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Structures, Deformation and Metamorphism of the Zanskar area

(Ladakh, NW Himalaya)

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Vorwort

Die Definition einer Dissertation lautet kurz und bündig: Selbständige wissenschaftliche Arbeit. Für mich war es mehr. Ich glaube, in den letzten 5 Jahren erlebte ich meine intensivste Lebensphase und zwar in jeder Beziehung - beruflich wie privat. Und doch hängt alles mit meiner Diss zusammen. Zu diesem, für mich so "folgenschweren", Dissertationsthema kam ich auf Umwegen, erst nachdem alle meine sorgfältig geschmiedeten beruflichen Zukunftspläne für die Zeit nach dem Diplom ins Wasser fielen. Was nun? Chaspi Honegger suchte genau zu diesem Zeitpunkt jemanden, der ihn nach Ladakh begleitete. So kam es, dass ich das erste Mal für mehrere Monate nach Asien reiste und nicht nur für kurze 4 1/2 Wochen wie das erste Mal bei einer geologischen Exkursion. Es war schön, es war eindrücklich, es war schwierig, es war überwältigend, es war einfach alles. So viele neue intensive Erfahrungen und Auseinandersetzungen, auch mit mir selber. Nach 3 Monaten in Ladakh / Kashmir reiste ich nach Nepal zum Bergsteigen und anschliessend auf dem Landwege nach Südindien. So viele verschiedene Menschen und Rassen, so viele verschiedene Religionen (Muslims in Kashmir und Ladakh, Buddhisten in Ladakh, Hinduisten in grossen Teilen Indiens und Nepals und Christen in Südindien). Die vielen Eindrücke in nur 5 Monaten und neuen Auseinandersetzungen waren fast zuviel. Asien liess mich nicht mehr los, wahrscheinlich für mein ganzes weiteres Leben nicht mehr. Nach meiner Rückkehr war ich zuerst mal einige Monate mehr oder weniger krank. Dann wagte ich mich an ein Dissertationsthema in Ladakh. Vorbereiten - reisen - schwimmen. Ich brauchte Jahre, um mich zurechtzufinden, mein Selbstvertrauen zu finden, Geologie-Diskussions-partner zu suchen, selbständig arbeiten zu lernen, mit meinen Resultaten in Form von Kongressvorträgen und Publikation nach aussen zu treten.

Auch eine Zeitspanne, wo ich alles aufgeben wollte, fehlte nicht (bei wem nicht ?). Doch etwas hielt mich, gab mir Kraft und Mut weiterzugehen, auch wenn mir der Weg oft unüberwindlich schwierig erschien. Mit dieser Arbeit begab ich mich auf einen Weg, auf den Weg zu mir selber. Ja - über die Geologie lernte ich für mich persönlich.

Jetzt bin ich froh, dass ich die Gelegenheit hatte, in dieser mir völlig neuen und fremden Kultur Feldarbeit zu machen. Ich musste einfach lernen. Man ist gefordert, flexibel zu werden. Sich anzupassen, geduldig zu sein, etwas anzunehmen wie es ist und nicht ändern zu können. Die vielen Stunden, die ich in tibetischen Klöstern verbrachte, die tiefen Eindrücke eines Klosterfestes und die Offenheit und Herzlichkeit der Ladakhis führte dazu, dass ich mich auch hier für Asien, die buddhistische Kultur und Religion zu interessieren begann. Vor zwei Jahren begann ich Aikido zu praktizieren, eine japanische Kampfkunst. Vor 1 1/2 Jahren kam Shiatsu (japanische "Version" der chinesischen Akupunktur) dazu und vor einem Jahr dann noch Karate-do, ebenfalls eine japanische Kampfkunst.

Gleichzeitig begann ich zu arbeiten, nachzuholen, zu lernen, meine Dissertation zu schreiben. Vor allem in den letzten beiden Jahren habe ich auf allen Ebenen gelernt und geübt, nicht nur in Aikido und Karate-do. Und ebenfalls gleichzeitig erhielt ich mehr und mehr Hilfe bei meiner Arbeit, aber auch privat. Ohne diese riesige Hilfe, die ich erhalten durfte, wäre diese Arbeit kaum jemals fertig geworden. Aus diesem Grunde möchte ich allen danken.

Als erstes möchte ich Chaspi Honegger danken. Seine Unterstützung machte es mir möglich, mich an ein Himalaya - Thema zu wagen. Von seiner langjährigen Erfahrung bei der Feldarbeit in Ladakh und beim auswerten der Resultate, konnte ich riesig profitieren und lernen, vor allem aber half er mir in unzähligen Diskussionen, die Geologie, bzw. die Probleme der Geologie des Himalaya und insbesondere des Ladakh mehr und mehr zu verstehen und zu sehen.

John Ramsay, meinem Doktorvater, möchte ich herzlich danken, dass er mir die Möglichkeit gab, diese Arbeit in Angriff zu nehmen. Sein Einsatz, mich in Ladakh zu besuchen, verdient eine besondere Würdigung, da die Zufahrtsstrasse nach Padum 1983 bis Mitte August geschlossen blieb und ich somit nur nach einem 9-tägigen Fussmarsch zu erreichen war. Aus diesem Grunde und wegen einer zusätzlichen 5-tägigen Verspätung infolge Gepäckverlustes von John verpassten wir uns und trafen uns 3 Wochen später als geplant "zufällig" mitten auf offenem Felde. Erst 2 Monate später erhielt ich das Telegramm, dass John und Dorothée später kommen würden.... Vor allem während meiner Schreibphase half er mir tatkräftig. So habe ich leider erst in den letzten Monaten begriffen, was ich gelernt bzw. hätte alles lernen können. Klar, kurz und sich verständlich ausdrücken - John Ramsays grosse Stärke - meine Schwäche.

Ein ganz besonderer Dank gebührt meiner Bürokollegin Dorothée Dietrich. Meine vielen Detailfragen wie "Geht das so? Kann man das so darstellen? Was heisst das eigentlich? Wie soll ich das schreiben? " beantwortete sie immer mit viel Aufmerksamkeit und Geduld. Auch half sie mir meine Schlussfolgerungen und Interpretationen klarer und verständlicher auszudrücken.

Volkmar Trommsdorff und Augusto Gansser möchte ich dafür danken, dass sie mir als Studentin die Gelegenheit gaben, an einer geologischen Exkursion durch Ladakh teilzunehmen, war dies doch der erste Schritt zu dieser Arbeit. Die immerwährende Begeisterung und das grosse Interesse an der Geologie des Himalaya von Herrn Gansser hat mich immer wieder verblüfft. Z.B. war ich eigentlich an einem Tage seines Feldbesuches zu müde (und zu bequem), um einen 6-stündigen Fussmarsch zu unternehmen, den man wenigstens zur Hälfte mit einem Lastwagen hätte machen können. Doch er meinte: "Diesen Spaziergang können wir doch machen". Auch war die Überquerung des schwierigsten Passes (Hagschu-la) über den Hauptkamm trotz schlechtestem Wetter kein Problem. Herzlichen Dank.

Rainer Kündig unternahm mit mir einige Wochen Feldarbeit. Die Arbeit im Kristallin beruht zu einem grossen Teil auf gemeinsam gemachter Feldarbeit. Für die zur Verfügungstellung seiner sämtlichen Proben und Daten möchte ich ihm herzlich danken. Mit meinen übrigen "Himalaya-Kollegen" Röbi Ottiger, Paul Bosshart, Antonio Grecco und Andreas Stäubli verbinden mich viele ähnliche Erfahrungen.

Von Stefan Schmid lernte ich viel über Mikrostrukturen und deren Interpretation. Er half mir auch "meine Scherzone" zu definieren und Martin Casey half mir den Versetzungsbetrag des Kristallins gegenüber der Sedimentbedeckung in der Scherzone zu berechnen. Beiden möchte ich für ihre Hilfe danken.

Arnauld Pêcher danke ich für sein grosses Interesse an meiner Arbeit. Die stundenlangen Diskussionen mit ihm waren zwar sehr anstrengend (er fragte immer so kritisch nach bei den heiklen Punkten), gaben aber daher viele neue Impulse und Denkanstösse, die ich leider aus Zeitgründen nur zum Teil umsetzen konnte. Aber ich hoffe, das noch nachholen zu können. Zusätzlich möchte ich ihm danken, dass er mir sämtliche seiner Daten aus dem Zanskar zur Verfügung stellte, inklusive geochemische Analysen von Leukograniten (Proben gemeinsam gesammelt mit Marc Brouand).

Patrick Le Fort möchte ich für sein Interesse an meiner Arbeit über die Leukogranite, die Diskussionen und seinen "review" des Leukogranitkapitels danken.

Riesigen Dank all jenen, die mehr aus dem "Hintergrund" hilfreich waren. So die Equipe aus der Schleifwerkstatt, vor allem Thomas Fröhlich, der die meisten meiner Schliffe machte, Urs Gerber, der immer im letzten Moment Dias und Fotos für mich machte (natürlich auch bei dieser Arbeit), Albert Uhr, der mir oft bei graphischen Problemen mit nützlichen Tips half und mir im letzten Moment noch beim Legenden schreiben half, Barbara Das Gupta vom Sekretariat, meinen Semesterkollegen und allen anderen aus unserer Gruppe, der Geologie, dem Haus und auch von auswärts an Kongressen. Sie alle leisteten einen Beitrag zu meinem heutigen Verständnis der Geologie.

Besonderen Dank gebührt meinen drei Gehilfinnen bei der Feldarbeit im Zanskar, nämlich Chrigi Egli, Olivia Braun-Masetto und meiner Schwester Ursi Herren. Sie verwöhnten mich, kochten, schleppten Steine und vieles mehr, und ermöglichten mir, mich auf die Arbeit zu konzentrieren.

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Schlussspurt. Ohne die grosse Hilfe, die ich in den letzten Wochen erhielt, wäre diese Arbeit nicht rechtzeitig fertig geworden. Myriam Bonanomi half mir beim Tippen, Korrigieren, Zusammenstellen des Manuskriptes und beim Ausmerzen vieler kleiner Fehler. Trotz Ferien, Grippe und Job hat sie dauernd für mich gearbeitet. Ihr gebührt riesigen Dank. Annelis Wegmann, Chrigi Egli, Markus Stromer, Bernhard Grobéty und Ruth Haas halfen mir beim Kleben, Kopieren, Zeichnen und Malen. Ich war sehr froh, diese "Nifeli"-Arbeit zum Teil abgeben zu können. Schliesslich danke ich Rolf und Brigitte Nüesch dafür, dass sie immer für mich eine Schlafgelegenheit bereit hielten.

Auf Englisch schreiben konnte ich diese Arbeit nur dank der Hilfe von Dave Olgaard, Tracy Rushmer, Roberta Mariani, Nicolas Deichmann, vielen andern und vor allem von John Ramsay, der immer noch prägnantere, kürzere Ausdrücke wusste. Von Dave lernte ich so

langsam meinen Schreibstil verbessern. Im letzten Moment sprang Gretli Früh-Green ein. Ihnen allen möchte ich ganz herzlich danken. Vor allem in den letzten Wochen kam ich immer im letzten Moment mit einigen Seiten neuem Text. Mit viel Geduld brachten sie mein lausiges Englisch in eine lesbare Fassung.

Dies ist die geologische Seite. Nicht vergessen möchte ich meine grossen Helfer im "privaten Hintergrund": Thomas Vögeli, Gabi Riedi und Hanna Hadorn. Ohne ihre Hilfe, ihre Unterstützung, ihre Begleitung auf einem Stück des Weges zu mir selber, hätte ich die Geologie längst aufgegeben. Meiner Wohnpartnerin Esther Baumann und meinen Freunden danke ich für die moralische Unterstützung.

Den grössten Dank möchte ich meinen Freunden vom Aikido und Karate-do und insbesondere meinen Lehrern Franz Villiger und Kiroku Fukutome aussprechen. Das gemeinsame Üben war für mich immer die schönsten Stunden der Woche. Am meisten habe ich dort gelernt.

Ich blicke zurück auf einige Jahre intensiver Erfahrung. Diese Dissertation ist für mich so etwas wie ein Gemeinschaftswerk all meiner Helfer, der genannten und ungenannten. Herzlichen Dank!

Preface

A dissertation can be defined concisely as an "independent research project". For me it was more. The last five years represent the most intense phase of my life, both private and professional, and everything was somehow related to this dissertation. The path leading to the field of research, which was to have such far-reaching consequences, took several detours. Initially after my diploma, I had envisioned heading more towards glaciology, but all the carefully made plans failed to materialize. Just at that time, Chaspi Honegger was looking for someone to accompany him on one of his field-trips to Ladakh. This is how I had the first opportunity to spend several month's in Asia, after an earlier geology excursion, that had lasted a mere four-and-a-half weeks. It was beautiful, impressive, and difficult; indeed, it was simply overwhelming, both in terms of outside experiences and of self-experience. After three months in Ladakh and Kashmir, I took some time for mountaineering in Nepal, and then travelled by train and bus to southern India. The manifold impressions and the exposure to so many different cultures and religions (Muslims in Kashmir, Buddhists in Ladakh, Hindus in Nepal and most parts of India and Christians in southern India) were almost too much to experience in less than five months. I had become hooked on Asia -- probably for the rest of my life. Upon my return, I was reconvalescent for several months. Only later did I work up enough courage to actually start upon a thesis of my own in Ladakh. The beginning was a time of planning, travelling and disorientation. It took several years to find my direction, to find self-confidence, to find people to talk to, to learn to work independently and to learn to put foreward my results at meetings and in publications.

There was even a time when I wanted to give up (who doesn't?). However something kept me going, gave me the strength and courage to continue even when it seemed impossible. With this work I began to travel the path to myself; in fact, geology became a personal teacher.

I am glad that I had the opportunity to do field work in such a foreign and for me totally new cultural setting. I simply was forced to learn to be flexible, to be patient and to accept things as they are without being able to change them. The many hours spent in Tibetan monasteries, the strong impressions of the religious festivities, and the openness and warmth of the Ladhakis led me to a deeper involvement with Asia and with Buddhist culture and religion. Meanwhile I have taken up Aikido and Karate-do, two forms of Japanese martial arts, as well as Shiatsu. In addition, I began to work, to catch-up, to learn, and to write my dissertation. In particular during the last two years, I learned and practiced at all levels, not only Aikido and Karate-do. At the same time, I also received more and more help, both professional and private. Without this enormous assistance from all sides, this dissertation would never have been completed. To all these helpers I want to express my gratitude at this point.

First of all, I want to thank Chaspi Honegger. His encouragement gave me the courage to tackle a thesis on the Himalayas. I was able to benefit from his long experience of working in Ladakh and interpreting the results, but mainly I was able to benefit from innumerable discussions that deepened my general geological understanding and led me to see and understand more clearly the particular geological problems of the Himalayas and Ladakh.

My sincere thanks go to my thesis director, John Ramsey, for giving me the possibility of undertaking this project. The effort which he made in order to visit me in the field deserves special mention. In 1983, the road to Padum was closed until the middle of August, so that I could only be reached after a nine-day hike. For this reason, and because he was delayed an additional five days due to his luggage having been lost, we missed each other at first, meeting almost by chance, three weeks later than planned, "on the road" (his telegram, announcing that he and Dorothee had been delayed, arrived two months later...). He was especially helpful during the writing phase of my thesis. Only in the last months did I realize what I had learned, or should have learned: to express myself clearly and concisely -- John Ramsey's strong point, my weak point.

Very special thanks are due to my office partner Dorothee Dietrich. My many detailed questions such as "is this OK? can one write that in this way? what does such and such really mean?" were always answered with care and patience. She also helped me formulate my interpretations and conclusions in a clear and more comprehensible way.

I want to thank Volkmar Trommsdorff and Augusto Gansser for giving me, while still a student, the opportunity to take part in a geology excursion through Ladakh. That represents the stepping stone towards this dissertation. The continuing enthusiasm and interest in the geology of the Himalayas on the part of A. Gansser has always amazed me. On one day of his visit during my field work, I was actually too tired (and lazy) to undertake a six-hour hike, at least half of which could have been accomplished by truck, but he insisted that it was just a short walk. Even crossing the most difficult pass accross the Main Range in very bad weather was no problem for him.

Rainer Kündig accompanied me for several weeks in the field: the section on the Crystalline areas is based largely on joint field work. I also want to thank him for making all his samples and data available to me. To my other Himalayan colleagues, Röbi Ottiger, Paul Bosshard, Antonio Greco and Andreas Stäubli, I am indebted in a similar way.

Stefan Schmid tought me a lot about microstructures and how to interpret them. In addition, he helped delineate "my shear zone"and Martin Casey helped me to calculate the approximate amount of shear within the Zanskar shear zone, for which I want to thank them.

I thank Arnauld Pêcher for his great interest in my work. The long discussions were very strenuous (he always asked the critical questions about all the weak points), but were all the more rewarding. I am sorry that for lack of time I was able to follow up on only a small portion of his many suggestions; I hope to make up for this at some later time. I am also

grateful for his making available to me all his data from Zanskar, including the geochemical analyses on leucogranite samples, which he collected together with Marc Brouand.

I want to thank Patrick Le Fort for the discussions about leucogranites, his interest in my work and for the review of the leucogranite chapter.

A big thanks to all those who were helpful in the "background": Thomas Fröhlich who made most of my thin-sections, Urs Gerber who prepared slides and photographs (usually at the last moment), Albert Uhr, who helped with the illustrations and who, in the end, helped with writing some figure legends, Barbara Das Gupta, our secretary, my semester-colleagues and all the others from our institute and elsewhere. They all contributed to my present understanding of geology.

Special thanks are due to my three helpers in the field, Chrigi Egli, Olivia Braun-Masetto, and my sister Ursi Herren. They cared and cooked for me, lugged stones, thus enabling me to concentrate on my work.

The field-work was supported financially by the ETH research grant Nr. 0.330.060.22/9, as part of the project "Large scale and small scale tectonic structures in the Himalaya of NE Pakistan and Ladakh".

Finally, without all the assistance of the last weeks I would not have been able to meet the deadline. Myriam Bonanomi helped with typing, correcting and compiling the manuscript: she worked continuously for me, regardless of vacation, fluh or job -- many thanks. Annelis Wegmann, Chrigi Egli, Markus Stromer, Bernhard Grobéty and Ruth Haas helped me with copying, pasting, drawing and colouring. I was very glad to have been able to delegate these tedious jobs. Rolf and Brigitte Nuesch offered me a place to stay close to the university, when needed.

Writing this thesis in English was only possible thanks to the help of Dave Olgaard, Tracy Rushmer, Roberta Mariani, Nicolas Deichmann, Gretli Früh-Green and many others, but above all of John Ramsay, who could always suggest a more concise and to the point way of expressing an idea. Especially in the last weeks, I would come again and again with new pages of text; very patiently they transformed my lousy English into a readable form. My sincere thanks to all.

Beyond the geological aspects I don't want to forget those helpers in the "private background": Thomas Vögeli, Gabi Riedi and Hanna Hadorn. Without their assistance, encouragement and companionship along the path to my self I would have given up geology a long time ago. I want to thank my housing partner, Esther Baumann and my friends for giving me moral support.

I want to express my greatest thanks to my friends from Aikido and Karate-do, in particular to my teachers Franz Villiger and Kiroku Fukutome. The hours devoted to our practice were always the highlight of the week and the times during which I learned the most.

I now look back on several years of intense experiences. This thesis is the result of a joint effort of all of my helpers, the named and the unnamed. Many thanks.

Summary

A complete geological section through the northwestern Himalayas with rocks ranging in age from Precambrian to Tertiary is well exposed in Ladakh (India). The collision between the Indian shield and the Tibetan platform caused large-scale intracrustal thrusting and piling up of the Himalayan nappes. This compressional event was accompanied by prograde regional metamorphism. The metamorphism ranges from low-grade (anchimetamorphism) in the Indus Suture zone in the northeast to upper amphibolite grade in the Higher Himalaya tectonic unit in the southwest.

In the Zanskar region (SE Ladakh) a rock sequence of highly metamorphosed High Himalayan crystalline basement rocks (Zanskar Crystalline unit) is overlain by its weakly metamorphosed Tethyan sedimentary cover. Four main lithostructural units showing differences in age, lithology and structural style can be distinguished. From southwest to northeast they are: the Zanskar Crystalline unit, the Late Precambrian - Cambrian Phe and Karsha Formation representing a reduced Late Precambrian - Paleozoic sedimentary sequence, the plateau basalts of the Permian Panjal Trap and the mainly carbonate platform Mesozoic sediments. A structural analysis leads to the following tectonic evolution: -

Pre-Himalayan structures related to a Cambrian orogeny are limited to the Phe and Karsha Formation and have been overprinted in the Zanskar Crystalline unit by Himalayan metamorphism. The orientation of the pre-Himalayan folds within the greywackes are predominantly N-S and often associated with a N-S trending schistosity. The shales, however, are totally overprinted by the Himalayan structures. Petrographic and field evidence indicates that the porphyritic granite gneiss layered intrusions within the Zanskar Crystalline unit are related to a widespread 500 Ma orogeny.

The ***main Himalayan compressional tectonic activity***, accompanied by the prograde regional metamorphism, deforms the different lithologies in different ways. The deformation mechanism depends on the competence behaviour of the involved lithologies. The predominant feature of the Himalayan structures is folding within the Tethys Himalaya and doming and folding within the Zanskar Crystalline unit. The only exception is the rigid Panjal Trap unit which generally deformed by brittle fracture.

The *Mesozoic formations* are folded into polyharmonic, disharmonic and chevron fold types as a direct consequence of their stratigraphy and characteristic lithostructural units. Independent of the fold types, the fold axial traces of this limestone / shale sequence shows a constant NW-SE orientation. Because the stratigraphy is consistent laterally over great distances, the folds are continous for tens of km.

The *Panjal Trap* unit generally shows a rigid and competent behaviour of deformation. The individual basaltic flows are welded together forming a rigid, competent, homogenous

sheet which is hard to fold under such low metamorphic conditions and which therefore deformed by faulting. Individual thrust sheets of the Panjal Trap unit are found as tectonically emplaced sheets within Mesozoic formations. The deformational profile is inhomogenous and dependant on the lithology. Only slight internal deformation is seen in the interlayered sediments and the amygdaloidal-rich basalts.

The *Phe and Karsha Formation*, with their greywackes, quartzites, shales and minor dolomites, show only locally developed NW-SE trending Himalayan folds because the stratigraphical units show lateral variations in thickness and competence. The pre-Himalayan schistosity and lineation, defined by the orientation of the quartz grains within the greywackes, are often not totally overprinted by the Himalayan deformational event and show a great scatter of their orientation and a considerable and complex internal deformation.

The *Zanskar Crystalline unit* consisting mainly of fine-grained biotite gneisses with layered intrusions of porphyritic granite gneisses and of fine-grained garnet- or tourmaline-bearing leucogranites was strongly overprinted by the prograde regional metamorphism. Three folding phases related to the Himalayan deformational event may be distinguished. The first one is simultanous with the peak of metamorphism. The Cambrian porphyritic granites where transformed to gneisses. A synmetamorphic dome (Haptal dome) and associated schistosity and lineation patterns were formed. The leucogranites were intruded within the upper part of the Zanskar Crystalline unit and are mainly localised in one valley, the Haptal Tokpo. They are not effected of the main deformational and metamorphic event. From the tectonic position, the relationship to other lithologies, petrographic investigations, and geochemical analyses these leucogranites are comparable with those described from Nepal, Buthan, and southern Tibet and are therefore interpreted to be of Teriary age. A second folding phase related to a low P / high T metamorphic phase and developed as small to mega scale folds, involved the Miocene leucogranites. A third phase which may be related to backfolding is only of minor regional significance. This ***backfolding event*** in the Tethys Himalaya lead to the formation of crenulation cleavage and kink bands within shale horizons together with small scale folds in the Zanskar Crystalline unit especially well developed on top of the Zanskar Crystalline unit. These folds show fold vergence opposite to those produced during previous folding phases.

The sharp boundary between the Zanskar Crystalline unit (affected by three Himalayan deformational phases) and the Tethys Himalaya (affected by only two) is controlled by late shearing on top of the Zanskar Crystalline unit: the ***Zanskar shear zone***. The end of the tectonic evolution is indicated by the formation of a ***northeast - southwest extension zone*** supperposed on top of the Zanskar Crystalline unit. This well exposed and morphologically prominent shear zone is 2.25 to 6.75 km wide, and can be followed from the northwest to the southeast for at least 80 km. In contrast to the main compressional tectonics, this shear zone indicates an extensional event within the Higher Himalaya tectonic unit. This

Zanskar shear zone involves granitic rocks, leucogranites of Miocene age, and various metasediments and, in general, separates the Late Precambrian - Early Cambrian sedimentary sequence (Phe Formation) from the underlying crystalline basement (Zanskar Crystalline unit). A "normal" (i.e. extensional) sense of shear has been determinated using asymmetric macroscopic and microscopic structures such as pegmatite boudins, feldspar augen, and crystallographic fabrics. The metamorphic isograds are very close within this shear zone as a result of shear deformation; the transition from upper amphibolite to lower greenschist facies occurs within a zone of reduced width (200 m). Movement in this zone occurred late in the metamorphic history under greenschist or lower metamorphic conditions, after the intrusion of the leucogranites. The closing together of the isograd surfaces was used to determine an approximate value of the amount of displacement; the minimum horizontal extension and vertical displacement are on the order of 16 km and 19 km, respectively.

The deformational style of the Zanskar area indicate that there are no nappes present within the Higher Himalayas, as suggested by some previous workers. The Tethyan sediments are the autochtonous sedimentary cover of the crystalline basement because Cambrian porphyritic granite gneisses and Miocene leucogranites are intruded into the biotite gneisses of the Zanskar Crystalline unit and into the base of the Phe Formation and show a gradual transition zone to the Tethys Himalaya. Locally observed tectonized contacts, especially between the Panjal Trap unit and the Phe respectively Karsha Formation, are controlled by different lithologies and do not appear to represent true nappe contacts.

The Zanskar area is only slightly affected by the backfolding event recognised in adjacent terrains (Suru region). Shearing in the Zanskar shear zone, however, was very large. Lithological, structural, and metamorphic comparisons suggest that the reasons for backfolding and for the development of the Zanskar shear zone are the same, namely a continous shortening of the northern margin of the Indian continent due to continous migration northwards of the Indian subcontinent towards Asia.

Zusammenfassung

In Ladakh (Indien) ist durch den NW Himalaya eine vollständige vom Präkambrium bis ins Tertiär reichende geologische Abfolge aufgeschlossen. Die Kollision des indischen Schildes mit der tibetischen Plattform bewirkte grossräumige interkrustale Abscherungen und ein Übereinanderstapeln der himalayischen Decken. Diese Kompressionsphase wurde von einer prograden regionalen Metamorphose begleitet, wobei der Metamorphosegrad von schwach metamorph (anchimetamorph) in der Indus Sutur Zone im Nordosten zu hoch metamorph (obere Amphibolitfazies) im Higher Himalaya im Südwesten reicht.

Im Zanskar (SE Ladakh) werden die hochmetamorphen Lithologien des Kristallins des Higher Himalaya von den dazugehörigen schwach metamorphen Tethys Sedimenten überlagert. Vier parallel liegende lithostrukturelle Einheiten können unterschieden werden, deren Unterschied sich in Alter, Lithologie und Baustil äussert. Von Südwesten nach Nordosten folgen aufeinander: das Zanskar Kristallin, die spät präkambrische-kambrische Phe und Karsha Formation - welche die reduzierte spätpräkambrische-paläozoische Sedimentabfolge darstellt -, die Plateaubasalte des Panjal Trap und die vorwiegend karbonatischen Plattformsedimente des Mesozoikum. Anhand einer Strukturanalyse konnte die folgende tektonische Entwicklung gezeigt werden:

Die ***prä-Himalayischen Strukturen***, welche nur in der Phe- und Karsha Formation beobachtet und im Kristallin durch die hohe Metamorphose vollständig überprägt wurden, werden einer kambrischen Orogenese zugeschrieben. Die prä-Himalayischen Falten in den Grauwacken streichen vorwiegend N-S und sind oft mit einer N-S streichenden Schieferung assoziiert. Die Schiefer hingegen wurden durch die Himalayische Gebirgsbildung vollständig überprägt. Lagige porphyrische Granitgneissintrusionen werden aufgrund von petrographischen und geologischen Vergleichen dem selben weitverbreiteten 500 Mio. Orogen zugeordnet.

Die ***kompressionstektonische Aktivität*** der ***Haupt-Himalayischen Gebirgsbildung*** ist von einer prograden regionalen Metamorphose begleitet und verformt die verschiedenen Lithologien in unterschiedlicher Weise. Der Verformungsstil der einzelnen lithologischen Einheiten ist abhängig von ihrem Kompetenzverhalten. Im Tethys Himalaya ist Faltung der vorherrschende Verformungsstil und im Zanskar Kristallin dominiert Dombildung begleitet von Faltung. Der rigide Panjal Trap, welcher generell mit Sprödbruch auf die Verformung reagiert, bildet dabei die einzige Ausnahme.

Die *mesozoischen Formationen* wurden aufgrund ihrer Stratigraphie in polyharmonische, disharmonische und "chevron" Typ Falten gefaltet und bilden somit charakteristische lithostrukturelle Einheiten. Unabhängig von ihrem Faltenstil streichen die Faltenachsenebenen dieser Kalk / Schiefer Abfolgen konstant in NW-SE-Richtung. Da die Stratigraphie lateral über grosse Distanzen konstant ist, können auch die Falten über mehrere km verfolgt werden.

Der *Panjal Trap* zeigt bezüglich der Deformation ein rigides und kompetentes Verhalten. Die einzelnen Basalt Flows sind zusammengeschweisst und bilden eine kompetente, homogene Platte, welche unter so schwach metamorphen Bedingungen schwierig zu verfalten ist und aus diesem Grunde ist der vorherrschende Verformungsmechanismus brechen und überschieben (thrusting). Einzelne Platten stecken sogar in mesozoischen Sedimenten drin. Das Deformationsprofil durch diese Einheit ist inhomogen und von der Lithologie abhängig. Untergeordnet ist interne Verformung vorhanden und nur in den zwischengelagerten Sedimenten und in den bläschenreichen Varietäten der Basalte beobachtbar.

Da die *Phe und Karsha Formationen* mit ihren Grauwacken, Quartziten, Schiefer und untergeordnet Dolomiten grosse laterale stratigraphische Variationen in Mächtigkeit und Kompetenz zeigen, sind nur lokal entwickelte NW-SE streichende Himalayische Falten beobachtbar. Die prä-Himalayische Schieferung und Lineation, welche durch die Orientierung der Quartz Körner in den Grauwacken definiert sind, sind durch die Himalayische Gebirgsbildung oft unvollständig überprägt. Die Phe und Karsha Formationen zeigen daher eine grosse Streuung der Orientierung ihrer Strukturen und eine ausgeprägte und komplexe interne Verformung.

Das *Zanskar Kristallin* ist vorwiegend aus feinkörnigen Biotitgneissen mit schichtparallelen Intrusionen von porphyrischem Granitgneiss und feinkörnigem Granat- oder Turmalin-Leukogranit aufgebaut und wurde durch die prograde Regionalmetamorphose stark überprägt. Drei Faltungsphasen sind beobachtbar und werden dem Himalayischen Deformationsereignis zugeordnet. Die erste davon wird mit dem Höhepunkt der Metamorphose korreliert und hat eine Vergneissung der kambrischen Granite zur Folge. Dabei entwickelt sich ein synmetamorpher Dom (Haptal Dom) unter Ausbildung einer Schieferung und einer Lineation. Die Leukogranite intrudieren in den oberen Teil des Zanskar Kristallins. Sie sind vorwiegend auf das Haptal Tokpo beschränkt und von dem Hauptverformungs- und Metamorphoseereignis nicht überprägt. Ihre tektonische Position, deren Beziehung zu den Umgebungsgesteinen, petrographische Untersuchungen und geochemische Analysen zeigen ihre Ähnlichkeit zu den Leukograniten aus Nepal, Buthan und Südtibet und werden daher wie diese als tertiäre Leukogranite interpretiert. Die zweite Faltungsphase wird mit der Tief-P / Hoch-T Metamorphose in Verbindung gebracht. Kleine bis mittlere Falten werden beobachtet und erfassen auch die Leukogranite. Die Rückfaltungsphase ist das dritte, nur schwach ausgebildete Ereignis. Kleine Falten mit einer umgekehrten Faltenvergenz bezüglich der vorherigen sind v.a. im oberen Teil des Zanskar Kristallins ausgebildet. Die ***Rückfaltungsphase*** drückt sich im Tethys Himalaya als Krenulationsschieferung oder als Kinkbänder in den Schiefern aus und im Kristallin vorwiegend im oberen Teil durch kleine Falten. Sie zeigen eine umgekehrte Faltenvergenz als diejenige in den vorherigen Falten.

Die scharfe Grenze zwischen dem von 3 Himalaya-Deformationsphasen erfassten Zanskar Kristallin und dem Tethys Himalaya, welcher von nur zwei Verformungsereignissen überprägt wurde, ist durch späte Scherung im oberen Teil des Zanskar Kristallins bedingt, der sog. ***Zanskar Scherzone***. Diese Scherzone, eine NE-SW streichende Extensionszone, welche den oberen Teil des Zanskar Kristallins überlagert, stellt das Ende der tektonischen Entwicklung dar. Sie ist gut aufgeschlossen, morphologisch auffällige, 2.25 bis 6.75 km breit und kann von Nordwest nach Südost über mindestens 80 km verfolgt werden. Im Gegensatz zu der hauptsächlichen Kompressionstektonik stellt diese Scherzone ein Extensionsereignis innerhalb des Higher Himalaya dar. Diese Scherzone involviert granitische Gesteine, miozäne Leukogranite und verschiedene Metasedimente und trennt im generellen die präkambrische-kambrische Sedimentabfolge (Phe Formation) von dem unterliegenden Basement (Zanskar Kristallin). Mittels asymmetrischer makroskopischer und mikroskopischer Strukturen, wie z.B. Pegmatitboudins, Feldspataugen und kristallographischer Orientierung konnte ein normaler Verwerfungsschersinn bestimmt werden. Wegen der Scherdeformation kommen die Isograde der Metamorphose sehr nahe zueinander zu liegen; der graduelle Übergang von oberer Amphibolitfazies zu unterer Grünschieferfazies ist im Feld nur 200 m breit. Die Scherung in dieser Zone erfolgte in einer späten Phase der Metamorphose (nach der Intrusion der Leukogranite) unter grünschieferfaziellen oder noch tieferen Metamorphosebedingungen. Die Ausdünnung der Isograde diente der Ermittlung des ungefähren Versetzungsbetrages: die minimale horizontale Extension ist in der Grössenordnung von 16 km, der vertikale Versatz von 19km.

Die Ergebnisse des Studiums des Deformationsstiles im Zanskar zeigen, dass im Gegensatz zu einigen früheren Arbeiten in diesem Abschnitt des Tethys Himalaya keine Decken zu finden sind. Die kambrischen porphyrischen Granitgneisse und die miozänen Leukogranite intrudieren in die Biotitgneisse des Zanskar-Kristallins und ebenso in die Basis der Phe Formation und zeigen somit einen graduellen Übergang zum Tethys Himalaya an. Lokal beobachtete tektonische Kontakte, v.a. zwischen dem Panjal Trap und der Phe-respektive Karsha Formation, sind durch die verschiedenen Lithologien bedingt und stellen somit keine richtigen Deckenkontakte dar.

Das Zanskar ist nur schwach von der Rückfaltungsphase überprägt, im Gegensatz zum westlich anschliessenden Suru Gebiet. Die späte Scherung dagegen ist hier gross. Lithologische, strukturelle und Metamorphose-Vergleiche zeigen, dass die Ursache sowohl für die Rückfaltung wie für die Zanskar Scherzone die gleiche ist, nämlich eine kontinuierliche Verkürzung bedingt durch die stetige nordwärts-Bewegung des Indischen Subkontinents relativ zu Asien.

1. Introduction

With the opening of the Ladakh area to tourism in 1975 geologists have found access to an important zone: it is the contact zone between the Indian and the Eurasian continent (Fig. 1.1). The Indus - Tsangpo Suture Zone (Gansser, 1964) is one of the major suture zones of the world. Before the opening of access this geological important region could not be studied in the Karakorum, Kohistan (Pakistan) and Ladakh (India) for political reasons. Until this time there were only few geological studies available which came from different expeditions until the first half of this century, e.g. Lydekker (1883), Stolizka (1865), Dainelli (1934), De Terra (1935), Wadia (1928) and (1937), Norin (1946), Auden (1935), Berthelsen (1953) and Heim and Gansser (1939). Later on only results of the investigations of Indian geologists were available (Tewari, 1964; Gupta and Kumar, 1975 and Shah et al., 1976).

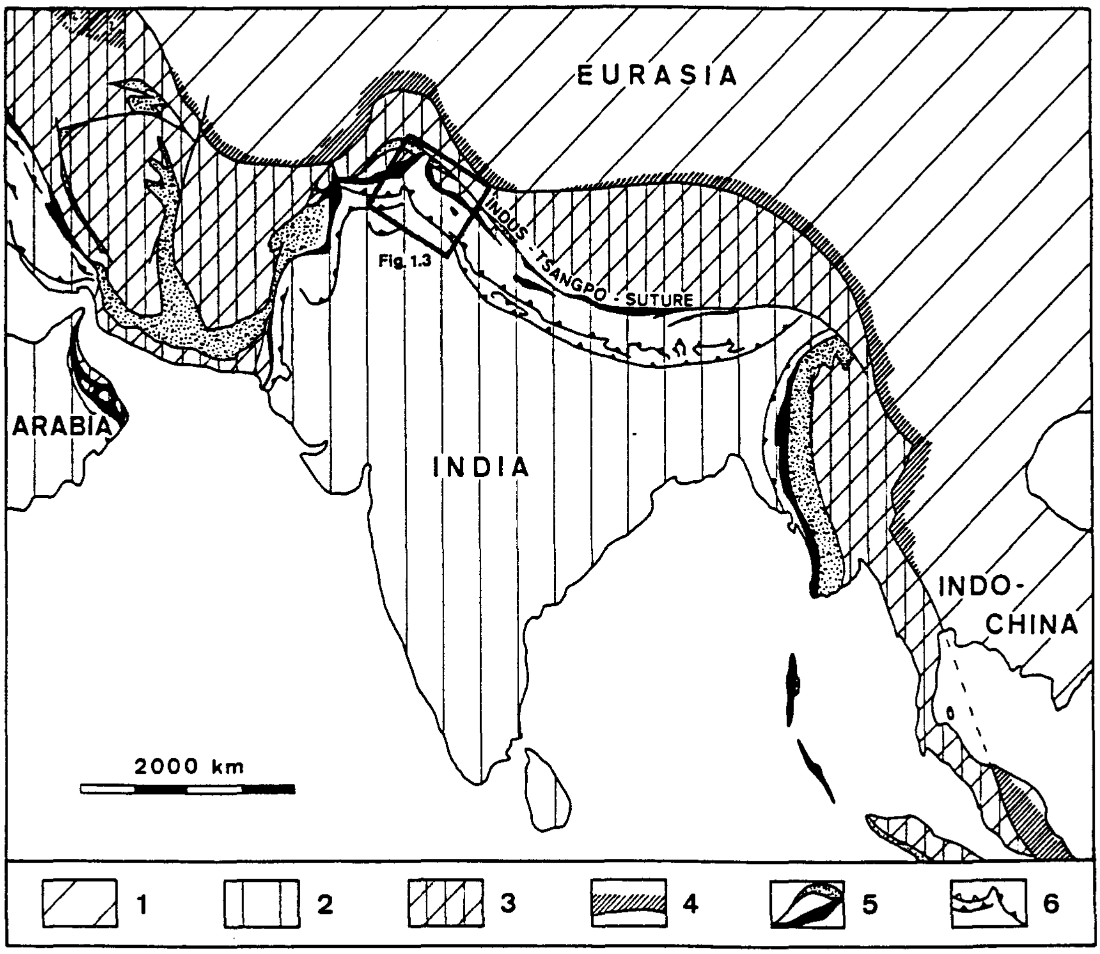


Figure 1.1: Tectonic map of South - Central Asia (after Stöcklin 1980, simplified).1 = Eurasia (Precambrian- and Hercynian - Indosinian consolidation), 2 = Gondwana (Precambrian consolidation with Deccan traps of India), 3 = Bloc intermediate (Mesozoic foldbelts with associated granites and late Alpine granites), 4 = Palaeo - Tethys suture (with associated lithologies), 5 = Neo - Tethys suture (outer and inner belt with associated lithologies), 6 = Fold belts (Himalayan and late Alpine marginal fold belts).

It was with the opening of the Ladakh area that a period of extensive work and publication about the geology of Ladakh started. Amongst these publications the works of the Zürich - Wien research group are still basic ones, e.g. Frank et al. (1977), Gansser (1977), Trommsdorff et al. (1982), Honegger et al. (1982) and Dietrich et al. (1983).

My own interest in the geology of Ladakh has started grown since in 1979 after having participated in a geological excursion to Ladakh. I was fascinated of this wonderful and spectacular country. I began to work in Ladakh in 1982. I was not only interested in the geology of Ladakh, I have taken the culture, the religion, the landscape and the lovely people to my heart.

1.1 Geographical and Geological introduction to the NW Himalaya

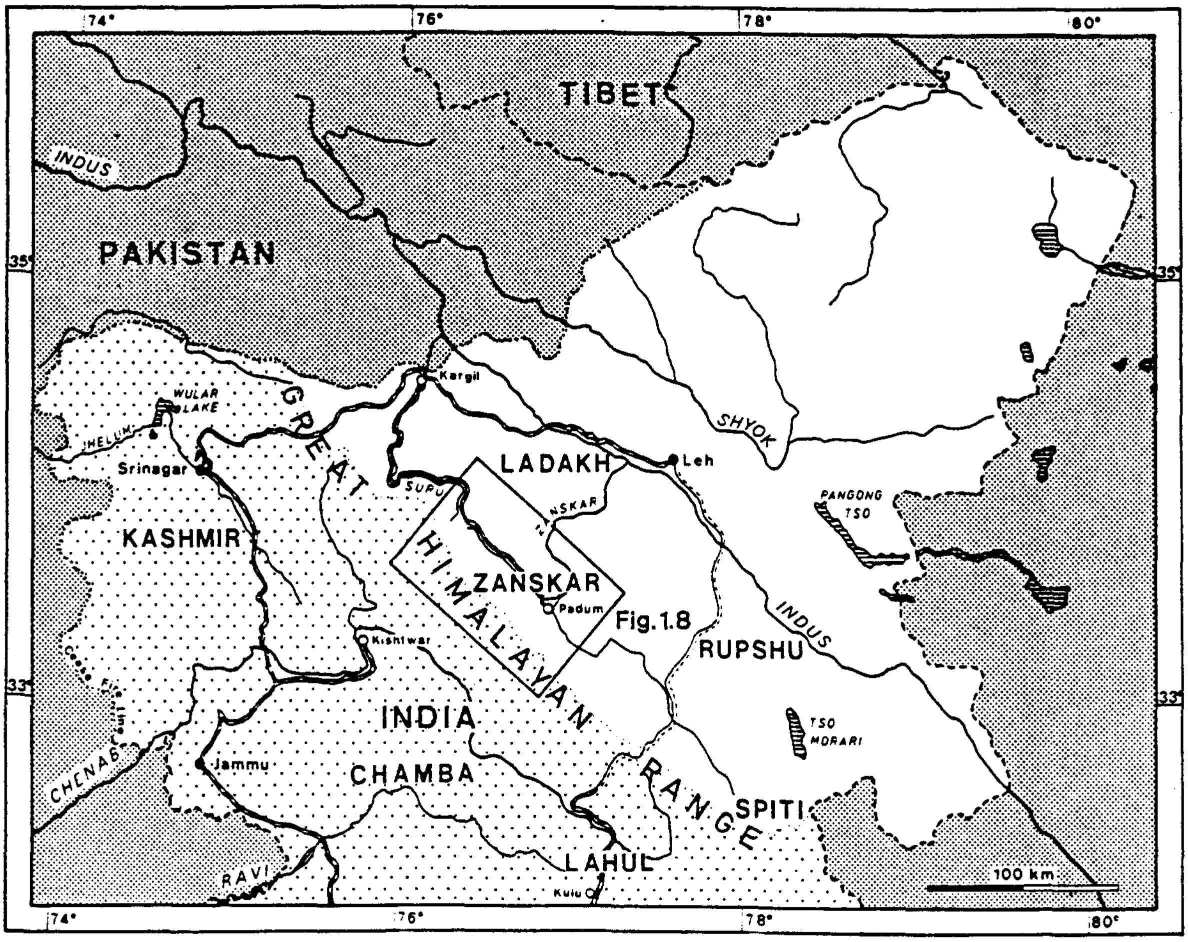


Figure 1.2: Geographical map of the NW India and adjouning Pakistan and Tibet. Stippled area: India southwest of the Great Himalayan Range. White area: wider Ladakh region, India northeast of the great Himalayan Range.

Geographical overview

Seen from a political point of view the NW Himalaya belongs to Pakistan, North India and Tibet. In the north of the main Himalayan Range lies Ladakh, a province of the Jammu and Kashmir State of India (Fig. 1.2). The western part of Ladakh borders on Pakistan. Tibet is the neighbouring country in the north and the east. At present Tibet is occupied by China. Because of the strategic importance of Ladakh there are border disputes with Pakistan and with China. A cease fire line has been drawn but the political boundaries are in dispute. That is the reason for the military road from Srinagar to Leh and further north to the Shyok valley. When this road had been finished in 1975 Ladakh was opened to foreigners. Thus it has been possible to visit three regions; namely the Muslim Kargil district (including the Suru valley) and the two Tibetan - Buddhist provinces, the Indus valley with the capital Leh and the Zanskar area with Padum as its centre.

Ladakh lies in the rain shadow of the main Himalayan Range and thus belongs to the Tibetan platform at a height of at least 3000 m. This rather wild and barren part of India with only poor vegetation is only sparsely populated.

Geological overview

It is convenient and customary to divide the geologic structure of the Himalaya into a series of units that trend parallel to the range (e.g. Gansser, 1964). These units can be traced for most of the length of the range. Consequently cross sections and tectonic maps of different parts of the range are quite similar to one another. A simple description of the gross features of the geology can be given using the tectonic map of NW Himalaya (Fig. 1.3).

From south to north:

1. North-Indian Shield
2. Sub-Himalaya
3. Lower (Lesser) Himalaya
4. Higher Himalaya
5. Indus Suture Zone

1\. North-Indian Shield:

The Precambrian basement is overlain on its northern border towards the Himalaya by young sediments deposited from the rivers coming from the Himalayan range (e.g. Chenab, Ravi, Beas). The alluvial land of the Punjab in the west, the Ganges and the Brahmaputra in the east form the present foreland basin of the Himalayan Orogen.

2\. Sub-Himalaya:

The foothills of the Himalaya Range are formed by this tectonic unit. They are built up of folded, partly imbricated and overthrust Miocene to Pleistocene Molasse sediments of the Siwalik and the Murree Formations. The northern border is the Main Boundary Thrust (MBT).

