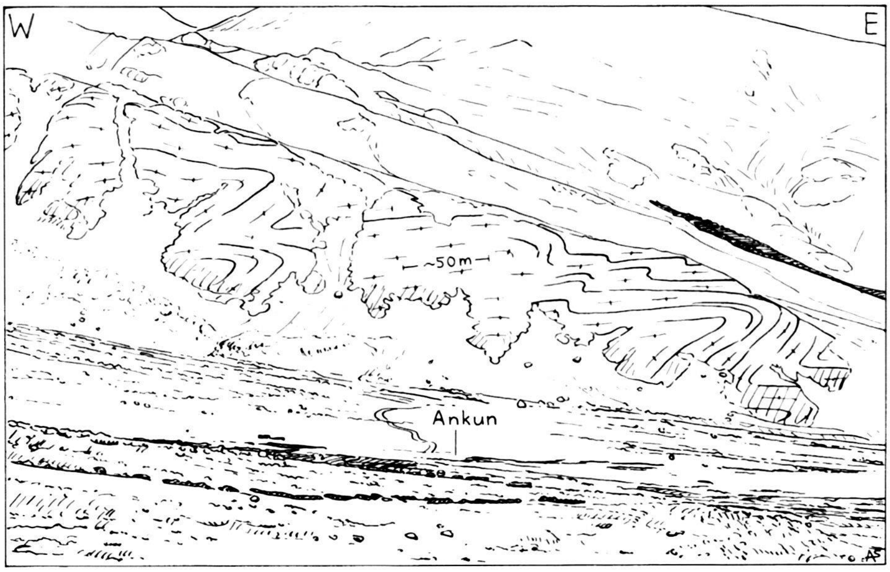

Fig. 15. NE-verging F4-folds in the Tso morari gneiss at Ankun on the Polokongka La - Puga trail.

tas) of the Tso Morari nappe. The crenulation cleavage has been formed under lower greenschist facies conditions (albite-epidote-chlorite). In the hanging wall of the Ribil fault, in the Sumdo complex, north of Ribil and Sumdo, top-to-the NE movement based on shear criteria have been observed parallel to a 30–70 NE plunging lineation and to the main schistosity of the metabasites. These extensional structures in the hanging wall of the Ribil fault are perhaps related to a major low-angle normal fault or shear zone. We propose that the gently NE-dipping crenulation cleavage in the footwall of the Ribil fault was formed in a zone of subvertical shortening below this major low-angle normal fault, in a similar way a crenulation cleavage developped in the footwall of the Simplon low-angle normal fault in the Alps (Steck, 1984, 1987). The main low-angle fault or shear zone was later cut by the high-angle Ribil normal fault. The Ribil fault (Plate 1, Figs. 17, 18 & 19) cuts the roots of the Tso Morari nappe and the overlying higher nappe structures of the Tetraogal and Mata nappes and juxtaposes the lower greenschist facies metabasites to the NE with the garnet – biotite schists, garnet amphibolites and meta-eclogites of the Tso Morari nappe to the S. The vertical offset on this 68° NE dipping normal fault is difficult to estimate; it may be on the order of some thousand to ten-thousand meters.

Late uplift of the Tso Morari dome on the Ribil normal fault and active Quaternary dome and basin structures

Different types of Quaternary structures, which remain active, are present in the map area (Plate 1). The N – S oriented Tso Morari normal fault (Berthelsen, 1953), the Mata range together with the Tso Kar – Kiagar La anticline to the north and the Phirse alluvial plain to the south are elements of an active Quaternary dome and basin structure (F5) of the Himalaya. Terraces of fluvial or lacustrine sediments on the border of the valleys, deeply eroded gorges and steep mountain walls are evidence of regions of active uplift. In contrast, large alluvial plains filling great valleys, like the Phirse Valley, indicate active depressions. The amplitude and wave length of these dome and basin structures are 3 to 5 km and 50 to 150 km respectively (Plate 1 and Fig. 1). One of the most spectacular active faults is the Tso Morari fault (Berthelsen, 1953) which is partially covered by Quaternary deposits and the Tso Morari. The narrow gorges of the Phirse Fu and of the E-flowing Gyamsharma River above its deflection into the S-flowing Yan River, as well as the steep slope of the latter gorge are consistent with the active fault structures. Some faults parallel to the main Tso Morari fault are exposed at the entrance of the Gyamsharma gorge. Other faults on the eastern slope of the Mata range above Kele (Plate 1) are either faults of the Tso Morari fault system or young superficial gravitational structures (Berthelsen, 1953). To the north of the Tso Morari, the main Tso Morari fault split into a fan of active faults which are easily recognized in the field and on Spot-satellite images. The Kiagar Tso is located between conjugate faults. At Puga, the hot sulfur springs are situated at the intersection of NNE-oriented active faults of the Tso Morari fault system and the Puga Valley. Another sulfur spring is situated at the intersection of another NNE-oriented fault and the Ribil normal fault to the east of the village of Ribil. Other N-S striking faults may be detected in the Ladakh intrusives to the north of the Indus River. The Tso Morari is located in a pull-apart depression created by the Tso Morari normal fault, related to dextral strike-slip movements parallel to the NW-SE-striking Indus Suture. This lake is dammed to the south by the Phirse alluvial fan. An alluvial terrace with up to 1m thick lacustrine limestones, is situated about 4 m above the present water level. The present low lake level may be explained by very strong evaporation which

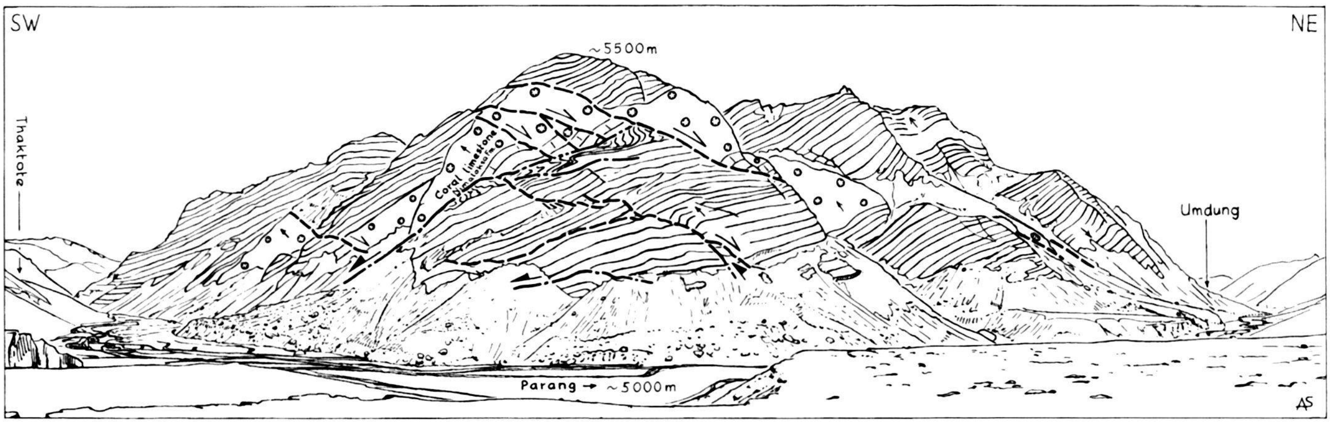

Fig. 16. Normal faults of the Dutung-Thaktote fault zone cutting and reactivating older thrust faults with SW-verging F1 folds in the Late Carnian-Early Norian marls and limestones of the Mata nappe; left side of the Parang Valley between Umdung and Thaktote. The white coral limestone layer with coral reefs in life position corresponds to the coral limestone at the limit of the Lower and Upper Member of the Nimaloksa Fm. (Garzanti et al. 1995).

cannot be compensated by the volume of water flowing in from the Phirse and Yan rivers. An analogous situation to the Tso Morari region is observed in the Tso Kar – Startsapuk Tso depression. The water levels of the Tso Kar and the Startsapuk Tso (salt lakes) are very low, presumably because of the high evaporation. An important fossil lake terrace is situated at about 4630 m, 50 m above the present lake level. Previously, under different climatic conditions, the lake level was 50 m higher and the water was probably drained westwards through the valley of Debring and the Tsara river. Fuchs and Linner (1996) indicate a N-striking normal fault to the west of Tso Kar. This structure is completely covered by Quaternary deposits and is probably responsible for the formation of the Tso Kar-Startsapuk Tso depression. The precise position of the fault (or faults) is unknown and for this reason it is not represented on the geological map (Plate 1). The deeply eroded gorges and the steep mountain walls on both sides of the Spiti suggest rapid uplift of this region at the present time. All these