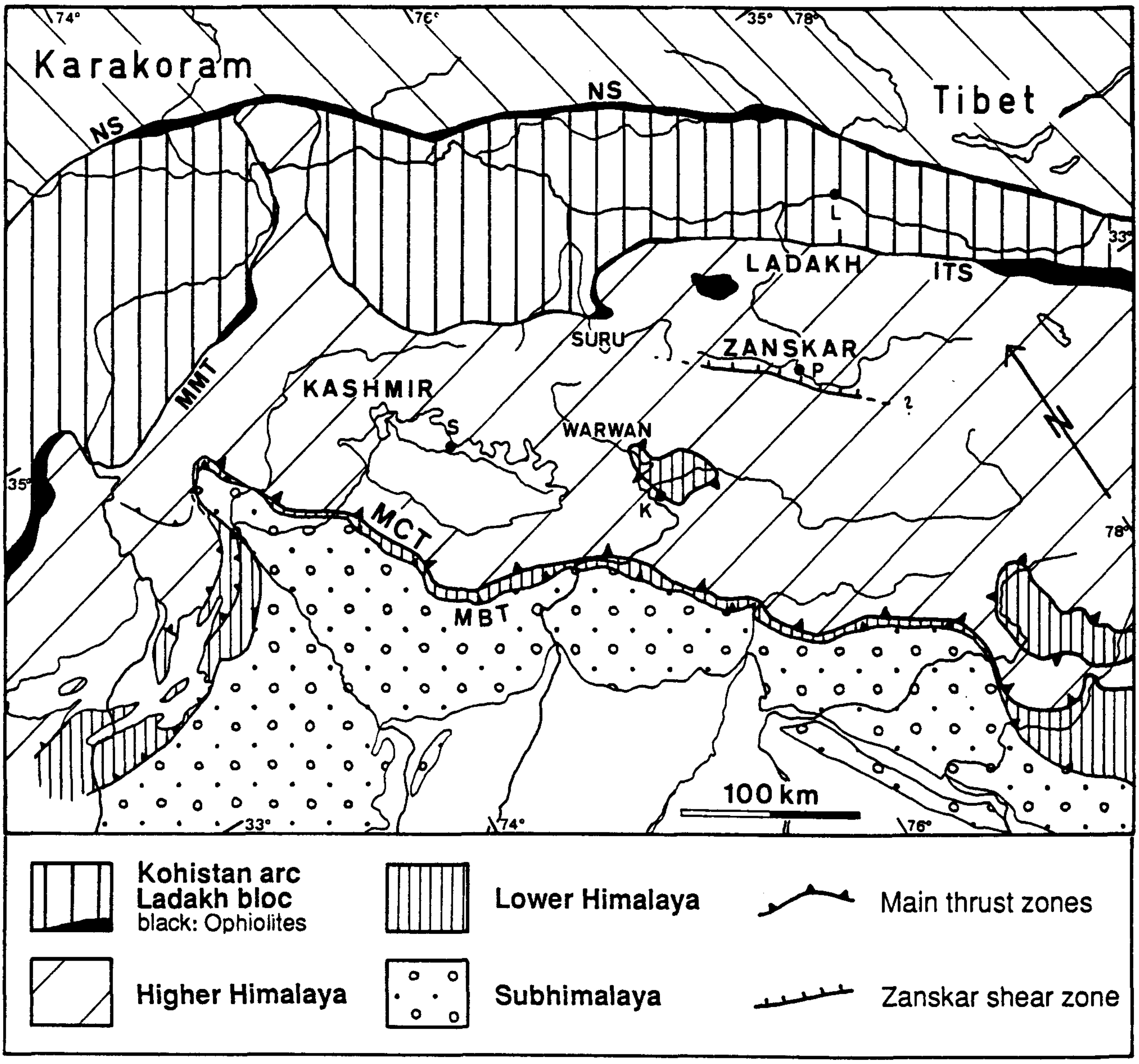


Figure 1.3: Tectonic map of northwestern Himalaya (after Honegger, modified). Abbreviations: NS = Northern Suture, ITS = Indus Tsangpo Suture, MMT = Main Mantle Thrust, MCT = Main Central Thrust, MBT = Main Boundary Thrust, S = Srinagar, K = Kishtwar, P = Padum, L = Leh.

3. Lower Himalaya:

This unit forms the low chains of the main Himalayan Range. It is built up of several nappes. The most southern one overthrusts the Tertiary Belt (Sub-Himalaya) along the MBT. In the north the Main Central Thrust (MCT) forms the boundary of this unit. Fossils are very rare in these rocks and the tectonics are rather complicated. Therefore there is much dispute regarding the age of the beds, their stratigraphic order, and the demarcation of structural units. In the region of the NW Himalaya this nappe zone is thinned out between the Sub-Himalaya and the Higher Himalaya. There are facies transitions to the higher unit of the Higher Himalaya. Within the Higher Himalaya the Lesser Himalaya is exposed in the tectonic windows of Kishtwar and of Kulu Larji Rampur. This fact indicates an minimum amount of overthrusting of the Higher Himalayan over the Lower Himalayan of more than 100 km.

4. Higher Himalaya:

This forms the main Himalayan Range with its highest elevations and glaciers. This unit can be divided into the High Himalayan Crystalline and its overlaying sedimentary sequence the Tethys Himalaya.

The High Himalayan Crystallines form a mostly high metamorphic crystalline nappe of Precambrian age with intrusions of granites of Cambrian and Tertiary age. The locally used name (in Ladakh) for this unit is the Zanskar Crystalline unit. The main Himalayan mountains are built up of this crystalline unit.

The overlaying Late Precambrian - Early Tertiary sedimentary cover, the Tethys - or Tibetan Himalaya, is in general unmetamorphosed or only found in anchimetamorphic state and represents the shelf sedimentary sequence of the northern border of the Indian Shield. The Mesozoic sediments in the Suru region (Fig. 1.3) are partly of exceptionally high metamorphic grade (upper amphibolite facies (Honegger, 1983)). The Zanskar - Lahaul - Spiti sedimentary basin lie north of the main Himalayan Range, the Kashmir - and Chamba basins, however, lie on the southern side.

In the south the Higher Himalaya overthrust the Lower Himalaya along the Main Central Thrust.

5. Indus Suture Zone:

This steeply dipping zone, the suture between the Indian subcontinent and Eurasia, is divided into several tectonic units. The sediments of the Lamayuru unit were deposited on the northern foreland of the Indian continent. The complex to the north of this foreland, the Ophiolitic Melange zone, shows relicts of the oceanic crust with its Mesozoic to early Tertiary sediments. Local development of blueschist indicates high pressure metamorphic conditions of a subduction zone. The Dras Volcanics lies to the north of this unit and is composed of volcanic and volcanoclastic rocks. They represent both extrusive and intrusive parts of an island arc complex of Cretaceous age bordered north and south by the Ophiolitic Melange. The Ladakh Intrusives trend parallel to the other units and form the Transhimalayan Range. They are transgressively overlain by the Tertiary Indus Molasse.

The tectonically highest rocks are found in the Spongtang Nappe (klippe). In the klippe Dras Volcanics and ultrabasic blocs of the Indus Suture Zone lie on Tertiary sediments of the Tethys Himalaya.

The Himalayan orogen is characterized by a sequence of southwards thrustsheets emplaced from the early Tertiary to the present. The Higher Himalaya was first thrust over the Lower Himalaya (MCT). Later the Lower Himalaya was thrust over the Sub-Himalaya along the MBT and finally the Main Frontal Thrust (MFT) was developed (Gansser, 1983). This last event is indicated by neotectonically active overthrusting of the Pliocene Siwalik Formation over alluvial terraces of the Indian shield.

1.2 Open questions which have lead to this work, geological overview of the Zanskar area and the work of the Zürich team.

In 1975 A. Gansser and V. Trommsdorff from Zürich and W. Frank from Wien started their investigations in the Ladakh area. They developed a new zonation of the Indus suture zone (Frank et al., 1977). Encouraged by this work K. Honegger began his studies for his thesis in 1978. He provided a more elaborated picture of the area from the suture zone, along the Suru Valley within the crystalline unit to the south, to the Warwan Valley and finally to the tectonic window of lower Himalayan units at Kishtwar. Perhaps the most important result of his work was the evidence he provided of the Himalayan age of the regional metamorphism.

In 1979 I had a chance to participate in a geological excursion to Ladakh. In the summer 1981, after having finished my diploma I accompanied K. Honegger as a field assistant to Lakakh. It was during the course of this work that I decided to start my own thesis in Ladakh. As the situation in the Muslim part of Ladakh proved to be rather inconvenient for female scientists I preferred to work within the Buddhist part of Ladakh. Thanks to K. Honegger and A. Baud (Lausanne) I become aware of an interesting problem which could be tackled by someone with especial interest in structural geology. In the Zanskar area (Figs. 1.2 and 1.3), within the Higher Himalaya, a spectacular angular discordance between Cambrian sediments and the Permian basalt, the Panjal Trap, (Fig. 1.4), had lead different workers to different conclusions. The basic question at issue was the following: is there a primary sedimentary gap

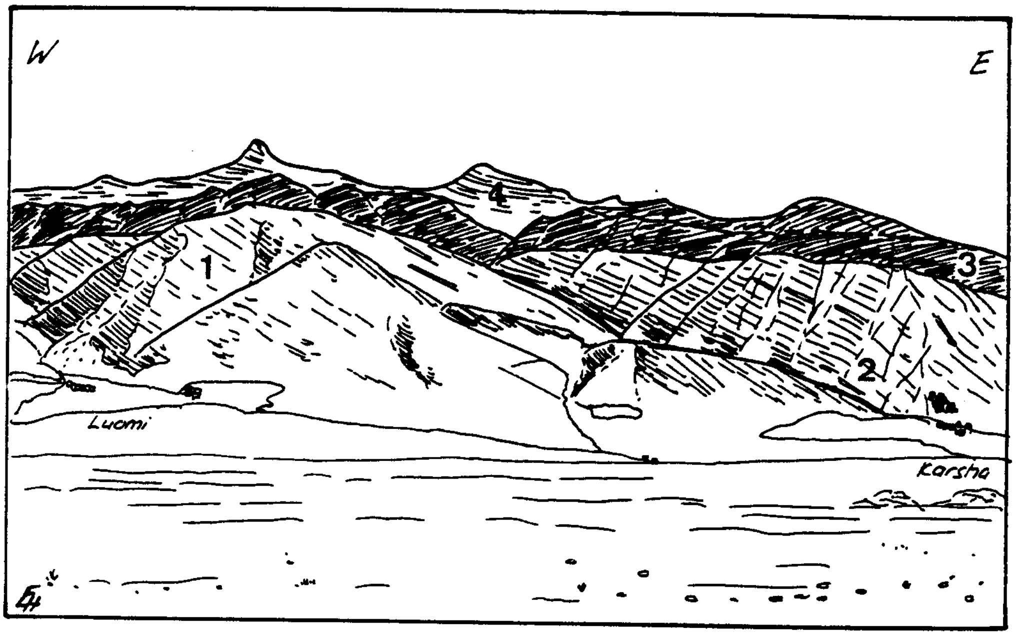


Figure 1.4: Angular discordance between the Late Precambrian - Cambrian unit and the Permian basalt, the Panjal Trap at Luomi and Karsha (Fig. 1.8). 1 and 2 = late Precambrian - Cambrian unit (1 = Phe Formation, 2 = Karsha Formation), 3 = Panjal Trap (Permian), 4 = Mesozoic unit (Lilang Formation, Triassic). Distance from Luomi to Karsha: 3.5 km.

between these two units (Srikantia et al., 1978) or is this impressive contact zone caused by large overthrusting of the Panjal Trap over the Paleozoic rock sequence (Baud et al., 1984)? The controversy required, for its solution, a detailed account of the tectonic history of the section in Zanskar.

Geology of the Zanskar region

The Zanskar region lies within the Higher Himalaya Tectonic unit on the northern side of the great Himalayan Range. (Figs. 1.2, 1.3 and 1.5). It consists of the Zanskar Crystalline unit and of its overlying sedimentary sequence, the Tethys Himalaya. Four main geological units can be distinguished from Southwest to Northeast (compare Figs. 1.6 and 1.7):

1) The Zanskar Crystalline unit consisting mainly of biotite gneisses with old (500 Ma) layered intrusions of porphyritic granite gneisses and leucogranites of Himalayan age.
2) This well-banded Zanskar Crystalline unit is overlain by a weakly metamorphosed Late Precambrian - Cambrian sedimentary sequence, called the Phe and Karsha Formation (Nanda and Singh, 1976; Baud et al., 1984).
3) After a long time gap the Permian basalt, the Panjal Trap was extruded. The spectacular angular discordance between this and the underlying Late Precambrian - Cambrian unit is visible all over the Zanskar region.
4) The Mesozoic sedimentary unit follows above the Panjal Traps with no discordance.

As each of these four units shows its own morphology it is possible to separate them relatively and to distinguish them on a satellite images, a feature that was a big help in mapping the area.

Although much excellent work has been previously carried out on the stratigraphy of the Tethys Himalaya sequence, especially the Mesozoic unit was recognised (e.g. Nanda and Singh, 1976; Srikantia et al., 1978; Baud et al., 1984; and Gaetani et al., 1983, 1985a) little previous knowledge was available about the metamorphism, structures and tectonics of this area (e.g. Nanda and Singh, 1976; Srikantia et al., 1978; Fuchs, 1981, 1982, 1985 and 1986; Baud et al., 1984; Gaetani et al., 1985b; Searle, 1983; and Searle and Fryer, 1986). As already mentioned, several different interpretations on the nature of the contact between the late Precambrian - Cambrian unit and the Panjal Trap have been suggested. Another controversial question concerned the contact zone between the Zanskar Crystalline unit and its overlaying Tethyan sedimentary sequence. All previous workers recognised the Zanskar Crystalline unit as a high-grade terrain in contrast to the low-grade late Precambrian sedimentary cover. However, they differed in their interpretation of the nature of the sharp metamorphic break between these two units.

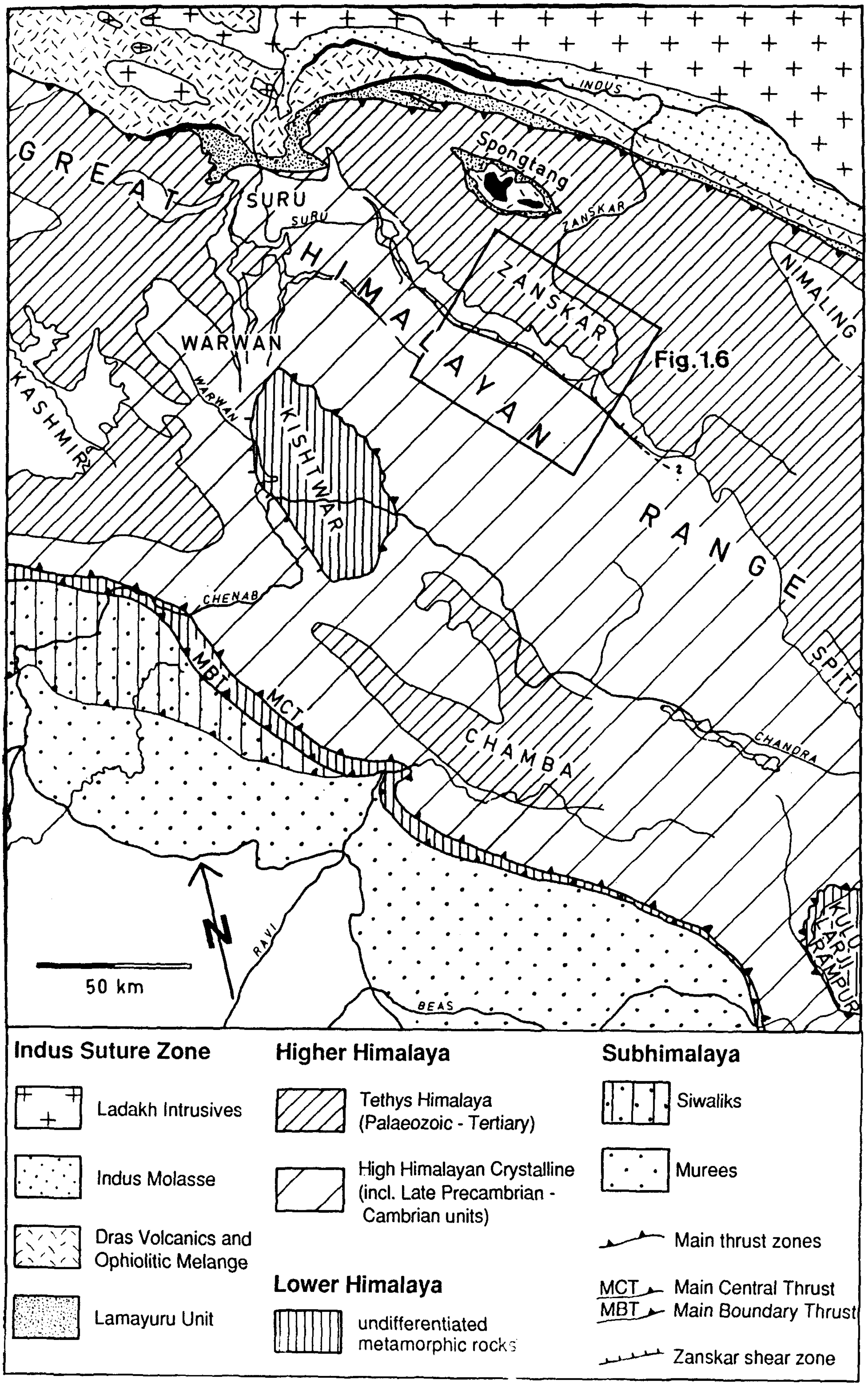


Figure 1.5: Tectonic map of Kashmir - Ladakh (after Honegger, 1983 and Frank et al., 1987, modified). (Black Ophiolites)

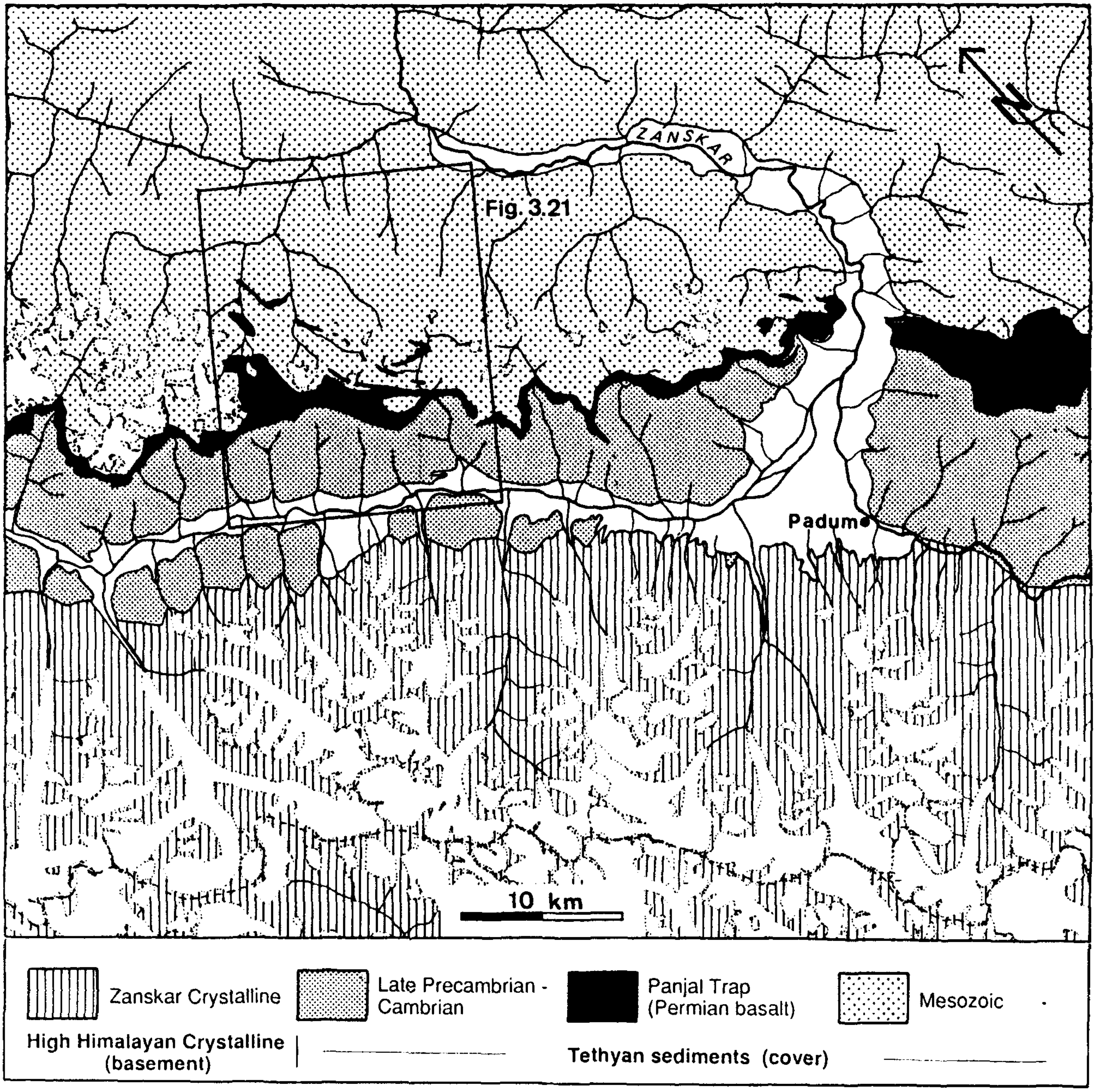


Figure 1.6: Generalized geological map of the Zanskar area. n.b.: north direction not vertical.

The previously published works about Zanskar helped me to focus my own investigations on structural and metamorphic aspects to try to solve the following "open" questions.

open questions:

- What is the nature of the contact zone between the Zanskar Crystalline unit and the overlying late Precambrian - Cambrian unit? What is the reason for the sharp metamorphic break between these two units?
- What is the nature of the sedimentary gap and the angular discordance between the late Precambrian-Cambrian unit and the Panjal Trap? This problem seemed to be most accessible for study in the Zanskar area because these two units have only been affected by low-grade metamorphism. The contact zone has not been overprinted and totally recrystallised by metamorphism as in the Suru region.

- Is it possible to compare the metamorphism, lithologies and tectonic evolution of the Suru - Warwan area (studied in detail by Honegger, 1983) with the neighbouring Zanskar area to the southeast?
- Is it possible to prove the existence of Himalayan leucogranites, as described by different authors in other parts of the Himalayan Range, in Ladakh?
- Is it possible to discover Pre-Himalayan structures in the crystalline basement rocks and in the Late Precambrian - Cambrian sedimentary sequence?
- How does the deformation vary in the different units? Is it possible to compare and contrast the deformation styles and to quantify them?

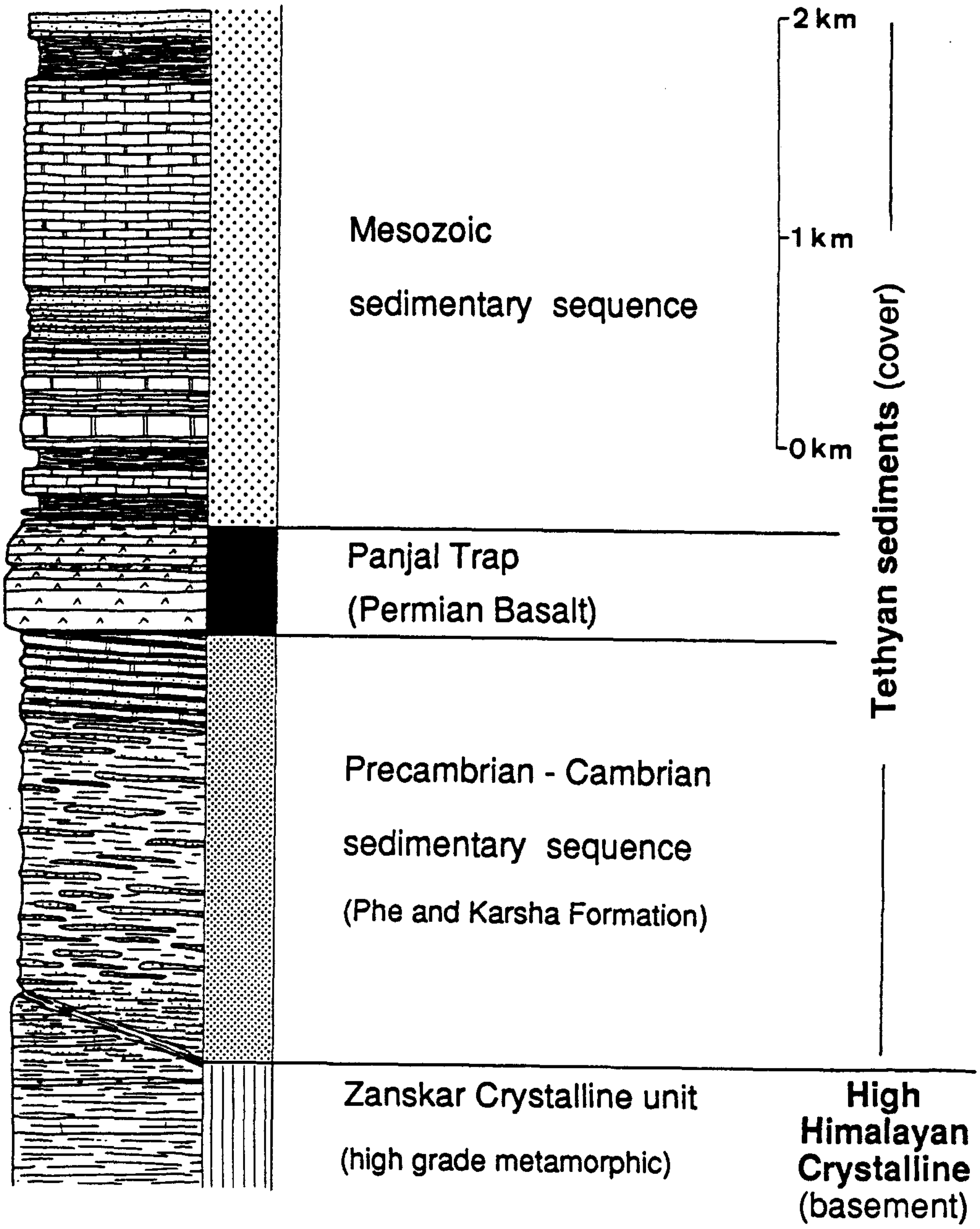


Figure 1.7: Lithological sequence (thicknesses (except Panjal Trap) and Mesozoics after Baud et al., 1984, modified).

Current work of the Zürich team in the "neighbourhood" of the Zanskar

The investigations of R. Kündig are currently providing an insight into the exact path of the metamorphism and a more detailed account of the metamorphic transition from the Suru valley (Honegger, 1983) to the Zanskar area (Fig. 1.5). A. Stäubli is currently studying the inverted metamorphism and the structures of the Kishtwar window (Lower Himalaya) (Fig. 1.5), especially along the overthrust zone, the Main Central Thrust.

1.3 Geographical overview of the Zanskar area and working methods.

Geographically the Zanskar area (Fig. 1.5) lies directly north of the Great Himalayan Range comprising the Doda -, Tsarap Lingti Chu - and the Zanskar valley (Fig. 1.8). All rivers drain into the Zanskar which flows northeastwards through a gorge into the Indus river. High passes have to be crossed to reach the Zanskar region. Over the lowest pass, the Pensi-La (4500 m) a road leads to the Zanskar coming from Kargil and ending at Padum, the largest village of the Zanskar. The minimum altitude of the valleys is 3500 m.

The access to Zanskar proved to be quite a problem: in winter it can only be reached through the Zanskar gorge and this only for a period of about two months when its river is frozen. In summer, however, for a period of four months people use the trade routes over the following passes which all reach some 5000 m: the Charchar La to the Indus Valley, the Parfi La to Lamayuru, the Shingo La to Kulu - Manali and the Umasi La to Kishtwar. For about six month a year the Zanskar area is totally isolated.

There are only about 7000 inhabitants living in the Zanskar area. They are mainly Buddhists and take their cultural inheritance from the Tibetan area. Their economy is generally considered to be self - sufficient: in order to satisfy their demand of cereals they export butter and wool.

Working methods

Most of the names of villages and passes used in this Dissertation were taken from the Indian "Trekking Route map of Jammu & Kashmir". Some, however, are added according to my own observations and written in a English transcription. The elevations where taken from the "quarter inch map", a map of the Anglo - Indian Survey of the year 1927, from several trekking maps and from new observations using a standard altimeter.

The geological maps are based on satellite images of MSS and RBV technique. The good quality of the RBV technique made it possible to map on a scale of 1 : 100'000, sometimes even 1 : 30'000.

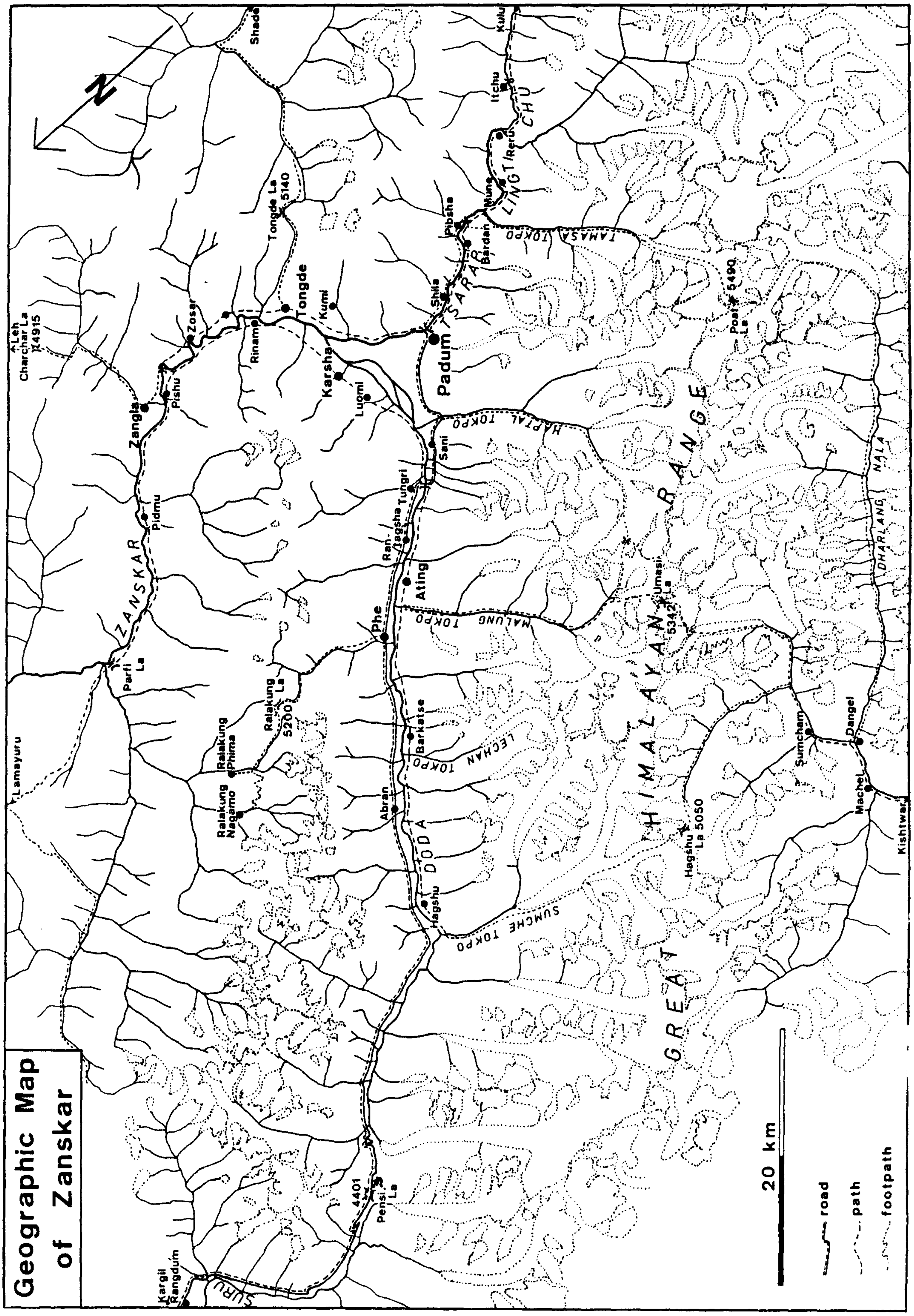


Figure 1.8: Geographical map of the Zanskar area.

Analytical techniques for geochemistry analysis

Major element bulk chemical X-ray fluorescence analyses of glass beads fused from ignited powders plus $Li_2B_4O_7$ were obtained on an automated Philips sequential spectrometer PW 1450 at the EMPA Dübendorf, Switzerland. FeO determinations were carried out by wet chemical methods. Nb, Zr, Y, Sr, U, Rb, Th, Pb, Ga, Zn, Cu, Ni, Co, Cr, V, Ce, Nd, Ba, La, Sc, and S trace element abundances were also analysed by X-ray fluorescence on 10-g powder samples using the synthetic background method, where major element contents were known. More details about analytical techniques are descriped in Honegger et al. (1982).

The logistical problems in the region were often very great. The rough landscape with mountains in part covered by glaciers, involved long and difficult walking. The steep scree slopes which often had to be climbed to reach the outcrops were often extremely tiresome and tiring. However, every geologist who had worked once in a similar region, will be familiar with such problems.

2. Geological description of the Zanskar Crystalline unit

The Zanskar Crystalline unit in the Zanskar region trends NW-SE parallel to the general tectonic unit pattern of the NW Himalayas. It is overlain by the Late Precambrian - Early Cambrian sedimentary sequence of the Phe Formation. The main part of the Great Himalayan Range consists of this unit. High elevations and wide-spread glaciers make detailed field investigations difficult, and it is especially difficult to obtain a comprehensive view of the structure.

The upper part of the Zanskar Crystalline unit is overprinted by local deformations associated with the Zanskar shear zone (Herren, 1987 and chapter 7). The northeastern limit of this shear zone bounds the top of the Zanskar Crystalline unit (Figs. 1.5 and 5.1) and follows the southwestern side of the Doda valley, passing Padum and trending into the Tsarap Lingti Chu valley (Fig. 1.8).

A reconnaissance study of the Zanskar Crystalline unit was made in the area from the Pensi La along the Doda valley into the Tsarap Lingti Chu valley to Reru and over the main Himalayan Range to the southwest to the Dharlang Nala (Fig. 1.8). More detailed studies were made from the Malung Tokpo over the Umasi La to the southwestern side, from the Haptal Tokpo to the highest mountains forming the main Himalayan Range and from the Tamasa Tokpo to the Poat La (Figs. 1.8 and 2.1). Part of the field investigations on which the results described below are based, were made together with R. Kündig. The structural analyses include data of A. Pêcher based on his fieldwork in the Malung - and Haptal Tokpo in 1985.

The Zanskar Crystalline unit consists mainly of fine-grained dark biotite gneisses with layered intrusions of two-mica porphyritic granites of a probable age 500 Ma (chapter 2.1) and fine-grained garnet- or tourmaline- bearing leucogranites of Himalayan age (Fig. 2.2 and chapter 4). Most of the imposing peaks are composed of the porphyritic granite gneisses (Figs. 2.2 and 4.4). This well-banded Zanskar Crystalline unit (Fig. 2.2) is well exposed. It is consistingly in a highly metamorphosed state (to upper amphibolyte facies, chapter 5) and strikes northwest - southeast (Fig. 2.1). The thickness of the individual layers comprising the gneissic banding gradually decreases northeastward, toward the top of the crystalline unit (Fig. 2.1) and into the shear zone, from a maximum of about 1500 m to only 0.1 m (Fig. 2.3). It is uncertain whether this change is original or only the result of tectonic thinning. The rock sequences from one valley to the next are more or less similar, only in the Haptal Tokpo is the abundance of leucogranites much higher than in all the other parts of the Zanskar Crystalline unit (chapter 4). The Zanskar Crystalline unit in the studied area represents a deep-seated tectonic level as indicated by the high metamorphism, the presence of localised

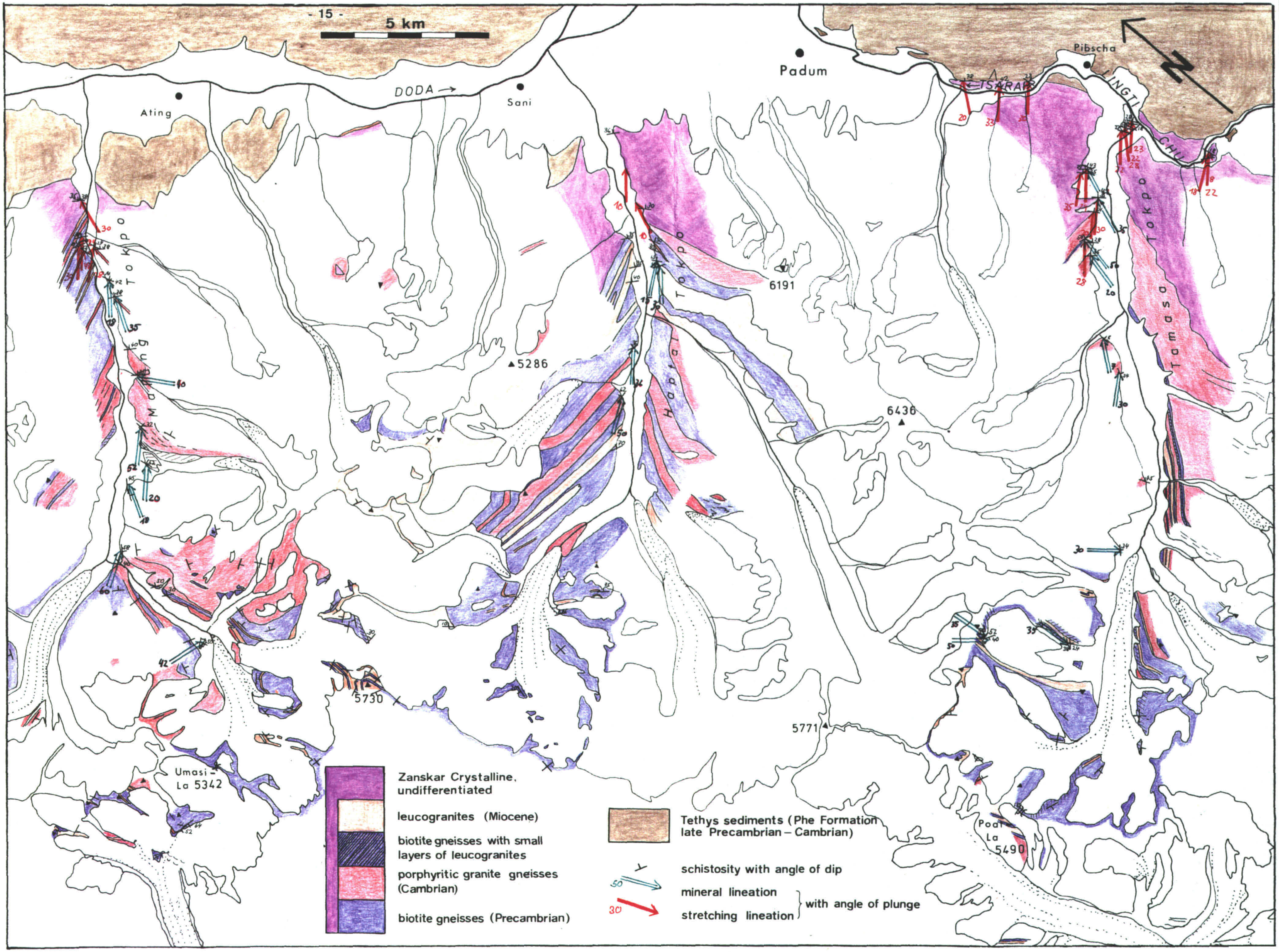


Figure 2.1: Geological scetch map of the Zanskar Crystalline unit in Zanskar including data of R. Kündig.

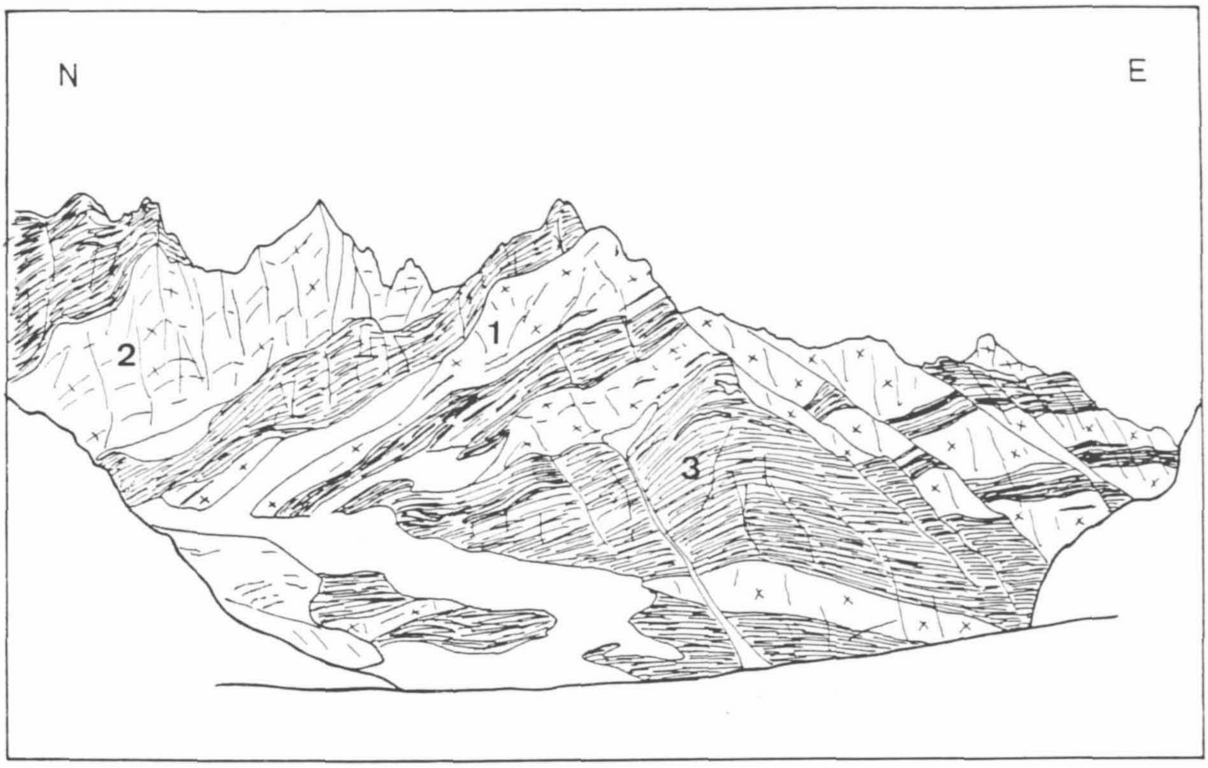


Figure 2.2: Zanskar Crystalline unit with its main lithologies: Leucogranitic (1) and porphyritic granite gneiss (2) intrusions within dark biotite gneisses (3).

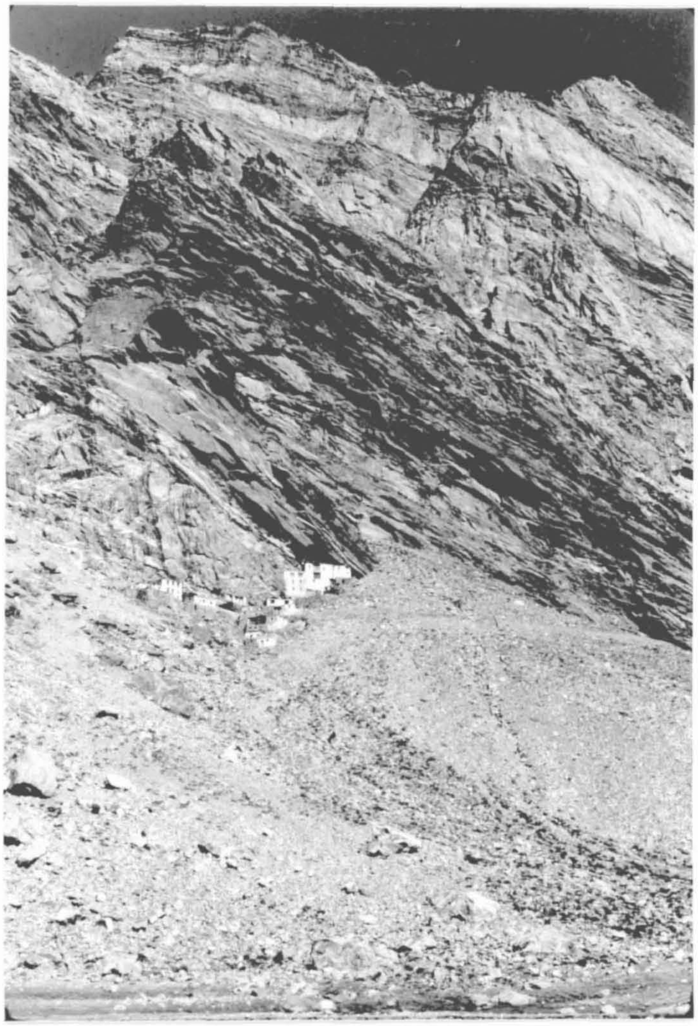


Figure 2.3: Upper part of the well-banded Zanskar Crystalline unit showing the main lithologies (leucogranites, porphyritic granite gneisses and dark biotite gneisses) as in Fig. 2.2 but with decreased thickness. Dzonkul Gonpa (tib.monastery) in the Malung Tokpo.

melting and migmatisation (chapter 5) and the absence of large-scale recumbent folds and nappes separated by Permian-Triassic wedges within the crystalline unit as are typical for the western joining Suru - Warwan region (Fig. 1.5 and Honegger et al., 1982). The present configuration of the metamorphic isogrades is complicated (Fig. 5.1) and in part appears to have been modified by the Zanskar shear zone (chapter 7).

Until now, the crystalline part of this region has been poorly investigated. The work of Honegger (1983) in the Suru- and Warwan region brought more light into the metamorphic and structural evolution of the Zanskar Crystalline unit. The work of Gapais et al. (1984) and especially the one of Gilbert (1986) in a part of the Suru dome within the same region were the first which dealt with the detail of the structures of the crystalline unit. In addition, Gilbert (1986) investigated the relation of the crystalline basement to the overlying Tethyan sediments. The suggestions made by Searle and Fryer (1986) that 30 - 50% of the Zanskar Crystalline unit consists of Miocene leucogranites, however, are not acceptable (chapter 4). The work of Pognante et al. (in prep.) differentiates between two metamorphic events, a probably Cambrian and a Tertiary one. Pognante et al. (in prep.) do not differentiate between the white leucogranites and the grey porphyritic granite gneisses in the Haptal Takpo (Fig. 1.8) which is there obvious (Fig. 2.2) and they interpret them belonging to the same Cambrian intrusion sequence. Only the Gumburanjon leucogranite in the Tsarap Lingti Chu, which they investigated and described carefully, was interpreted to be a Tertiary granite. As shall be demonstrated further on, their interpretations about the metamorphism and the granite intrusion history are contradictory to those presented in this work (compare 2.1). The current work of Kündig (in prep.) deals in detail with the petrography and metamorphism of the Zanskar crystalline unit within the wider Zanskar region. His work is especially focused on the problem of the origin and evolution of the dome structures which characterise the large scale geometry of the structure of the region.

2.1 Lithology and Petrography

Figure 2.2 shows the three main rock types of the Zanskar Crystalline unit: the biotite gneisses, the layered intrusions of porphyric granite - gneisses and the leucogranites. Although complicated, it is possible to distinguish between metasediments (gneisses) and two different intrusion successions.

Metasedimentary rocks

These consist predominantly of fine-grained, well foliated sillimanite-biotite gneisses (semipelites). In the Zanskar area, nearly all of the crystalline unit is of upper amphibolite metamorphic grade (chapter 5), sillimanite is widespread and a characteristic mineral of this rocktype. Small (some millimetres) layers of these gneisses and thick (hundreds of metres) layers are similar in mineralogy and grainsize. The most abundant minerals are quartz (20 - 30%), plagioclase (10 - 15%), biotite (15 - 25%), sillimanite (10 - 20%), K-feldspar (0 - 10%, content dependant on metamorphic grade, chapter 5), garnet (0 - 5%) and muscovite (1 - 5%), also dependant on metamorphic grade, chapter 5). Accessory minerals are apatite, tourmaline, opaques, zircon and locally clinozoisite, monazite and sphene.

Variations of the predominant lithology are brownish-red weathered layers, typical near the main Himalayan Range. Notwithstanding the unusual colour, mineralogically these layers are quite similar to the usual ones. Within the highest metamorphic regions, in the core of the Haptal dome (chapter 2.2), small occurences of calcsilicates are interlayered with the biotite gneisses (Fig. 4.7). Toward the top of this unit mineralogical variation is larger and the primary sedimentary character of these lithologies is clear. Small alternations of metasandstones and semipelites are present. Near the top of the crystalline unit again calcsilicate and locally marble layers are present (Fig. 2.13). One of the narrow Permian - Triassic wedges south of the Rangdum area (Fig. 1.8) thins toward southeast and trends directly into the shear zone (R. Kündig, pers. comm.). Within all valleys from the Pensi La to Malung Tokpo (Fig. 1.8) a well defined calcsilicate rich layer is present. It is not yet resolved whether this layer is of Permo - Triassic age and if Permo - Triassic Formations do continue into the Zanskar area.