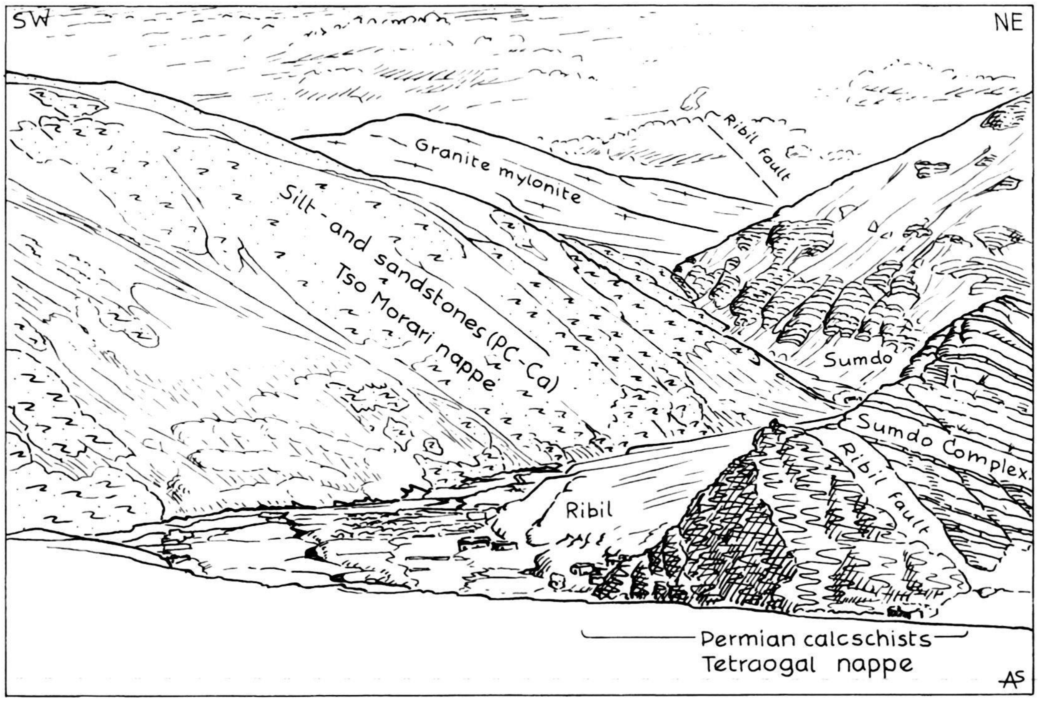

Fig. 17. View of the Ribil fault at Ribil and Sumdo in the Kalra Valley. The steep NE-dipping normal fault cuts discordantely the gently NE-dipping main meta-basalt layers, stratification and schistosity in the Sumdo complex in the hangingwall and the Tetraogal and Tso Morari nappes in the footwall. A well developed gently dipping crenulation cleavage deforms the the Permian calcschists of the Tetraogal nappe and the Upper Precambrian to Cambrian silt- and sandstones of the Tso Morari nappe.

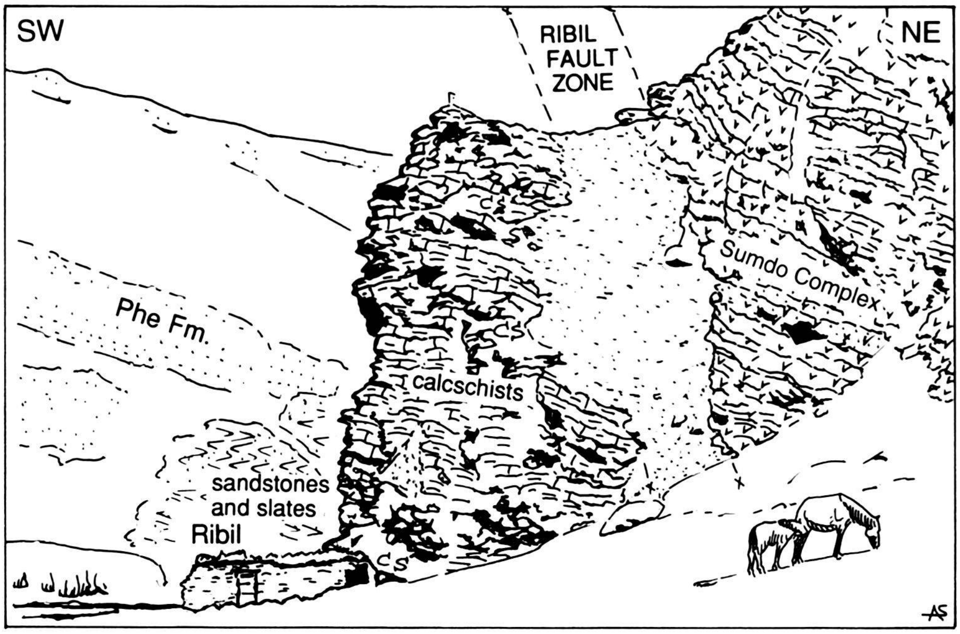

Fig. 18. Near the village of Ribil the steep NE-dipping Ribil fault zone separates Permian calcschistes (cs) from the greenschists of the Sumdo complex. The cataclastic fault zone is covered by Quaternary deposits. Note the discordance between the steep fault and the gently NE-dipping stratification and crenulation cleavage (horse for scale: 16 hands, 1hand = 4 inches).

Quaternary structures are compatible with a still active dextral transpression regime that create N-S striking normal faults, W – E (to NW-SE) striking dome and basin structures in a main dextral shear zone, oriented parallel to the NW-SE-striking Indus Suture.

Relation between tectonic events and metamorphism

A correlation between the main tectonic events and the metamorphic phases is proposed, based on thin section petrography. The regional distribution of eclogites, relics of an early high-pressure metamorphism, and of the index minerals of a younger medium-pressure metamorphism are represented on Fig. 8. A very intense deformation under high temperatures, creating at least two phases of isoclinal folding (Fig. 7a), testifies to a multistage history of the Tso Morari gneiss. These deformations are principally related to the subduction and the high pressure metamorphism. It is difficult to separate the amount of deformation related to the later extrusion and recrystallization under medium pressure amphibolite facies conditions of the Tso Morari nappe from the earlier internal deformation at high pressure.

The Tetraogal and Mata nappes have been deformed together under medium-pressure regional metamorphic conditions. The regional metamorphic grade increases from south to north from unmetamorphosed sediments with kaolinite and Illite/smectite minerals (Philippe Thélin, pers. comm.) in the Chikkim area (Spiti Valley) and the upper Parang Valley south of Dutung, through the chlorite zone in the lower Parang Valley, to the biotite zone from Narbu-Sumdo to Karzok Gompa (with chloritoid in Permian metapelites near Kiangdom). This metamorphism of the Mata and Tetraogal nappes passes gradually to the garnet-kyanite-sillimanite-staurolite zone in the Tso Morari nappe (Fig. 8). It is unclear if the regional metamorphism of the Mata and Tetraogal units is of the same age and phase as the retrograde amphibolite facies metamorphic phase in the Tso Morari unit. The NE-verging F4-backfolds formed under the peak conditions of the medium pressure regional metamorphism. The normal fault movements in the Sumdo complex occurred under greenschist facies conditions, with the critical mineral assemblage albite-epidote-biotite-chlorite-actinolite. These early synmetamorphic normal fault structures in the Sumdo meta-basites and the nappe stack are cut by the younger Ribil fault. A strong horizontal crenulation cleavage is developed in a 2–3 km wide zone in the Tetraogal and Tso Morari nappes in the footwall of the Ribilt fault. The intensity of this crenulation cleavage reaches its maximum close to the normal fault (Fig. 7c & 19). This crenulation cleavage was formed under lower greenschist facies conditions, with albite-epidote-chlorite, as the critical mineral assemblage. Pressure solution is the main deformation mechanism. The quartz fabric indicates plastic deformation by dislocation gliding, grain boundary migration and polygonisation (formation of subgrains with low-angle limits) typical of deformation temperatures of about 250°C (Voll, 1976).

A kinematic model

A synthetic geological section of the Tso Morari, Tetraogal and Mata nappe stack is shown on Fig. 11 and a model of the structural and metamorphic evolution since 50 Ma of a geological transect of the NW Himalaya and through the investi-