Intrusives

Within the studied area the intrusive complex is mostly of granitic type. Basic material occurs only as sills or lenses of dolerite within the porphyric granites. In general the situation here is similar to the well investigated Suru - Warwan region (Honegger, 1983). Honegger describes stocks, lenticular bodies and sills of granitoid rocks partly associated with basic (dolerite) and even ultrabasic rocks. Because all the granitoids appeared to belong to the same intrusive sequence and were overprinted and effected by the Himalayan orogenic activity he concluded that all were representatives of a pre-Himalayan intrusive (and orogenic) sequence. The magmatic activity of Himalayan age is documented only by dykes (tourmaline pegmatites and aplites).

In the Zanskar area, however, we can clearly distinguish between two magmatic episodes, a pre-Himalayan one (porphyric granites) and a Himalayan one (leucogranites). All along the Himalayas young leucogranites are well known (e.g. Le Fort et al., 1987 and chapter 4). In the Suru - west Zanskar area granites of two ages have not been demonstrated. Searle and Fryer (1986) have suggested that late (Himalayan) leucogranites make up to 30 - 50% of the Zanskar Crystalline unit. As will be demonstrated in chapter 4, such high proportions seem to be exaggerated.

In the Zanskar area the leucogranites are concentrated in the Haptal Tokpo where layers of leucogranites up to 600 m thick are present. The valleys to the northwest, southeast and southwest show smaller occurences of leucogranites and within all the other studied areas (Warwan - Suru - Kashmir - Zanskar) no Himalayan leucogranites have been definitely identified (Honegger, 1983; Kündig, in prep.; Stäubli, in prep.). The small leucogranite occurences in the Haptal Tokpo and of the surrounding valleys were investigated in detail, the data is presented in chapter 4.

Old (pre-Himalayan age) magmatic activity in the Zanskar area appears to have led mostly to the formation of sills of granitoids. Due to the high metamorphic conditions of the main part of this unit and the strong structural overprinting in the northeastern part (Zanskar shear zone), it is difficult to be sure if these porphyric granitoids substantially predate the Himalayan deformation. In the lower-grade metamorphic zones of the western joining Suru - Warwan area, however, the intrusive character of several stocks and lenticular bodies of porphyric granitoids is well preserved (Honegger et al., 1982; Honegger, 1983). By analogy it is concluded that the porphyric granitoids in the Zanskar region probably belong to the same pre-Himalayan intrusion sequence.

The main part of these granitoids are porphyric two-mica granites. Subordinate are coarse grained two-mica granites, garnet-biotite granites and muscovite granites. Some doleritic dykes of a thickness up to 2 m are present. Locally, the primary ophitic magmatic texture is still visible and the old mineral assemblages are only partly overprinted by the high grade regional metamorphism. Sometimes totally overprinted and recrystallized dykes are now present as biotite - or garnet amphibolites.

From field observations the relative as well as the absolute ages of these granitoids remain uncertain. In the Suru region, Honegger et al. (1982) have tried to date these granitoids but, until now, no Rb - Sr whole-rock dating has been successful. Fluids liberated during the Himalayan medium - to high - grade metamorphism appear to have disturbed the Rb - Sr whole-rock systematics and have led to anomalously low apparent ages (Honegger et al., 1982). Within the Kulu - Lahul area (Fig. 1.5) nearly identical granitoid rocks have been dated (Frank et al., 1977) yielding a widespread 500 Ma intrusive event (Bhanot et al., 1970; Le Fort et al., 1980; Jäger et al., 1971; Bordet et al., 1971; Metha, 1977; Ferrara et al., 1983 and Stutz and Thöni, 1987). Because of similar isotope geochemistry and petrography Honegger et al. (1982) concluded that the granitoids of the Suru region were originally related to this magmatic phase. As the Zanskar region lies between these two regions and the rocks are also similar, it seems that the porphyric granitoids of the Zanskar region are related to the same 500 Ma, Proterozoic - Cambrian, magmatic phase.

2.2 Structures

The area studied in detail is situated on the northeast side of a dome (Haptal dome, Fig. 2.4) of 20 km radius and its center in the Haptal Tokpo northeast the main Himalayan Range. The dome form is developed in the regional foliation. The mineral lineation pattern shows individual linear directions which are more or less perpendicular to the foliation trajectories

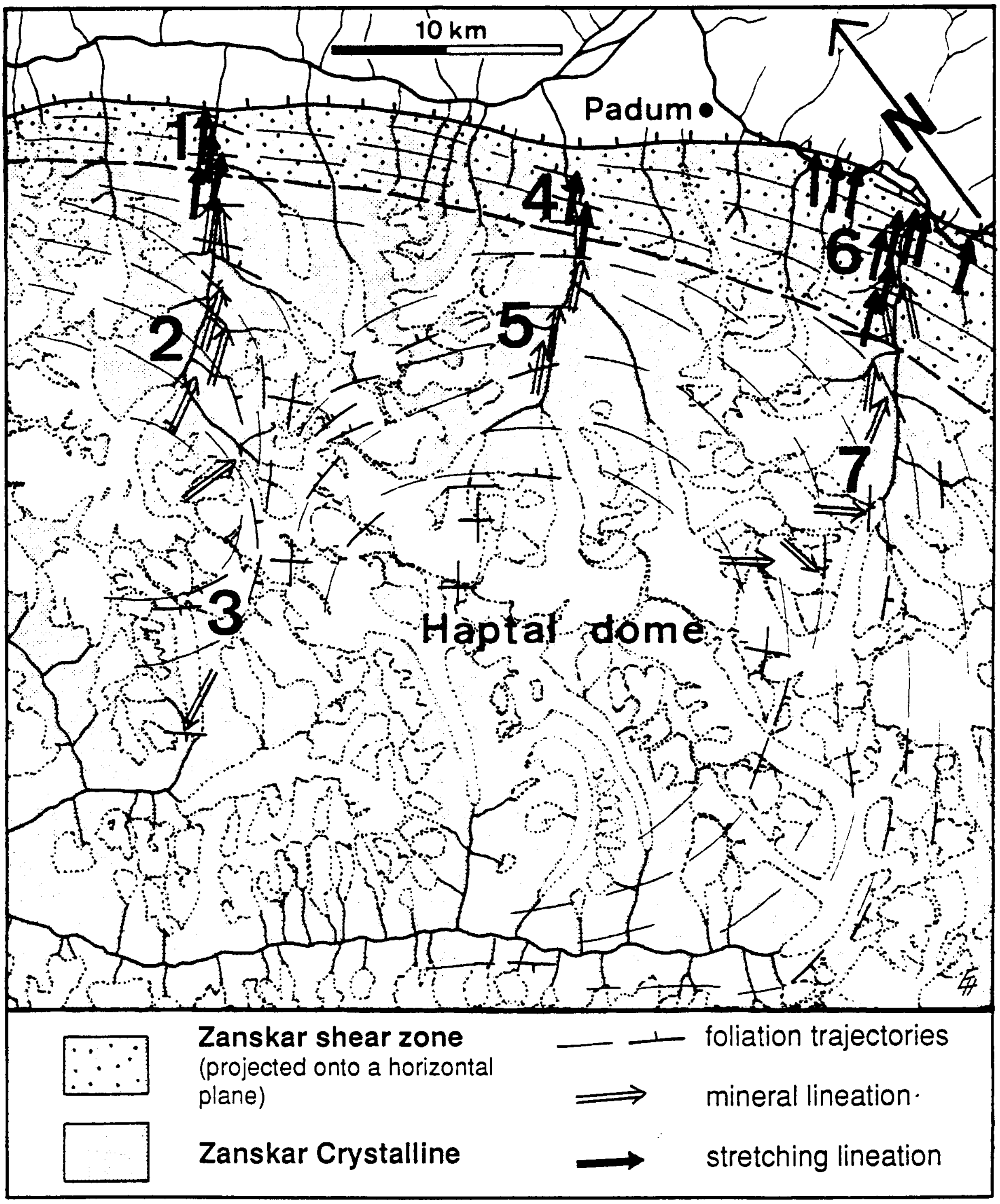
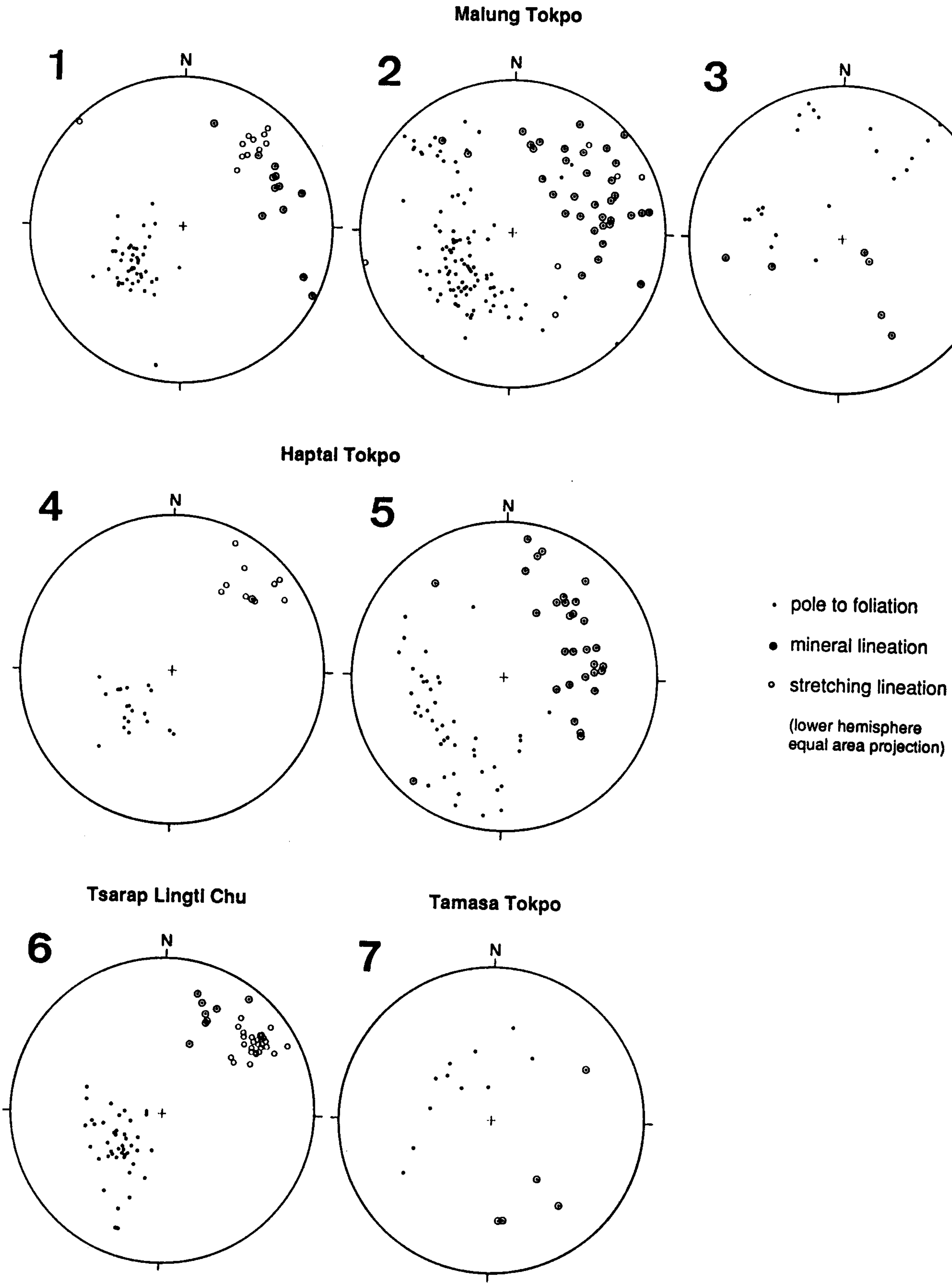


Figure 2.4: Generalized structural map of the Zanskar Crystalline unit of the Haptal dome. Chiffres correspond to the stereoplot of Figure 2.5. 1 - 3: Malung Tokpo; 4 and 5: Haptal Tokpo; 6 and 7: Tamasa Tokpo.



Malung Tokpo

Haptal Tokpo

Tsarap Lingti Chu

Tamasa Tokpo

Figure 2.5: Equal area projection of the structural data of the Zanskar Crystalline unit. The numbers correspond to Figure 2.4. 1 - 3: Malung Tokpo: 1 = measurements of the Zanskar shear zone, 2 = unsheared crystalline rocks, 3 = Umasi La and south side, unsheared; 4 and 5: Haptal Tokpo: 4 = sheared, 5 = unsheared; 6 and 7: Tamasa Tokpo: 6 = sheared, 7 = unsheared.

Equal area projection of the Malung and Haptal Tokpo are including data of A. Pêcher. The mineral lineation is related to the main deformational event, the stretching lineation to the Zanskar shear zone.

(Fig. 2.4). The foliation is horizontal in the center of the dome as it is between this dome and that to the northwest, in the Malung Tokpo (Fig. 2.4). In detail the deformation pattern is more complex. A first generation of folds and foliation is overprinted by a second generation of folds and in part, a related foliation. Deformational activity at the end of the structural evolution led to the development of the Zanskar shear zone and the overprinting the north-eastern part of the Zanskar Crystalline unit. This penetrative event, developed late in the metamorphic history, brings into parallelism all the earlier structural elements. The metamorphic isograd pattern (Fig. 5.1, distance between the individual isograd varying from valley to valley) and the parallel lying lithological boundaries in the hanging wall of the shear zone (Fig. 5.1) indicate an uplift of the Zanskar Crystalline unit relative to its sedimentary cover.

Structures of the main deformation phase (synmetamorphic)

Due to the deep level of exposure of the crystalline rocks, large scale folds of cover rocks such as are found in the Suru region (B1 folds), are not present. In the Zanskar region a penetrative regional foliation defined by the orientation of micas is well developed especially within the biotite gneisses. The Cambrian granites are transformed to granite gneisses. A mineral lineation defined by elongate mineral aggregates such as micas is sometimes present. The orientation of these lineations is in general down dip to the foliation plane (Figs. 2.4 and 2.5) and the lineation appears to be synchronous with the development of the foliation during regional metamorphism.

Structures of a later phase (syn - postmetamorphic)

A late generation of folds is sometimes present. These structures refold the main foliation producing folds of various sizes ("B2 folds"). In scale the wavelengths range from kilometric (e.g. when thick leucogranitic layers are folded together with biotite gneisses, Fig. 4.6), to metric (e.g. when thin leucogranitic layers are folded together with biotite gneisses, Fig. 4.7) and down to the smallest scale (millimetric) of a crenulation cleavage within well foliated gneisses (Fig. 2.6). The azimuths of the fold axes trend in general from NE to SE and have a plunge of 10^{o} - 40^{o} (Fig. 2.7). There is in general no associated foliation plane present (Fig. 4.7). Locally, however, within the porphyric granite gneisses a crenulation cleavage as well as sub-parallel small scale shearplanes are sometimes developed (Fig. 2.6). In some outcrops where the gneisses are folded on a fine-scale, small sillimanite needles have grown on the axial plane of the folds and form a foliation plane (Fig. 2.8). Often the first and overprinting phases coincide and are indistinguishable. Sillimanite nodules appear to have been generated at the peak of the metamorphism (chapter 5) and generally show a spherical form (Fig. 2.9). In other localities, however, they are ellipsoidal due to deformation. Systematic studies of this geometric variation have not been carried out but further work in this field would lead to a deeper understanding of the evolution of the Zanskar Crystalline unit because these ellipsoids probably represent the strain ellipsoid of the later deformation.

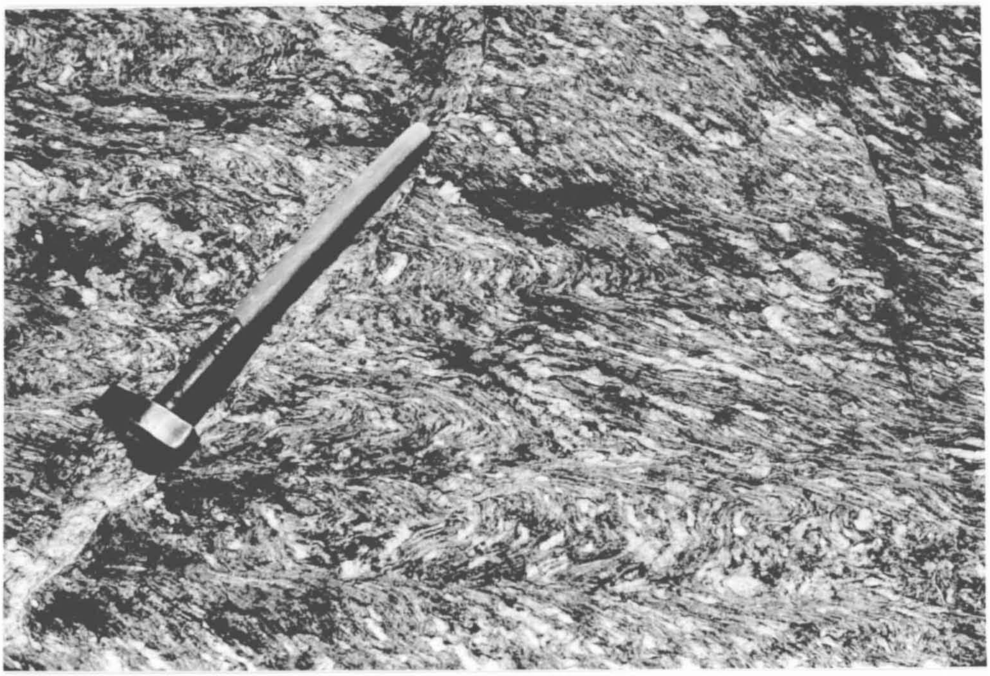


Figure 2.6: Porphyric granite gneiss with slight crenulation cleavage and locally horizontal lying synmetamorphic shearplanes.

In the Suru region B2 fold axes show a constant E-W orientation and are associated with a horizontal foliation plane (Gilbert, 1986). Honegger (1983) and Gilbert (1986) relate this second folding phase with the backfolding of the units of higher tectonic positions (thrusting of the Lamayuru unit northwards and overturning of the metamorphic isograd planes). In the Zanskar region, however, such a correlation is more difficult to make, especially because of the strong overprinting of the upper part of the Zanskar Crystalline unit by the Zanskar shear zone: a feature which is not found in the Suru region (chapter 7).

The present available data allow us to divide the structures into those which relate to the main deformational event and those overprinting them. Whether this later phase can again be divided into a second and a third generation of structures or consist only of one phase postdating the first one is not yet resolved. Several observations suggest that it may be subdivideable. The "B2 folds" observed in the Zanskar area are of different ages. The folds within the high metamorphic environment developed close to the peak of the metamorphism (e.g. sillimanite needles growing on fold axial planes and folded leucogranites which are still effected by the high T / low P metamorphism (chapter 4)) and show variable senses of vergence. Other folds, especially those within the sheared rock zone, seem to be related directly to the shearing event which post dates the peak of the metamorphism. Their fold vergence is consistent with the backfolding event and not compatible with the first event generated by continous southwest thrusting of the crystalline unit.

The "B2 folds" of Gilbert (1986) are backfolding-related folds (A. Pêcher, pers. comm.) and show homogeneous orientations. The orientations of the "B2 folds" of Honegger

(1983), however, show greater variations which may indicate that these folds are of several generations; folds generated within high metamorphic conditions as well as folds generated later in the metamorphic history during the backfolding event.

Different generations of folds were not differentiated in the field because they are never present together in the same locality. Therefore the results are summarized in one stereoplot (Fig. 2.7).

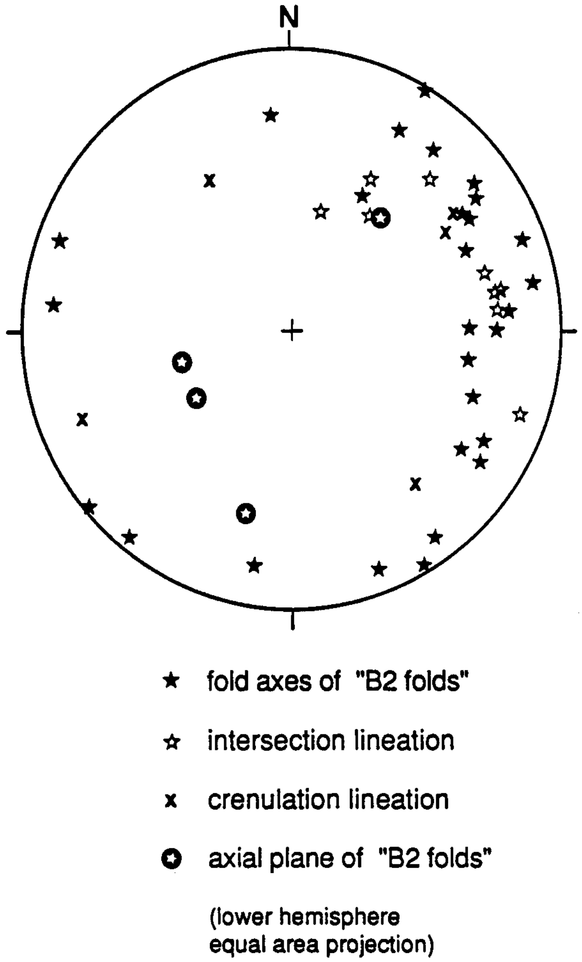


Figure 2.7: Equal area projection of overprinting structures, including data of A. Pêcher.

According to Honegger (1983: Fig. 56) the backfolding event within this part of the Higher Himalayan unit is defined by a steepening of all units, by the development of small scale folds. In the Zanskar area this backfolding event is only minor developed defined by the development of small scale folds. Characteristic of the Zanskar region is the development of the Zanskar shear zone late in the metamorphic history (chapter 7). The older structural elements are brought locally into parallelism with the dominant stretching lineation of the shearing event with the lineation indicating the transport direction (Figs. 2.4 and 2.5). Small scale folds within the mylonite belt in the Tsarap Lingti Chu show exactly the same orientations as the stretching lineations, having azimuths varying from 50° to 60° NE and plunges varying from 15° to 35° NE (Figs. 2.4, 2.5 and 2.7).

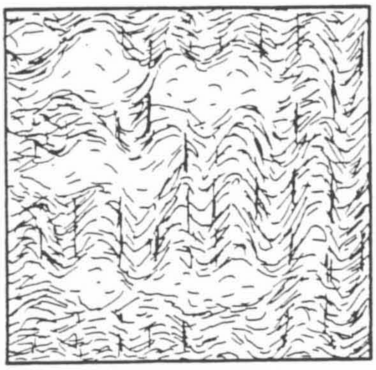


Figure 2.8: Sillimanite needles growing on the fold axial plane of slightly crenulated sillimanite - biotite gneisses. Haptal Tokpo, near the main Himalayan Range. The scale is approximately 1 : 1.

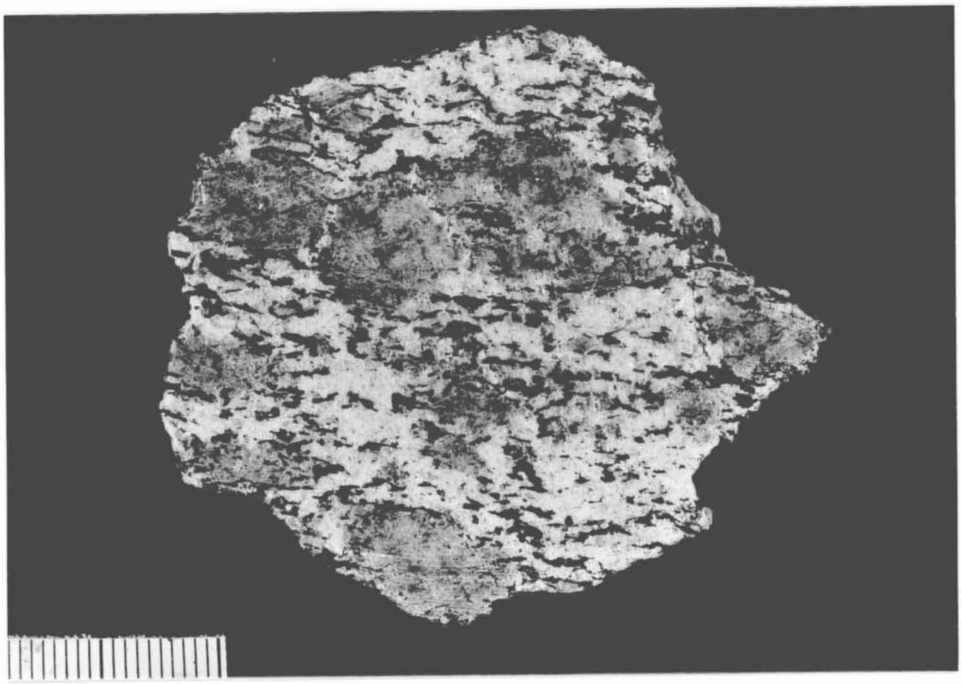
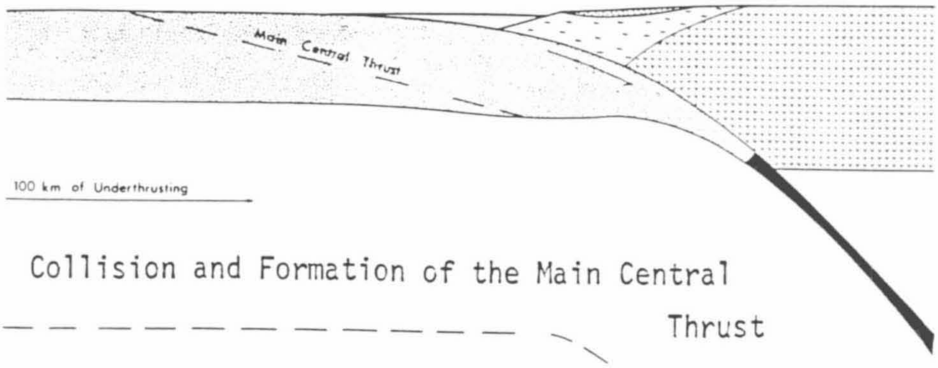


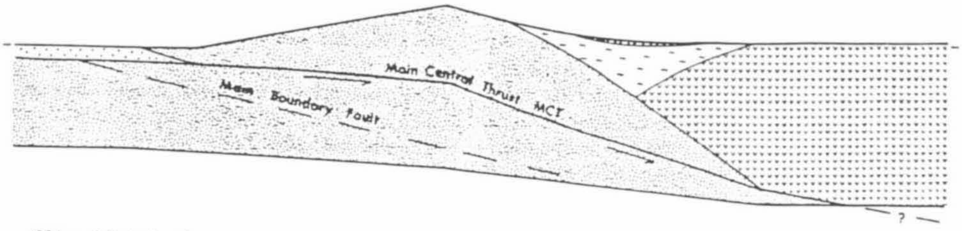
Figure 2.9 Spherical sillimanite nodules (diameter 1 cm) within a coarse-grained biotite granite gneiss (Suru region, sample of K. Honegger).

The uplift and doming of the central parts of the Zanskar Crystalline unit, simultanous with and outlasting the activity of the Zanskar shear zone (chapter 7), would explain the scattering of the second phase fold axes. Current earthquakes are confined to a narrow belt at depth of 15 km and gravity anomalies seem to indicate that the Moho must steepen and that the Main Boundary thrust plane suddenly changes from a very low angle to high angle. The sequence above this thrust zone and the units in front of the thrustplane are effected by a very high uplift rate (Lyon-Caen and Molnar, 1983 and P. Molnar, pers. comm.) a feature which probably explains the inhomogeneous and not simultanous uplift history of the different regions of the Himalaya. This feature may also be the reason for the slight folding of previous thrust planes as the Main Central Trust. Figure 2.10 shows a sequence of idealized cross sections through the entire Himalaya from the collision to the present (from Lyon-Caen and Molnar, 1983). Inhomogenous thrusting along the MBT along the trend of the tectonic units of the Himlayas may explain different timing of the uplift maxima in different places and the subsequent development of tectonic windows such as the Kishtwar window of lower units a)



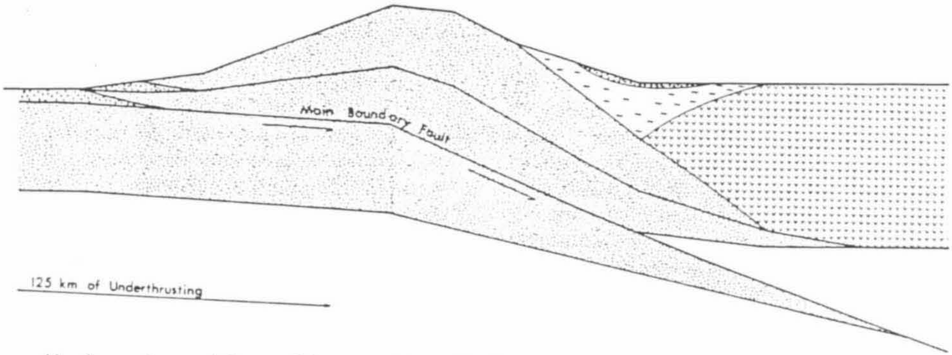
Collision and Formation of the Main Central Thrust

b)



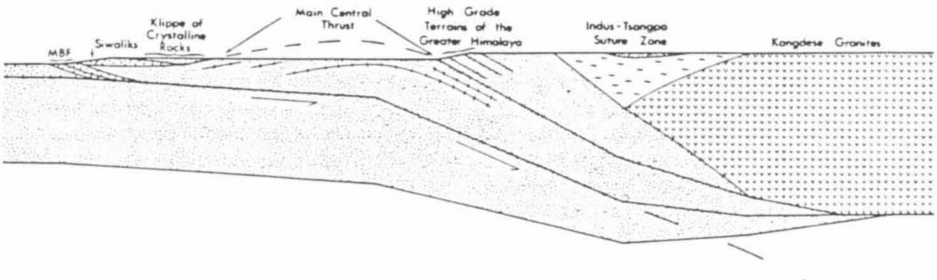
Underthrusting Along the MCT and Formation of the Main Boundary Thrust

c)



Understrusting Along the Main Boundary Thrust

d)



Analogy with Present Geologic Structure

Figure 2.10: Sequence of idealized cross sections from the collision to the present (from Lyon-Caen and Molnar, 1983). a) Formation of the Main Central Thrust after (an arbitrarily assumed amount of) 100 km of subduction of part of the northern margin of India. b) Formation of the Main Boundary Thrust after (an assumed) 125 km of understrusting of India along the MCT. Note the marked uplift of material over the MCT. c) Underthrusting of (an assumed) 125 km of India along MBT. Note that again pronounced uplift occurs where the MBT changes dip. d) Same as c), but with material eroded to the level of the present topography. Note that many features of the present Himalaya are present: the overthrust sediments are analogous to the Siwalik sequence of Miocene terrigenous sediments at the Himalayan front, the klippe of crystalline rocks transported by the MCT to the south is present, in NW Himalaya tectonic windows showing underlying overthrusted formations of the Lesser Himalaya (Kishtwar - and Kulu-Larji-Rampur window, Fig.1.5), the MCT dips at a gentle angle to the south on the Lesser Himalaya but more steeply to the north beneath the Higher Himalaya, the metamorhosed sediments in the Lesser Himalaya are domed slightly, and high-grade metamorphic rocks are present above the MCT.

(Fig. 1.5). The abnormal high rate of uplift of the Zanskar Crystalline unit in the wider Zanskar region might be explained by the same mechanism. The uplift started during a period when the MCT was still active (front of the understrusting Indian plate beyond upper parts of the crystalline unit) and continued until the present day disturbances giving rise to the strong asymmetric river pattern near the main Himalayan Range especially on the southwestern side (Fig. 2.11). Very deep seated levels of the crystalline unit are therefore exposed, a feature well demonstrated by the metamorphic isograd pattern (Fig. 5.1).

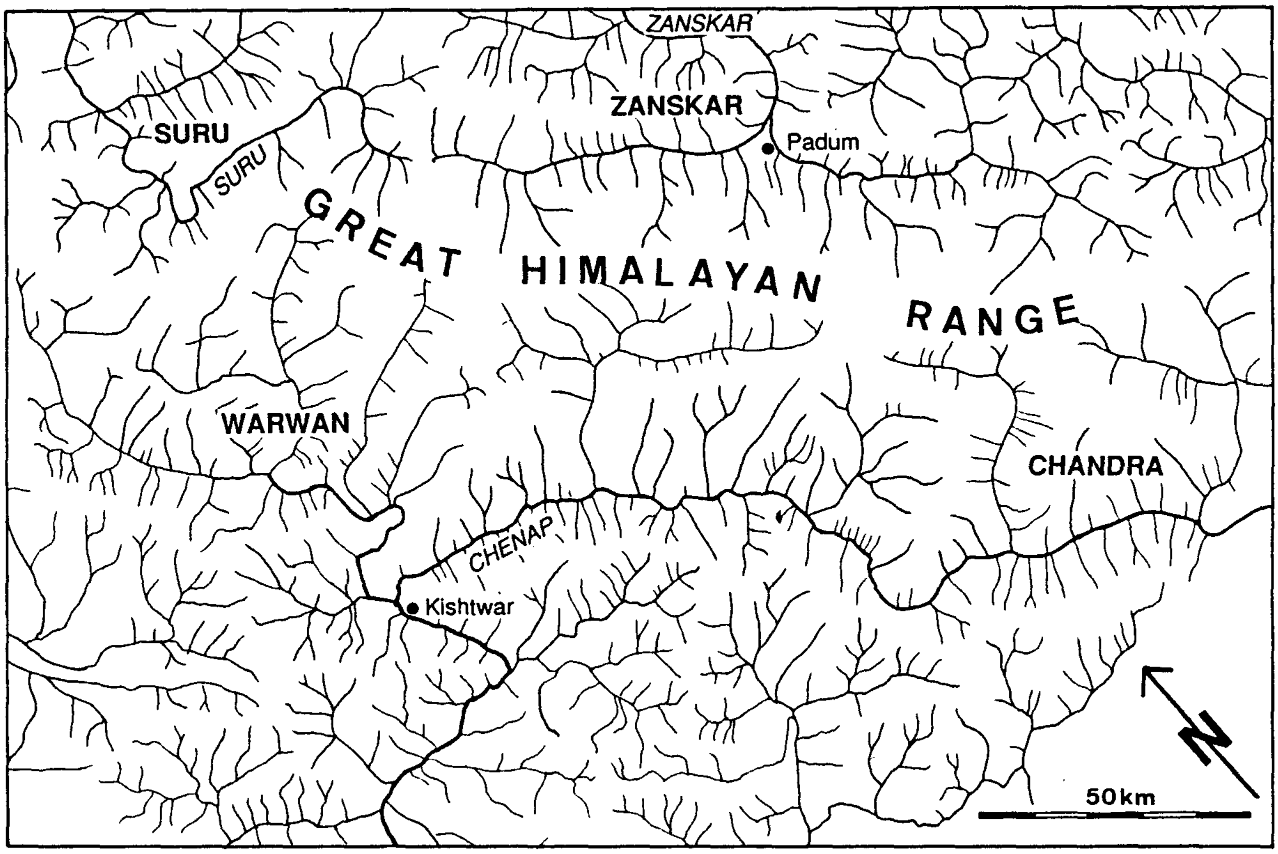


Figure 2.11: Scetch map of the river pattern of NW - Himalaya. Note the strong asymmetry especially south of the Great Himalayan Range and the more or less symmetric river pattern south of the upper Chenap river (before Kishtwar) what indicates a stronger uplift near the main Himalayan Range related to the southern lying mountain Ranges. In the Zanskar region and joining southern sides of the Himalayan Range where the exposed levels are very deep, the rivers trend parallel the main Himalayan Range. More to the east and west, however, the river pattern is no more so regular.

2.3 Transition to the Phe Formation

Toward the top of the Zanskar Crystalline unit a transitional zone of pelitic-psammitic rocks intercalated with porphyritic granite gneisses and leucogranites is present. Figure 2.12 shows three profiles through the contact zone of the Zanskar Crystalline unit to the Phe Formation. The pelitic-psammitic layers of the transitional zone appear to represent a gradational change from the crystalline basement rocks to the overlying Late Precambrian - Early Cambrian sedimentary sequence of the Phe Formation. Petrographically, these sediments are indistinguishable from the Phe Formation and are here regarded as part of the same formation. The sill - like intrusions of porphyritic granite gneisses and of leucogranites are petrographically similar to those found in the underlying gneissic formations. An

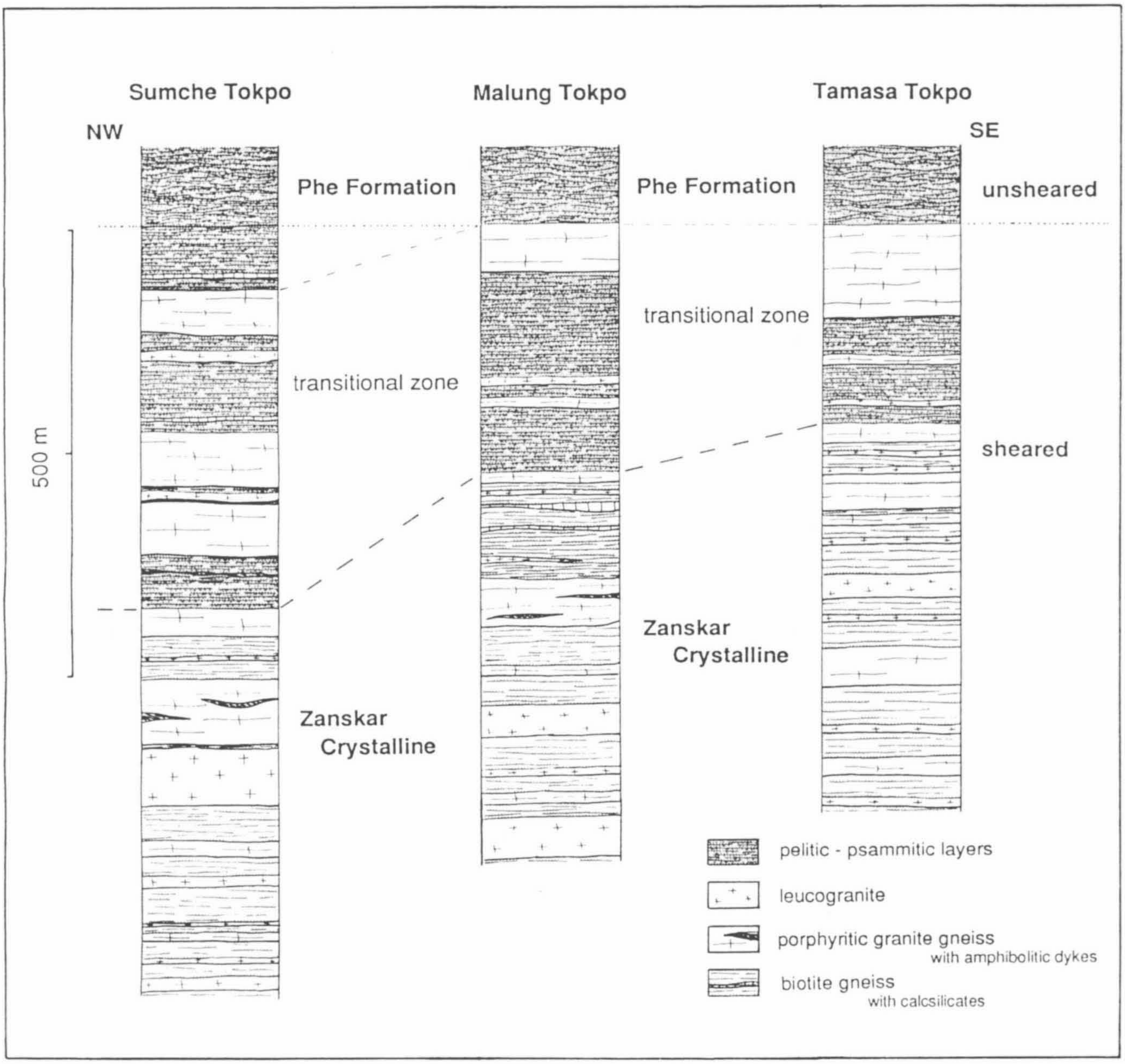


Figure 2.12: Profiles through the contact zone between the Zanskar Crystalline unit and the Phe Formation.

uppermost 50 - 150 m thick two-mica porphyritic granite gneiss sill belonging to the 500 Ma age granite suite (based on petrographically similarities) is continuous from northwest to southeast and marks the upper boundary of the transitional zone of the Phe Formation. The transitional zone of the Phe Formation varies in width from 500 m (Sumche Tokpo) to 150 m (Tsarap Lingti Chu Valley, Figs. 1.8 and 2.12).

Nanda and Singh (1976); Srikantia et al. (1978); Thakur (1980); and Fuchs (1981, 1982) have also recognised a transition from the crystalline to the sedimentary sequence of the Tibetan Zone as it is generally found all along the Himalaya (Fuchs, 1982). In Zanskar the transitional zone of the Phe Formation is in a highly metamorphosed state and strongly deformed by the Zanskar shear zone (chapter 7). Previous workers (e.g. Nanda and Singh, 1976; Srikantia et al., 1978 and Baud et al., 1984) have placed the contact between the Zanskar Crystalline unit and the Phe Formation on the northeastern boundary of the Zanskar shear zone (chapter 7). Figure 2.13 illustrates schematically the tectonic evolution of the transitional zone of the Phe Formation. From these new observations I conclude that the contact between these two units is farther southwest than that where previous workers have placed it. It would appear that the Phe Formation is a sedimentary sequence above the Zanskar Crystalline unit and that this is a separate Formation as Baud et al. (1984) and Gaetani et al. (1985b) have stated.

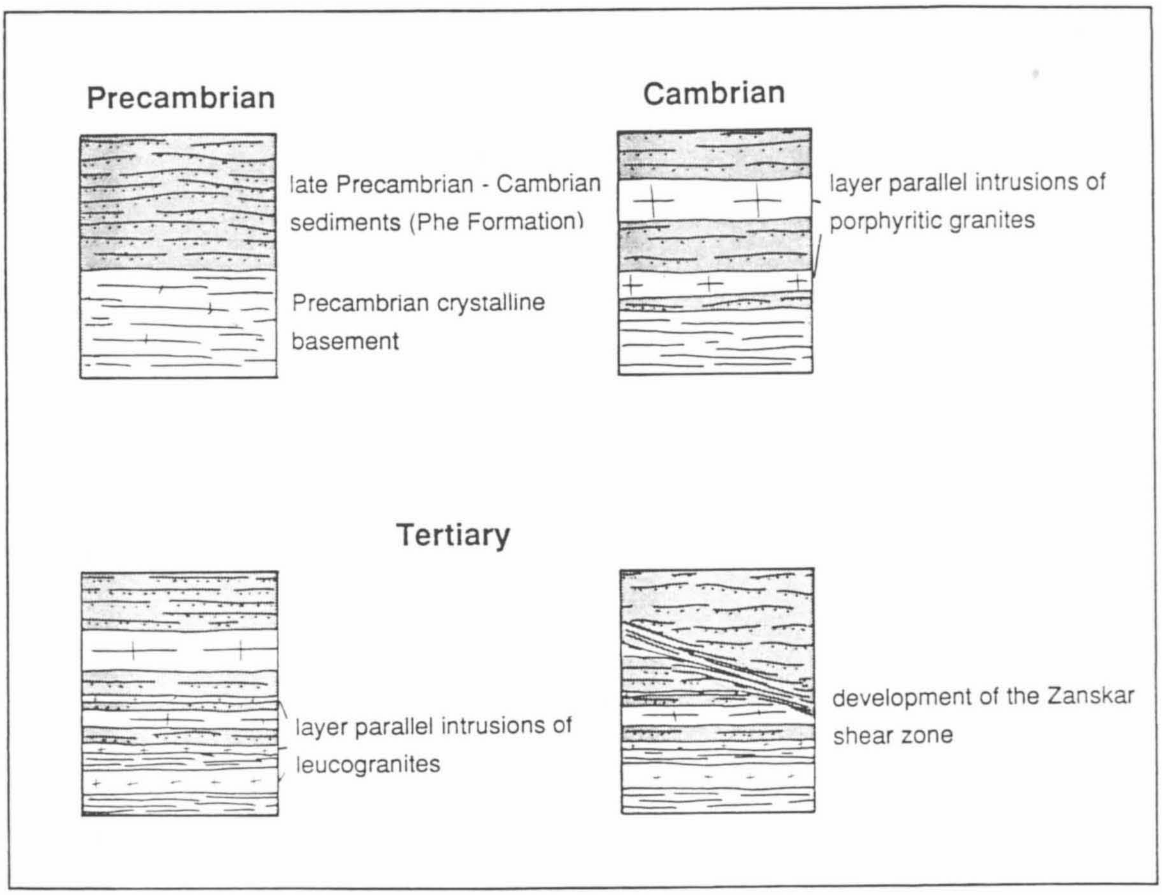


Figure 2.13: Generalized summary of the different events of the Zanskar Crystalline unit and the Phe Formation.

The high metamorphic state of the Zanskar Crystalline unit does not enable further subdivisions of the metasedimentary sequences. The Zanskar shear zone thins out gradually toward the Suru region (chapter 7) and although we come in this region into higher tectonic levels the rocks continue to show a high metamorphic state. Infact the Suru region is of unique high metamorphic conditions as compared with all the other parts of the Himalayas. It is only possible to follow the base of the Phe Formation to Sumche Tokpo (Fig. 1.8) where the metamorphism affects higher levels and enters into the Mesozoic units. All maps (Figs. 1.5 and 5. 1) showing the Zanskar and Suru regions, do not differentiate the Zanskar Crystalline unit and the overlying Precambrian - Cambrian sedimentary sequences (Phe and Karsha Formation).

3. Geological description of the Tethyan sedimentary sequence

The weakly metamorphosed Tethyan sedimentary sequence in the Zanskar region trends NW-SE parallel to the general tectonic pattern of the NW - Himalayas (Fig. 1.5). This sedimentary sequence of the Higher Himalayas forms the southwestern limit of the high elevated Tibetan platform, always laying northeast of the main Himalayan Range.