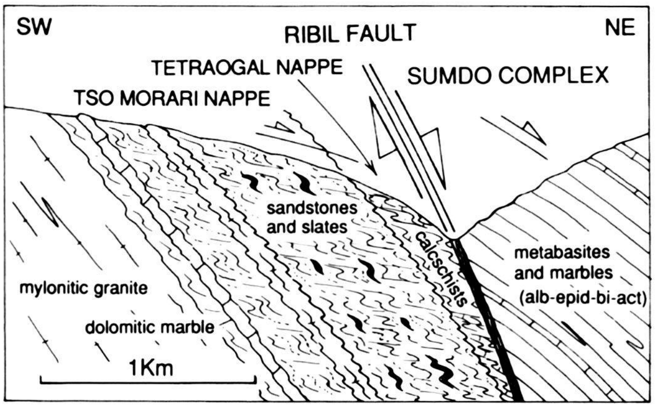

Fig. 19. Simplified geological section through the Ribil fault near Ribil and Sumdo. Note the discordance between the steep normal fault (Azi 055°/68°) and the gently NE-dipping older structures. A critical greenschist paragenesis of albite-epidote-biotite-actinolite crystallized syncinematically with the formation of the main schistosity with normal fault sense of movement in the Sumdo complex. The Ribil fault zone is covered by Quaternary deposits. The fault zone is probably filled up with fault gouge. A well developed crenulation cleavage (Azi 320°/10°) formed under very low-grade metamorphic conditions (albite-epidote-chlorite-calcite) overprints older amphibolite facies structures in the Tetraogal nappe and amphibolite and eclogite facies rocks in the Tso Morari nappe.

gated region is proposed in Fig. 20. This model is constrained by the following main conditions, the studied geological section exposed on the Earth's surface (geological profile on Plate 1 and geological profiles in Steck et al. 1993a &b and Epard et al. 1995), the age relations between structural and metamorphic events observed on the outcrop and thin-section scale, the radiometric cooling ages of metamorphic micas and the generally accepted concept, that the Indian crust was subducted to the NE below the Ladakh batholith and Asia:

- The continental collision between India and Asia occurred, according to Patriat & Achache (1984) and Garzanti et al. (1987), some 50 Ma ago, and is indicated by a strong decrease of the relative northward velocity of the Indian plate, and by the end of marine sedimentation in the forearc basin. At this stage the Permian to Cretaceous marine sediments of the North Indian shelf have a N-S width estimated by Vannay (1993) and Steck et al. (1993 a & b) of 200–300 km.
- The underthrusting of the North Indian continental border below Asia is responsible for the subduction of the future Tso Morari unit to a depth of 70 km, corresponding to a pressure of 20 ± 3 kb and temperature of 565 ± 50 °C obtained for the eclogite mineral assemblages by De Sigoyer et al. (1997). The formation of the Mata (and Tetraogal) nappe occurred by shearing off and accretion of the upper Indian crust and shelf sediments, followed by a regional medium pressure metamorphism. The formation of the intra-continental Shikar Beh Nappe is approximately of the same age. The NE-directed thrust may be created by the reactivation of a preexisting SW-dipping extensional fault (Steck et al. 1993a & b, Vannay & Steck, 1995, Epard et al. 1995).
- Before 30 Ma the Tso Morari slab is sheared off the subducted Indian crust during continuation of underthrusting of India below Asia and moved by the buoyancy force (Chemenda et al. 1995 & 1996) along the surface of underthrusting toward the Earth surface, cooling down below 300 °C some 30–29 Ma ago ($^{40}Ar/^{39}Ar$ phengite and biotite ages, Mike Cosca, pers. comm. and De Sigoyer et al. 1997). During this process the Tso Morari slab is deformed by pure and simple shear. The medium pressure/ high temperature retrograde metamorphism occured at this time. The end of the Mata nappe emplacement is contemporaneous with the extrusion of the Tso Morari nappe. The SW-verging folds of the foreland fold belt of the Mata nappe are folding the frontal thin-skinned structures of the Shikar Beh nappe. The Ribil normal fault was active in a late stage of updoming of the Tso Morari nappe and its cover, the higher Mata (+ Tetraogal) nappe.
- The age of the extrusion of the Crystalline nappe along the Main Central Thrust (MCT) is constrained by the Rb/Sr mica cooling ages of 21–16 Ma in the Kullu Valley (Frank et al. 1977). The extension on the Dutung – Thaktote normal faults may be related to this extrusion.
- The Himalayan Frontal Thrust (HFT), the Main Central Thrust and late dome and basin structures of a wavelength of 50–150 km and an amplitude of some thousand meters are active at present. N striking normal faults, like the Tso Morari fault, which form an angle of 45° with the Indus suture, are related to active dextral transpression.

The suggested kinematic model supports the physical models of Chemenda et al. (1995 and 1996), in which slabs of light crustal rocks are detached from the subducted plate and pushed by buoyancy forces back to the Earth's surface along the active zone of subduction. The difference between the models discussed by Chemenda et al. and our model remains in the different geometry of the zones of collision interpreted by Chemenda et al. and the studied Tso Morari – Spiti transect. Another model, supported by field and laboratory studies, is proposed by Burchfiel et al. (1992). They suggest the simultaneous development of two conjugate faults in a thrust system, the Main Central Thrust at the base and a normal fault at the top of the Crystalline nappe, accomodating the extrusion of crustal material.

Conclusions

The Tso Morari – Spiti transect offers a continuous section through different tectonic levels of the Himalayan chain. In this geological section it is possible to study the transition between the ductile recumbent fold nappes of a deep tectonic level to the north and the thin skinned thrust sheets of a high tectonic level of the Himalayan chain to the south. The Mata

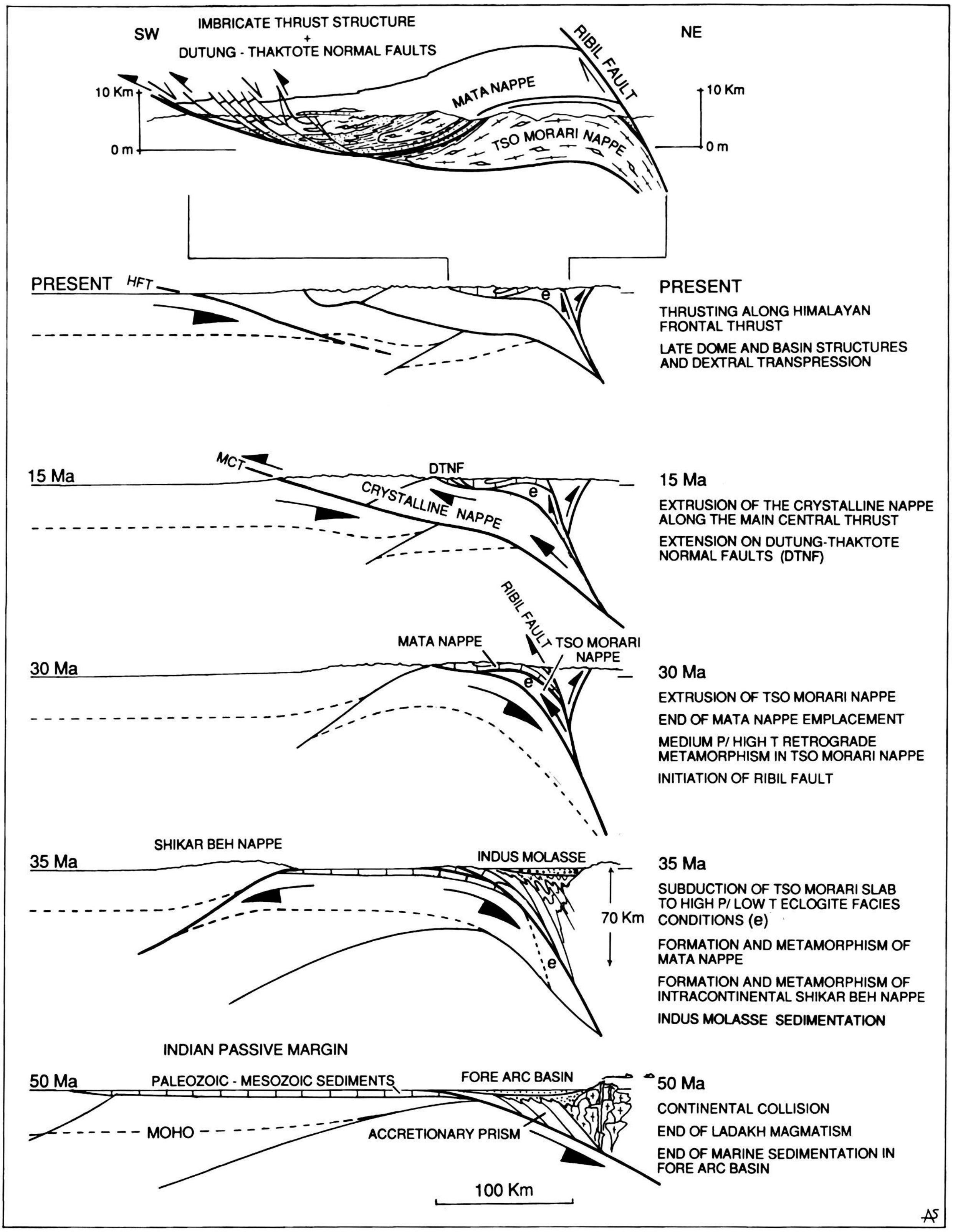

Fig. 20. Tectonic model for the Tso Morari – Spiti – Mandi Transect of the north-western Himalaya.