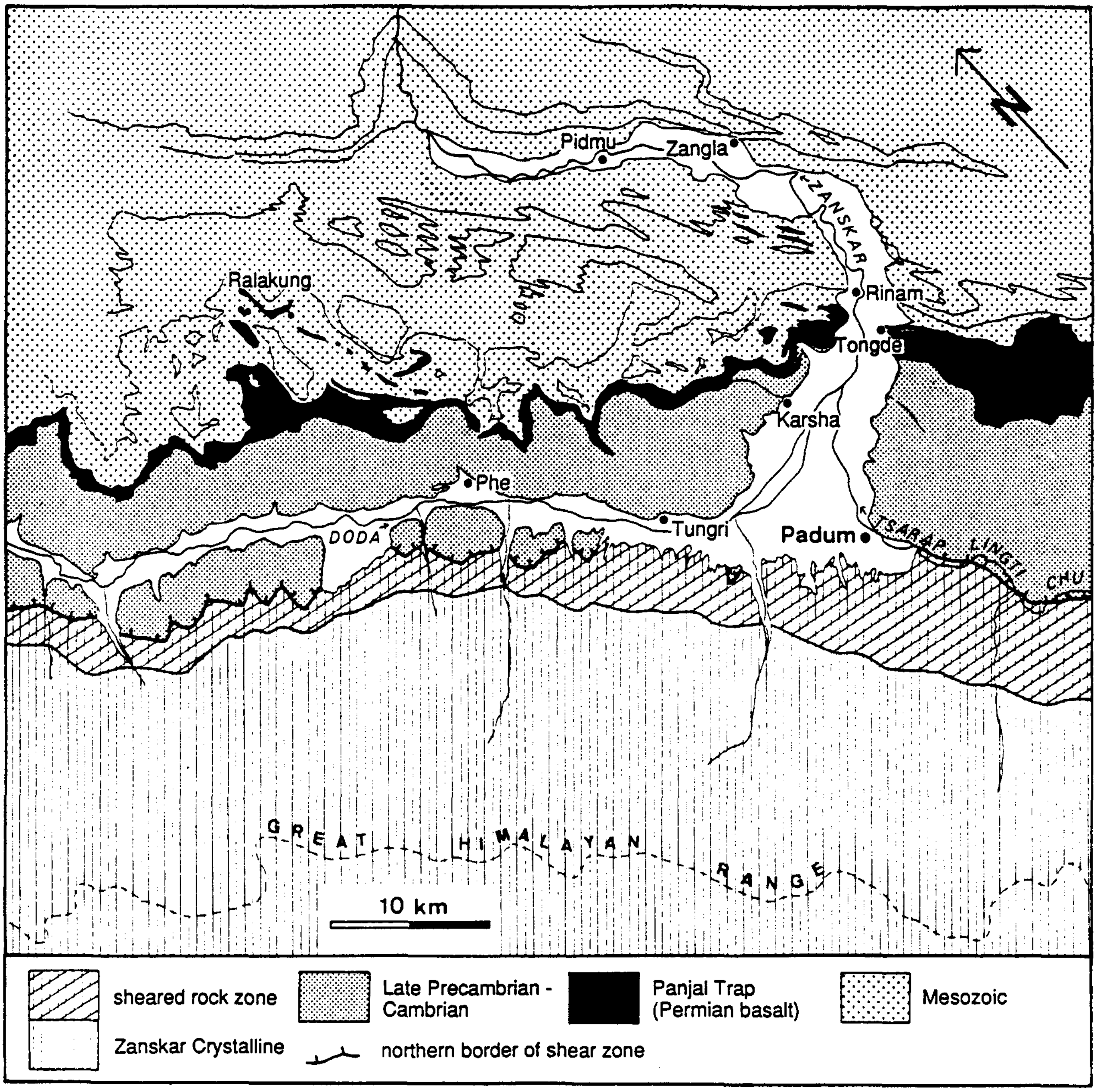


Figure 3.1: Geologic-tectonic map of the Zanskar area showing the four main geological units varying in their age, lithologies and structural styles.

In the Zanskar area (Fig. 3.1) the base of this unit follows the southwestern side of the Doda valley, passing through Padum, and trends into the Tsarap Lingti Chu valley. This boundary between the darker sedimentary sequence and the transitional zone of the Phe Formation (chapter 2.3) is readily visible in Landsat images and corresponds in the field to a morphological depression. The metamorphic grade and structural style change rapidly across this zone and can be attributed to the development of the Zanskar shear zone (chapter 7). A reconnaissance study of the Tethyan sedimentary sequence was made in the area from the Pensi La along the Doda valley into the Tsarap Lingti Chu valley parallel to strike, on a roundtour from the Tsarap Lingti Chu towards the northeast passing Shade and Tongde La and finally into the Ralakung region (Figs. 1.8 and 3.1). More detailed studies were made for the Phe and Karsha Formation from Phe towards Ralakung and from Tungri to Karsha and Karsha Chu (the river which drains to Karsha village). The Panjal Trap was carefully studied along two profiles, one on the way from Phe to Ralakung, the other beyond Karsha along the Karsha Chu. The Mesozoic sediments were studied on a cross section on both river sides of the Zanskar river from Padum to Zangla and from Tungri to Pidmu (Figs. 1.8 and 3.1).

The Tethyan sedimentary sequence consists of three parallel lying main geological units (Figs. 3.1, 3.2 and 3.3). The differences of these units can be correlated with their age, lithology and their structural style. From southwest to northeast they are:

1) The mostly terrigenous sediments (late Precambrian - Cambrian) of the *Phe and Karsha Formation* (Nanda and Singh, 1976; Baud et al., 1984), which include Cambrian rocks with dolomitic layers.
2) Plateau basalts of Permian age known as *Panjal Trap* (Lydekker, 1883 and Wadia, 1961).
3) The mainly carbonatic platform *Mesozoic sediments* ranging in age from late Permian to Cretaceous (Stoliczka, 1866; Hayden 1904, 1908; Nanda and Singh, 1976; Srikantia et al., 1978 and Baud et al., 1984).

Many recent publications describe the Tethys Himalaya of Zanskar. Most of these papers deal with the stratigraphy and sedimentology of the Mesozoic units. Nanda and Singh, (1976) as well as Srikantia et al. (1978) are basic works, the first to carefully investigate of the different formations and to produce geologic maps. The work of Baud et al. (1984) clarifies the differing stratigraphic nomenclature proposed by earlier workers. Further work of an Italian group (Gaetani et al., 1985a, Jadoul et al., 1985, Gaetani et al., 1983, and Nicora et al., 1984) has investigated in more detail the different formations, especially those of Mesozoic age.

For the descriptions of the Mesozoic lithologies, I will follow the nomenclature of Baud et al. (1984). Concerning the structures and tectonics of the Zanskar region my interpretations differ somewhat from those of Baud et al. (1984) and Gaetani et al. (1985b). These

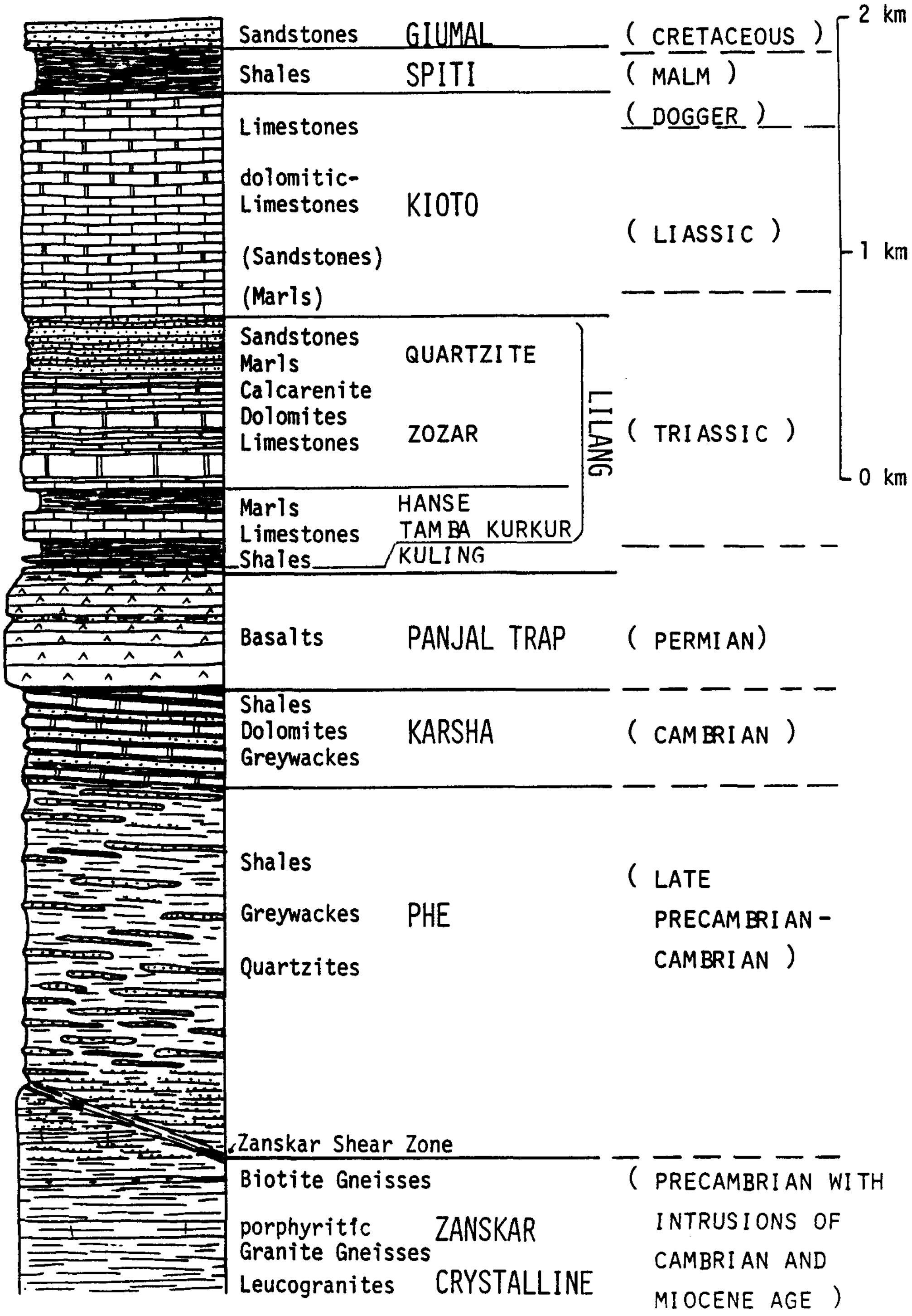


Figure 3.2: Stratigraphic column of the lithologies outcropping in the Zanskar area. Thickness and age of the individual formations after Baud et al. (1984). The thickness of the Panjal Trap differs from that given by Baud et al. (1984) as a result of new observations.

differencies will be demonstrated further on in this chapter and in chapters 7 and 8. I do not agree with their nappe concept. Therefore I do not use their tectonic units e.g. Phuctal Nappe (Paleozoic formations) and Zangla Nappe (Permian up to Paleocene - Early Eocene, Baud et al., 1984 and Gaetani et al., 1985b). Further structural work needs to be done to clarify certain issues, especially in a wider regional context, and to allocate the individual formations to tectonic units.

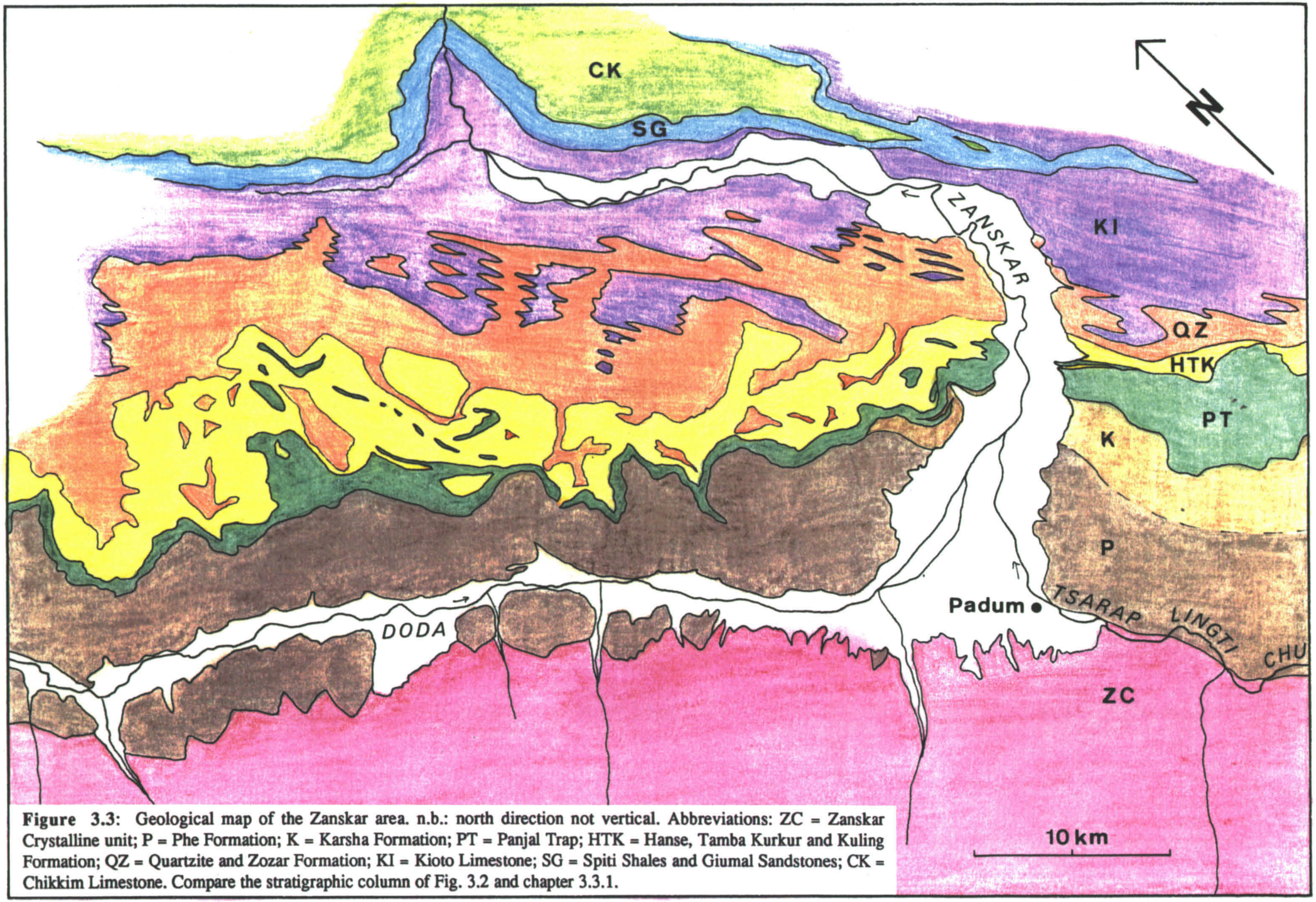


Figure 3.3: Geological map of the Zanskar area. n.b.: north direction not vertical. Abbreviations: ZC = Zanskar Crystalline unit; P = Phe Formation; K = Karsha Formation; PT = Panjal Trap; HTK = Hanse, Tamba Kurkur and Kuling Formation; QZ = Quartzite and Zozar Formation; KI = Kioto Limestone; SG = Spiti Shales and Giumal Sandstones; CK = Chikkim Limestone. Compare the stratigraphic column of Fig. 3.2 and chapter 3.3.1.

3.1 Late Precambrian - Cambrian sedimentary sequence

The Zanskar region represents a geological northwestern continuation of the Lahaul - Spiti basin with its well described complete Tethyan sedimentary sequence ranging in age from Late Precambrian to Mesozoic (Hayden, 1904). Towards the Zanskar region, the individual members of the Paleozoic successions gradually thin out from top to bottom (Nanda and Singh, 1976; Srikantia et al., 1978). In the studied Zanskar area only the two lowest formations of the Lahaul - Spiti region are present, namely the Phe and Karsha Formation and they are in a low metamorphic state (lower greenschist conditions). Going further to the northwest, the Karsha unit also thins out a few km northwest of Karsha (Figs. 3.1 and 3.3). The Phe Formation can be followed to the northwest as far as Rangdum (Fig. 1.8). Due to increasing regional metamorphism (chapter 5) and due to the effects of the Zanskar shear zone (chapter 2.3) the exact northwestern continuation of this unit is difficult to establish, probably this formation continues to thin towards the Suru region. The maximum thickness of these formations is at least 2500 m (Baud et al., 1984).

All along the Doda valley the upper northeast boundary is found near the top of the first mountain Range and is formed of the overlying Panjal Trap. Often an angular unconformity is present, the most prominent example lies north of Karsha (Fig. 1.4).

3.1.1 Lithology and Petrography

Phe Formation (Nanda and Singh, 1976; Baud et al., 1984)

The Phe Formation is made of a monotonous succession of grey-green shales and sandstones in beds of variable thickness. The sandstones (petrographic classification after Pettijohn, 1975) are mostly quartzwackes and feldspatic greywackes (described below together as greywackes) and subordinate quartzarenites (transformed by the metamorphism to quartzites); some of which are micaceous rich types. The Phe Formation is devoid of any fossils except trace fossils and remains undated. Since it normally underlies the fossiliferous Karsha Formation, a Late Precambrian or Early Cambrian age is assigned to the Phe Formation (Srikantia et al., 1978).

At the base of the Phe Formation, seen at outcrops on southwestern side of the Doda valley, a rhythmic alternation of shales and extremely fine-grained greywackes and micaceous quartzites is present with a thickness of the individual layers of approximately 1 - 5 cm. On the other (northeastern) side of the Doda valley, higher up in the stratigraphic column, the greywacke / quartzite layers become thicker, and most are on the order of 30 cm.

Towards the top of this unit (because of the discordance to the overlying Panjal Trap in the Ralakung region it is not yet resolved whether the uppermost topographically highest exposed units of the Phe Formation represent the stratigraphic top - probably not) the shale content becomes larger, and the mud / sand ratio is approximately 5 : 1. This feature is morphologically expressed by the lack of exposed outcrops, round hills are typical in this landscape. For this reason, it is not possible to obtain a continous data profile from the bottom of the Doda valley to the overlying Panjal Trap at the top of this unit. It is clear that, from base to top of the succession the greywacke content of the sandstones becomes greater, while pure quartzites become rarer. The shales of this formation are always very dark as a result of richness in pyrite, and it is possible to differentiate between quartz slate and slate (originally slightly metamorphosed laminated siltstone and mudstone).

On the base of this formation the clasts within the greywackes are mostly quartz, subordinate feldspar grains (plagioclase) and sporadic individual calcite grains. Higher up, the feldspar content decreases, the calcite content on the other hand increases. The grain size of the quartz clasts increases from about 0.2 mm up to 1 mm. The clay matrix content of the greywackes varies between 30 - 50% in the lower and between 30 - 70% in the upper part of the section with the general trend of increasing matrix content with the younging direction. The quartz-rich slates appear first in the middle part of the Phe Formation and increase in proportion upwards in content for all lithologies. The (micaceous) quartzites are only present from the base to the middle part of the Phe Formation. The upper part of the Phe Formation shows a great variation of rock types with all transitions between these types (in contrast to the base, where consistent alternations of quartzite and greywacke - shales (slates) are present).

The greywackes show graded bedding at some localities, but due to the very fine grain size and the very slight variation in grain size from bottom to top of each cycle, this feature is hard to recognise directly in outcrop and has, unfortunately, only clearly been identified in loose rock samples. In addition, there are other sediment structures characteristic of turbidites (e.g. load casts) but limited time did not allow these to be thoroughly investigated.

Within the Phe Formation the individual sandstone layers do not show great lateral constancy, and individual bed units are in general impossible to follow for more than about 50 m.

The base of the Phe Formation is intruded by layer parallel sills of Cambrian porphyritic granites and Miocene leucogranites (chapter 2.3). Crosscutting basic dykes (dolerites) or even small doleritic stocks are also locally present. The primary mineral assemblages within the dykes are totally transformed to chlorite - calcite - plagioclase assemblages as a result of regional metamorphism, but the primary ophitic texture can still be recognized. These dykes may be related either to the Panjal Trap or to the Cambrian intrusion sequence. The small doleritic stock at the entrance to the Sumche Tokpo (Fig. 1.8) shows good primary magmatic ophitic textures, and the primary minerals, such as clinopyroxene and plagioclase, are only partly transformed to actinolitic hornblende, chlorite, clinozoisite and plagioclase.

Karsha Formation (Nanda and Singh, 1976; Baud et al., 1984)

The Karsha Formation is characterized throughout by the presence of massive brown weathering dolomitic beds (0.5 m up to 10 m thick) interbedded with a terrigenous sequence.

The top of the exposed Karsha Formation shows dolomitic layers reduced in their thickness and a greater shale content than normal. Some limestone layers are also present. The age is Middle - Upper Cambrian according to lithological correlation with the Spiti area where Trilobites indicate an age from Middle to Upper Cambrian (Srikantia et al., 1978). The dolomites are of grey colour, of micritic nature, fine-grained (grain size less than 0.4 mm) and recrystallized. Associated with the dolomite are thick beds of dark shales, now transformed by deformation to quartz-slates and slates, and greywackes. Petrographically and sedimentologically the argillaceous and arenaceous sediments are similar to those of the underlying Phe Formation. The individual layers of this unit can be followed over greater distances than those of the Phe Formation (up to some km). The most abundant sediments are greywackes (petrographically quartzwackes and feldspatic greywackes, Pettijohn, 1975) with a general matrix content ranging from 15 to 80%. The matrix content within the feldspatic greywackes varieties is less, only 15 - 30%. Subordinate quartzites, subarkoses and sandy carbonates also occur.

3.1.2 Depositional Environment

Most previous workers have infered a deep-water flysch - trough environment for the Phe Formation, whereas the Karsha Formation indicates sedimentation under progressively shallower conditions (Nanda and Singh, 1976; Srikantia et al., 1978 and Fuchs, 1982). Nanda and Singh (1976) have suggested a depositional environment as follows: the black shales at the base of the Phe Formation were sedimented in a lagoonal restricted environment (these shales are only exposed southeast of the studied area in southeastern Zanskar). The following sandstone / shale alternations shows characteristic features of flysch sediments, namely rhythmic banding, graded bedding, current ripple laminations and abundant sole markings at the base of the sandstone layers.

These sediments were deposited within a deep marine trough of geosynclinal nature under unstable tectonic conditions and rapid subsidence. The overlaying Karsha Formation, with its interlaminated micritic dolomites and fine pelitic material containing trilobites, was formed under more shallow sedimentary conditions during a period of relatively slow subsidence and stable tectonic conditions. The lack of tidal waves and currents in the environment led to reducing conditions which caused black colour of the shales. The depositional environments of the Phe Formation and the Karsha Formation indicate a change from geosynclinal to stable marginal shelf conditions.

The recent work of Garzanti et al. (1986), however, differs in the interpretation of the depositional environment during Late Precambrian - Cambrian time. Garzanti et al. (1986) suggest the whole sequence was deposited in a shallow environment because indications of shallow water depth are very common in the Phe Formation. The widespread occurrence of rhythmic sand / mud ripple-bedded units showing markedly changing current directions is typical of subtidal to intertidal zones. The action of tidal currents is also indicated by bidirectional megaripple cross-bedding. This terrigenous sediments with high mud/sand ratio, common lenticulate bedding and occurrence of tidal channels and mudcracks suggest depositions on a tidal flat. The interbedded dolomites of the Karsha Formation mark stages of low terrigenous influx in a shallow subtidal environment. Toward the top of the Karsha Formation the water - depth increase to restricted outer shelf environments.

The two different opinions about the depositional environment are based on different observations on the nature of the sediment structures and lithologies of the main different rock types. My own regionally incomplete reconaissance sedimentological studies of these two formations do not allow to clarify the nature of the depositional environment. The abundant greywackes and few quartzites (predominantly at the base of the Phe Formation), the rhythmic alternation of sandstones and shales, the abundant graded bedding (especially within the very fine grained greywackes (distale greywackes) in the upper part of the Phe Formation), local load casts and the consistent dark colour of the shales suggest a transition from deeper water turbidite environment ("geosynclinal") at the beginning of sedimentation (Phe Formation) to shallow water conditions (stable marginal shelf) during Early Cambrian time (Karsha Formation) as described by Nanda and Singh (1976).

Probably lateral facial transitions might be the reason for the different interpretations of the deopositional environment of the Phe Formation. The investigated area of Garzanti et al. (1986) lies more than 30 km southeast of Padum than that described below.

3.1.3 Structures

The structures within the Phe and Karsha Formation are very complicated and difficult to interpret. The monotonous lithological succession, the absent of characteristic marker horizons, the small scale lateral inconstancy and variations of the lithological succession (chapter 3.1.1) and the difficult outcrop conditions (which would need a good topographic map in a small scale and was not enough for satelite images of a scale 1:100'000) made it difficult to evaluate the deformational history of this section of the Zanskar. The following part is a summary of the deformation evolution of the Phe and Karsha Formation as it seems reasonable to draw from the data available.

Main structural elements

Folds: Large scale open anticlines within the Phe Formation predominate all along the northeastern side of the Doda valley. Morphologically they form great terrasses (Fig. 3.4). The associated synclines, however, are very tight (Fig.3.5). The wavelength of these anticlines and synclines are approximatly up to 100 m, and the strike of their axial planes is NW-SE, parallel to the Doda valley. Due to the stratigraphic characteristics, it is not possible to follow individual layers over great distances (chapter 3.1.1), similarly it is not possible to follow the traces of the folds over great distances.

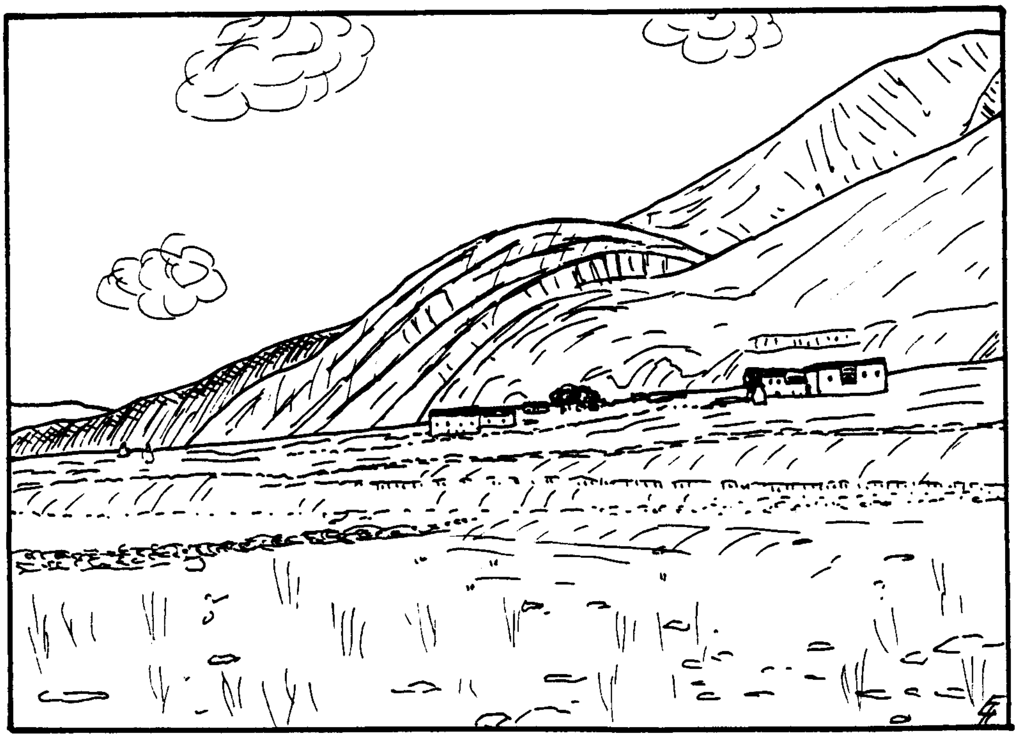


Figure 3.4: NW-SE trending large scale open anticline within the Phe Formation morphologically forming a large curved terrasse. Northern side of the Doda valley near Abran (Fig. 1.8), view northwards.The anticline has a wavelength of approximately 600m.

Smaller scale folds are mostly present within the middle part of the Phe Formation just northeast of the Doda valley (Fig. 3.6). The average wavelength of these folds are 5 - 30 m. The amplitude only 1 - 5 m. Therefore the wavelength is great compared with the amplitude and the folds are only open undulations of the bedding planes. The strike of their fold axial planes is N-S.

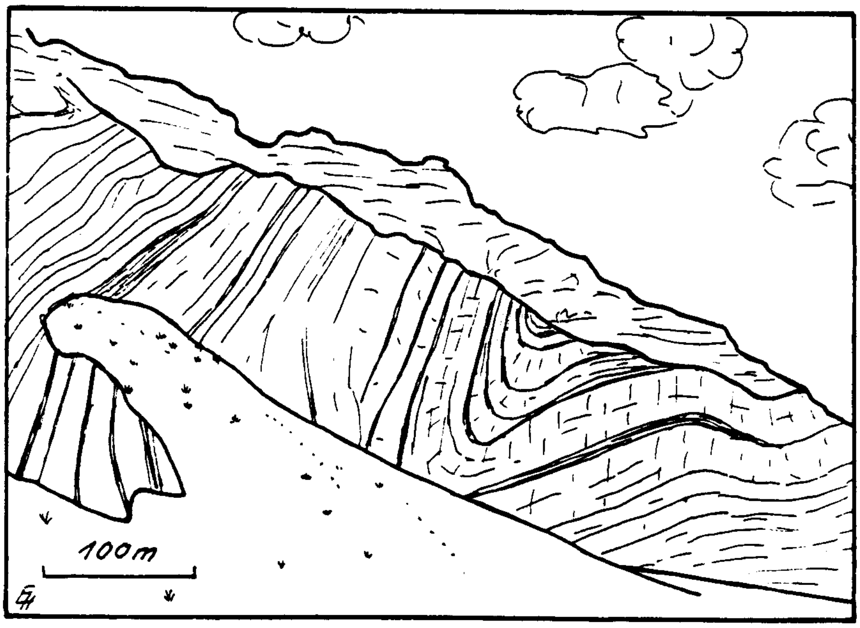


Figure 3.5: NW-SE trending tight syncline within the Phe Formation, northern side of the Doda valley near Phe (Fig. 3.1), view southeastwards.

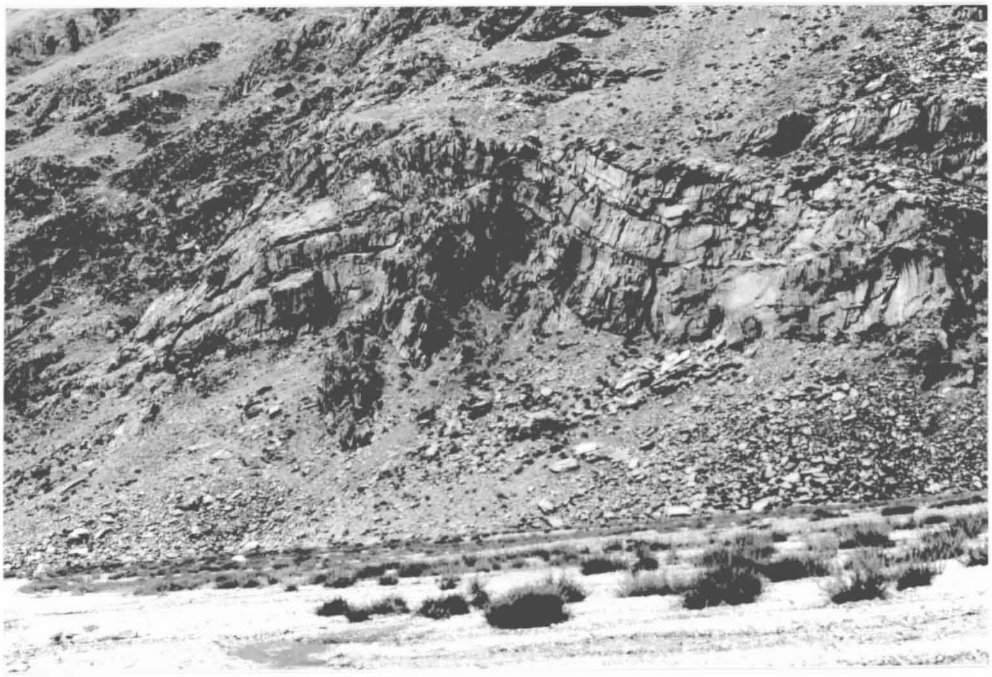


Figure 3.6: N-S trending open small scale fold within the Phe Formation with associated schistosity. Northern side of the Doda valley, wavelength approximately 20 m. View northwards (photograph by J. Ramsay).

Within the base of the Phe Formation the individual folds are not possible to group together in style and their axes and axial planes show different orientations.

From a distance, the folds are easily to identify but their open form makes an accurate determination of the fold axes impossible. Deformation fabrics, such as schistosity and lineation are only weakly developed. Only broad regional orientations of the fold axial planes could be measured, these mapped mostly from the trend observations taken over great distances (Fig. 6.1). There appears to be a tendency for the development of two main orientations and two main fold types. The timing relations between these two foldtypes are hard to estimate because no clear intersection relationships were observed.

Within the upper part of the Phe Formation few folds were observed and these were without a clear systematic orientation (Fig. 3.7). The paucity of folds is due to the bad outcrop conditions.

The Karsha Formation does not show folds and the layers are only curved (e.g. dolomitic layers).

The measurements of schistosity and bedding planes from Tungri to Karsha (Fig. 3.1) indicate several folds because their relationships (which plane has a steeper dip) changes systematically indicating different fold limbs (Ramsay and Huber, 1987, p. 467). Macroscopical folds are not visible.

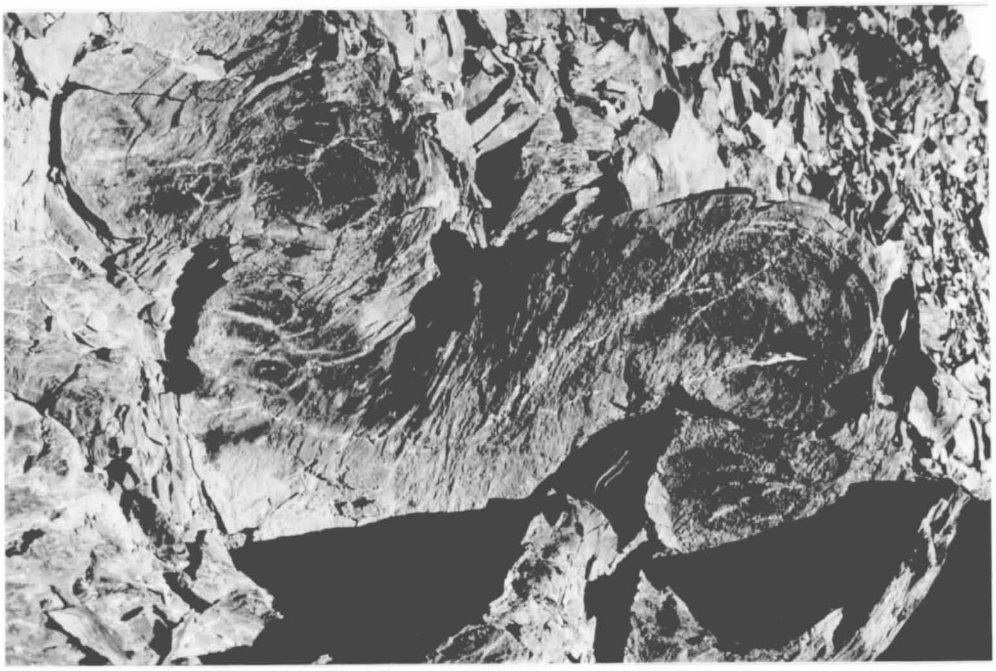


Figure 3.7: Small scale fold within the upper Phe Formation near Phe (Fig. 3.1). Note the layer parallel stretching on the outer side of a fold hinge and the shortening on the inner side inducing a schistosity. The width of the picture corresponds to approximately 2 m (photograph by K. Honegger).

Bedding: Clear traces of bedding planes are generally only visible in the sandstone (greywackes, quartzites) and dolomitic layers, and only weakly developed within shales. The shales are mostly too overprinted by tectonic cleavage to show their primary bedding plane. It is not generally possible to follow individual layers over large distances, except in the case of dolomites. The scattering for their orientation (Fig. 3.8) is great, especially within the Karsha Formation (Fig. 3.8b). Only near the Karsha Gonpa (Fig. 3.1), where the individual layers are slightly turned around (compare Discussion-Conclusion), the average orientation of bedding has a strike of 10^{o} - 80^{o} E and dips 65^{o} - 90^{o} NW (Fig. 3.8c).

Schistosity: Schistosity, related to both principle fold directions, is developed. In some localities, especially within greywackes, measurements of the schistosity related to the folds is impossible, e.g. the tight syncline near Phe (Fig. 3.5) does not show a clear schistosity. The schistosity is best developed in the micaceous lithologies (shales, greywackes and micaceous quartzites) by the preferred dimensional orientation of layer silicates forming a slaty cleavage.

Within the greywackes the schistosity is, in addition to mica plate orientations, defined by the planar orientated elongated quartz grains and visible in thin sections. The strike of the schistosity is in general within the Phe Formation E-W to NNE-SSW with an average strike of NW-SE. The dip varies between 20^{o} - 85^{o} NE with an average dip between 40^{o} - 60^{o} NE (Fig. 3.8a). On Figure 3.8a it is not differentiated between measurements relating to the N-S folds and those related to the NW-SE trending folds. The schistosity orientations within the Karsha Formation show a greater scattering than those of the Phe Formation (Figs. 3.8b and 3.8c).

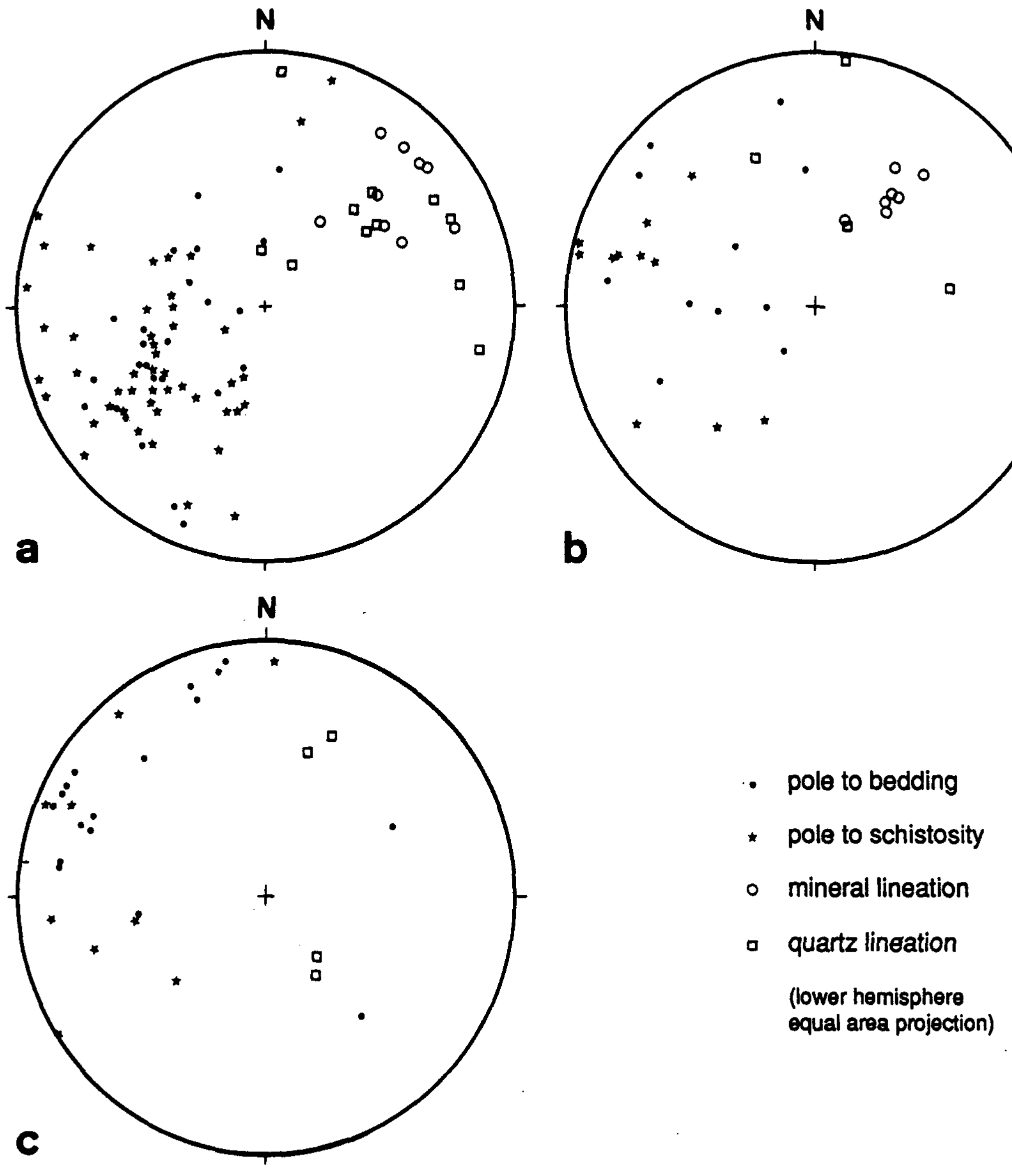


Figure 3.8: Equal area projection of the bedding planes, schistosity, mineral lineation and quartz lineation within a) the Phe Formation, b) the Karsha Formation and c) within the Karsha Formation around the Karsha Gonpa.

Lineations: Three types of different lineations may be distinguished namely (1) a mineral lineation, defined by preferred orientations of inequant minerals such as micas. This lineation is mostly found within shales but also within micaceous rich sandstones. It has an azimuth varying from 20° to 70° NE (mean 35°). The plunge changes from 17° to 80° NE (mean around 40°). (2) Due to the deformation the quartz grains within the greywackes are "flattened" and elongated forming a planar schistosity and a linear element within the schistosity. This elongated quartz grains lineation shows a greater scattering than does the mineral lineation. (3) The intersection lineation, defined by the bedding plane and schistosity plane, indicates the orientation of the fold axes (Fig. 3.9). The scattering is very great. The trend is an azimuth ESE and with plunge changes from 10° to 60° (mean plunge 30° - 50°, Fig. 3.9).

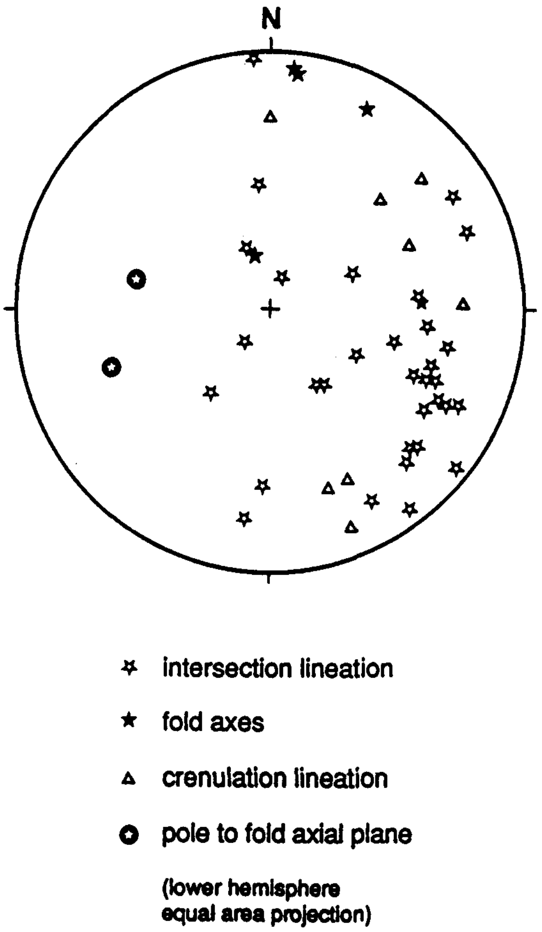


Figure 3.9: Equal area projection of the intersection lineations, fold axes and fold axial planes within the Phe and Karsha Formations.

Crenulation cleavage - kink bands: Within the shales a fine scale crenulation cleavage is developed. The hinge zones of crenulation cleavage microfolds form a clear linear element but the cleavage plane is sometimes difficult to measure with accuracy. The crenulation cleavage is defined by orientation of layer silicates (micas) and it shows either symmetric or asymmetric forms.

At some localities kink bands (sometimes conjugate) (Fig. 3.10) are present. It is not certain if these correspond to crenulation cleavage seen elsewhere or if the kink bands are separate and later phase of deformation.

On some places several crenulation cleavages are developed (up to three), apparently formed during different deformational events. To resolve the deformational history on one outcrop is not always possible. The summary of the measurements, presented in Figure 3.11, shows the average orientations for the several different crenulation cleavages (Fig. 3.8), namely (1): the same orientation as the schistosity and (2): a new orientation namely a strike of in general 120° - 175° SE with a dip no longer towards NE namely 20° - 50° SW.

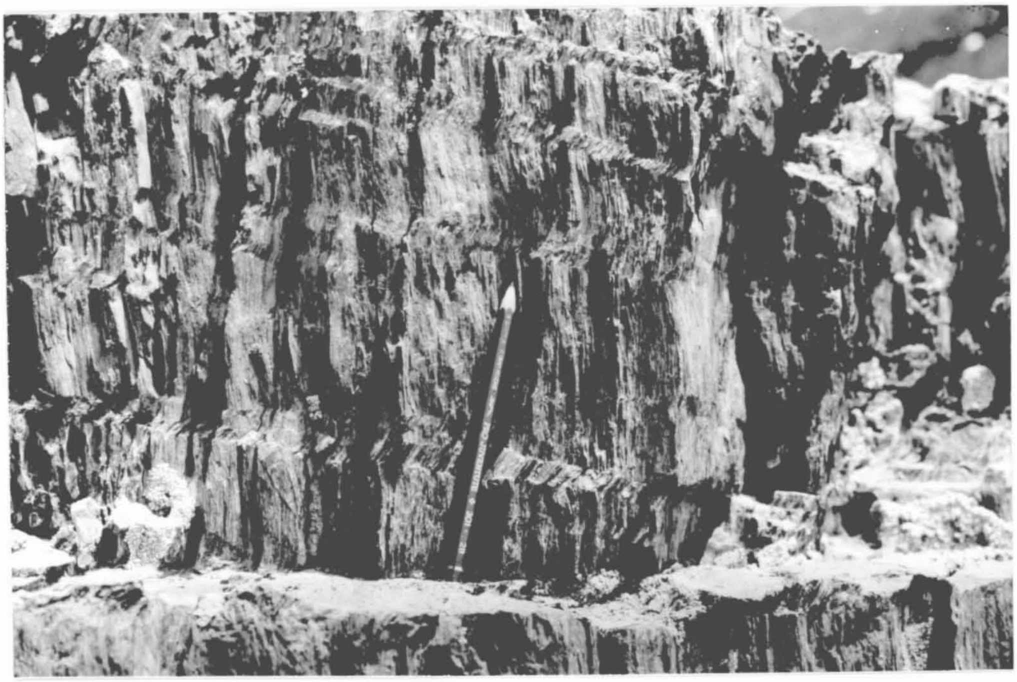


Figure 3.10: Kink bands within a shale of the Phe Formation (photograph by J.Ramsay).

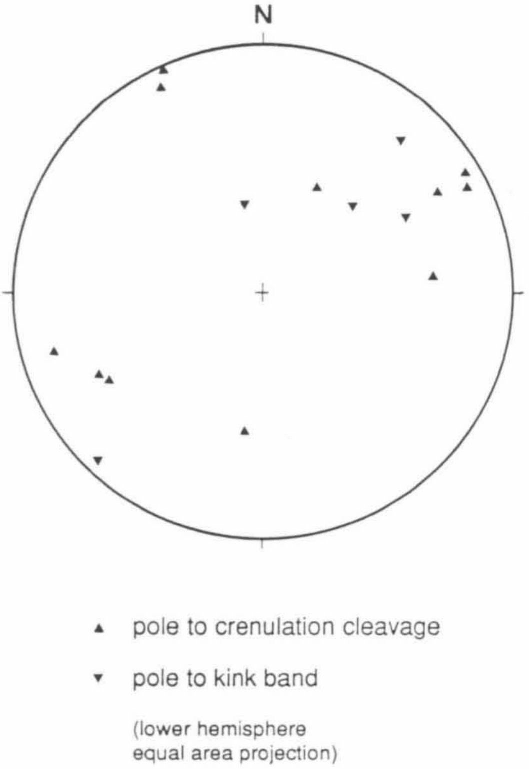


Figure 3.11: Equal area projection of the crenulation cleavage and kink band within the Phe and Karsha Formations.

Microstructures: The different lithologies show different deformational behaviour. The recrystallized quartzites show a partly preferred orientation and elongation of the quartz grains. The shales (always crenulated) have concentrations of "insoluble" components (e.g. phyllosilicates) in the fold limbs of the crenulation folds due to pressure solution processes. An evaluation of the amount of internal deformation within the quartzites and shales is very difficult and needs more specific work. The dolomites of the Karsha Formation are recrystallized and do not show an internal deformation. The greywackes, however, show a strong internal deformation, namely by the orientation of the quartz grains within the ductile matrix and by the elongation of these grains (Fig. 3.12). Because the matrix content is high (up to 60%, chapter 3.1.1), the individual grains do not touch each other and reorientation results from the overall deformational field. The linear orientations of the individual elongated quartz grains show a great scattering (Fig. 3.8) due to the rotational behaviour of the grains to overprinting deformational processes and only qualitative estimations of the internal deformation within greywackes are possible. For quantitative interpretations of the extent of deformation of the different phases a study of samples around different generation folds which clear relationship is required.

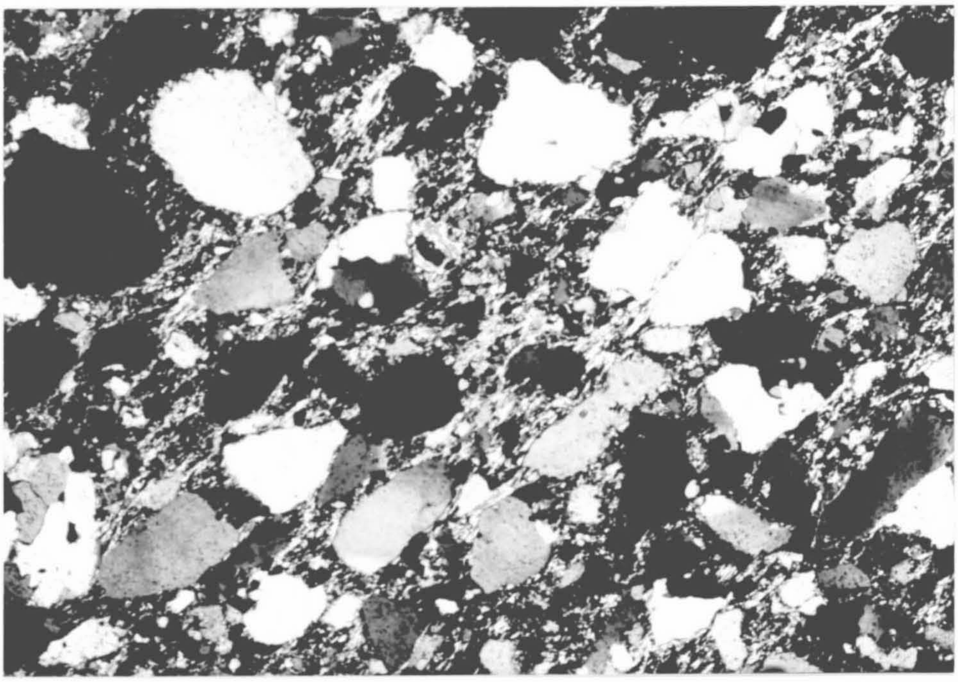


Figure 3.12: Thin section of a greywacke of the Phe Formation showing the elongated and oriented quartz grains. Crossed nicols. The width of the picture is 3 mm.

Discussion - Conclusion

From their orientations of the fold axial planes the small scale folds with axial planes trending N-S are interpreted to be pre-Himalayan folds. This orientation has nothing in common with structures clearly identified to be Himalayan ones, e.g. all the folds within the Mesozoic sediments show a NW-SE orientation (chapter 3.3.2). Therefore, the large scale folds of second generation trending parallel the Doda valley are interpreted to be Himalayan folds. The tight syncline investigated near Phe (Fig. 3.5) has quartz grain lineations within the greywackes indicating Himalayan structures.

The other structural elements are often hard to interpret as belonging either to the pre-Himalayan or to the Himalayan deformational events. The mineral lineation within the shales shows a "Himalayan" orientation especially within the Karsha Formation and within the Phe Formation (but with a greater scattering, Fig. 3.8). The elongated quartz grain lineation shows a great scattering (Fig. 3.8). Because at least two deformational events effected this region their orientation of the lineation as seen today probably illustrates only the finite grain state resulting from a complex deformation path. However, some suggestions can be made to interpret the observations. The greywackes layers were first layer parallel thickened, inducing a reorientation of the quartz grains within the matrix and a flattening of the individual grains. This phase is interpreted as pre-Himalayan, probably during the Cambrian tectonic and intrusive activity. During the Himalayan event these already deformed greywackes were effected again by deformation, but with other directions of the principal strain axes (NE-SW compression). The quartz grains within the competent greywackes shows an intermediate orientation due to the earlier deformation and especially to the extent of the overprinting Himalayan deformation. Their orientations today indicate that they are not totally overprinted and that they now have a mixed orientation between that of the old (Cambrian) and new (Himalayan) deformational events.

Garzanti et al. (1986), Srikantia et al. (1978) and Fuchs (1982) have shown that the relationships of the sediments indicate a Cambro-Ordovician orogenic event in the northwestern Himalaya. In Middle Cambrian times the carbonate platform (depositional environment for the Karsha Formation) underwent gradual drowning and outer shelf / slope shales, with intercalations of tuffaceous material erupted from a nearby immature volcanic arc, were deposited. The shales are overlain by basinal turbidites attesting to the growth of a sandstone lobe. In the Middle Ordovician, unconformable alluvial fan conglomerates and braidplain sandstones derived from uplifted sedimentary sequences indicate erosion of a newly formed orogenic belt. Srikantia et al. (1978) describe within the Thango Formation (next following formation in younging directions after the Karsha Formation) "cannibalistic conglomerates" (i.e. clasts derived from the formation itself) and interpret orogenic conditions during the sedimentation. They term this the Kurgiakh Orogeny. The investigations of Srikantia et al. (1978) were undertaken in an area from Lahaul to west Zanskar. In the Spiti region Cambrian rocks were cut by an angular erosion surface and overlain uniformably by the Ordovician conglomerates (Fuchs, 1982). The N-S (NE-SW) trending folds they investigated were only found within the Phe and Karsha Formation and, therefore, they related this folding phase to the Kurgiakh Orogeny. During the Kurgiakh Orogeny there was geosynclinal sedimentation of the Thango Formation and the magmatic phase of the porphyritic granites (500 Ma, chapter 2.1). Thus, during this episode there was an important correlation of sedimentation, orogeny and granitic intrusion. Later in time there is no evidence for a further orogenic event until the Himalayan one (Srikantia et al., 1978; Baud et al., 1984, and Garzanti et al., 1986).

The schistosity also shows a "mixture" between pre-Himalayan and Himalayan orientations (Fig. 3.8). The Himalayan schistosity relating to the folds are in some places developed as penetrative schistosity, in other places (generally within shales) as a crenulation cleavage (Fig. 3.11). The crenulation cleavage is a later structure whose development is dependant on rock lithology.

On some places the pre-Himalayan schistosity might also be a crenulation cleavage (due to the preexisting tectonic lamination of these shales). In such instances the Himalayan deformation has given rise to a second or even third overprinting crenulation cleavage.

The orientation of the southwest dipping crenulation cleavage (Fig. 3.11) is related to the backfolding event. This overprinting, the last deformational event, however, is not uniformly developed and only present within some layersilicate rich rock types (schists). The kink folds also generally seem to be best attributed to this last deformational event.

The orientation of the intersection lineation is also variable. In places it is not clear whether the intersection lineation between bedding and schistosity formed around Himalayan or pre-Himalayan folds (Figure 3.9). The mineral lineation near the Karsha Gonpa (Fig. 3.8c), however, shows a Himalayan orientation.

Deformation within the Phe and Karsha Formations was mostly taken up by internal deformation of the greywackes. Only a small part led to folding of individual layers. A clear separation of the individual deformation phases is often not possible because layers are laterally discontinuous and marker horizons are absent. Himalayan structures are distinguishable because their orientations agree with structures within the Mesozoic unit affected only by the Himalayan deformation phase. Since the evidence for the deformations is only qualitative, it is not possible to reconstruct the previous lithological orientations of the Phe and Karsha Formations.

Baud et al. (1984) describe a large fold, the Karsha syncline (Fig. 1.4), within the Karsha Formation just northwest of Karsha (Fig. 3.1). Although it appears to be an overturned fold from a distance, on closer examination the dolomitic layers are not overturned but are only boudinaged (Fig. 3.13) and bent into an orientation striking NE and plunging 80^{O} SE (Fig. 3.8c). Within the apparent fold hinge just over the Karsha Gonpa, no folded layers were recognized. Graded bedding and the lack of fold symmetry within the "inverted limb" of this so-called syncline indicate that it is normal. In addition, the dolomitic layers within the "inverted limb" are thinner, less abundant, and of a different lithological succession than those in the "normal limb". It is unlikely that this difference was due to tectonic thinning because the dolomites were very rigid, deforming by boudinage and lacking any internal deformation. Bedding is always steeper than the schistosity and, therefore, the schistosity is not related to the syncline. Instead, the schistosity appears to be related to the largest Himalayan folds. This evidence indicates that it is not a Himalayan fold, while study of the geometric relationships of small scale folds related to pre-Himalayan events to the overall layering suggests that it is not a fold at all.

Near the upper part of the Karsha Formation the dolomitic layers has been reorientated subparallel to the overlying Panjal Trap by local sliding of the Panjal Trap over the Karsha Formation (Fig. 3.14 and chapter 3.2.2).

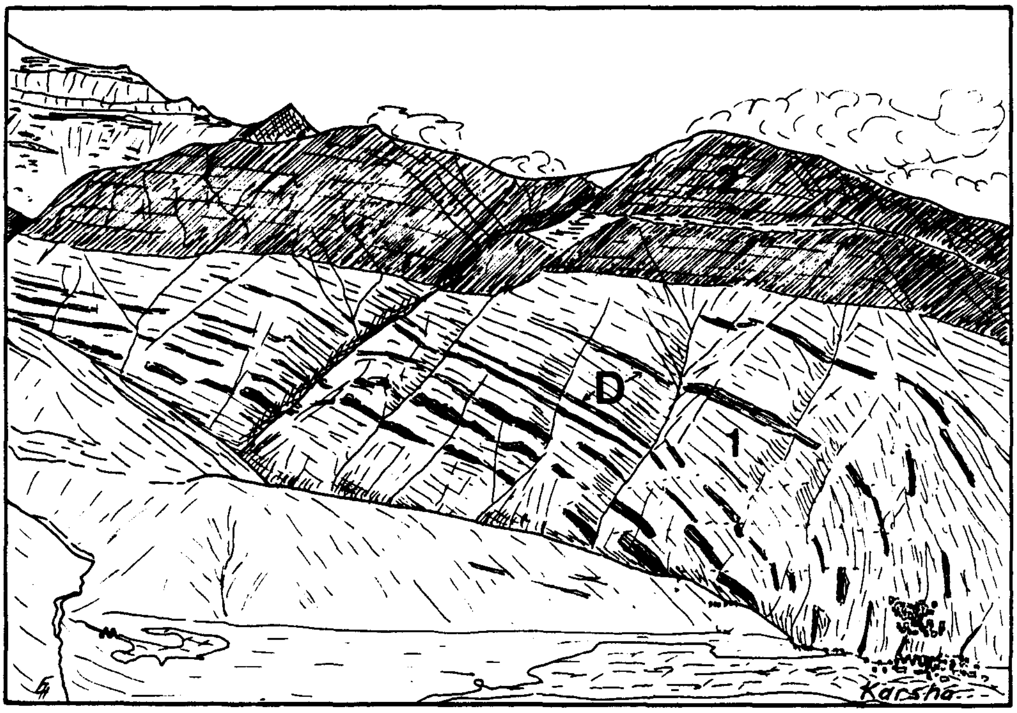


Figure 3.13: Karsha Formation (1) overlain by the Panjal Trap (2) at Karsha. Note the bondinaged and curved dolomitic layers (D) at Karsha. View northnortheastwards. The width of the picture corresponds to 1.5 km.

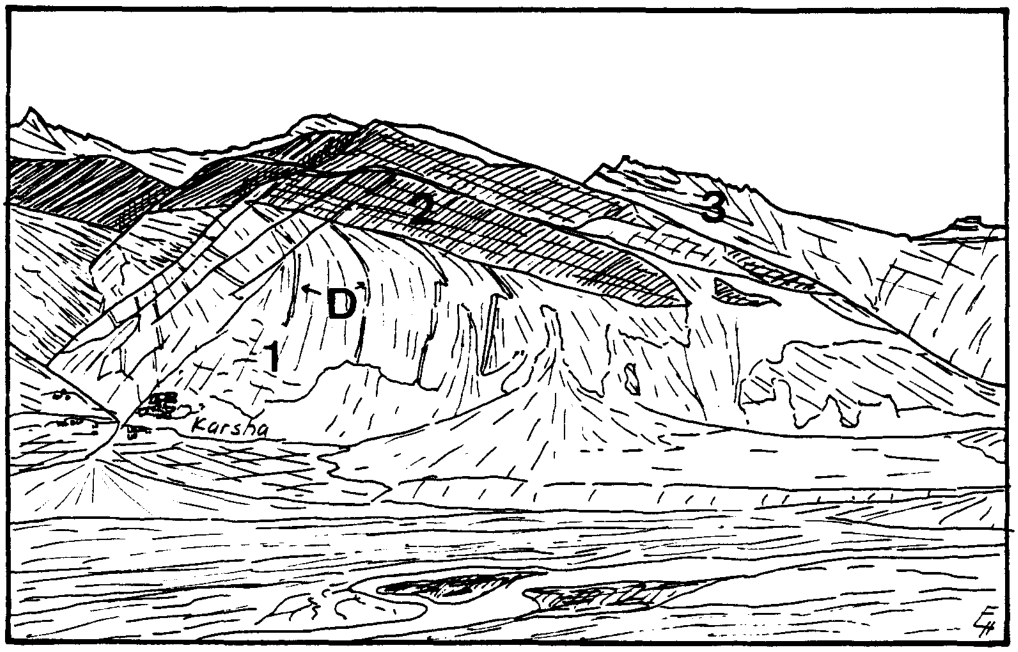


Figure 3.14: Karsha Formation (1) at Karsha (village and Gonpa) with overlying Panjal Trap (2) and Mesozoic unit (3). Note the slightly curved dolomitic layers (D) within the Karsha Formation. The width of the figure corresponds to 3 km. View northwards.

3.2 Panjal Trap - Permian basalt

The NW-Himalaya is characterized by a thick volcanic and volcanoclastic sequence of upper Carboniferous and Permian age (Pareek, 1976). The volcanic activity started with the acid to intermediate deposition of pyroclastics and Tuff forming the Agglomeratic Slates. Later the thick plateau basalts, called Panjal Trap, erupted under subaerial, marginal marine to terrigineons conditions (Bhat and Zainuddin, 1978). In the Kashmir basin these volcanites reach a maximum thickness of 2100 to 2400 m. To the west, the Panjal Trap reaches over the Hazara Syntaxis in Pakistan. Towards the east the Panjal Traps wedge out in the Lingti valley in Lahaul (Fig. 1.5; Nanda et al., 1976; Baud et al., 1984). Most of the volcanic rocks are basalts, sometimes 33 flows follow one another (Bhat and Zainuddin, 1979). Rhyolite and Trachyte are seldom present. In the Zanskar region the Agglomeratic Slates are not developed.

All along the Doda and Tsarap Lingti Chu valley (Figs. 1.8, 3.1 and 3.3) the dark green-black basalts of the Panjal Trap form the morphological prominent ridge on top of the Phe and Karsha Formation and trend parallel the general strike. This dark prominent band in thickness up to 800 m is readily visible on Landsat images.

The Panjal Trap Formation in Zanskar is composed of several basaltic flows interlayered with sediments yielding fossils of Permian affinity (Nanda et al., 1976) and of sediments of the overlying sedimentary Formation (Kuling Formation). These sedimentary interlayers are partly primary, and in part due to tectonic repetition. Where the Panjal Trap is tectonically repeated (Karsha and Ralakung region), there are several kilometre thick units of Mesozoic sediments between two Panjal Trap plates (Ralakung region).

The metamorphic overprinting is low (lower greenschist conditions, chapter 5) compared with the Suru region where the Panjal Trap flows are partially transformed to amphibolites (Honegger, 1983).

3.2.1 Lithology and Petrography

Figure 3.15 illustrates a typical profile through the Panjal Trap in the Ralakung area (Fig. 3.1). The base of the Panjal Trap unit here and all over the Zanskar region is a chlorite shale with different thickness from 30 cm up to 1 m. Calcite is very abundant, sometimes clasts of quartz grains are present. This shale is probably a tuff layer transformed to a chlorite slate during the regional metamorphism. At the base of the tectonically emplaced thrustslices of Panjal Trap, this chlorite shale is not present.

Basaltic flows follow with thickness up to 30 m. The Panjal Trap comprises up to 10 major flows and several minor flows. At the base, the flows are very massive and compact. Toward the top of an individual flow they get more and more amygdaloidal rich, a feature which makes it possible to separate one flow from the other. Towards the top of this unit, the thickness of the individual basaltic flows decrease and the massive and compact varieties of basalts become less common, whereas the vesicle-rich varieties increase. In some places, mostly found on loose boulders, the flow surface shows ropy and braded structures (Fig. 3.16), a partial "Pahoehoe" surface is developed. Basaltic columns described by Bhat and Zainuddin (1978) from the Kashmir region are not present. No pillow lavas have been found in the Zanskar area, whereas in the Kashmir region they are present (Nakazawa and Kapoor, 1973; Honegger, 1983).

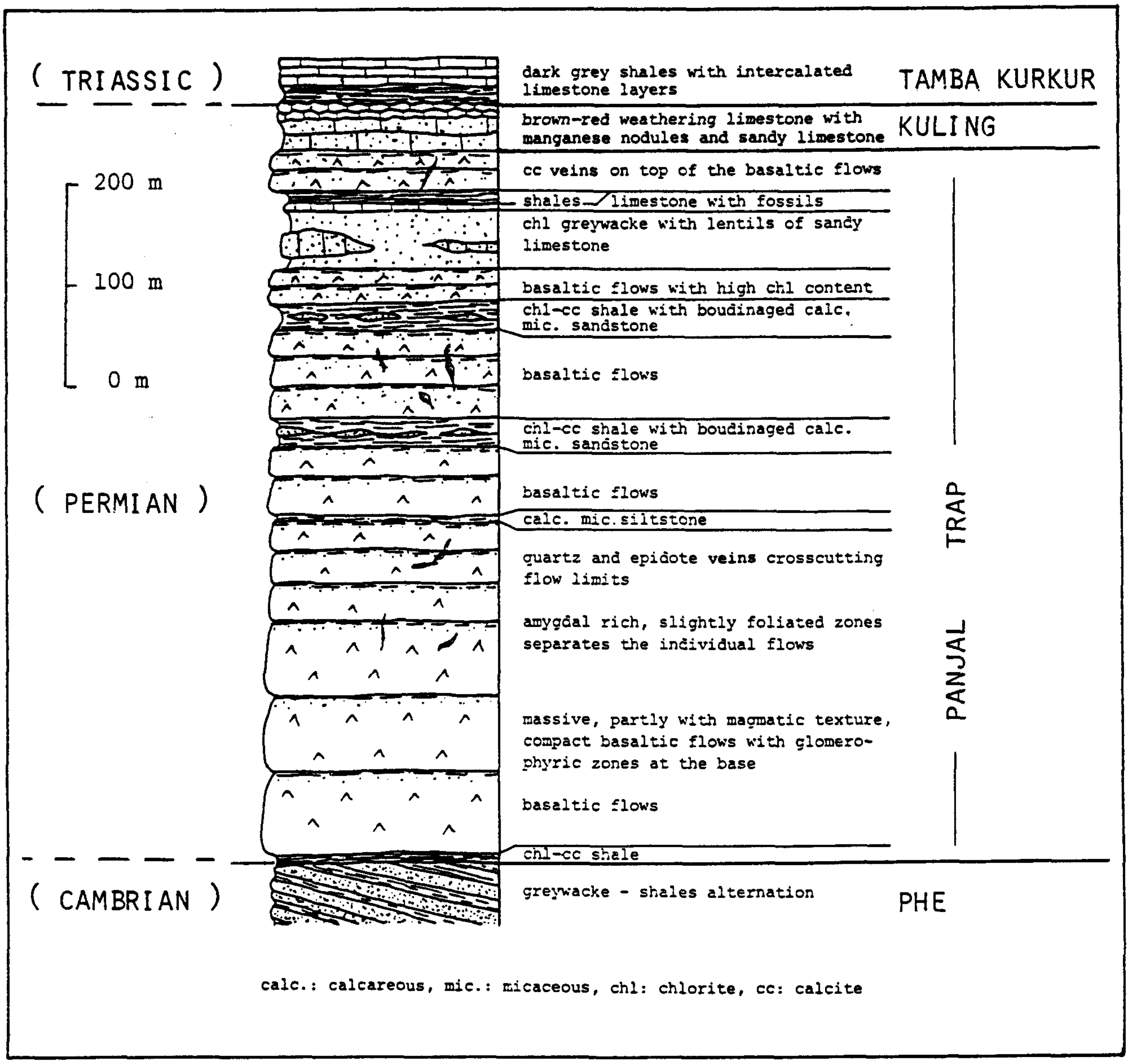


Figure 3.15: Schematical profile through the Panjal Trap volcanics in the Ralakung area. Scale only approximate.

Between superposed flows there are local sediment layers and volcanoclastic layers similar to those found at the base of this unit. These interlayered sediments are micaceous sandstones (partly calcareous rich, petrographically quartzites or greywackes (with matrix content up to 60 %)) and limestones with brachiopod fauna indicating a Permian affinity (Nanda et al., 1976). Although in the Ralakung area, there are several intertrap beds (Fig. 3.15), in the Karsha area only one 20 m thick zone of sandstone and shales is present between the thick succession of Panjal Trap. The presence of sedimentary beds inbetween the flows, as seen in the Ralakung and Karsha area, indicates some interruption in the volcanic activity and the development of local aqueous conditions. In the Tongde area (Fig. 1.8), layers of limestones with a fauna similar to those of the overlying Kuling Formation are present (own observations and Baud et al., 1984). It is not yet resolved whether these sediments indicate a tectonic doubling of the Panjal Trap or whether they represent only an interruption in the volcanic activity. In contrast to the views expressed by Baud et al. (1984) that these features are due to tectonic activity, I tend more towards an explanation for this situation based on a normal unduplicated succession. For example, no clear-cuts cross-cutting fault surfaces have been observed which would indicate tectonic repetition of lava and sediment horizons. However, in a few localities tectonic duplication of the Panjal Trap is certainly present. For instance in the valley between Karsha and Rinam (Figs. 3.1 and 3.3) a slice of Panjal Trap lies completely within Mesozoic sediments (Fig. 3.23). More details of the tectonic phenomena of the Panjal Trap will be described in the following chapter.

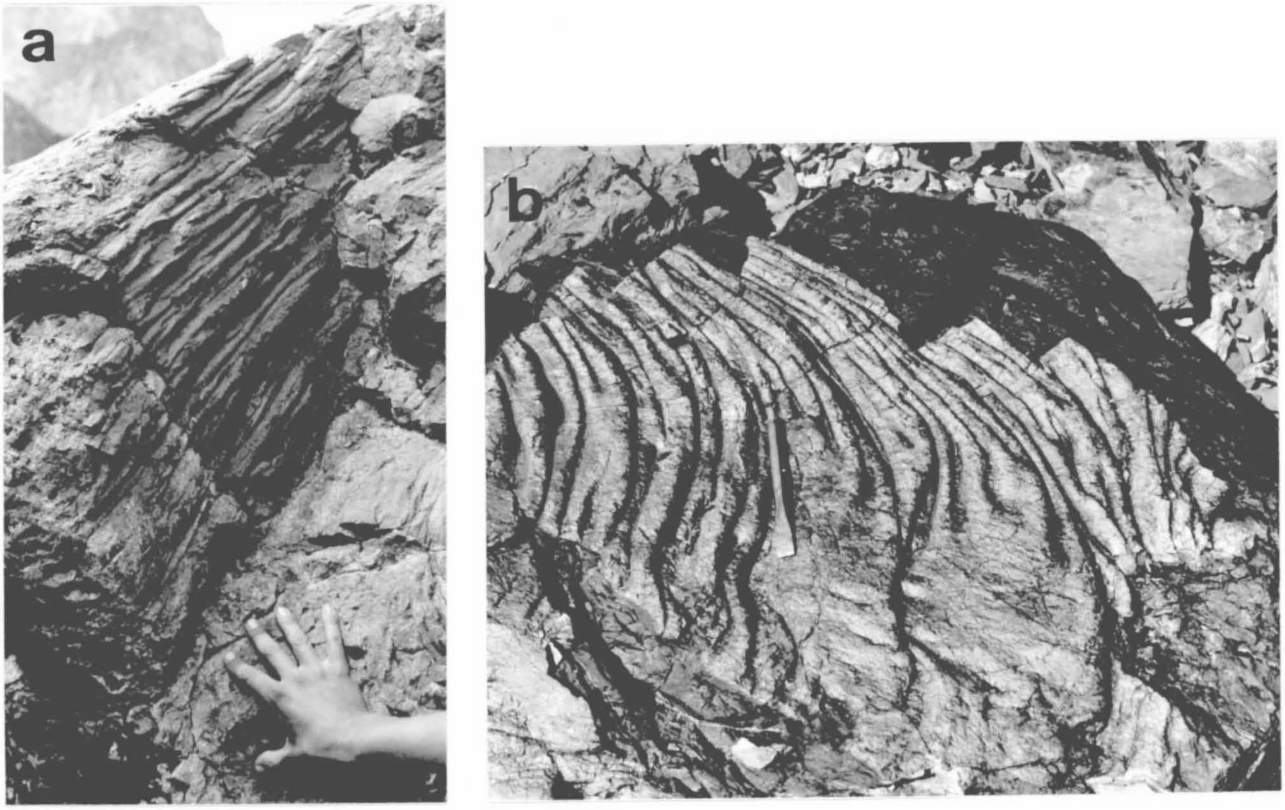


Figure 3.16: Surface of a basaltic flow showing a) braded and b) ropy structures.

Petrographically the basalts are massive, fine-grained and aphyritic with amygdaloidal rich surfaces. Partial glomerophyric zones (consisting of plagioclase), especially within the flows at the base of this unit are present. Some primary magmatic mineral relicts of clinopyroxene and plagioclase are still recognizable. The recystallized matrix consists of the new mineral assemblage of epidot / clinozoisite - quartz - chlorite - albite - green biotite -

leucoxene / sphene / ilmenite - hematite. The spherical or mostly ellipsoidal vesicles are filled, concentricly, by several minerals such as epidote / clinozoisite, chlorite, albite, quartz and calcite within the more massive varieties and by only chlorite within the more amygdal rich varieties.

Geochemically the Panjal Traps are mainly silica-saturated (quartz-normative) or nepheline-normative basalts belonging to the tholeitic and alkaline series (Honegger et al., 1982).

The Panjal Traps generally show extensive growth of secondary minerals and widespread overprinting by regional metamorphism of medium - low greenschist facies, but these features decrease in occurence from the Pensi-la in the northwest to east Zanskar (chapter 5).

3.2.2 Structures

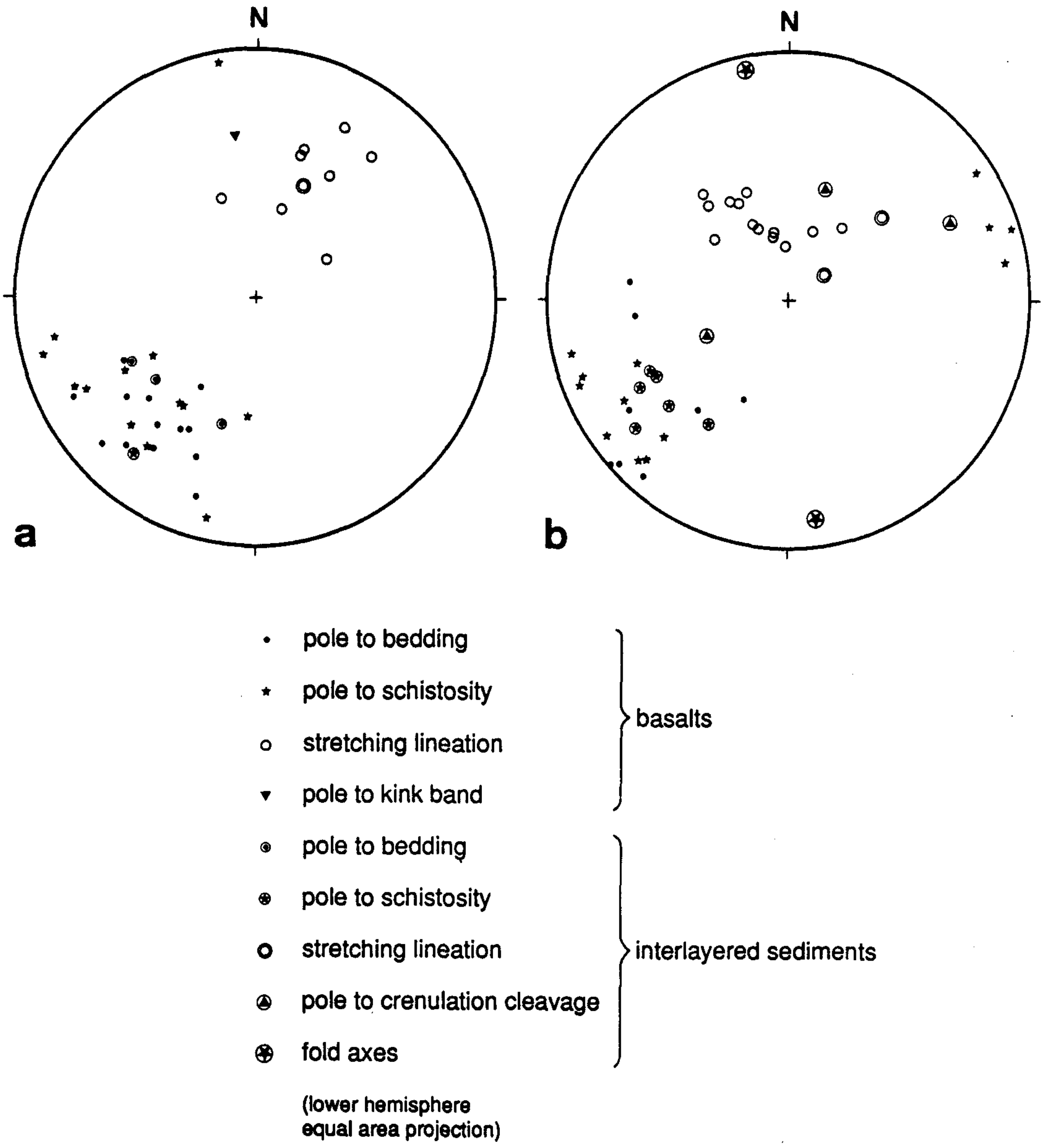


Figure 3.17: Equal area projection of the structural data of the Panjal Trap unit, basalts and interlayered sediments. a) general situation, b) Tongde area (Fig. 3.1).

Within the Panjal Trap, primary sedimentary layers within basaltic flows are strongly interleaved with tectonically repeated basaltic flows and it is difficult to distinguish and to separate the structures that are tectonic from the original depositional features.

Main structural elements within the Panjal Trap unit

Bedding: The bedding planes within the basaltic flows are defined by ropy and braided flow surfaces between flows and by by a change from amygdaloidal rich basalts at the tops of individual flows to compact, massive basalts at the base. A few limestone layers are the only evidence of bedding in the intercalated sedimentary layers (Fig. 3.15).

Schistosity: A schistosity, defined by the preferred shape orientations of layer silicates such as chlorite, has developed in the amygdaloidal rich portions near the tops of individual flows. The orientation of this schistosity strikes 120° - 160° SE and dips 50° to 80° NE (Fig. 3.17). The lower parts of individual flows do not show any structure.

Stretching lineation: Within the amygdaloidal-rich parts of the basaltic flows, especially within the upper flows of this unit, the vesicles of diameters between 2 and 6 mm (Fig. 3.18) are elongated, filled with chlorite and define a stretching lineation (Fig. 3.17) parallel to the Himalayan structures. The sandstone layers between flows contain elongated quartz grains within a ductily deformed matrix that define a stretching lineation of the same orientation as the vesicles (Fig. 3.17). Near Tongde (Fig. 3.1) the orientations of the vesicles are mostly 310° - 350° NW with a plunge of 40° - 70° NW suggesting a lateral movement and deformation component.

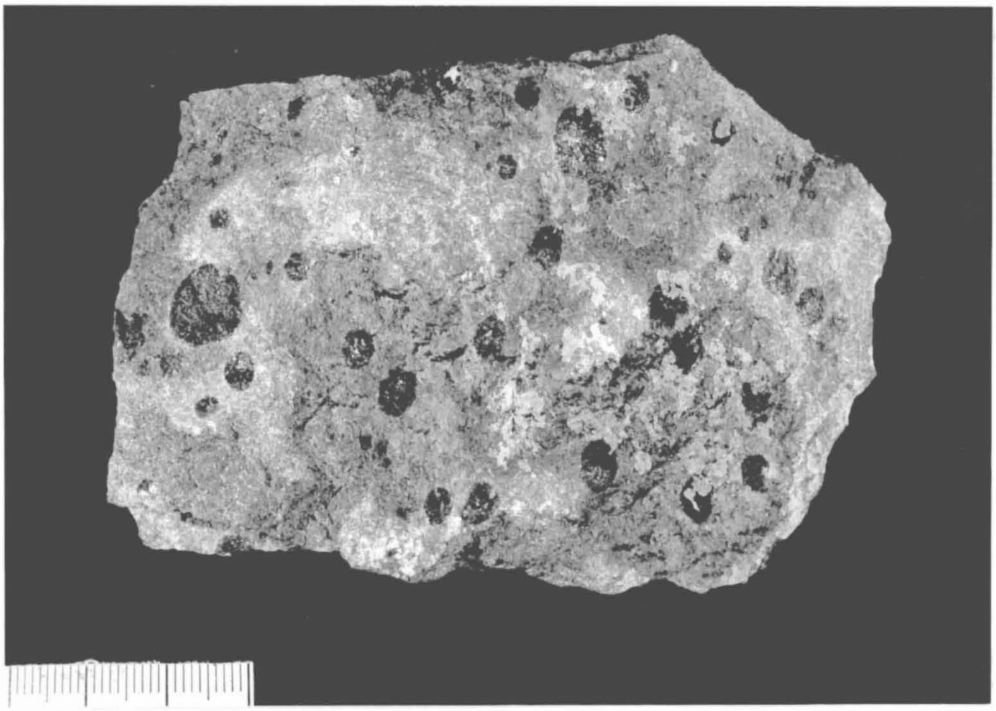


Figure 3.18: Basaltic rock of the Panjal Trap unit with elliptical, chlorite filled vesicles. The scale bar in the lower left has 10 mm major devision.

Micro and small-scale structures: The elongated quartz grains within the greywackes intercalated in the basaltic flows are similar to those of the Phe and Karsha Formation. The deformation amount seems to be greater because the axial ratio of the elliptical shaped quartz grains as well as of the matrix are greater (Fig. 3.19). The vesicles within the amydaloidal-rich basalts show different ellipsoidal forms depending on the content of layer silicates. The rocks with chlorite-filled vesicles are more deformed than those filled with calcite and epidote. E.g. chlorite-rich basalts with chlorite-filled vesicles show axial ratios between 1.8 : 1 and 2.5 : 1 (20 vesicles from three outcrops). In one outcrop it was possible to measure a shear angle of 57° from pipe-like vesicles that were originally perpendicular to the flow surfaces (this fact was often seen on loose boulders). The glomerophyric basalts at the base of the basaltic flows are not internally deformed.

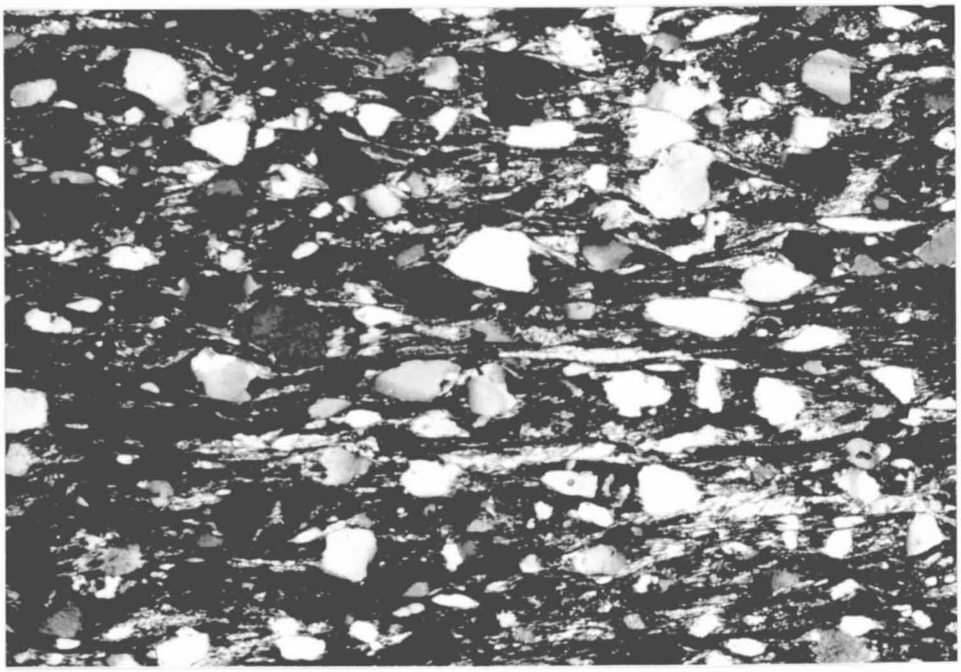


Figure 3.19: Thin section of an interlayerd greywacke showing the ellongated quartz grains. The width of the picture correspond to 3 mm, crossed nicols.

Veins crosscutting basaltic rocks are filled with chlorite suggesting that the associated deformation was simultanous with the regional metamorphism. Other veins are of primary origin and filled with recrystallized epidote.

Megastructures: Because of the rigidity of the basaltic rocks, the Panjal Trap is not folded but thrusted into slices. Near Karsha, a hanging-wall ramp is present (Fig. 3.20) and the Panjal Trap is doubled. In the Ralakung region (Fig. 3.1) the Kuling, Tamba Kurkur, Hanse and Lilang Formation was thrusted together with the Panjal Trap (Fig. 3.21). Between Phe and Ralakung (Fig. 3.1), the Permian Kuling Formation (Fig. 3.15) lies directly over the Phe Formation (Figs. 3.22 and 3.23). Small thrust slices of Panjal Trap occur within the

Tamba Kurkur Formation at the end of the valley northeast of Karsha (Figs. 3.3 and 3.24).

The widespread Panjal Trap outcrop northwest of Ralakung (Fig. 3.21) is a flow surface, sligtly folded with a wavelength of several kilometers and an amplitude of about 50 meters. This outcrop is a good illustration of the dependence of the initial wavelength on competency and thickness of a layer (Ramsay, 1967).

Figure 3.20: Hanging wall ramp of a basaltic thrust sheet of the Panjal Trap. 5 km east of Karsha. The width of the figure corresponds to 2 km.

The lower contact of the Panjal Trap: The angular unconformity between the Phe and Karsha Formation (Figs. 3.13 and 3.14) near Karsha appears obvious from distance but on closer view it is not so clear (Fig. 3.25). The layers of the Phe and Karsha Formation are discordantly overlain by the chlorite shale at the base of the Panjal Trap (Fig. 3.15). The contact zone of these shales to the underlying rocks is not sharp. The massive, compact basalts immediately above these shales have a 20 cm-thick contact zone with a schistosity first parallel to the contact and then curving into the overall more steeply dipping schistosity orientation (Figs. 3.26 and 3.27). Fifty centimeters above the base of the first basalt flow the basalts are massive and do not show any deformation structures. In the Ralakung and Karsha area no chlorite shale occurs at the base of the small individual thrust slices: the massive basalts lie directly over the overthrusted lithologies.

There is no microscopic evidence for internal deformation within the pure chlorite shales. The calcite-rich shales, however, contain twinned calcite grains that indicate slight movements after the peaks of fabric development and metamorphism (Fig. 3.28).

Figure 3.21: Detailed geological scetch map of the Ralakung region showing the individual Panjal Trap thrust sheets.

Figure 3.22: Thrust sheet of Panjal Trap showing in the right side of the figure Mesozoic sediments directly overlying the Phe Formation. Near Phe, view eastwards.

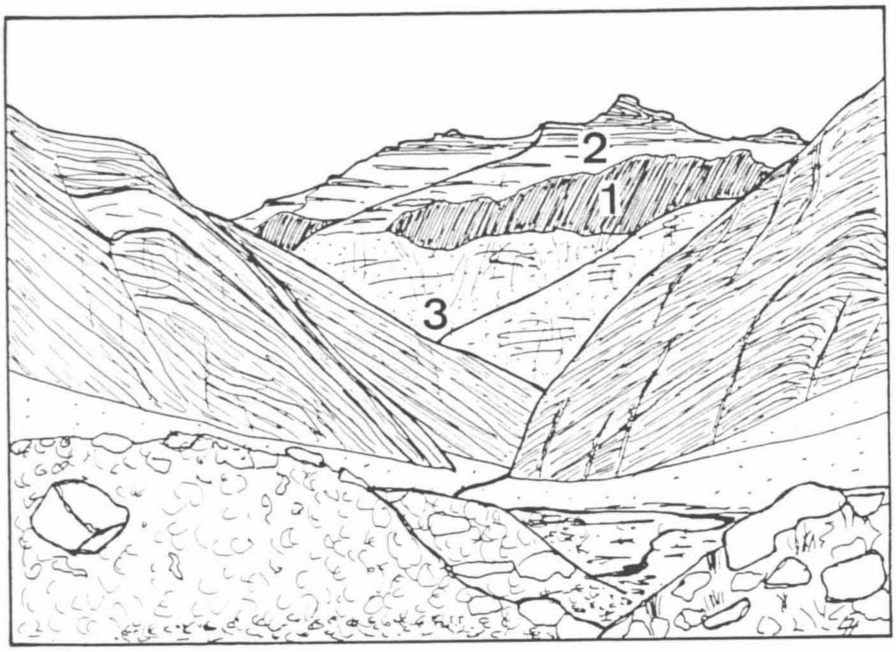


Figure 3.23: Panjal Trap (1) thrusted lateral to pieces (near Phe). Therefore Mesozoic rocks (2) lie directly over the Phe Formation (3) late Precambrian - Cambrian Formations. View from the Malung Tokpo northeastwards.

Figure 3.24: Thrust sheet of Panjal Trap within Triassic sediments. End of the valley northeast of Karsha (Fig. 3.3), view northwards. The width of the thrust sheet correspond to approximately 200 m.

Figure 3.25: Lower contact zone of the Panjal Trap unit to the underlying Karsha Formation showing the angular discordance between these two units. Note the bad exposed contact zone. Karsha Chu valley, view northwards. The width of the picture correspond to approximatly 3 km.

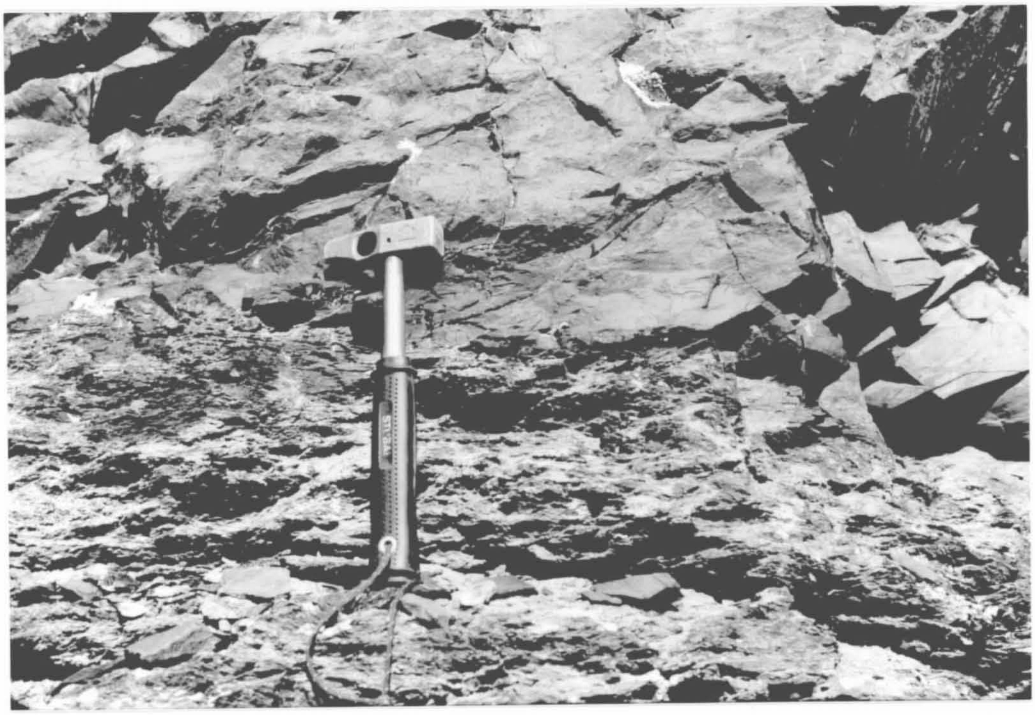


Figure 3.26: Detail of the contact zone of the Panjal Trap unit to the underlying Karsha Formation showing the massive basalts over the chlorite shales.

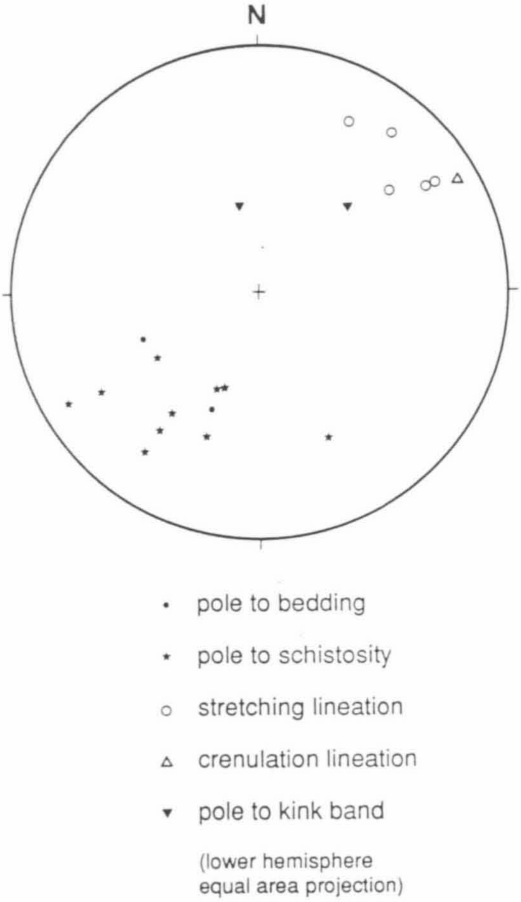


Figure 3.27: Equal area projection of the structural data on the contact zone Panjal Trap underlying Phe respectively Karsha Formation.

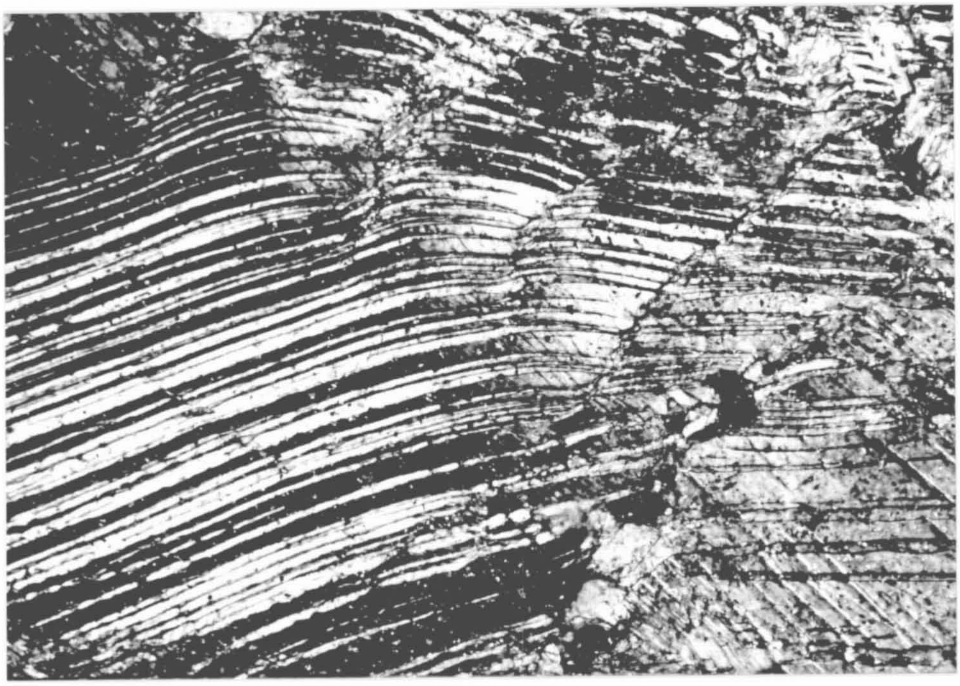


Figure 3.28: Thin section of the chlorite shale from the contact zone Panjal Trap underlying Phe Formation showing twinned calcite grains. The width of the picture correspond to 0.83 mm, crossed nicols.