nappe is a good illustration of the tectonic model proposed by Argand (1916) in relation to similar structures in the Alps (Fig. 12, Steck, 1987, Escher et al. 1993, Steck & Hunziker 1994). The structures observed in this section are similar to those described for the Nyimaling – Tsarap nappe on the Leh – Rohtang La transect farther to the W (Steck et al. 1993). *The imbricate thin skinned nappe stack of the frontal part of the nappe is* related to a large *ductile shear zone at a deep tectonic level.* A kinematic model for this kind of nappe structure has been proposed by Steck et al. (1993). This model differs from the interpretation proposed for the Zanskar nappes by McElroy et al. (1990), where *a frontal imbricate fan is related to a main basal detachment thrust.* The latter duplex model leads to a very significant overestimation of the thrust distance. In a volume balanced model, the total amount of overthrusting is different. We estimated overthrusting by simple shear for the Nyimaling – Tsarap nappe to be about 100 km (Steck et al. 1993a & b). In the case of the Mata nappe such an estimate is not possible, but the amount of thrusting may be of the same magnitude. A numerical model for this kind of nappe structure has been proposed by Epard & Escher (1996). Two phases of extrusion of slabs of the subducted Indian crust may be distinguished. The Tso Morari nappe was extruded some 30 Ma ago (Mike Cosca, personal communication and De Sigoyer et al. 1997). The extrusion of the Crystalline nappe along the Main Central Thrust occured later, since about 20 Ma (Frank et al. 1977). The Dutung –Thaktote normal faults probably formed during the Crystalline nappe extrusion. The main driving force for the exhumation of crustal rocks in a zone of subduction are buoyancy forces (Chemenda et al. 1995, 1996).

Acknowledgments

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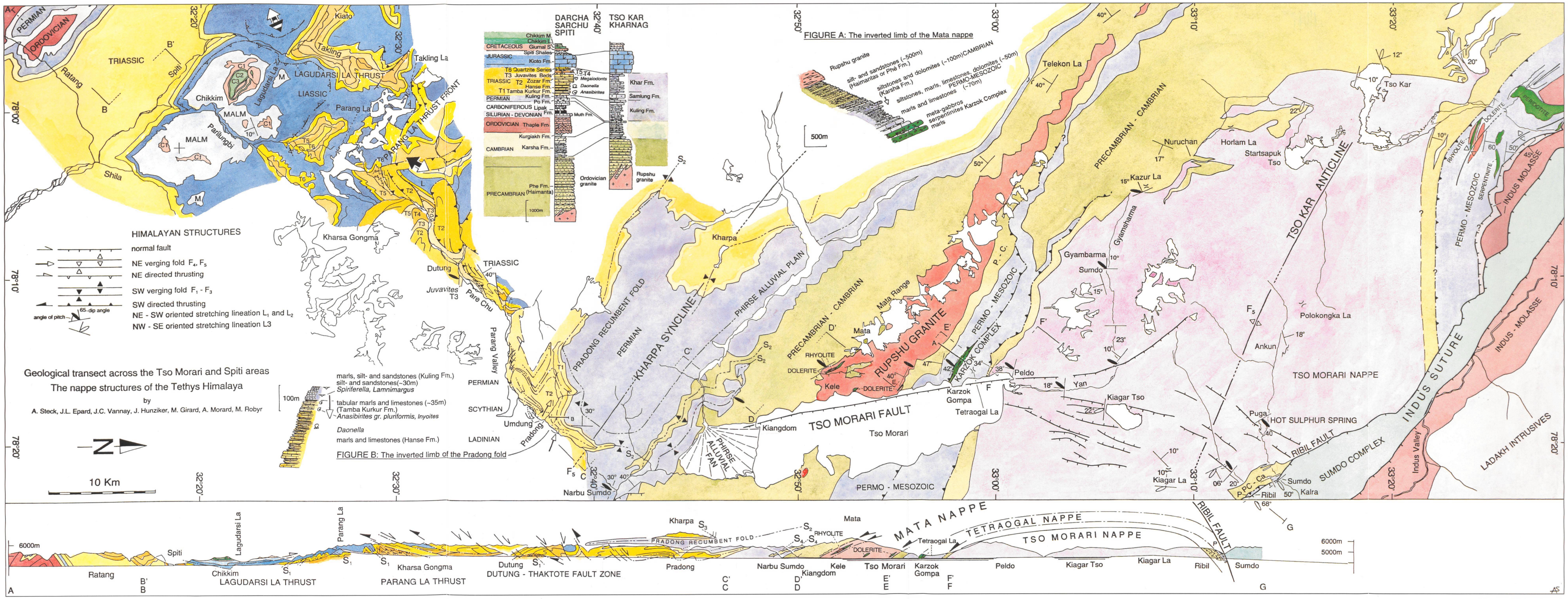
Plate 1. Geological map of the Tso Morari and Spiti areas. The geological map has been compiled using summer 1996 and 1997 field observations and the analysis of Spot-satellite images and published geological maps and descriptions (Hayden, 1904, Thakur & Virdi, 1979, Steck et al. 1993, Fuchs & Linner, 1996).