Discussion - Conclusion

The regional deformation is taken up by the Panjal Trap in an obvious large scale deformation and subordinate in the internal, small scale deformation. The basaltic flows welded together to form a rigid, competent plate which deformed by breaking into pieces. The large-scale anticlines and synclines in the Ralakung area were inhereted from the initial wavelengths of folds in this plate. As the folds developed buckling stresses increased and ductile folding was replaced by fracture behaviour. The interlayered sediments do not appear to have greatly influenced this overall deformational behaviour of the Panjal Trap.

A direction of movement parallel to the strike of the Panjal Trap is suggested by the stretching lineation within the Panjal Trap near Tongde (Fig. 3.17b) and by the presence of Mesozoic lithologies lying directly over the Phe Formation (Fig. 3.23).

The internal deformation is absorbed in the amygdaloidal-rich basaltic flows and the interlayered sediments, especially the matrix-rich greywackes. The base of the basaltic flows are not internally deformed. Therefore, it is not possible to estimate the total deformation within this unit. The deformation does increase in all cases towards the top of each flow as indicated by the elongation of the vesicles and the refraction of the schistosity.

3.3 Mesozoic sedimentary sequence

A mainly carbonatic sedimentary sequence follows concordantly over the Panjal Trap. The formations have a time span within the investigated area, from Late Permian (Kuling Formation) to Late Jurassic / Cretaceous (Figs. 3.2 and 3.3) and reach about 3000 m in thickness (Baud et al., 1984). The rifting phase began with the Panjal Trap effusion, inducing a marine transgression in the latest Permian. In general (compare Fig. 3.3), the Triassic sequence becomes thicker from east to west. Due to the slightly southeast plunging fold axes (chapter 3.3.2) northeast of the Zanskar river, the Triassic and Liassic levels are especially well exposed. On the other side of the river, higher levels (namely Cretaceous formations) are well exposed. These sediments were deposited on the passive continental margin of the Indian Plate.

Some of these carbonatic layers (especially those of the Lilang Formation) have a very characteristic weathering colour which enables rapid mapping of the formation over great distances. Detailed investigations are generally impossible because of the presence of great gorges formed within the Mesozoic units. Most of the profiles through this unit are not accessible in summertime, e.g. from Ralakung to the Zanskar river (Fig. 3.1) and the Shade gorge (Fig. 1.8) is only passable in late October. In the period of time available for this study, it was only possible to investigate profiles along the Zanskar river between Tongde and Zangla, respectively Rinam and Pidmu (Fig. 3.1).

3.3.1 Lithostratigraphy, Sedimentology and Depositional Environment

The lithological and sedimentological descriptions of this unit shown in Figure 3.2 are summarized from Baud et al. (1984) and for the Cretaceous formations from Gaetani et al. (1983).

Kuling Formation (Stoliczka, 1866)

Above the Panjal Trap follows a sedimentary sequence with a variable thickness up to 55 m. The lower part is composed of a whitish quartzarenite with local enrichments of fossil fragments. Poorly bedded quartzarenitic biomicrites, very rich in Brachiopods, follow, indicating an age of Late Permian. The sequence ends with marly shales (50 - 100 m) containing phosphatic nodules representing a transgressive unit.

Lilang Group (Hayden, 1908; Baud et al., 1984)

This thick, mostly carbonate sequence reaches an average thickness of about 1000 m. Four lithostratigraphic units can be distinguished; from bottom to top they are:

1) *Tamba Kurkur Formation* (Srikantia et al., 1978): This unit consists of bedded limestone followed by sandy, sericitic shales with rare limestone beds covered by alternating shales and nodular, thin bedded limestones and bedded limestones with subordinate shales

reaching up to 100 m in the Tongde area. The passage to the overlying Hanse Formation is sharp in eastern Zanskar but transitional in the Tongde area, where it is associated with a gradual increase in the thickness of the shales.

2) *Hanse Formation* (Srikantia et al., 1978): This unit seems to be reduced in thickness in the area near Rinam (on the Zanskar river, Fig. 1.8) compared with the eastern Zanskar (Phirtse La area about 450 m, Baud et al., 1984). The base is characterised by grey marls and black, thin bedded limestones with thin marly intercalations with abundant Daonellas. The next lithofacies is formed by grey marls with isolated nodules, sometimes containing Ammonoids with metric intercalations of black, thin bedded limestones which are locally rich in large crinoids. Black, yellowish weathered limestones characterize the upper extremely monotonous lithofazies. The Tamba Kurkur and the Hanse Formations represent mostly basinal sequences, but a decrease of depth is marked by an increase of bioclasts in the upper 20 m of the Hanse Formation.

3) *Zozar Formation* (Baud et al., 1984): This unit is about 400 m thick and well exposed all over the Zanskar. The base of this upper Triassic sequence is made of few encrinitic beds followed by calcarenite layers characterized by Bryozoans, Brachiopods, Gastropods, Pelecypods, Solenoporaceans, algae and rare coral fragments. A distinctive thick, white dolomitic bed follows. The overlying main body of the unit is formed by a monotonous sequence of cross-bedded calcarenites, limestones, dolomitic limestones and stromatolitic dolomites. The topmost layer is a 5 - 10 m thick, white dolomitic bed followed by the first micaceous siltstone and quartzose sandstone layers.

The depositional environment is subtidal, with increasing depth towards the east.

4) *Quartzite Series* (Hayden, 1904): The unit is continous throughout western Zanskar with constant features and thickness (about 120 m), whereas in eastern Zanskar this unit is reduced or even not present. The base is made of calcarenites with abundant crinoidal remains and marls (subordinate sandstones). A mostly arenaceous middle portion follows. The upper part of the unit consists of quartzose bio- and oosparite layers, interbedded with micaceous marls which have yielded benthic foraminiferas. Carbonates, extremely rich in Neomegalodon, marked by alternance the boundary to the overlying Kioto Limestone.

By the sandstone petrography a cratonic, partly direct and partly polycyclic provenance of the siliciclastics is strongly suggested. The unit was deposited in shallow subtidal to beach environment during latest Norian - Rhaetian age (Baud et al., 1984; Gupta, 1976, 1977).

Kioto Limestone (Hayden, 1908)

The lower part of this uniform thick (up to about 600 - 900 m) calcareous / dolomitic unit contains dolomitic limestones in 50 - 100 cm thick beds, rich in Neomegalodon, still interbedded with quartzarenites or subarkoses and silty marls. A monotonous sequence of limestones of 2 - 5 m thick beds follows. In the topmost part, beds very rich in belemnites crop out near Zangla.

Giumal Sandstone (Stoliczka, 1866)

This unit crops out from Zangla to Rangdum Gonpa area, and shows an increasing thickness from about 200 m in the east to 300 m to the west. The Giumal Sandstone consists of grey to green, locally cross- or graded-bedded, very fine to fine grained sandstones with intercalated layers of black shales. It is followed by the Chikkim Limestone with a very abrupt clear-cut boundary.

The depositional environment of the Giumal Sandstone is controversial. The formation is sandwiched between two pelagic, bathyal units. The petrographic composition suggests a mixed-source provenance with deposition on an outer shelf 100 - 200 m deep.

Chikkim Formation (Stoliczka, 1866)

This outcrops in an area from Zangla to the Spanboth Chu (valley north of Rangdum Gonpa). Features of these well-bedded limestones and grey marly limestones indicate a pelagic depositional environment. The thickness is about 90 - 100 m, and the age middle to upper Cretaceous.

Kangi la Formation (Fuchs, 1977)

This Formation crops out between Zangla and Spanboth Chu - Kangi La. Lithologically it consists of dark grey marls, calcareous siltstones and shales with sandstones in the uppermost part. The thickness ranges from 400 to 600 m. The depositional environment is from bathyal to sublittoral. The age is upper Cretaceous.

In the field the boundaries between the Kuling, Tamba Kurkur and Hanse Formations are often difficult to map because they form round hills (Fig. 1.4) with rare outcrops, especially in the Ralakung area. The overlying Zozar Formation and Quartzite Series, however, constitute a spectactular cliff-forming element of the landscape throughout the investigated area. The different and contrasted colours, thicknesses and lithological compositions of the individual layers form an imposing, colourful unit often with beautifully developed polyharmonic folds (chapter 3.3.2). The top of the first Ranges northeast of the Doda and Tsarap Lingti Chu valleys are formed of this unit (Figs. 1.4 and 3.14).

In contrast to these two formations, the overlying grey Kioto Limestone formation gives rise to monotonous and topographically rather uniform land forms.

On Satelite images the Kioto Limestones can be easily distinguished from the Zosar and Quartzite Formations. The overlying light coloured Spiti shale Formation is also easily mappable on Satelite images.

The depositional environment can be described as follows (after Baud et al., 1984): In the latest Permian, the rifting phase began with the Panjal Trap effusion leading to a marine transgression. Pelagic conditions were reached in the early Triassic. The rapid sedimentation along with a decreasing rate of subsidence led to the filling up of the basin and to peritidal conditions after the Middle Carnian. Shallow-water sedimentation went on until the Middle Jurassic, when subsidence of the carbonate platform led to a "drowning" of the Kioto Limestone. A bathyal stage was reached in the Late Jurassic. After the siliciclastic event of the Giumal Sandstone pelagic sedimatation was renewed.

After the upper Cretaceous the seafloor depth was reduced by active sedimentation and decreasing subsidence. The close of the Cretaceous is characterized by a regressive terrigenous event. The sedimentation seems to have been controlled more by global eustatic cycles than by regional tectonic movements. The subsidence rate, in fact, never reaches very high values in the Zanskar area, and moderate stretching of the underlying continental crust seems to have only occured in the Middle Triassic.

3.3.2.Structures

The dominant deformational mechanism within the colour contrasted formations of the Mesozoic unit is folding of different wavelengths, amplitudes and foldstyles. These beautiful folds show clearly the dependence of deformational pattern on lithological competence.

The individual formations have been grouped into lithostructural units of differing overall lithologies which control the deformational patterns and foldstyles (Figs. 3.2 and 3.3).

Main structural elements

Folds: The large scale well developed folds are the characteristic and dominant deformational phenomena of the Mesozoic lithologies. The *Kuling, Tamba Kurkur and Hanse Formations* are characterized by limestone layers intercalated with many shale horizons (chapter 3.3.1). The **foldstyle** is consequently **polyharmonic** (Fig. 3.29). The incompetent shales form shear zones between the competent limestone layers. The largest wavelengths of the folds are controlled by the thickest limestone layer of the Tamba Kurkur Formation.

The *Zozar and Quartzite Formations* are characterized by limestones, dolomites and calcarenites and subordinated shales (chapter 3.3.1). They show a **disharmonic foldstyle** because of the several contrasting lithologies with variable thickness and competence behaviour (Fig. 3.30).

The *Kioto Formation* with its homogenous lithological sequence of alternating limestones and dolomites (chapter 3.3.1) shows **chevron type folds** (Fig. 3.31) with very regular wavelengths of some hundred metres and with amplitudes of the same order. Within this formation deformed (flattened) belemnites were found (Fig. 3.33) indicating ductile deformation mechanism.

The *Spiti Shales and Giumal Sandstones* form, together with the *Chikkim Formation,* a megascale fold; a syncline near Zangla (Figs. 3.3 and 3.32). The wavelength of the so called Zangla Syncline is in the order of 2 km and the amplitude around 1.5 km. The fold axes cannot be measured directly but the outcrop situation indicates a slightly northwestward

Figure 3.29: Polyharmonic foldstyle within the Kuling, Tamba Kurkur and Hanse Formations (lower Triassic lithostructural unit) northwest of Rinam (Fig. 3.1). The width of the figure corresponds approximately to 1 km.

Figure 3.30: Disharmonic foldstyle within the Lilang and Quartzite Series (Upper Triassic lithostructural unit), again northeast of Rinam (Fig. 3.1). The width of the figure corresponds approximately to 700 m.

Figure 3.31: Chevron type folds within the Kioto Formation southeast of Zosar. The width of the figure corresponds approximately to 2.5 km.

Figure 3.32: The Spiti Shales and Giumal Sandstones (darkest lithologies in picture) form together with the Chikkim Formation (light lithologies) a megascale fold: the "Zangla syncline". The width of the picture corresponds to approximately 5 km.

plunging fold (the syncline opens toward NW and closed towards SE). This fold is very prominent in the field and on Satellite images. The Spiti Shales and Giumal Sandstones are also folded into smaller scale structures as described previously.

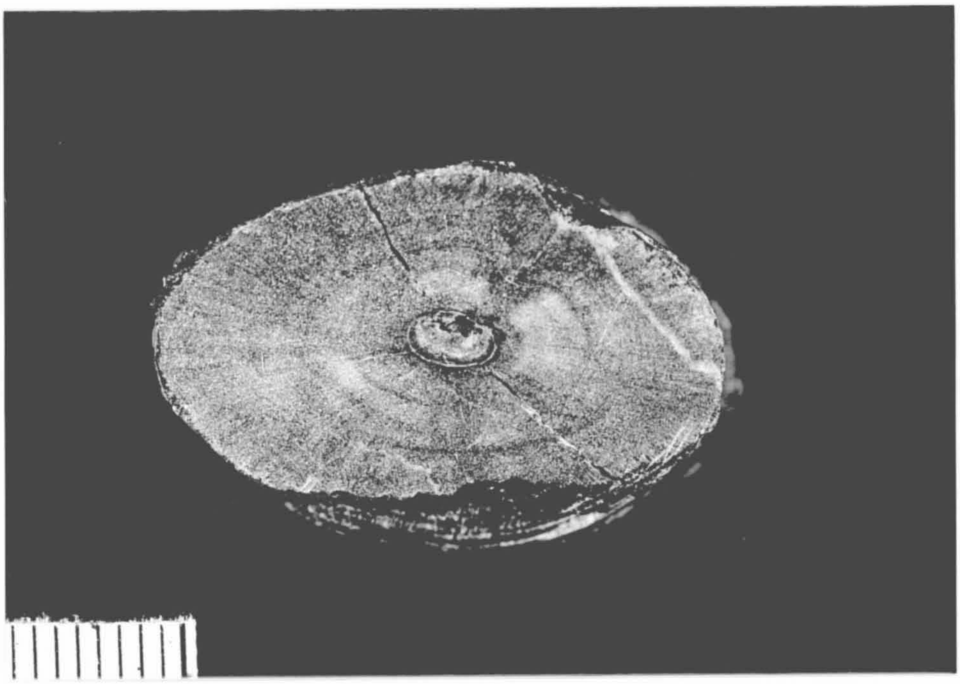


Figure 3.33: Cross-section of a deformed (flattened) belemnite indicating ductile deformation mechanism. The scale bar in the lower left has 1 mm devision.

The orientations of fold axes are difficult to determine even though the folds are frequent and predominant in Zanskar. Directly measured fold axes (only 4 observations) have azimuths of 340° and plunge of 10° - 60° NW (Fig. 3.34a). Many measurements have been made along the Zanskar river from a distance using the method of determining the azimuth of a vertical bedding plane around a fold (giving the azimuth of the fold axes) and the plunge determined from measurements of bedding located perpendicular to this plane (also measured from distance). The trend of the fold axes is from 138° - 162° and plunges vary from 4° - 12° SE (Fig. 3.34b). The fold plunge can be described as horizontal to slightly inclined (Turner and Weiss, 1963).

The individual folds are axially continous for several tens of kilometres due to the homogenous lateral succession of the individual layers. Therefore some traces of the fold axial planes are easy to map on Satellite images (Fig. 6.1) especially those involving lithologies of different weathering colour. For example, the boundary between the Quartzite Series and the Kioto Formation is very obvious and easy delimited on a map (Figs. 3.3 and 3.35). In general the fold axial planes developed with schistosity planes have a continous average strike of 140° NW independant of lithology and foldstyle. The dip, however, varies with the foldstyle. It is more or less constant within the Kuling, Tamba Kurkur and Hanse Formation forming the first lithostructural unit namely 60° - 80° NE. Within the Kioto Formation the dip gets steeper namely 80° - 90° NE. Within the Zozar and Quartzite Formations, with their disharmonic foldstyle patterns, the fold axial planes show different orientations. The strikes are the same but the dip varies greatly from 80° NE to 60° SW ("Kofferfalten" in Fig. 3.30).

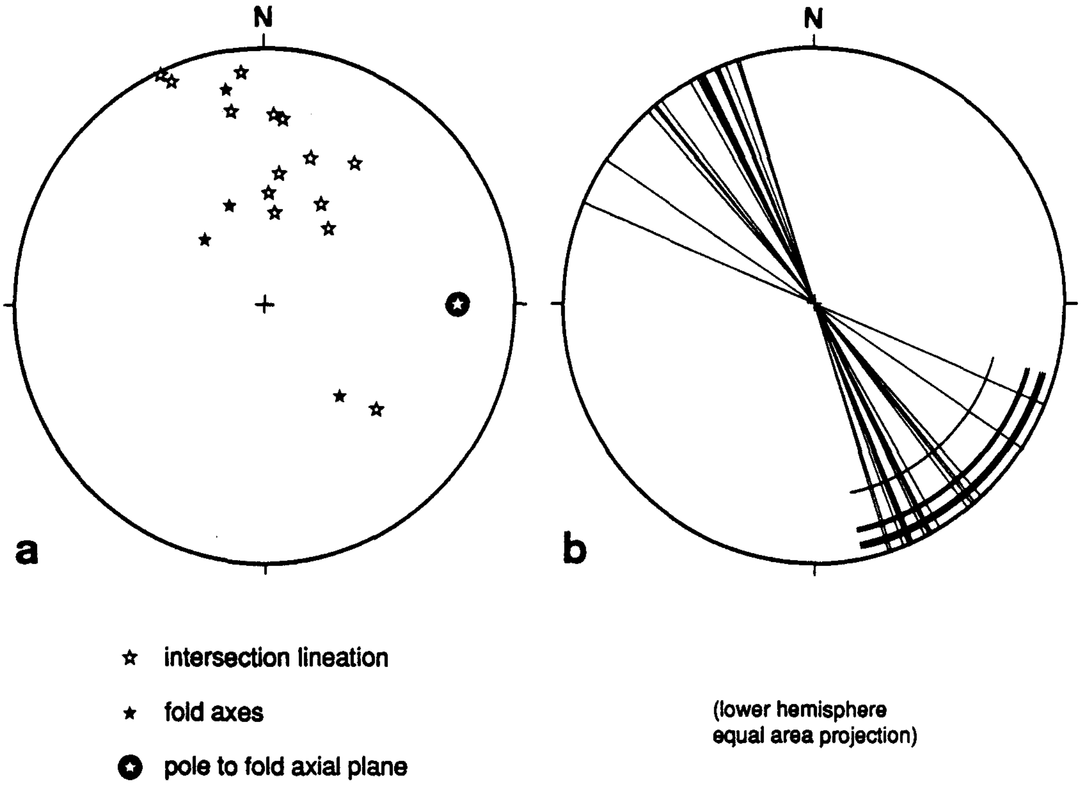


Figure 3.34: Equal area projection of a) the intersection lineation, fold axes and fold axial planes and b) of the constructed fold axes (for explanation compare text).

The outcropping section of the Mesozoic formations from Tongde towards the northwest progressively increases in thickness (Fig. 3.3). For instance, the lower Triassic lithostructural unit is in the Tongde area small compared with that in the Ralakung area in the northwest. There are no lateral facies transitions (chapter 3.1 and Baud et al., 1984) which lead to the different thicknesses of outcropping formations. The difference of outcrop width correlates best with differences in the structural development of the compared regions. Several features give rise to the observed situation: (1) The fold axial planes within the lower Triassic lithostructural unit have, in general, a smaller dip northwest of the Zanskar river than on the southeast of the river. (2) The fold axes near Rinam (Fig. 3.1) plunge slightly towards SE (Fig. 3.34b). The map, however, indicates that in general the folds plunge subhorizontal to slightly towards NE (Figs. 3.3 and 6.1) because the age of the fold lithologies in the fold cores became gradually younger following any individual fold from southeast to northwest. On the other (towards southeast) river side, near Zosar, the fold axes plunge also slightly towards NW. (3) The structural geometry of the Ralakung area is controlled by a special situation related to the thrust sheets of Panjal Trap associated with Triassic lithologies (Fig. 3.21).

Figure 3.35: Folded boundary between the Quartzite Series (light) and the Kioto Formation (dark). Note the different weathering colour which makes this limit easy to map. View northwestwards from Pidmu (Fig. 1.8).

Bedding: Bedding planes are generally clearly defined within all layers except for shales where often only the schistosity can be distinguished. The orientations of the bedding in the fold limbs which define the general formation trends have strikes of 115° - 180° SE and dips of 40° - 80° NE (Fig. 3.36).

Schistosity: The schistosity is defined by the preferred dimensional orientation of layer silicates within the shales and marls. The average orientation shows strikes of 145° - 175° SE and dips varying from 40° - 85° NE. The average dip is 70° - 80° NE (Fig. 3.36). The scattering is smaller than those of the bedding. The schistosity is associated with fold geometry and is sub-parallel to the fold axial planes.

Lineation: The lineations are defined by the preferred linear orientation of layer silicates within the schists and marls forming a "stretching" lineation (X-lineation). The linear variation is very small in the shales and greater in marly rocks (Fig. 3.36). The average orientation of this lineation shows azimuths of 35° - 45° NE and plunges between 40° and 55° NE. The lineations are sub-perpendicular to the fold axes. A schistosity - bedding intersection lineation shows an orientation towards the north different from that of the constructed fold axes (Fig. 3.34b) but similar to the general trend of fold axes indicated by the outcrop situation (Figs. 3.3 and 6.1).

Crenulation cleavage - kink bands: The last deformational event produced a crenulation cleavage within the shales. This crenulation cleavage is often perpendicular or inclined to the previous schistosity plane and dips towards the southwest indicating a new and different orientation from previously formed structures (Fig. 3.36). At some localities conjugate kink bands are present and appear to be synchronous. The crenulation cleavage appears to relate to a backfolding event. The limestone layers are too massive to show this last deformational event and show no crenulation cleavage. These limestone layers, however, are locally slightly bowed towards the northeast forming limbs of the large open folds which have axial planes parallel to the crenulation cleavage orientation (Fig. 3.35).

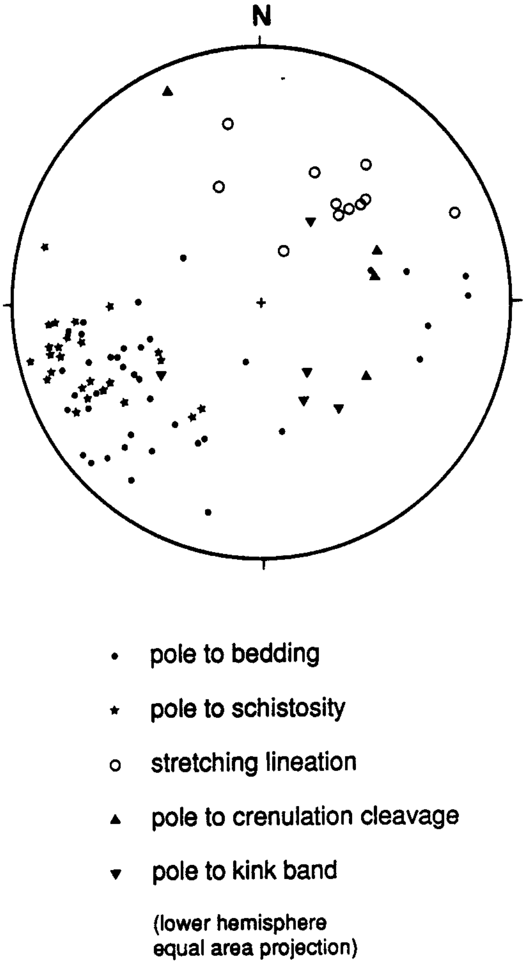


Figure 3.36: Equal area projection of the structural data of the Mesozoic formations.

Microscopic structures: Features indicative of the mechanism of internal deformation of these lithologies are very few. Within all units no vein systems are present and also no pressure solution phenomena were seen. Slight ductile internal deformation are indicated by the ductile deformation of the belemnites within the Kioto and Giumal Formations (Fig. 3.31), the belemnites showing elliptical crossections of an average axial ratio of 1 : 1.8 and are concentrated to same lithological horizons.

Additional deformational mechanism: At the base of the sedimentary sequence above the Panjal Trap, within the Kuling, Tamba Kurkur and Hanse Formations the deformation situation is often difficult to evaluate, especially in the Ralakung area (Fig. 3.21) where the deformation is more complicated than on other places and appears to be interlinked with thrust sheets of the Panjal Trap. These three formations have many shale horizons (chapter 3.3.1) and it is difficult to see whether some lithologies are repeated or not (Fig. 3.22). The deformational style within the thrust Mesozoic slice is similar to that generally seen in the Panjal Traps. The shortening amount, as recordet by layer length changes, however, seems to be greater.

Discussion - Conclusion

The deformation is taken up mostly by folding and with only slight internal deformation (forming the schistosity). The internal deformation has only been positively identified by ductilely deformed belemnites. This fact indicates still slightly tempered deformational environment or a very slow strain rate. Only the late development of localised kink bands deformation indicates more brittle deformation mechanism for the last deformational (backfolding) event. A part of the deformation might be taken up by layer parallel gliding of the individual layers during folding especially within the Kioto Formation where small shale layers allow this deformation mechanism. Therefore, only a slight internal deformation is present.

Although the geometric features of some of the major structures in these Mesozoic rocks might be compared with those of the Helvetic nappe terrain of Switzerland this unit is not directly comparable. Widespread vein systems and pressure solution deformation mechanism which are a characteristic feature for the Helvetic nappe terrain were not observed in the Zanskar region. Also no nappes are present.

Within the Zanskar section of the Mesozoic units there appears to have been only one main deformational event, which gave rise to megascale folds (e.g. the Zangla Syncline) and to smaller scale folds (e.g. all the described folds within the Triassic - Liassic lithologies). All these formations were then only slightly overprinted by the backfolding phase, which formed some crenulation cleavage and which set up a slight bending towards the northeast of the previously formed old axial planes. This phase, however, is nowhere near as important and penetrative as it is in the Suru region where several units (e.g. the Dras unit) are refolded to the north to form a recumbent fold (Honegger, 1983).

The deformational pattern is similar all over the investigated area with the only exception of the Ralakung area where the Panjal Trap including Mesozoic lithologies up to the Lilang Formation is repeated.

4. Leucogranites

Leucogranitic intrusions, crosscutting crystalline basement rocks as well as overlying Precambrian, Paleozoic and Mesozoic sediments in the Higher Himalaya, are known all along the Himalaya Range (Fig. 4.1). From the Nanga Parbat (Pakistan) in the west until Mönlakarchung (Bhutan) in the east they follow the highest elevations of the Main Himalaya Range, some of these leucogranitic intrusions reach present topographic heights of 8000 m and many of the others surpass the 7000 m elevation (Gansser 1964, 1983; Le Fort, 1973).

They lie on top or to the north of tectonically thick zones of migmatitic gneisses of the High Himalayan Crystalline (Tibetan Slab in Nepal, Zanskar Crystalline unit in Ladakh) which are generally of high grade metamorphism (Barrovian - type metamorphism of Neogene age with sillimanite or even higher grade minerals).

They are known and well described by different authors especially those from Nepal (e.g. Le Fort, 1973, 1975, 1981; Le Fort et al., 1987; Vidal et al., 1982; Deniel et al., 1983) and also from Bhutan (Dietrich and Gansser, 1981; Gansser, 1983 and Blattner et al., 1983), southern Tibet (Burg et al., 1984; Wang et al., 1981; Debon et al., 1984, 1986); and from the Kumaon Himalaya (Auden, 1933; Heim and Gansser, 1939; Gansser, 1964; Seitz et al., 1976; and Blattner et al., 1983). From the NW Himalaya only few works are available (Pakistan: Nanga Parbat, Misch, 1949 and from Ladakh: Searle and Fryer, 1986 and Pognante et al., 1987).

The High Himalayan leucogranites are of special interest because they are one of the rare magmatic products of the Himalayan collision zone. They are interpreted to be a product of anatectic melting of crustal material based on field evidence, their trace element chemistry and isotopic composition.

During the work on this dissertation and also by the work of Kündig (in prep.) and Stäubli (in prep.) it became more and more clear that the typical High Himalayan leucogranites are also present in Ladakh but in only a very small occurrence. Therefore these leucogranites are investigated in more detail than the other lithologies of the Zanskar Crystalline unit and presented in this particular chapter. This chapter might be the base for further and more careful investigations of the High Himalayan leucogranites in NW Himalaya.

4.1 Geological setting

In the wider Zanskar area the occurence of leucogranites are limited to the Gumburanjon leucogranite in the Tsarap Lingti Chu (Figs. 1.5 and 1.8) (Srikantia et al., 1978, and Pognante et al., 1987) and to the Haptal Tokpo valley in Zanskar (Figs. 1.5 and 1.8).

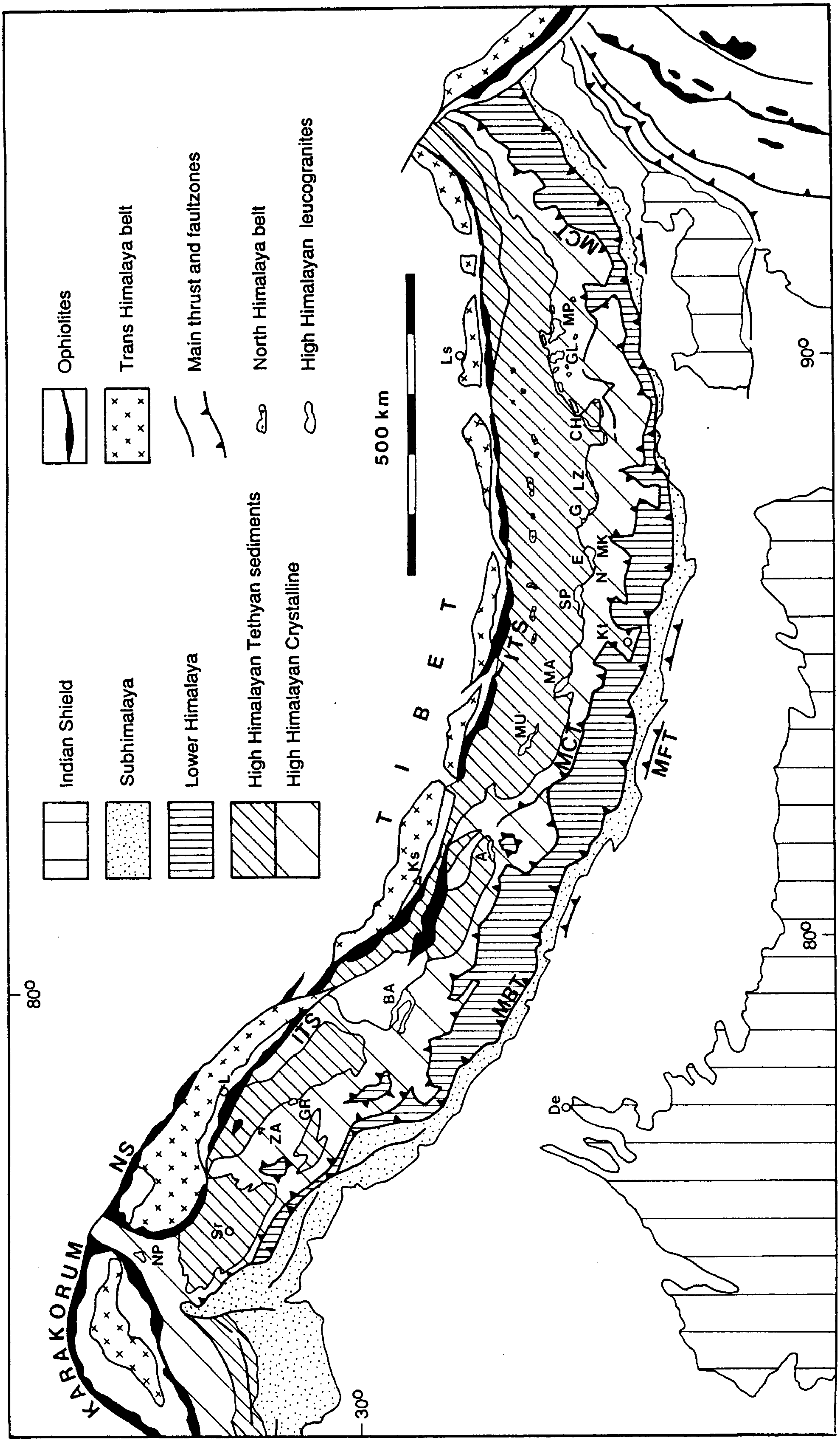

Indian Shield
Subhimalaya
Lower Himalaya
High Himalayan Tethyan sediments
High Himalayan Crystalline
Ophiolites
Trans Himalaya belt
Main thrust and faultzones
North Himalaya belt
High Himalayan leucogranites
500 km
KARAKORUM
NS
T I B E T
ITS
ITS
MBT
MCT
MCT
MFT
NP
Sr
ZA
GR
L
BA
Ks
A
MU
MA
SP
E
G
LZ
CH
GL
MP
Ls
Kt
N
MK
De
80°
80°
90°
30°

Figure 4.1: Tectonic map of the Himalayas showing the major occurences of Tertiary (Neogene) leucogranites in the Higher Himalaya (map after Gansser 1983 simplified and modified after Honegger (1983), leucogranites after Dietrich and Gansser, 1981; Le Fort et al., 1987).
From NW to SE: NP = Nanga Parbat, ZA = Zanskar, GR = Gumburanjon, BA = Badrinath, A = Api, MU = Mustang, MA = Manaslu, SP = Shisha Pangma, N = Nyalam, E = Everest, MK = Makalu, G = Gabug (= Yadong), LZ = Lhozag, CH = Chung La (= Chomolhari), GL = Gophu La, MP = Mönlakarchung - Pasalum.
Abbreviations: De = Delhi, Sr = Srinagar, L = Leh, K = Kailas Mt., Kt = Kathmandu, Ls = Lhasa. Main structural units: NS = northern Suture, ITS = Indus Tsangpo Suture, MCT = Main Central Thrust, MBT = Main Boundary Thrust, MFT = Main Frontal Thrust.

Searle and Fryer (1986), however, suggest that the 30 - 50% of granite which comprises the Higher Himalayan crystalline part in this region are of the leucogranite type. My own investigations are limited to those of the Haptal Tokpo including neighbouring valleys, but the suggestion that the occurence of leucogranites is rather limited is supported by the work of Honegger (1983), Kündig (in prep.), and Stäubli (in prep.), covering the upper Doda valley, the Suru-, Kishtwar-, Warwan-, and Kashmir region (Fig. 1.5).

The fine-grained tourmaline- or garnet- bearing leucogranites of the studied area (Fig. 4.2) occur, in general, as concordant intrusions with the layers within the dark fine-grained well foliated biotite gneisses (Fig. 4.3) of the upper part of the Zanskar Crystalline unit. The thickness of the individual layers reach from 5mm up to maximum 600 m (Fig. 4.2). The thickness of the leucogranitic layers as well as the other lithologies of the Zanskar Crystalline unit gradually decreases toward the northeast to the top of the Zanskar Crystalline unit and towards the Zanskar shear zone (compare chapters 2 and 7). Near the top of the Zanskar Crystalline unit, however, a 30 m thick leucogranitic layer is present. It is one of the easiest outcrop to reach, 500 m west of the "Tungri bridge", between Sani and Ating (Figs. 1.8 and 4.2). In the neighbouring surrounding valleys of the Haptal Tokpo (Malung Tokpo, Tamasa Tokpo and Dharlang Nala), the thickness of the leucogranitic layers decreases to maximal 2 m (Fig. 4.4). Here the leucogranitic layers are still identifiable but no longer mappable (Fig. 4.2). Away from the surrounding valleys of the Haptal Tokpo (upper Doda valley, Suru-, Kishtwar-, Kashmir region), only dykes representing this magmatic event are present (e.g. Honegger, 1983). It is, however, not yet resolved whether these dykes belong to this event, to the older (Cambrian), or to both. Careful field investigations and geochemical analyses are needed to solve this problem.

In contrast to the occurences of single large leucogranitic plutons found within Tethyan sediments of up to Cretaceous age in Nepal (Le Fort, 1973), and of up to Jurassic age in Bhutan (Nautiyal et al., 1969), the Zanskar leucogranites are found within high grade basement metamorphic rocks (upper amphibolite facies rocks, Fig. 4.5) and as far as the base of the Tethyan sediments of the Precambrian-Cambrian Phe Formation (chapter 2.3). In Nepal and Bhutan the leucogranite stocks are also found in amphibolite facies rocks (P. Le Fort, pers. comm.), the exposed levels of the Higher Himalaya, however, are higher than that of Zanskar.

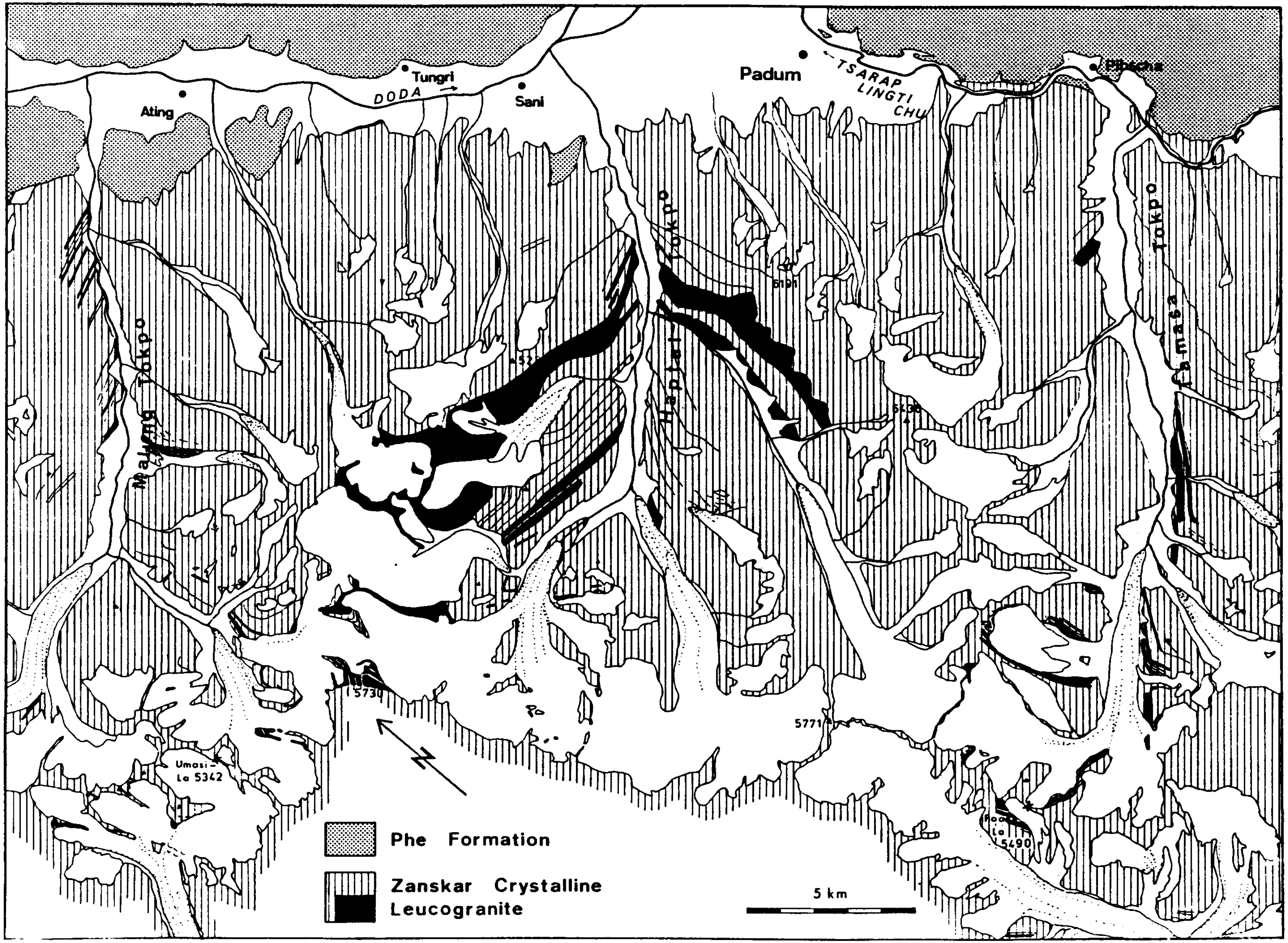


Figure 4.2: Geological map showing the occurence of leucogranites in the Zanskar area.

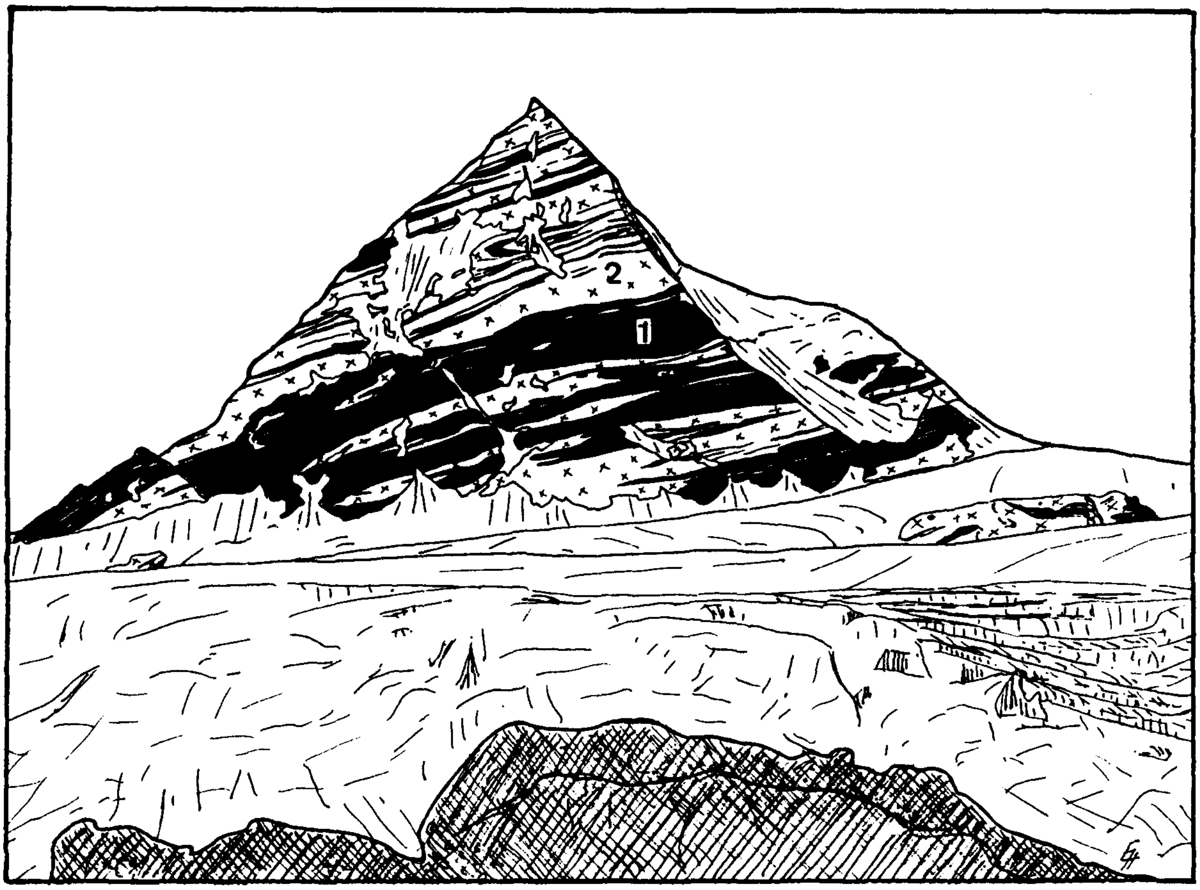


Figure 4.3: Dark biotite gneisses (1) with leucogranitic layers (2). Upper Haptal Tokpo, view westwards. The width of the figure correspond to approximately 1.5 km.

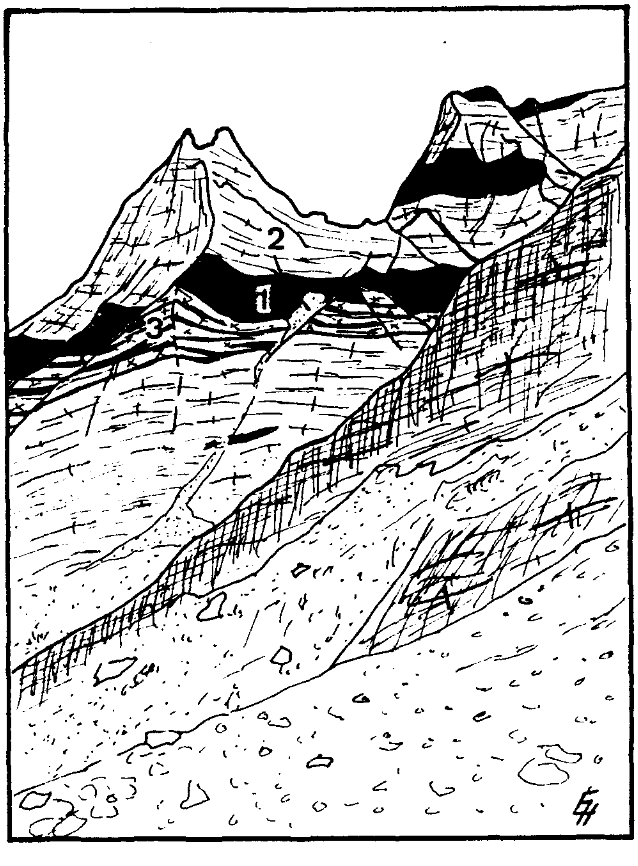


Figure 4.4: Within the dark biotite gneisses (1) are porphyritic granite gneiss intrusions (2) and small layers of leucogranites (3). Tamasa Tokpo, view eastwards.

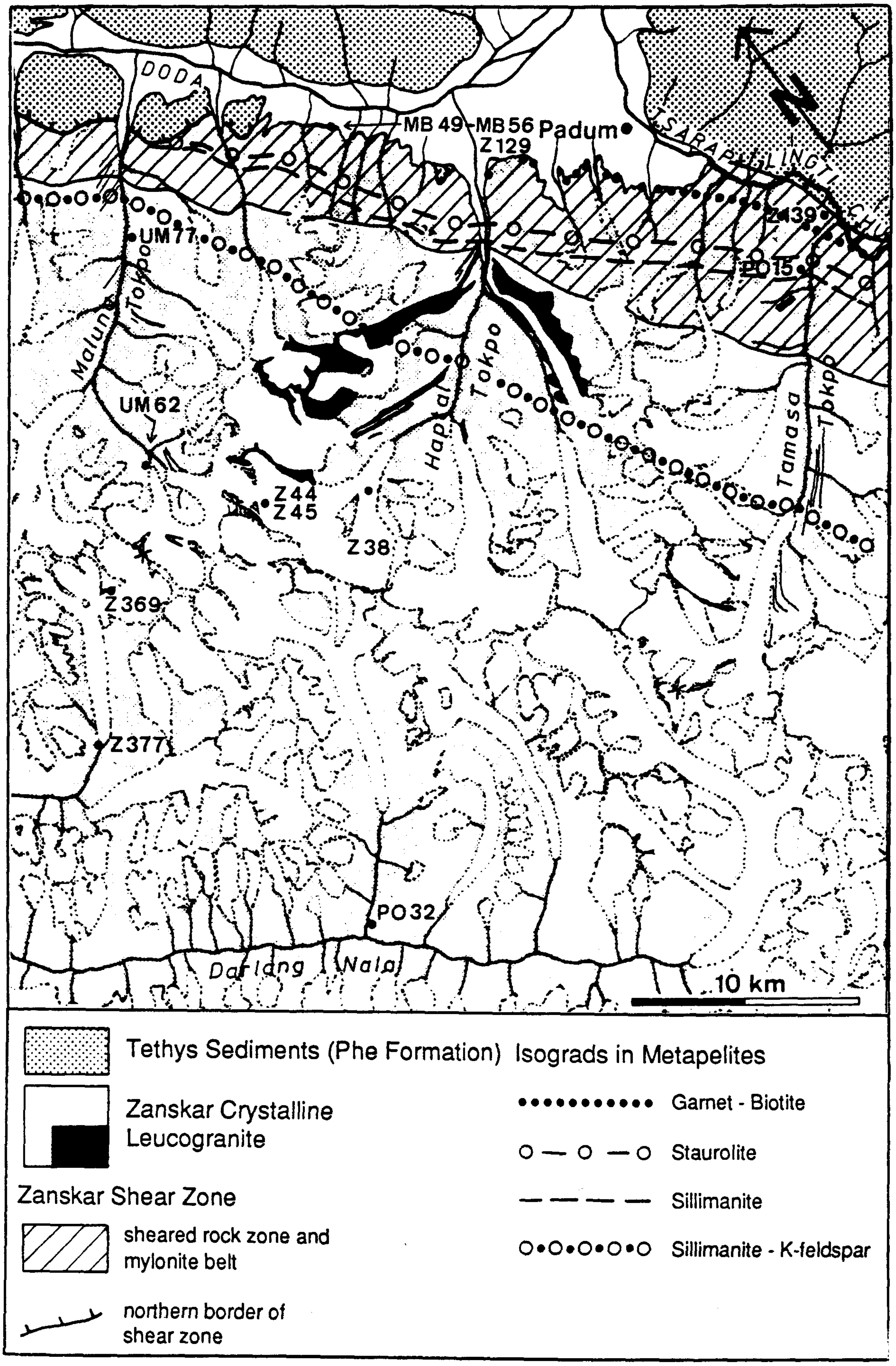


Figure 4.5: Geologic map of the Zanskar region and southern adjoining part of the main Himalayan Range showing sample locations for geochemical analyses, metamorphic isograds, and Zanskar shear zone.

The leucogranitic layers within the upper parts (tectonically speaking) of the Zanskar Crystalline unit are overprinted by the Zanskar shear zone (chapter 7).

In the main Himalayan Range, the area which has been subjected to the highest metamorphic conditions (Fig. 4.5) contains small stocks of leucogranites. There the leucogranitic layers are folded together with the biotite gneisses (Figs. 4.6 and 4.7). The exact orientations of these fold axes are difficult to record directly due to the inaccessibility of the terrain (glaciers, altitude), but the axial trends appear to be generally NW-SE. There is no associated foliation present. The folds are therefore interpreted to be folds of a late phase (chapter 2.2) in the regional context.

Within this part of the Zanskar Crystalline unit no dykes are present, whereas they are abundant in the upper part of the Zanskar Crystalline unit. Late shearing, however, related to the development of the Zanskar shear zone (chapter 7), makes it difficult to separate the different generations of dykes and to determine the relationships of the dykes to the surrounding rocks. Only in the Sumche Tokpo (Fig. 1.8) dykes which crosscut the surrounding crystalline rocks may be identified.

4.2 Petrography

The most distinctive features of the leucogranites are their relative homogeneous grain size, very similar mineralogical composition, and geochemical signature (see Table 1). In the Zanskar area, two different varieties can be distinguished (from careful microscopic investigations of 36 leucogranitic samples). The first is characterized by high tourmaline content (3 - 10 %), muscovite (3 - 10 %), plagioclase (35 - 40 %), K-feldspar (23 - 28 %) and by the accessory contents of chrysoberyl, garnet and biotite. The second is characterized by a higher proportion of garnet (1 - 7 %), a higher K-feldspar content (25 - 35%), lower plagioclase content (30 - 35 %), and presence of biotite (2 - 10 %), muscovite (3 - 10 %), sillimanite (0 - 10 %) and with tourmaline as the main accessory mineral. In both varieties the quartz content is similar, namely 30 - 35 % and accessory amounts of apatite, opaques (ilmenite) and monazite.

From their mineralogical composition (presence of garnet and/or tourmaline), the Zanskar leucogranites are more comparable with the border facies of the Manaslu leucogranite (Le Fort, 1981) than with the mineral assemblage of the granite itself.

The texture is in general massive and no foliation is present. The grain size of the mainly non-equigranular irregular fabric varies from 1 mm to approximately 3 mm.

The characteristics of the different minerals are the same within the two varieties. Quartz shows intensively serrated contacts and shows undulatory extinction. K-feldspar is very irregularly shaped, anhedral, often penetrated by plagioclase, and frequently with plagioclase and quartz inclusions. Sporadically perthitic K-feldspar is present. Weakly zoned plagioclase

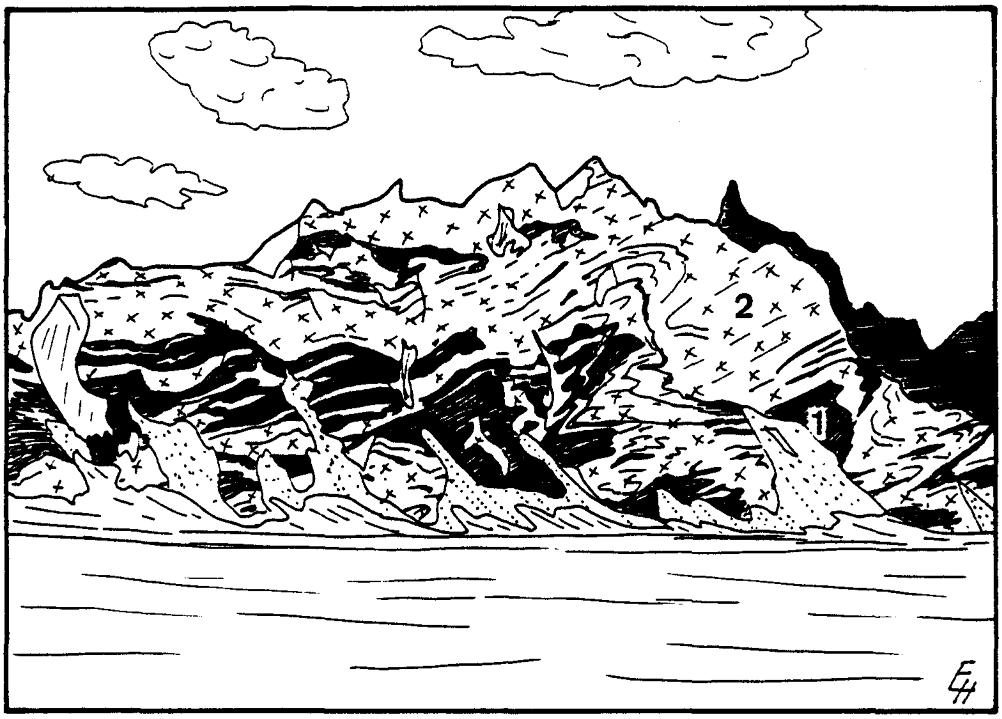


Figure 4.6: Biotite gneisses (1) with intrusions of leucogranites (2) folded together. Upper Haptal Tokpo, view eastwards. The width of the figure correspond to approximately 2 km.

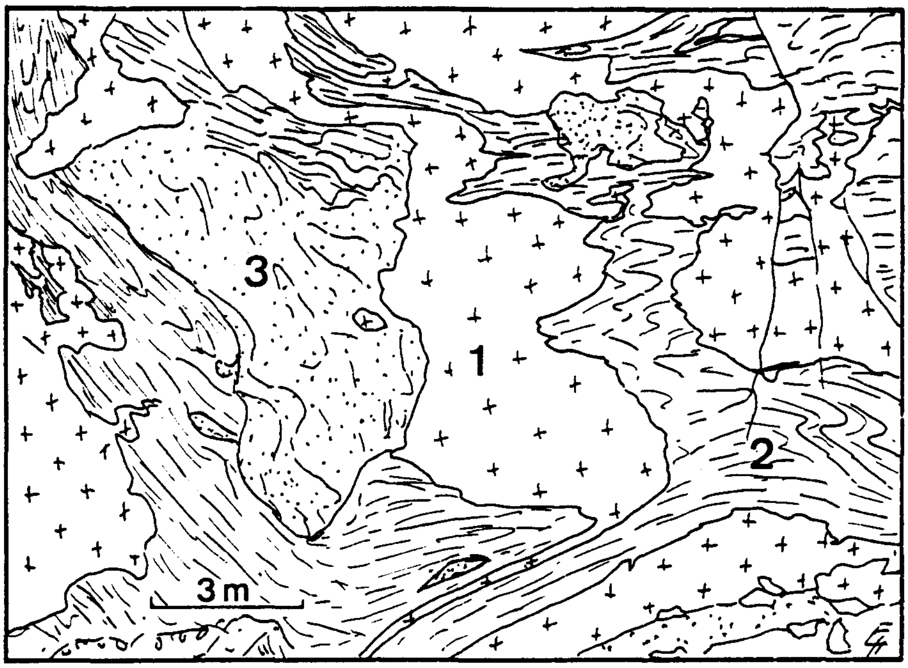


Figure 4.7: Outcrop in the upper Hapal Tokpo showing cuspate - lobate folds of leucogranites (1) within biotite gneisses (2) associated with calcsilicates (3). Samples Z 44 and Z 45 (Fig. 4.5) are taken from this outcrop.

occurs as subidiomorphic grains partly with drop-shaped inclusions of quartz and with inclusions of small mica flakes. The rim of the grains is often free of inclusions. Twins are only sporadically present as are also myrmekitic rims or lobes. The entire intergrowth of quartz, K-feldspar and plagioclase is indicative of an eutectic crystallisation and a magmatic texture.

The muscovite is normally developed as euhedral crystalls, partly as large flakes. Near the main Himalayan Range, in the area of highest metamorphic conditions (Fig. 4.5) the muscovite is partially changed to K-feldspar as a result of regional metamorphism (Fig. 4.8 and chapter 5). In the same area of high metamorphic conditions sillimanite - fibrolite often occurs fringing the muscovite or biotite.

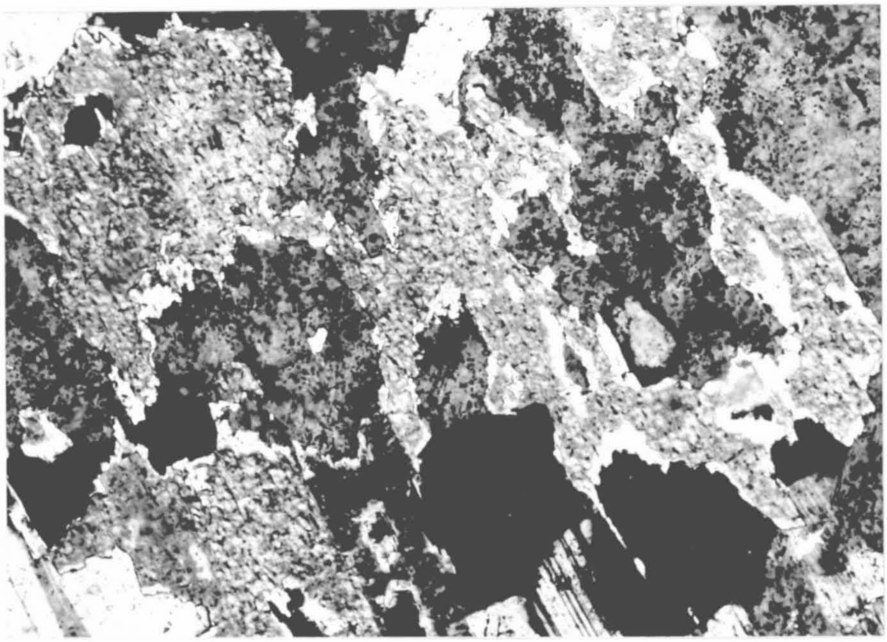


Figure 4.8: Muscovite reacting to K-feldspar within high metamorphic environment (upper amphibolite facies). The width of the figure correspond to 0.8 mm, crossed nicols.

Reddish - brown biotite, sporadically chloritized (plus ilmenite needles), often occurs as fine-grained shreds, partly intergrown with muscovite along (001). Euhedral small flakes of kyanite have been found only in one leucogranitic sample (PO 15) of the Tamasa Tokpo (Fig. 4.5) within amphibolite facies rocks. The grains are partly intergrown with muscovite along (001). The occurence of kyanite is probably dependent on the regional metamorphic grade. But as kyanite is found only within one sample and because this sample (PO 15) seems not to be a really typical leucogranite (chapter 4.4), perhaps this sample is from an intrusion formed during the Cambrian orogenic activity. It is therefore not possible to make a definitive statement of the significance of the occurrence of kyanite. Garnet occurs as euhedral grains of different size from 0.1 mm until 5 mm or even greater. Blue-green and yellow-green tourmaline is irregularly distributed or occurs as isolated aggregates of a few mm or cm size. The fine to coarse grained angular and euhedral fragments can be grouped according to their optical properties mainly as schorl. Within the highest metamorphic environment (Fig. 4.5), drop-shaped quartz inclusions are present and give the tourmaline grains a partial skeletal habit. Chrysoberyl is a characteristic mineral in nearly all samples containing tourmaline and is even abundant (up to 4 %) in some cases. Small euhedral fragments are often intergrown with tourmaline.

The leucogranitic layers on the top of the Zanskar Crystalline unit are affected by the Zanskar shear zone (Fig. 4.5). The sheared and mylonitic features of the texture indicate that these rocks have suffered a deformation after their latest recrystallisation (chapter 7).

4.3 Relative age and mode of intrusion

The leucogranitic layers at the base of the intrusion suite within highest metamorphic conditions (Fig. 4.5) show metamorphic mineral reactions (muscovite reacting to K-feldspar, Fig. 4.8) and metamorphic minerals which indicate that the leucogranites are affected by high T / low P regional metamorphism (chapter 5). They do not show a foliation and are not transformed to gneisses, features which indicate that the regional metamorphic overprint was not accompanied by an overall penetrative deformation. In some areas they are folded together with the biotite gneisses (Figs. 4.6 and 4.7). The folds ("B2 folds") are only locally developed. These cuspate - lobate folds (Ramsay, 1967) illustrate the competent nature of the leucogranites relative to that of the biotite gneisses. The competence contrast, however, is low (Ramsay and Huber, 1987) which is somewhat surprising considering the lithological difference between these two lithologies (foliated biotite gneisses with about 25 percent biotite versus crystalline mica poor leucogranite). Many geologists would have expected that contraction would have led to the development of ptygmatic folds, as a result of a high competence contrast between these two lithologies. The regional P / T conditions and the temperatures of the folded layer must also play a role in this history. It is possible that the high regional temperature may have reduced the competence contrast between these two lithologies. This foldstyle indicates layer parallel shortening which increases layer thickness at the expense of layer length (Fig. 4.7). The absence of a foliation within the granite suggests their intrusion after the main deformation / metamorphic event. As they are folded by a later event and contain assemblages of the high T / low P metamorphism, the leucogranites were probably intruded after the main deformation event, during the high T / low P conditions of the regional metamorphism and before folding of the following event. The leucogranitic layers were already crystallized before folding. The schistosity pattern in and around the fold indicates only slight initial layer parallel shortening and little shortening normal to the fold axial surface (Fig. 4.7, explanation after Ramsay, 1987, p. 465) and the absence of a schistosity associated with the fold within the leucogranitic layer and within the surrounding biotite gneisses. The temperature during folding apppears to have been rather high (e.g. crystallization of sillimanite needles on fold axial surfaces of "B2 folds", Fig. 2.8).

In the upper part of the intrusive bodies, the P / T conditions of the regional metamorphism were too low, or there was no water or other fluids present to produce metamorphic overprinting reactions within the leucogranites. The P / T conditions of the intruded leucogranites within the biotite gneisses, however, were probably not lower than greenschist facies because the Zanskar shear zone formed under middle to low greenschist conditions (chapter 7) and the leucogranites are affected by this shearing event.

Within the main mass of and in the roof of the intrusions, the leucogranites do not show a metamorphic overprint or foliation and they are not folded, not even locally. No cooling rim and no contact metamorphism with the surrounding biotite gneisses has been found.

Within the roof of the intrusion crosscutting dykes are present and suggest that stress conditions led to intrusions of magma into extension fractures. As all this zone has been overprinted by the Zanskar shear zone (chapter 7) no dyke intrusion history can be reconstructed.

4.4 Geochemistry

Eleven leucogranitic samples from the Zanskar area have been chosen for detailed bulk chemical analyses (Table 1). The leucogranites occur in an area of about 1100 km^2 (Fig. 4.5) and the samples are taken from a variety of leucogranitic layers and dykes with some selected from the Zanskar shear zone. The purpose is to show that these analyses show the homogeneity of the rocks even though the localities and geologic positions differ widely and to underline the suggestion that these leucogranites belong to the High Himalayan leucogranitic intrusion sequence described all over the Himalayas. Because no samples are available from the thickest and probably most important leucogranitic layers in the Haptal Tokpo (Fig. 4.5) it is not possible to describe and define the "typical" Zanskar leucogranite. Eight leucogranitic samples from one outcrop near the "Tungri bridge" (Figs. 1.8 and 4.2) have been chosen for detailed bulk chemical analyses by Brouand and Pêcher (Table 2, unpublished data). They are from a 30 m thick sheared tourmaline leucogranitic layer. All of these leucogranites are chemically similar to the leucogranites from Bhutan (Dietrich and Gansser, 1981) and those from Nepal (Le Fort, 1981; Vidal et al., 1982; and Le Fort et al., 1987), and show no significant chemical variation. They are aluminium rich granites: with SiO_2 between 73.7 and 75.5 wt.% (72.4 and 75.4 wt %, Brouand and Pêcher) and Al_2O_3 between 14.2 and 15.3 wt.% (13.8 and 15.6 wt %, Brouand and Pêcher) respectively.

The analyses of the major elements are presented in three Debon and Le Fort (1983) chemical - mineralogical diagrams (Fig. 4.9) and their data compared with the analyses of the Manaslu leucogranite (Le Fort et al., 1987).

Table 1: Bulk chemical compositions of selected leucogranites from Zanskar (Fig. 4.5).

Sample No.	Z38	Z44	Z45	Z129	Z139	Z369	Z377	P015	P032	UM62	UM77
Major elements [Wt.-%]											
SiO2	74.54	73.67	74.00	74.56	73.70	74.36	74.75	75.00	75.50	75.40	74.55
TiO2	0.08	0.22	0.02	0.04	0.04	0.06	0.03	0.04	0.05	0.07	0.04
Al2O3	14.83	14.22	14.80	15.17	15.22	14.36	14.70	15.11	14.52	14.16	14.43
Fe2O3	0.20	1.62	0.14	0.54	0.78	0.39	0.13	0.08	0.21	0.52	0.05
FeO	0.40	0.15	1.15	0.01	0.25	0.20	0.90	0.65	0.25	0.02	0.45
MnO	0.02	0.02	0.19	0.01	0.08	0.02	0.08	0.05	0.02	0.01	0.03
MgO	0.02	0.18	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
CaO	0.88	1.43	0.75	0.46	0.53	0.48	0.41	0.67	0.68	0.60	0.75
Na2O	3.60	3.33	2.55	4.86	4.18	3.60	3.96	2.80	4.07	2.68	2.57
K2O	4.82	4.06	4.02	3.57	4.01	4.34	4.67	4.86	4.01	5.59	5.98
P2O5	0.16	0.12	0.10	0.18	0.19	0.22	0.18	0.18	0.20	0.20	0.14
H2O	0.35	0.28	0.34	0.40	0.43	0.60	0.07	0.47	0.31	0.57	0.20
CO2	0.05	0.06	0.05	0.04	0.06	0.03	0.03	0.05	0.04	0.04	0.04
Total	99.95	99.36	98.13	99.86	99.49	98.68	100.51	99.98	99.88	99.88	99.25
Trace elements [ppm]											
Ba	177	10	70	116	39	105	<10	81	213	84	364
Rb	236	282	143	233	320	228	269	218	196	224	164
Sr	82	24	34	52	28	36	<15	50	74	64	60
Pb	52	62	61	51	35	33	28	33	68	46	51
Th	<5	9	<5	<5	<5	<5	<5	<5	<5	<5	<5
U	<10	27	<10	<10	<10	<10	<10	<10	<10	<10	<10
Nb	8	16	<4	<4	<4	<4	7	4	5	5	<4
La	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Ce	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15
Nd	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25
Y	24	20	7	7	14	13	9	12	11	7	9
Zr	34	32	23	25	30	26	14	26	20	20	16
V	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Cr	<6	<6	<6	<6	<6	<6	<6	<6	<6	<6	<6
Ni	<3	3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Co	12	28	4	6	16	16	6	11	15	6	4
Cu	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Zn	17	26	<7	43	58	7	26	13	20	<7	<7
Ga	17	17	9	12	16	10	13	10	11	10	11
Sc	3	<2	<2	<2	<2	<2	<2	<2	2	3	<2
S	<50	<50	<50	<50	<50	<50	<50	<50	<50	854	<50

Table 2: Bulk chemical compositions of leucogranites from one outgrop in Zanskar (Fig. 4.5). Analysed by Brouand and Pêcher in CRPG, Nancy (unpubl. data).

Sample No.	MB 49	MB 50	MB 51	MB 52	MB 53	MB 54	MB 55	MB 56
Major elements [weight %]								
SiO2	72.99	73.14	72.41	75.39	73.02	74.64	72.70	73.65
TiO2	0.12	0.16	0.10	0.06	0.08	0.06	0.03	0.05
Al2O3	15.22	15.58	15.29	13.81	14.86	14.36	14.96	15.21
Fe2O3	0.67	0.79	0.94	0.40	1.03	0.68	0.89	0.74
MnO	0.04	0.03	0.04	0.04	0.05	0.03	0.04	0.04
MgO	0.03	0.03	0.17	0.00	0.23	0.23	0.00	0.00
CaO	0.43	0.50	0.41	0.26	0.48	0.42	0.46	0.45
Na2O	4.19	4.01	4.30	4.57	4.14	4.20	4.36	4.22
K2O	4.32	4.54	4.21	4.13	3.99	4.40	4.13	4.20
P2O5	0.21	0.22	0.14	0.15	0.17	0.23	0.22	0.21
I.L.	0.77	0.81	1.22	0.32	0.80	0.50	0.77	0.73
Total	98.99	99.81	99.23	99.13	98.85	99.75	98.56	99.50
Trace elements [ppm]								
Ba	211	232	165	77	116	110	168	171
Rb	297	305	309	289	321	293	326	321
Sr	107	105	92	52	51	43	108	98
V	14	<10	<10	<10	22	<10	11	<10
Co	<10	<10	<10	<10	10	<10	<10	<10
Cr	11	<10	<10	<10	11	<10	<10	<10
Cu	<10	<10	<10	<10	<10	<10	<10	<10
Ni	<10	<10	<10	<10	<10	<10	<10	<10

In the "nomenclature" diagram (Fig. 4.9a) the Manaslu samples are centered on the adamellite sector. The extensions of the contoured field towards the granodiorite and granite sectors reflect the variability of the Na / K ratio. The variation of the Zanskar samples is greater. Figure 4.10 shows a negative correlation between the sodium and potassium oxides, the sum (Na_2O + K_2O) varying only slightly between 8 and 8.5. The results from Zanskar show a greater variation (varying in general between 7.9 and 8.6) but they fit well with those of Nepal of the Manaslu granite (Le Fort, 1981; Vidal et al., 1982).

In the "characteristic minerals" diagram (Fig. 4.9b), the Manaslu and also the Zanskar samples form an aluminium rich and very leucocratic association.

In the Q - B - F diagram (Fig. 4.9c) all samples correspond to a quartz - poor association.

Three samples (Z 44, Z 45, and PO 15) do not fit well with the results from the Manaslu leucogranite (presented in brackets, Figs. 4.9a - c and 4.10). They show e.g. a smaller sum of the sodium and potassium oxides (varying between 6.57 and 7.66, Table 1) than normal and in Figures 4.9a and 4.10, the data does not coincide with that from the Manaslu samples. Z 44 has an exceptionally high value for Ca, therefore it is in Figure 4.9a in the same range as the other samples (only two samples presented in brackets). Z 44 and Z 45 are the samples taken from an outcrop in the Haptal Tokpo (Figs. 2.7, 4.5 and 4.7) where calcsilicates are folded together with biotite gneisses and leucogranites. Because of element redistributions during folding they might not represent a characteristic leucogranite. PO 15 is a very strongly sheared sample and perhaps also does not fit well with the other samples for this reason. Samples UM 62 and UM 77 show very high potassium values in contrast to the low sodium values, therefore in Figure 4.9a they fall in the granite sector, right of the abscisse.

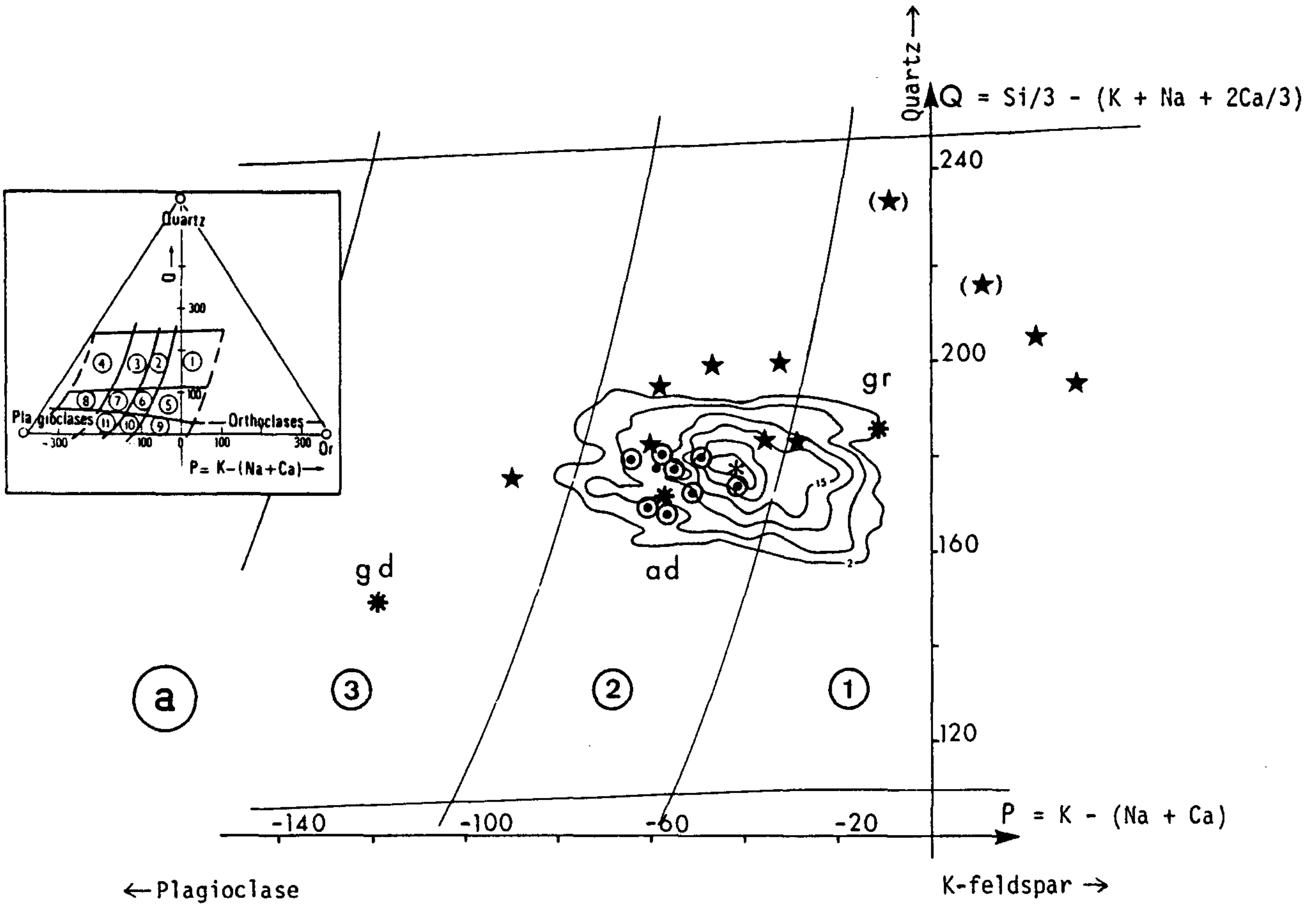


Figure 4.9: The chemical composition of the Zanskar leucogranites (stars; new samples described in this Dissertation; circles: Brouand and Pêcher) in comparison with the Manaslu granite (Le Fort et al., 1987; 284 analyses presented as density curves) presented in the three chemical - mineralogical diagrams of Debon and Le Fort (1983).
a: Nomenclature diagram. Its parameters are expressed as gram-atoms x 10^3 of each element in 100g of rock. Abbreviations for the inset: 1 (gr) granite, 2 (ad) adamellite, 3 (gd) granodiorite, 4 (to) tonalite (trondhjemite), 5 (sq) quartz syenite, 6 (mzq) quartz monzonite, 7 (mzdq) quartz monzodiorite, 8 (dq) quartz diorite (quartz gabbro = quartz anorthosite), 9 (s) syenite, 10 (mz) monzonite, 11 (mzgo) monzogabbro (monzodiorite), 12 (go) gabbro (diorite - anorthosite). The two stars in brackets are sample Z 45 and PO 15. The six branch star is the average point for the Manaslu leucogranite. The contours are for 2, 5, 10, 15, 20 and 25 samples in an area of 1.4 x 0.7 units.

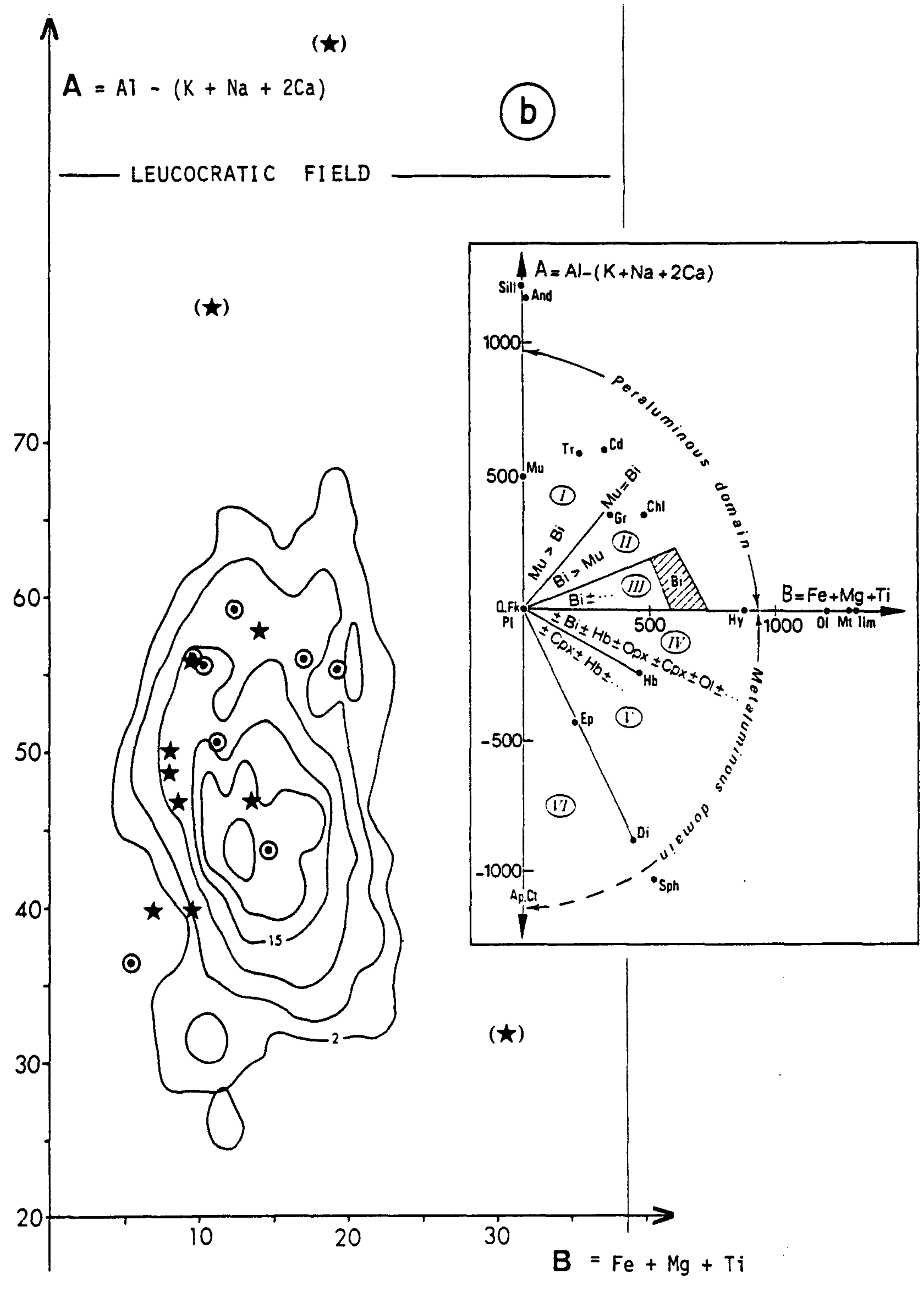


Figure 4.9b: Characteristic minerals diagram. The two parameters are in gram-atoms x 10^3 in 100g of rock. The A parameter is a classical index of the more or less aluminous character of igneous rocks. The B parameter is proportional to the content by weight of dark minerals in granitoids. Only the peraluminous leucocratic field is shown. Contours as in Fig. 4.9a, area 3 x 1.5 units. The vertical line at B = 38.8 represents the upper limit of the leucocratic field. The following minerals have been plotted in the inset, using actual theoretical compositions: And = andalusite, Ap = apatite, Bi = biotite (hatched field), Cd = cordierite, Chl = chlorite, Ct = calcite, Di = diopside, Ep = epidote, Fk = K-feldspar, Gr = pyralspite, Hb = hornblende, Hy = hypersthene, Ilm = ilmenite, Mt = magnetite, Mu = muscovite, Ol = olivine, Pl = plagioclase, Q = quartz, Sill = sillimanite, Sph = sphene, Tr = tourmaline.

Sample Z 44, Z 45 and PO 15 shows distinct deviation and are therefore presented in brackets.

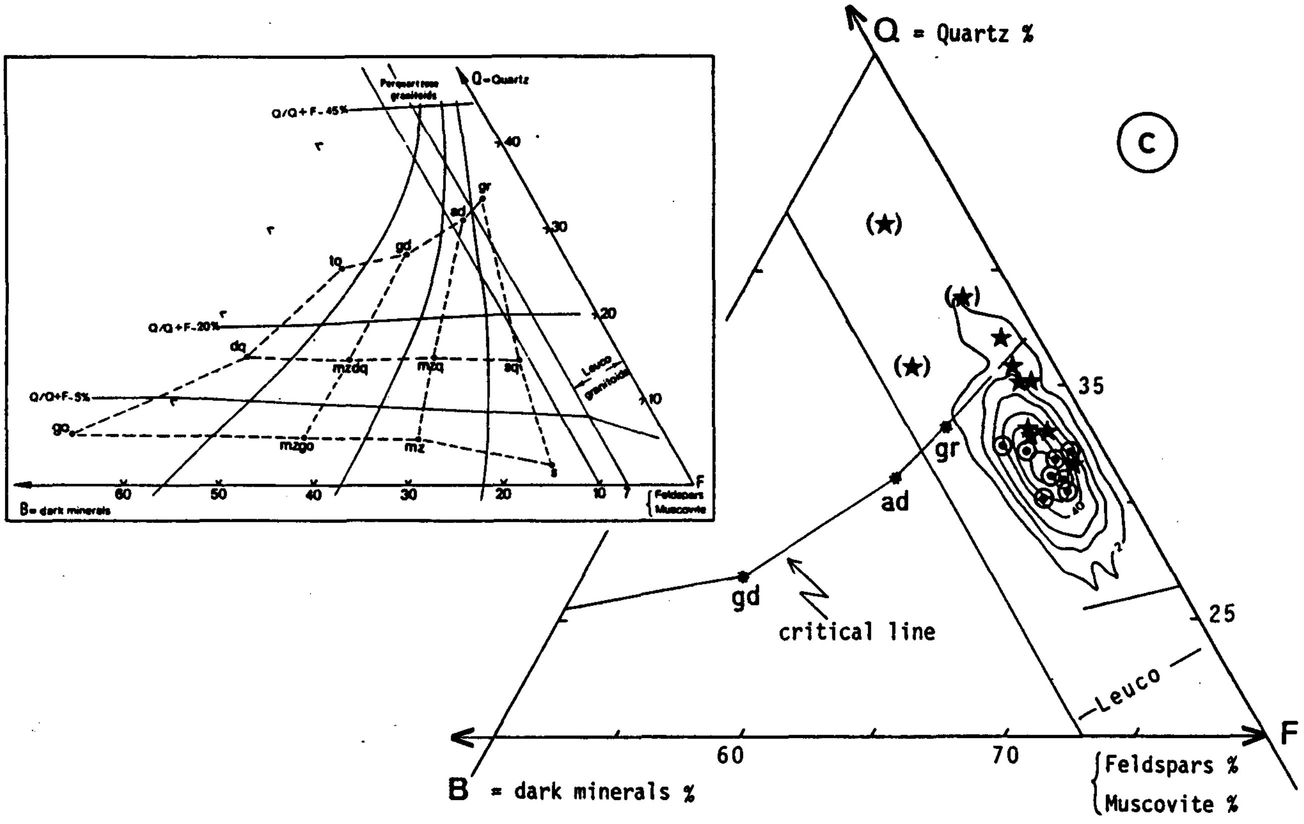


Figure 4.9c: Q (quartz) - B (dark minerals) - F (feldspar and muscovite) triangular diagram. Parameters in weight percent directly calculated from chemical analyses. The critical line passing through the tonalitic to granitic reference points is shown; it discriminates the three main subtypes of aluminous associations, into quartz-rich, normal and poor subtypes (accordingly located above, on or below the "critical line"). Again sample Z 44, Z 45 and PO 15 (in brackets) shows distinct deviation from the other samples, they fall in the field of the quartz-rich subtypes whereas the others, however, fall into the quartz poor field. Contours for 2, 10, 20, 40, 60, and 80 samples in an area of 1.4 x 0.7 units. Abbreviations for the inset as in Fig. 4.9a.

4.9a they fall in the granite sector, right of the abscisse. The sum of these two oxides is still in the same order as the other samples (Fig. 4.10). These two samples are taken from the Zanskar shear zone.

Results of the analyses made by Brouand and Pêcher (unpublished data) are also presented in the same three Debon and Le Fort (1983) chemical - mineralogical diagrams (Fig. 4.9). Because the samples were collected from only one outcrop, the analyses shows smaller variations than my own. Only within the "characteristic minerals diagram" (Fig. 4.9b) are the variations of the same order of magnitude as my own analyses. Also in Figure 4.10, showing the negative correlation between Na_2O and K_2O the variation of the results are very small, they are directly comparable with the Manaslu samples.

The Zanskar leucogranites are, in general, comparable with the other High Himalayan leucogranites. They correspond to homogeneous association varying only in their Na vs K content.

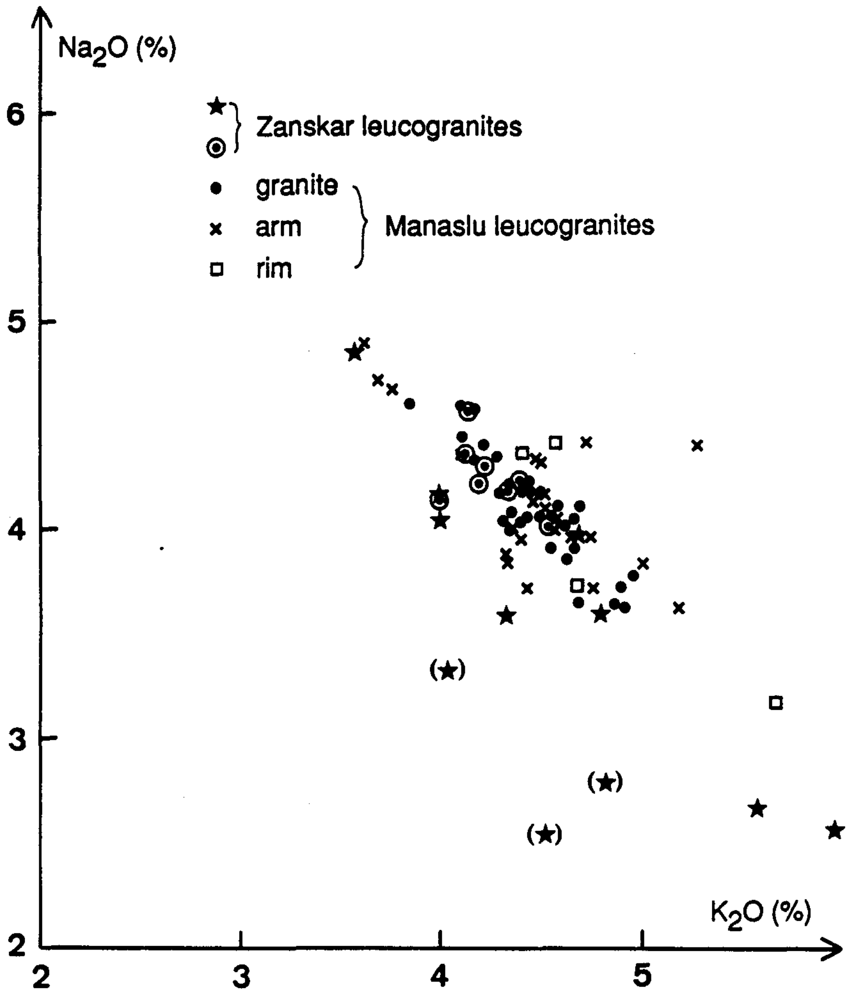


Figure 4.10: Na_2O versus K_2O (weight percent) diagram for the Zanskar leucogranites in comparison with the Manaslu leucogranites (Le Fort, 1981; and Vidal et al., 1982) showing the negative correlation between the two oxides. The sum remains more or less constant. For the Manaslu leucogranite there appears no important difference between the granite itself, the Chhokang arm, or the rim facies. My Zanskar samples (stars) shows a greater variation, the others, (Brouand and Pêcher, circles) however, fit very well with the Manaslu samples.

The chemical composition of the Zanskar leucogranites has been compared with the average chemical composition of the Bhutan leucogranites (Dietrich and Gansser, 1981; 17 samples, Table 2). Figure 4.11 shows the most important major and trace elements (normalized) of the Bhutan leucogranites. The mean standard deviation is indicated by the stippled area. The average chemical composition including the standard deviation (hatched area) of the Manaslu leucogranite (Le Fort et al., 1987) is shown on the same figure and shows no great deviation. As the geochemical analyses of the Bhutan and the Zanskar leucogranites were carried out on the same elements and by the same analytical techniques it seems reasonable to compare them.

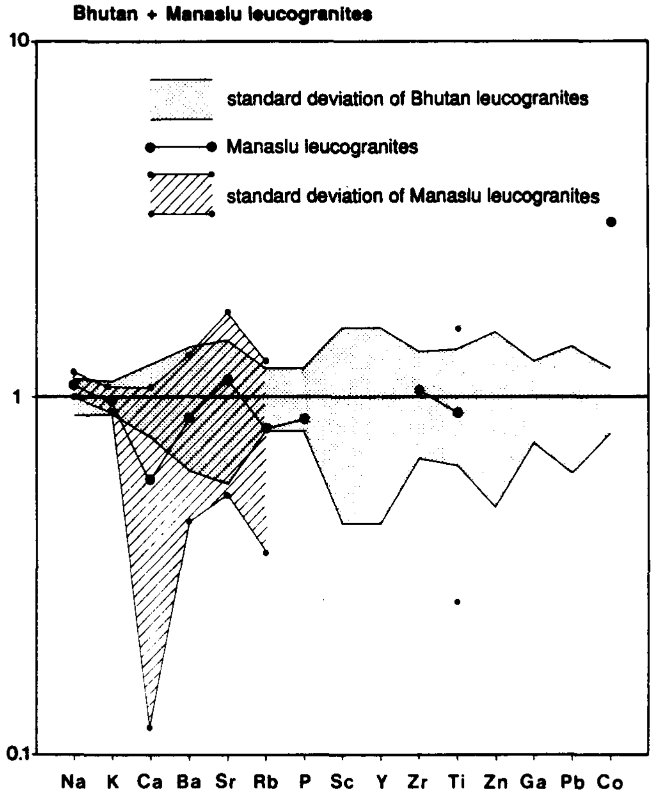


Figure 4.11: Bhutan leucogranite - normalized diagram for the most important major and trace elements (17 samples). The mean standard deviation is indicated by the stippled area (values compare Table 2 of Dietrich and Gansser, 1981). The average chemical composition of the Manaslu leucogranite (Le Fort et al., 1987) including the standard deviation is indicated by the hatched field.

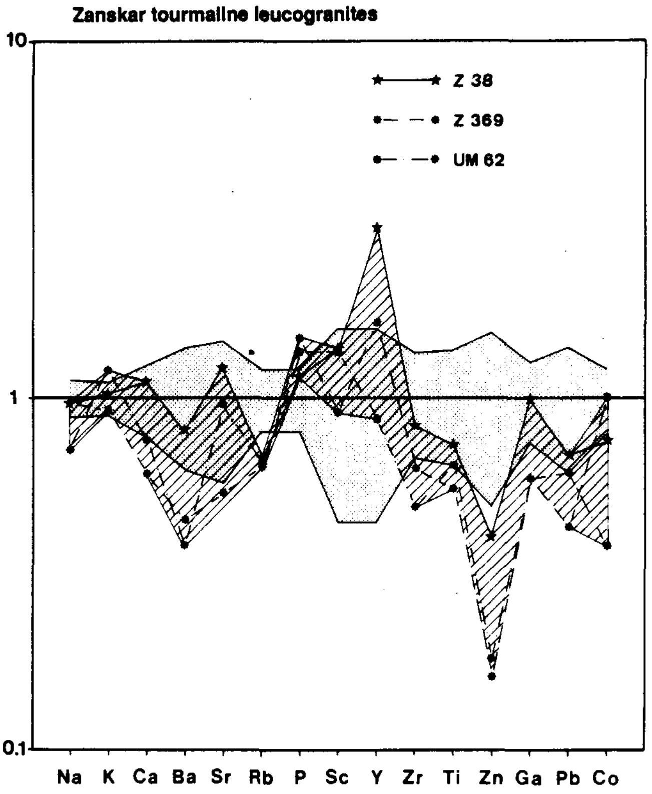


Figure 4.12: Bhutan - normalized element pattern for the Zanskar tourmaline-bearing samples.