Geological transect across the Tso Morari and Spiti areas
The nappe structures of the Tethys Himalaya
by
A. Steck, J.L. Epard, J.C. Vannay, J. Hunziker, M. Girard, A. Morard, M. Robyr
HIMALAYAN STRUCTURES
normal fault
NE verging fold F4, F5
NE directed thrusting
SW verging fold F1 - F3
SW directed thrusting
NE - SW oriented stretching lineation L1 and L2
NW - SE oriented stretching lineation L3
angle of pitch
65-dip angle
10 Km
DARCHA SARCHU SPITI
TSO KAR KHARNAG
CRETACEOUS
JURASSIC
TRIASSIC
PERMIAN
CARBONIFEROUS
SILURIAN - DEVONIAN
ORDOVICIAN
CAMBRIAN
PRECAMBRIAN
Chikkim M.
Giumal S.
Spiti Shales
Kioto Fm.
Quartzite Series
Juvavites Beds
Zozar Fm.
Hanse Fm.
Tamba Kurkur Fm.
Kuling Fm.
Po Fm.
Lipak Fm.
Muth Fm.
Thaple Fm.
Kurgiakh Fm.
Karsha Fm.
Phe Fm. (Haimanta)
Ordovician granite
Khar Fm.
Samlung Fm.
Kuling Fm.
Rupshu granite
1000m
FIGURE A: The inverted limb of the Mata nappe
Rupshu granite
silt- and sandstones (~500m) (Haimantas or Phe Fm.)
siltstones and dolomites (~100m) (Karsha Fm.) CAMBRIAN
siltstones, marls, limestones, dolomites (~50m) PERMO-MESOZOIC (~70m)
marls and limestones
meta-gabbros serpentinites Karzok Complex marls
500m
FIGURE B: The inverted limb of the Pradong fold
marls, silt- and sandstones (Kuling Fm.)
silt- and sandstones (~30m)
Spiriferella, Lamnimargus
tabular marls and limestones (~35m) (Tamba Kurkur Fm.)
Anasibirites gr. pluriformis, Inyoites
Daonella
marls and limestones (Hanse Fm.)
100m
PERMIAN
SCYTHIAN
LADINIAN
PERMIAN
ORDOVICIAN
TRIASSIC
LIASSIC
MALM
LAGUDARSI LA THRUST
PARANG LA THRUST FRONT
Chikkim
Ratang
Spiti
Shila
Parilungbi
Lagudarsi La
Parang La
Takling La
Kiato
Kharsa Gongma
Dutung
Juvavites
Pare Chu
Parang Valley
Umdung
Pradong
Narbu Sumdo
PRADONG RECUMBENT FOLD
KHARPA SYNCLINE
PHIRSE ALLUVIAL PLAIN
PHIRSE ALLUVIAL FAN
Kharpa
PRECAMBRIAN - CAMBRIAN
RHYOLITE
DOLERITE
Kele
Mata
Mata Range
RUPSHU GRANITE
KARZOK COMPLEX
PERMO - MESOZOIC
Kiangdom
TSO MORARI FAULT
Tso Morari
Karzok Gompa
Tetraogal La
Peldo
Yan
Kiagar Tso
Telekon La
Nuruchan
Kazur La
Gyamsharma
Gyambarma
Sumdo
Horlam La
Startsapuk Tso
Tso Kar
TSO KAR ANTICLINE
Polokongka La
Ankun
TSO MORARI NAPPE
Puga
HOT SULPHUR SPRING
RIBIL FAULT
Kiagar La
Ribil
Sumdo
Kalra
SUMDO COMPLEX
INDUS SUTURE
Indus Valley
INDUS MOLASSE
LADAKH INTRUSIVES
SERPENTINITE
6000m
5000m
MATA NAPPE
TETRAOGAL NAPPE
TSO MORARI NAPPE
PRADONG RECUMBENT FOLD
DUTUNG - THAKTOTE FAULT ZONE
PARANG LA THRUST
LAGUDARSI LA THRUST
Kiagar La
Ribil
Sumdo
A
B'
B
C'
C
D'
D
E'
E
F'
F
G