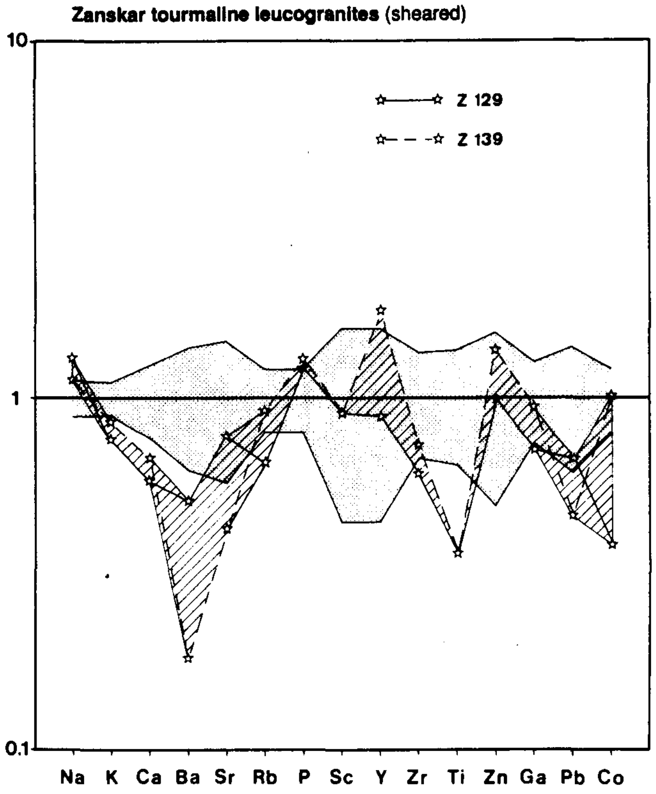


Figure 4.13: Bhutan - normalized element pattern for the sheared Zanskar tourmaline-bearing samples.

The tourmaline-bearing varieties (Fig. 4.12) are low in Ba, Rb, Zr, Zn, and Pb in comparison with the Bhutan samples. The dykes show a trend of low concentrations in most of the investigated elements, but do not show an overall significantly different element distribution. The sheared tourmaline leucogranites (Fig. 4.13) in comparison to the Bhutan samples, however, are strongly depleted in Ba and also in Ti. In addition, the K content is smaller. The Zn, in the unsheared varieties (see above) is the most depleted element (Fig. 4.12), whereas in the sheared samples it remains with the same range as the Bhutan samples. Sr is more depleted than Rb.

The garnet-bearing samples can be divided into biotite rich samples (Fig. 4.14) and those without biotite (Fig. 4.15). Within the former, Ca, Ba, Sr are in the same range as the Bhutan samples, only Rb, Zr, Ti and Zn are depleted. In the latter, however, Ba, Sr, Pb and Co are also depleted. Ti is also much more depleted. Ba, Sr and Ti are elements found in biotite which possibly explains the difference between these two diagrams. The sheared samples as well as the dykes do not show a distinct different trend. In general the biotite content is less within the Zanskar samples than within the other described High Himalayan leucogranites (Le Fort, 1981; Le Fort et al., 1987; and Dietrich and Gansser, 1981).

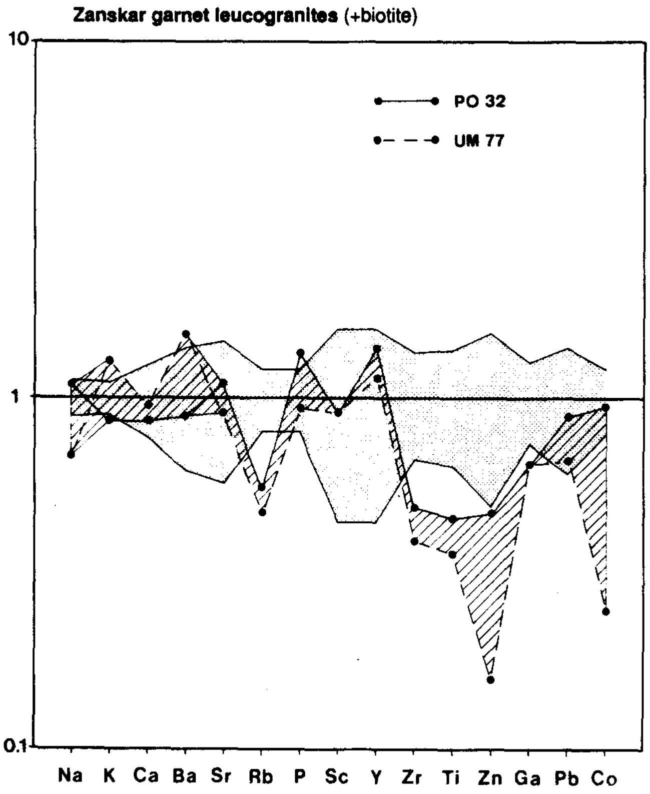


Figure 4.14: Bhutan - normalized element pattern for the Zanskar garnet-bearing (including biotite) samples.

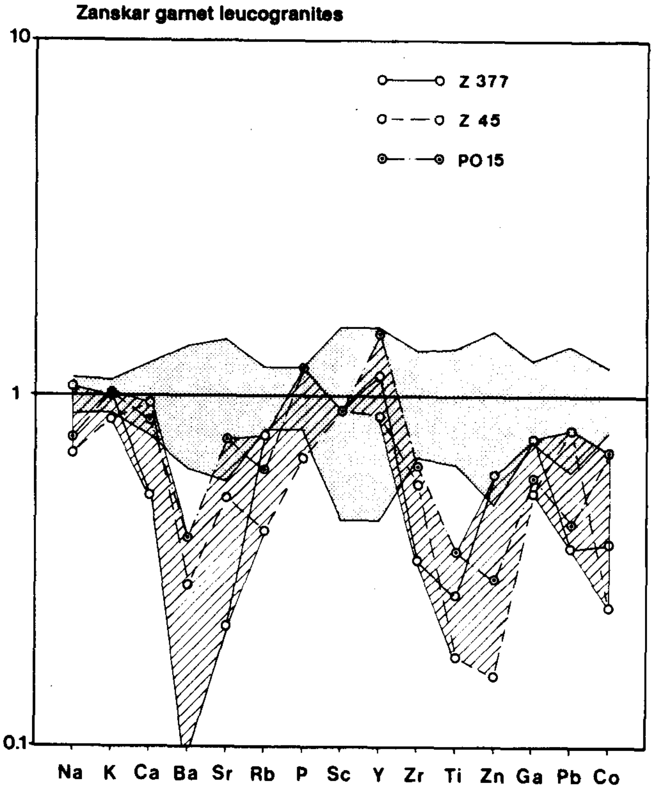


Figure 4.15: Bhutan - normalized element pattern for the Zanskar garnet-bearing samples.

All this discussion (Figs. 4.11 until 4.15) has been presented in order to better understand and explain the concentrations of the major and trace elements of the leucogranites. The number of analyses is very small, therefore further work is needed to verify this discussion.

As already mentioned, the petrography (chapter 4.3) of the Zanskar samples is more similar to the border facies and dykes of the Manaslu leucogranite (Le Fort, 1981) than to the core of this body. A comparison with the Bhutan leucogranites shows similar contrasts.

Within the Kashmir - Suru - Warwan - Kishtwar - Zanskar area other leucocratic rocks are present. These are two mica granite gneisses, pegmatites, and aplites. The question is whether it is possible to distinguish them from the "real" leucogranites. Field evidence is often not sufficient, especially for the dykes, in areas where no associated leucogranitic layers are present. Geochemical analyses gives a possible approach to solve the problem of whether a leucocratic rock is a young typical leucogranite or whether it belongs to another older intrusion sequence. The Bhutan as well as the Zanskar leucogranites have been compared with samples from the Suru region (V. Trommsdorff, unpublished data). These rocks show distinct differences. The analyses of light two-mica granite gneisses (Fig. 4.16) illustrates a great enrichment of Ca, Ba, Sc, Y, Zr, Ti, and Zn in comparison to Bhutan as well as to the

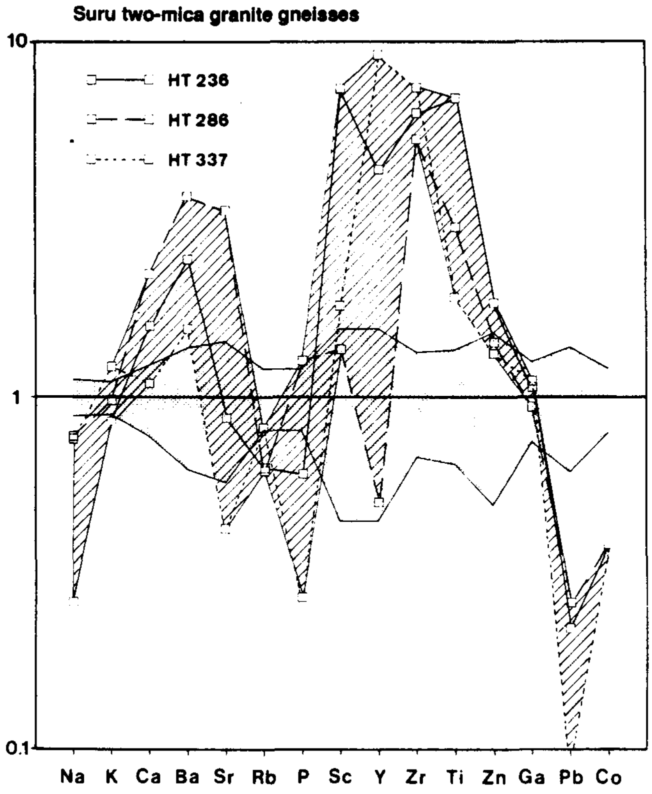


Figure 4.16: Bhutan - normalized element pattern for the Suru two-mica granite gneiss samples (V. Trommsdorff, unpublished data).

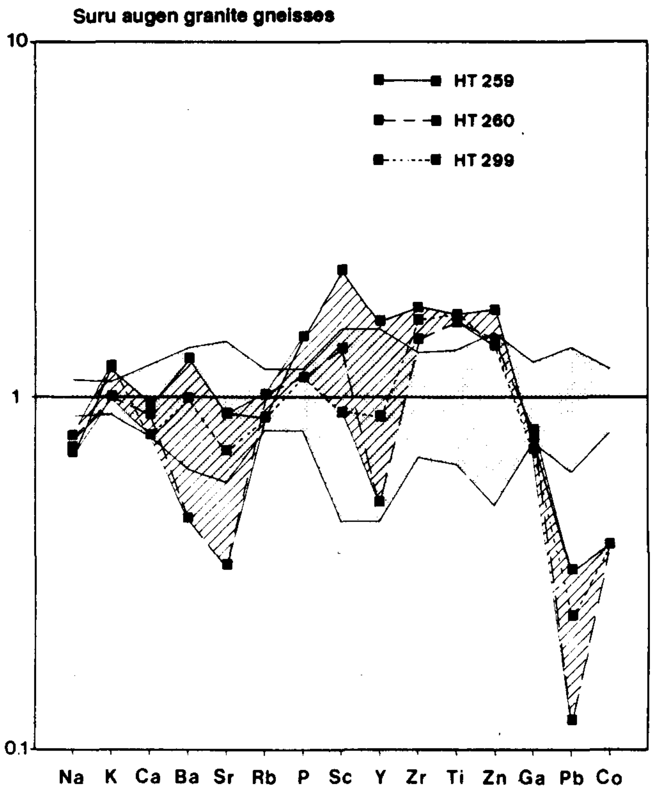


Figure 4.17: Bhutan - normalized element pattern for the Suru two-mica augen granite gneiss samples (V. Trommsdorff, unpublished data).

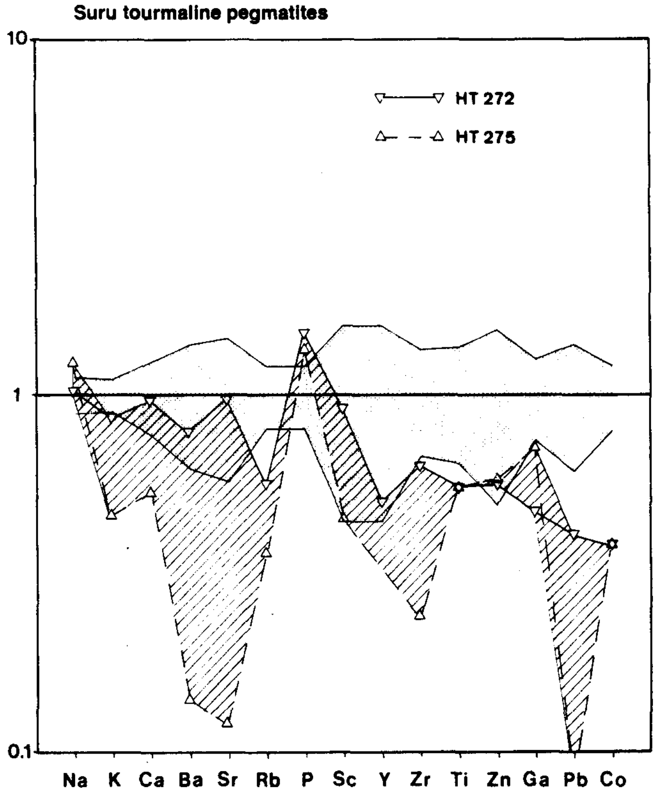


Figure 4.18: Bhutan - normalized element pattern for the Suru tourmaline pegmatite samples (V. Trommsdorff, unpublished data).

Zanskar leucogranites. The content of Na is less which indicates less plagioclase. The Pb content is also less. The analyses of two-mica augen granite gneisses (Fig. 4.17, from the Rangdum area, Fig. 1.8) shows also a higher content of Sc, Zr, Ti, and Zn, but not of Ca and Ba. Again the Na and also the Pb content is less. There are little differences between the analyses of tourmaline pegmatites from the Suru region (Fig. 4.18) and the tourmaline leucogranites of Zanskar. For example TH 272 is only distinguishable from the Zanskar tourmaline leucogranites (Figs. 4.12 and 4.13) by its low Y content. Compared with garnet leucogranites (Fig. 4.15), however, it shows a normal Y content. Whether this sample is therefore a young pegmatite or whether the geochemical analyses is insufficient to distinguish between the old and young pegmatites has not been resolved. More field investigations as well as more geochemical analyses are needed.

Analyses of leucogranites and associated metasedimentary rocks (biotite gneisses) made by Searle and Fryer (1986) from the Zanskar, Kulu, and Lahoul area, have been compared with the analyses of leucogranites, two-mica granite gneisses and augen granite gneisses of the Zanskar and Suru region (Figs. 4.12 to 4.18). Only four samples of the 9 analysed samples fit more or less together with the Zanskar leucogranites. The other five samples correspond to the two-mica granite gneisses from the Suru region (Fig. 4.16). These analyses suggest that the rocks investigated are from two different granite types (two-mica granites (Cambrian) and High Himalayan leucogranites (Miocene)) and not only from the High Himalayan leucogranites and their associated metasedimentary rocks as Searle and Fryer (1986) suggested.

4.5 Generation and emplacement of the High Himalayan leucogranites

From detailed work of the Manaslu granite in Nepal and of other plutons a model has been proposed for the generation and emplacement of the Himalayan leucogranites by Le Fort (1975, 1981, 1986); Vidal et al. (1982) and Le Fort et al. (1987): "This model associates thrusting on a continental scale along the MCT, generation of inverted metamorphism, liberation of large quantities of fluid and anatectic melting of the crust. Thrusting along the MCT brings hot portions of the deep continental crust, the Tibetan Slab (High Himalayan crystalline), over little metamorphosed Midland formations (Lower Himalaya in Nepal). This continuous process heats the Midlands from top to bottom and induces the synkinematic inverted metamorphism. In turn, dehydration and decarbonation metamorphic reactions within the Midlands release a large amount - several weight percent - of fluids that rise above the MCT. In the portion of the Tibetan Slab that is hot, these fluids induce partial anatexis and produce melts close to minimum melt compositions. This melt is emplaced at high levels, at the top of the Tibetan Slab, at the disharmonic limit between the infrastructure (High Himalayan crystalline) and the superstructure (Tethys Himalaya)" (Le Fort et al. (1987)).

Geochemical investigations (mostly done on samples of the Manaslu granite) have been used to improve this model (e.g. Vidal et al., 1982; Cuney et al., 1984; Le Fort et al., 1987 and France - Lanord, 1987). The characteristics are the following (after Le Fort et al., 1987): The major elements indicates a very homogeneous, aluminous very leucocratic (Fig. 4.9b) and quartz-poor association (Fig. 4.9c) (adamellite, Fig. 4.9a) and vary only in their Na vs K content (Fig. 4.10). The trace elements fit well with the hypothesis that the leucogranites are generated from the Tibetan Slab (High Himalayan crystalline). The Pb isotopic characteristics (Vidal et al., 1982) are also comparable with Formation I of the Tibetan Slab, the rocks invoked as the source of the leucogranites. A 25 Ma U-Pb age has been obtained on monazite from a sample of the central part of the Manaslu (Deniel, 1985). Rb-Sr systematics: The initial ^{87}Sr / ^{86}Sr ratios are very high and indicate a remelting of crustal rocks. They are also heterogeneous (most lie between 0.74 and 0.78). Whole rock isochron ages have generally not been determined because of initial heterogeneity (insufficient mixing of the generated magma) and the young ages of formation (Vidal et al., 1984). Until now only one whole rock age of 18.1 Ma has been obtained on a 100-m long outcrop of the Manaslu pluton (Deniel at al., 1983). Comparing this figure with the 25 Ma age (U-Pb) age it appears that the magmatic activity lasted for at least 7 Ma (Deniel, 1985). A number of younger Rb-Sr mineral ages have been obtained on various plutons; they mainly range from 14 to 20 Ma and support the K-Ar mineral ages. The ^{87}Sr / ^{86}Sr initial ratios also fit well with Formation I of the Tibetan Slab (Deniel, 1985). Sm-Nd systematics: Very low ^{143}Nd / ^{144}Nd initial ratios and very heterogeneous and strongly negative Nd isotopic compositions (ε_i Nd from -13 to -17) suggest a remelting of old continental crust (Allègre and Othman, 1980). The measured Nd isotopic ratios are directly comparable to those measured in the Formation I gneisses (Deniel et al., 1983, 1985; Vidal et al., 1984). Stable isotopes: The oxygen isotope compositions are strikingly uniform and show particularly high whole rock $\delta^{18}O$ values: from 11.0 to 14 ‰ for most samples (Blattner et al., 1983; Sheppard et al., 1983; Vidal et al., 1984; Ferrara et al., 1985; Debon et al., 1986; and France-Lanord, 1987). The high $\delta^{18}O$ value of the granite support an origin of the granites by anatexis of continental basement and probably implies a sedimentary pelitic bearing source for the magma. This result is compatible with Formation I of the Tibetan Slab being the source material. All these observations implies an origin of the leucogranites from anatectic melting of crustal material.

There is no controversy in the literature on these conclusions. The French group (e.g. Le Fort et al., 1987) supports the proposed model by geochemical analyses and have suggested that the lower part of the High Himalayan crystalline (Tibetan Slab in Nepal) is the source material for the generation of leucogranites. Their conclusions fit well with their proposed model.

From a geophysical point of view (Molnar et al., 1983), there is not enough data available to prove the "French" model. The problem is that in only a few of million years the "sawtooth" geotherm, created by overthrusting along the Main Central thrust, would disappear (Molnar et al., 1983, Fig. 3). Within this short time, while the geotherm relaxes (decrease of temperature below levels where anatectic melting is possible) an inverse prograde metamorphism within the units below the thrust fault should occur. This process would liberate fluids which are necessary to reduce the melting temperature of this crustal source region and produce the leucocratic magmas.

Molnar et al. (1983) have shown that temperatures reach the solidus for granite melts by various plausible combinations of parameters and these deductions include the possibility of no shear heating (a situation that requires frictional stresses of 100's of MPa on the MCT). This variety of different possible combinations of physical parameters exist because of the uncertainties in the age of the granites, in the depth at which they formed, in the amounts of heat flux supplied to the base of the lithosphere and in the amount of radiogenic heat production in the crust and in the value of the coefficient of thermal conductivity. In other words, geophysical considerations and calculations made by Molnar et al. (1983) are unable to constrain more precisely the "French" model.

The recent work of France-Lanord (1987), however, supports very well the "French" model. His stable isotopic studies in Nepal of the units below (Lower Himalaya, Midlands) and above (Higher Himalaya, Formation I) the Main Central Trust (MCT) as well as of the Manaslu granite itself shows clear evidence for Formation I being the source rocks for the leucogranite. The chemical features of the Midlands Formation seem to preclude major infiltration and circulation of fluids as the schists are dehydrated (2 to 5 wt % H_2O). These liberated fluids appear to be controlling factor enabling melting to proceed in the heated

Formation I above the MCT. The stable isotopic situation within this Formation is quite similar to that seen in the Manaslu granite, but it differs from the underlying Midlands Formation, e.g. due to the fact that these units are probably older than those above the MCT.

Another argument against the geophysical arguments is the fact that the high temperatures at the base of the overthrust Higher Himalayas are due to regional metamorphism, and not directly related to frictional heating generated by thrusting. The "sawtooth" geotherm after thrusting will not relax in such a way as it is suggested by Molnar et al. (1983). The heating of the units below the thrust should be much greater than the cooling above it, features which indicate that such a sudden decrease of the temperature within the base of the Higher Himalayas is insufficient to allow anatectic melting.

Jaupart and Provost (1985) point out that the thermal conductivity of sedimentary rocks is usually much lower than that of crystalline rocks. Sedimentary layers within overthrusted large - scale thrust sheets (as the Higher Himalaya) would therefore act as a barrier to transport of heat. A temperature maximum would develop at the basement - sedimentary interface and this might explain the occurence of the leucogranites at the top of the basement slab. These leucogranites, however, are not generated in situ at the top of the crystalline unit but have been remobilized as indicated by field evidence (no restites, or only small occurences, around leucogranites; leucogranites crosscutting older structures; leucogranites intruded within already deformed, metamorphic terrain or intruded within folded Mesozoic units). The thermal barrier of the sedimentary sequence may, however, be the reason why the young leucogranites cannot intrude easily into higher levels within sedimentary sequences and why they are confined to a narrow zone at the top of the High Himalayan crystalline (Fig. 4.1).

4.6 Conclusions

From geological, petrographic and geochemical points of view the Zanskar leucogranites are comparable with the other High Himalayan leucogranites. They are therefore interpreted to be of Miocene age. However, they are rather similar to the border facies of the greater granite bodies e.g. the Manaslu pluton of Nepal. The small differences in chemical compositions may be due to the fact that the source material for the Manaslu granite (probably Formation I gneisses of the Tibetan Slab) is not directly comparable with that of the Zanskar leucogranites. In the wider Kishtwar region geochemical investigations which might better define a probable source material have not yet been carried out. The geological environments (e.g. dome structures, Kündig, in review, a) of this region are more complicated than those of Nepal where the High Himalayan crystalline is easily divided into three unfolded formations. The greater scattering of the geochemical analyses of the Zanskar samples may be due of the choice of the analysed samples. Because the field work was not done with any special focus on the leucogranites, the collected samples indicate small variations of the leucogranites which does not seriously counter the general mineralogical and geochemical homogeneity of the leucogranitic types.

The amount of leucogranites in the Zanskar - Suru - Kashmir - Kishtwar area is very small compared with the great granite bodies of the eastern part of the Himalayas. Volumetrically, there are not so many leucogranites present as Searle and Fryer (1986) suggested. The correlation that has been proposed between thickness of underlying Tibetan Slab and occurrence of leucogranitic plutons (Le Fort et al., 1987) does not appear to be valid in NW Himalaya. In Nepal where Formation I of the Tibetan Slab is thickest, and where the metamorphism is high, migmatization is wide-spread and the several kilometres thick Manaslu pluton occurs above the migmatite zone. In the region discussed in this Dissertation, however, the High Himalayan Crystalline is also very thick (Fig. 1.5), the metamorphism is very high (chapter 5) and migmatization is wide-spread. In spite of the very deep levels of the High Himalayan crystalline exposed here (chapter 5 and 7), only a few leucogranitic occurences are present. These occurences are limited to the regions of deepest exposed levels of the Zanskar Crystalline unit. Perhaps the small occurrences of leucogranites here could be due to gathering of the magma in layered bodies which were subsequently eroded. To explain these facts we need more investigations of the entire Higher Himalayan crystalline within this part of the Himalayas.

The Zanskar leucogranites seem to be unusual in their occurences in the deep levels of the High Himalayan crystalline. The folding that occured within the leucogranites seems also rather special. Only in the Lhotse area (Nepal) have large scale recumbent folds in leucocratic granite bearing rocks been described (Bortolami et al., 1976). On top of the intrusion sequence, however, the Zanskar leucogranites reach only the base of the Tethys Himalaya, the Precambrian - Cambrian Phe Formation.

5. Regional Metamorphism

Within the studied area the rock units have been affected by a Barrow-type regional metamorphism. Mineral assemblages in widely distributed metapelitic rocks were investigated in detail in order to establish the facies variations of the regional metamorphism. Figure 5.1 illustrates the metamorphic isograds of the metapelites in the Suru - Warwan - Kishtwar area (Honegger, 1983) and in the Zanskar region. In W Ladakh the metamorphic grade in general increases gradually from the Indus Suture zone in the north towards the south and reaches the highest grade of metamorphism near the main Himalayan Range in the central parts of the Higher Himalayas. Continuing towards the south, the metamorphic grade decreases and becomes inverted within the Lower Himalaya. In the Suru region (Fig. 5.1, left) Permo - Triassic rocks are strongly and recumbently folded within the Zanskar Crystalline unit. The isograds crosscut these structures indicating a Himalayan age for the metamorphism (Honegger et al., 1982). The cooling history has been dated by Rb / Sr isotopes, giving an age of 20 - 25 Ma for muscovite and 10 - 15 Ma for biotite (Honegger et al., 1982).

The situation in the studied Zanskar area differs from that of the Suru region. Figure 5.1 shows that the metamorphic isograds of the metapelites converge in the Zanskar shear zone (chapter 7). From Sumche Tokpo to Malung Tokpo, the isograds of biotite-garnet, staurolite, and sillimanite are condensed to a 200 - 250 m wide zone. The convergence of the isograds is interpreted as a direct consequence of shearing during a late stage in the Himalayan tectonism (chapter 7), resulting in the formation of a thinned transition zone between the upper amphibolite facies Zanskar Crystalline unit and the lower greenschist facies to anchimetamorphic sedimentary Tethys Himalaya.

In the following the characteristic mineral assemblages will be described for the different units. The metamorphism in the Zanskar Crystalline unit will be described in detail.

Mesozoic sedimentary sequence

The limestone / dolomite layers are not recrystallised. Deformation locally set up recrystallisation in limestone layers. The pelites contain detrital muscovites and phyllosilicates. Chlorite was not observed. The ductile deformation of belemnites indicates that they deformed at moderate temperatures or that they deformed with slow strain rates. Baud et al. (1984) tried to assess the maximum temperatures reached using the Conodont Color Alteration Index (CAI) method. They determine the CAI index within conodonts of the Lilang Group with temperatures reaching 250^{o} - 300^{o} C. They concluded that temperatures probably exceeded 200^{o} C even at the top of the Mesozoic unit in the Zanskar area. According to Kelemen and Sonnenfeld (1983) the grade of metamorphism in the Zanskar platform is generally very low grade. The sediments of the Zanskar Synclinorium (equivalent to the Zanskar region) are sub-greenschist facies, while in the Honupattah Anticlinorium further to the north, the

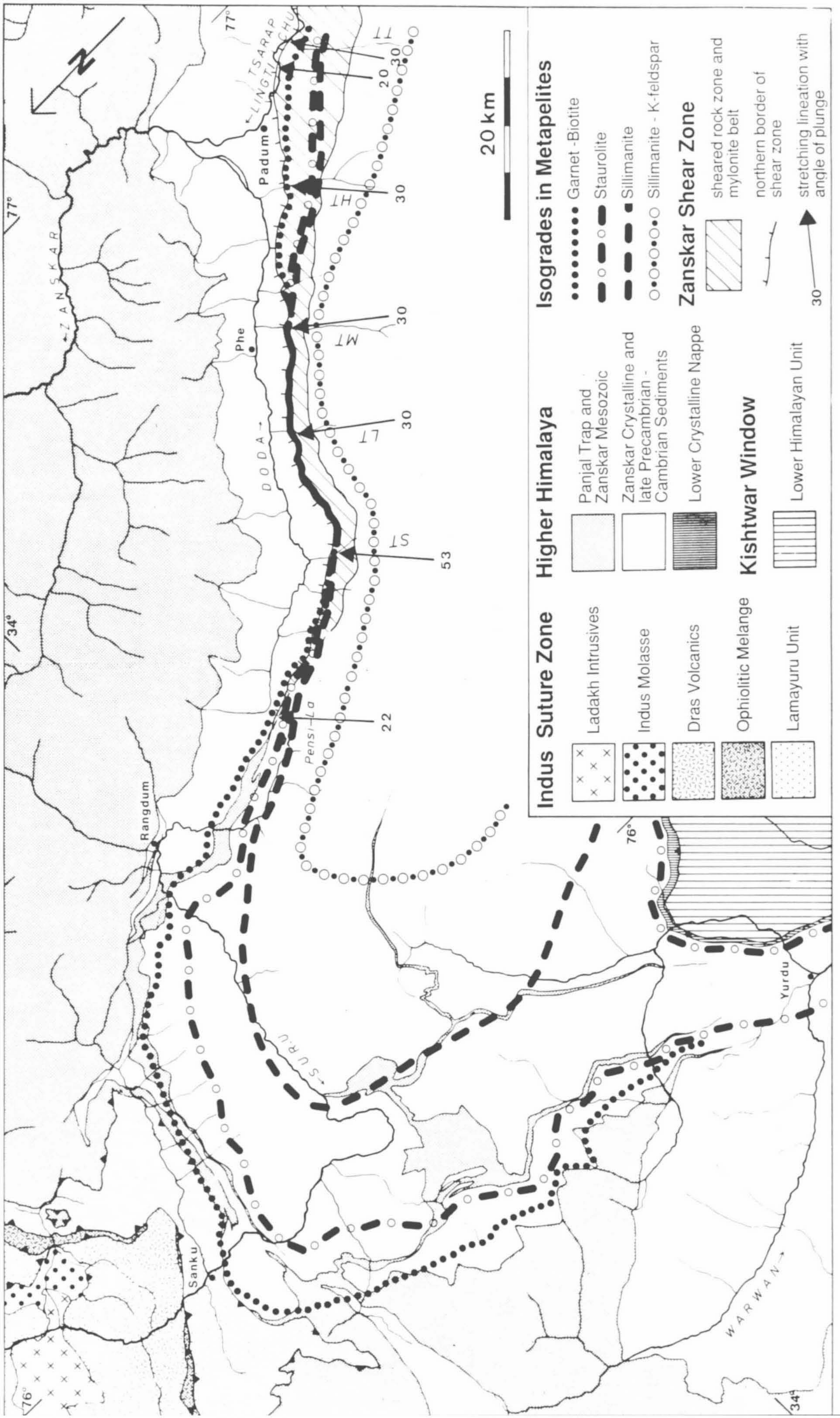


Figure 5.1: Metamorphic map of southwestern Ladakh (northwest part after Honegger, 1983): ST = Sumche Tokpo; LT = Lechan Tokpo; MT = Malung Tokpo; HT = Haptal Tokpo and TT = Tamasa Tokpo.

ubiquity of phyllites and low-grade chlorite schists suggests lower greenschist facies regional metamorphism.

Panjal Trap - Permian basalt

Within the basalts of the Panjal Trap primary magmatic ophitic textures and some primary magmatic mineral relicts of clinopyroxene and plagioclase are still recognizable, especially within the glomerophyric zones of a basaltic flow. The matrix, however, has been completely recrystallized to the mineral assemblages of actinolite - albite - quartz - epidote / clinozoisite - chlorite - leucoxene / sphene / ilmenite - haematite ± stilpnomelane ± biotite indicating lower greenschist metamorphic conditions.

A slight regional gradient from northwest to southeast can be observed within the Panjal Trap unit. In the area near the Pensi La (Figs. 1.8 and 5.1, second valley northeast from the Pensi La) brown biotite has been found. In the Ralakung area, 30 km further southeast, green biotite is developed. From the Karsha region 25 km southeastwards biotite is no longer stable. This regional gradient fits well with the garnet - biotite isograd indicated on Figure 5.1 which shows also a slight inclined trend to the units in the Zanskar area.

Phe and Karsha Formation - late Precambrian - Cambrian sedimentary sequence

In the mostly metapsammitic lithologies of the Phe and Karsha Formation the primary sedimentary texture has been destroyed as a result of recrystallization due to regional metamorphism. The characteristic mineral assemblages at the base of the Phe Formation are quartz - feldspar - chlorite - muscovite ± biotite ± calcite and ± clinozoisite and on top of the Phe Formation and within the Karsha Formation quartz - feldspar - chlorite - sericite (muscovite) ± calcite and ± biotite indicating greenschist conditions.

A slight regional gradient from bottom to top of the Phe Formation can be observed. Light green to redbrown biotite is widespread at the base of the Phe Formation, whereas in the upper parts biotite was not observed. Chlorite is found within the greywackes, partly as individual chlorite clasts (Fig. 5.2), partly as small grains within the recrystallized matrix. Clinozoisite was observed only at the base of the Phe Formation. Calcite is widespread within this formation but is only recrystallized in the lower parts. Within higher levels calcite grains are locally recrystallized as a result of deformation and not of regional metamorphism. Muscovite is found at the base as newly grown minerals and on top as small sericitic flakes and larger detrital grains. The doleritic stock at the entrance of the Sumche Tokpo (Fig. 1.8, chapter 3.1.1) contains mineral assemblages of actinolitic hornblende - chlorite - clinozoisite - albite - quartz - brown biotite and sphene / ilmenite, indicating higher metamorphic conditions compared to the Panjal Trap unit. The primary magmatic ophitic textures and the primary minerals such as clinopyroxene and plagioclase are locally preserved. The primary minerals within the crosscutting basic dykes (dolerites) are totally transformed to chlorite - calcite - plagioclase assemblages as a result of regional metamorphism, although the primary ophitic texture can still be recognized.

The regional metamorphism within the Karsha Formation is similar to that developed in the top of the Phe Formation. The dolomitic layers are not recrystallized.

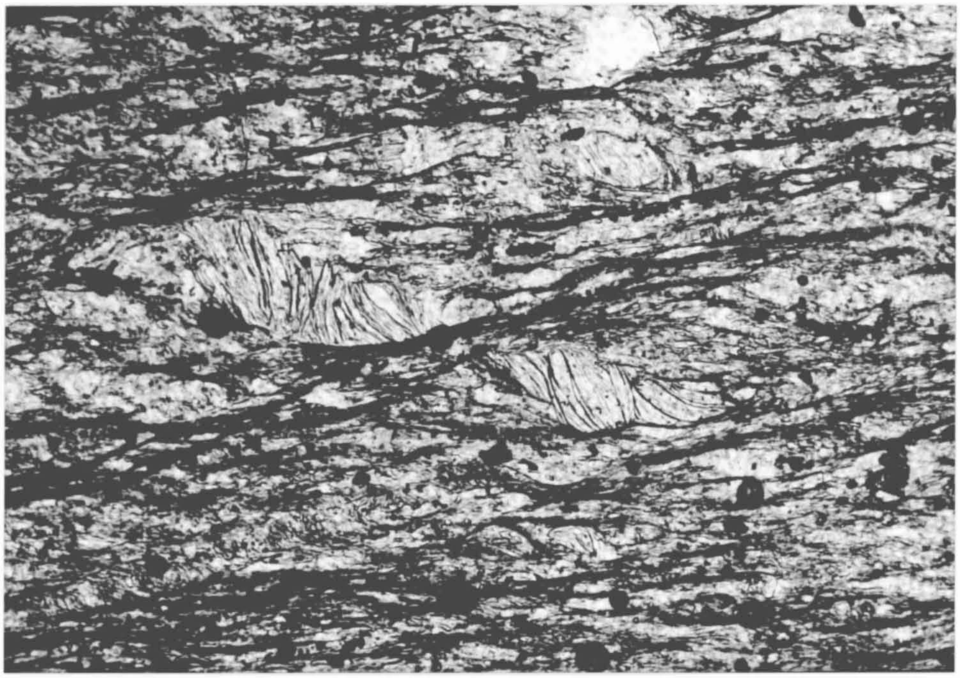


Figure 5.2: Chlorite blast within greywacke of the Phe Formation. The width of the picture correspond to 0.83 mm.

Zanskar Crystalline unit

Metapelites or, more exactly, semi-metapelites are widespread within the Zanskar Crystalline unit and allow a subdivision of the regional metamorphism. The characteristic pelitic mineral assemblages and the metapelitic isograds are indicated in Figure 5.3. Quartz and muscovite are present within all mineral assemblages and are therefore not indicated on the metamorphic map. The distribution of the mineral zones have been affected and directly controlled by the Zanskar shear zone so that the original width is no longer preserved.

In the Malung Tokpo the top of the Zanskar Crystalline unit contains biotite - garnet assemblages, whereas in the Tamasa Tokpo further southeast, garnet is not present within the top of the Zanskar Crystalline unit. The **garnet - biotite mineral zone** lies oblique to the strike of the top of the Zanskar Crystalline unit. Further southwestwards a thin **staurolite - biotite - garnet mineral zone** is observed, but it is difficult to define clearly because of strong overprinting by the Zanskar shear zone as well as a scarcity of lithologies with the chemical potential to develop staurolite. The staurolite - biotite - garnet isograd is defined by the first appearance of staurolite. Staurolite and kyanite are kinked and partly boundinaged in the shear zone (Fig. 5.4). The **sillimanite mineral zone** is defined by the first appearance

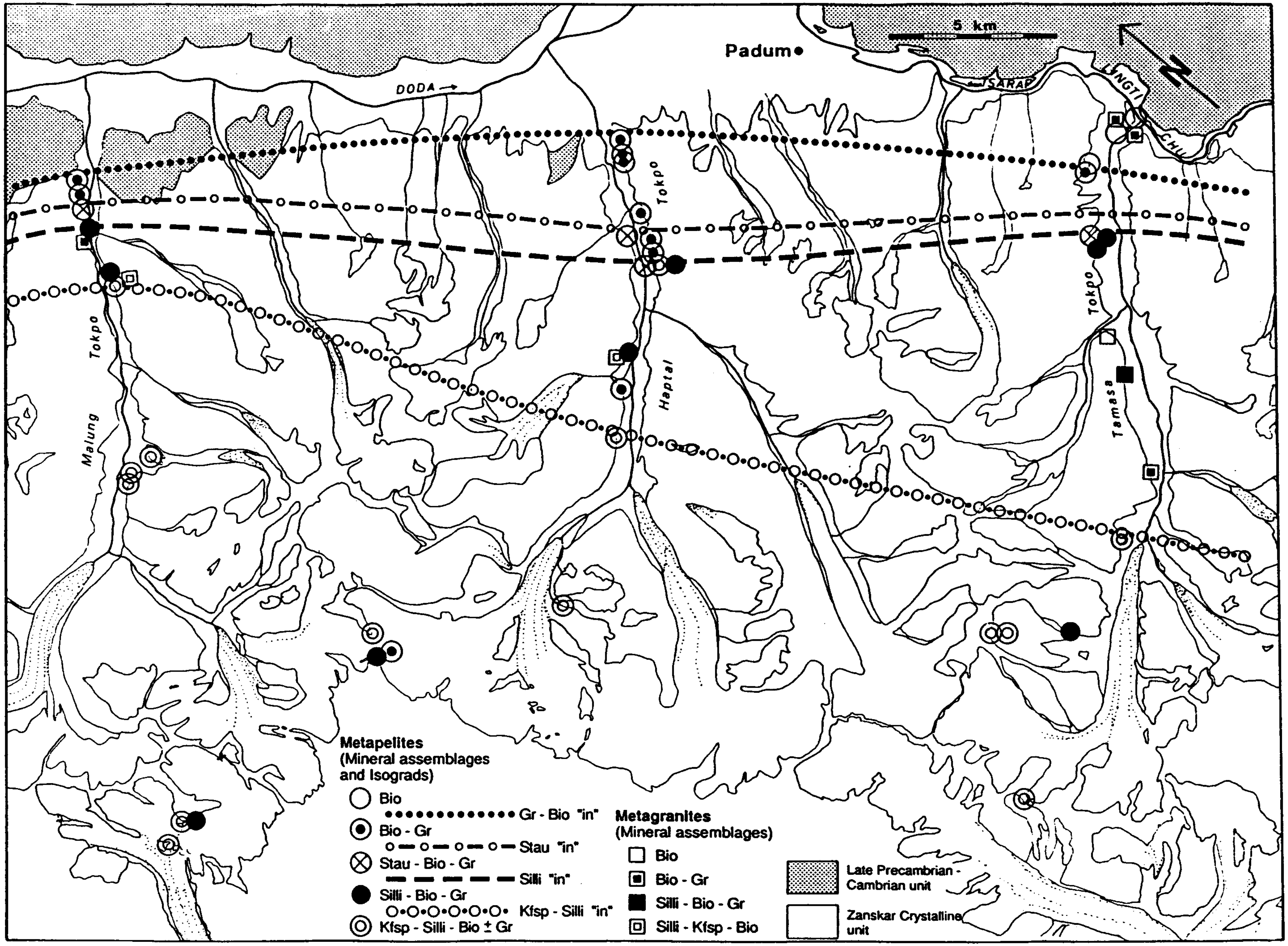


Figure 5.3: Detailed metamorphic map of the Zanskar Crystalline unit in Zanskar showing the pelitic mineral assemblages with the associated isograds and granitic mineral assemblages.

of fibrolitic sillimanite. This mineral zone widens from the Malung Tokpo to the Tamasa Tokpo more in the southeast (Fig. 5.3) as shearing within the Zanskar shear zone decreases towards the southeast (Fig. 5.1 and chapter 7). The **K-feldspar - sillimanite mineral zone** is defined by the first appearance of K-feldspar and forms the highest metamorphic region. Within the sillimanite mineral zone muscovite has begun to break down and is often incompletely decomposed within the K-feldspar - sillimanite mineral zone (Fig. 4.8). Within this upper amphibolite facies region local migmatisation is observed (Fig. 5.5). Migmatites with a clear neosome and a leucosome are uncommon (Fig. 5.6).

Only a few samples contain kyanite and the exact extent of the regional distribution of this mineral zone is unclear. Cordierite - kyanite - biotite mineral assemblages as described by Honegger (1983) from the Suru - Warwan region were not observed.

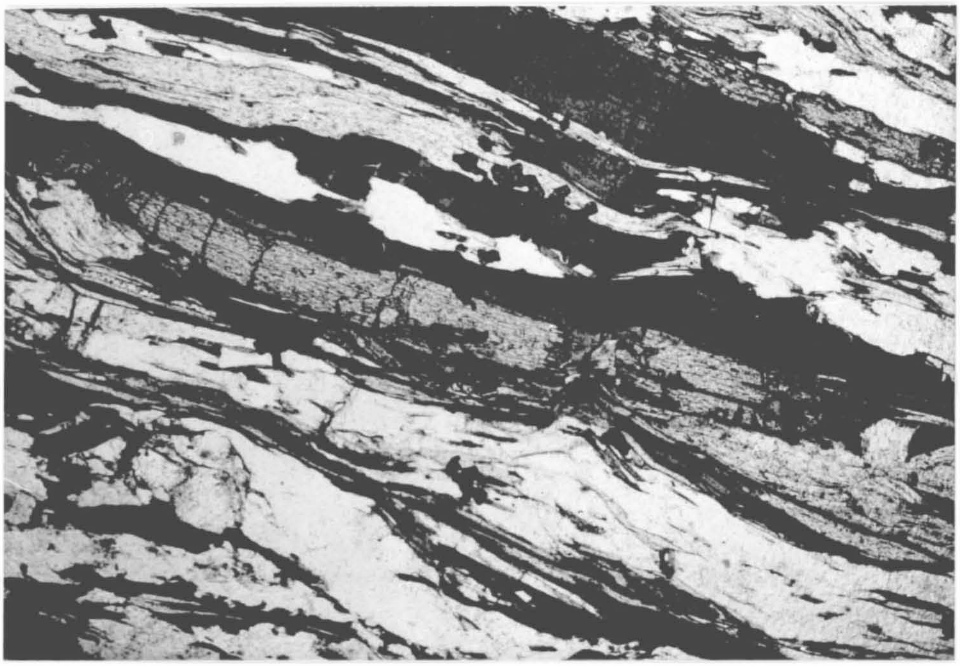


Figure 5.4: Staurolith grown during regional metamorphism (M1) and boudinaged by shearing late in the metamorphic history. The width of the picture correspond to 3 mm.

Metamorphism - Deformation

In Figures 5.1 and 5.3 the sillimanite mineral zone is defined by the first appearance of fibrolitic sillimanite. Kündig (in prep., a) could show that the sillimanite growth is highly complicated and in general is related to a later low P / high T phase of metamorphism (called M2), subsequent to the main high P / high T phase (M1) of Himalayan regional metamorphism. Sillimanite occurs on the fold axial planes of second phase folds within biotite gneisses (Fig. 2.8) and forms an embrionic schistosity (chapter 2.2). This situation is similar to that described in the Swiss Central Alps as a result of retrograde metamorphism during uplift (Bühl, 1981).

Figure 5.5: Beginning of migmatisation within a sillimanite - biotite gneiss. Tamasa Tokpo; the width of the figure correspond approximately to 1 m.

Figure 5.6: Migmatisation showing the neosome and leucosome. South of Poat La.

The two phases metamorphism within the Zanskar Crystalline unit allow the age of a the leucogranite intrusions (chapter 4) to be relatively dated. The leucogranites have not been affected by either the main phase of regional metamorphism (M1) or the main deformational phase and, therefore, have neither been transformed to gneisses, nor developed a schistosity. They are folded by the second phase folds (Figs. 4.6 and 4.7) and sillimanite associated with M2 is found within the leucogranites (chapter 4). The intrusion of the leucogranites is therefore interpreted to be after the high P / high T (M1) metamorphic phase and during the low P / high T (M2) metamorphic phase.

Andalusite was observed only within the Zanskar shear zone. Together with quartz, it forms nodules on biotite gneiss surfaces but was not observed within the biotite gneiss itself. As andalusite was not found at contacts to granitic rocks, it can be assumed that it is not related to contact metamorphism. The andalusite grains are locally boudinaged and were probably formed during hydrothermal activity. A clear relation of these boudins to the shear zone has not been established. The surrouding quartz is strongly deformed by shearing, the grains are elongated and recrystallized forming a dominant stretching lineation.

No contact metamorphism of the biotite gneisses surrounding the Cambrian porphyritic granites and the Miocene leucogranites was observed.

6. Compressional tectonics: Comparison - Summary - Discussion

Within this chapter the different deformational styles of the four major lithostructural units, the Zanskar Crystalline unit, the Tethys Himalaya with its Precambrian - Cambrian unit, the Panjal Trap and the Mesozoic formations shall be discussed.

6.1 Comparison of the different deformation structures within the Tethys Himalaya units.

Folds

Folds are the dominant deformational feature within the Precambrian - Cambrian and Mesozoic units. The fold axes orientations, the fold styles and the lateral continuity of the folds differs significantly. Figure 6.1 illustrates the fold axial traces of the individual folds mapped. From the axial plane orientation and the axial trace length it is possible to distinguish five different groups of folds:

1. Folds with short N-S trending axial traces (length of axial traces is tens of meters) within the Precambrian - Cambrian Phe and Karsha Formations.
2. NW-SE trending folds with axial traces at most 3 km long, also within the Precambrian - Cambrian unit.
3. A NW-SE trending syncline and anticline of slightly folded Panjal Trap sheet in the Ralakung region which can be followed over approximately 2 km.
4. NW-SE trending folds within the Mesozoic unit with fold axial traces that are continous over tens of kilometers.
5. The several km wide NW-SE trending Zangla Syncline which involves the Mesozoic Kioto Limestone, Spiti Shales, Giumal Sandstones and Chikkim Limestone.

Fold groups 2 - 5 show a sub-parallel NW-SE orientation of fold axial traces. This NW-SE orientation is attributed to the Himalayan Orogeny (Srikantia et al., 1978 and Gaetani et al., 1985b). The Precambrian - Cambrian unit also shows N-S trending folds (group 1). In agreement with Srikantia et al. (1978) they are here related to the pre-Himalayan Kurgiakh Orogeny. Sedimentary evidence (Garzanti et al., 1986) and a widespread 500 Ma intrusive event (Honegger et al., 1982; Frank et al., 1977; Bhanot et al., 1970; Jäger et al., 1971; Metha, 1977 and Ferrara et al., 1983) underline the presence of tectonic activity (chapter 3.2.2) corresponding in time with the terminal episode of the Pan - African orogeny (Powell and Conaghan, 1978). Srikantia et al. (1978) describe major and minor folds of NE-SW

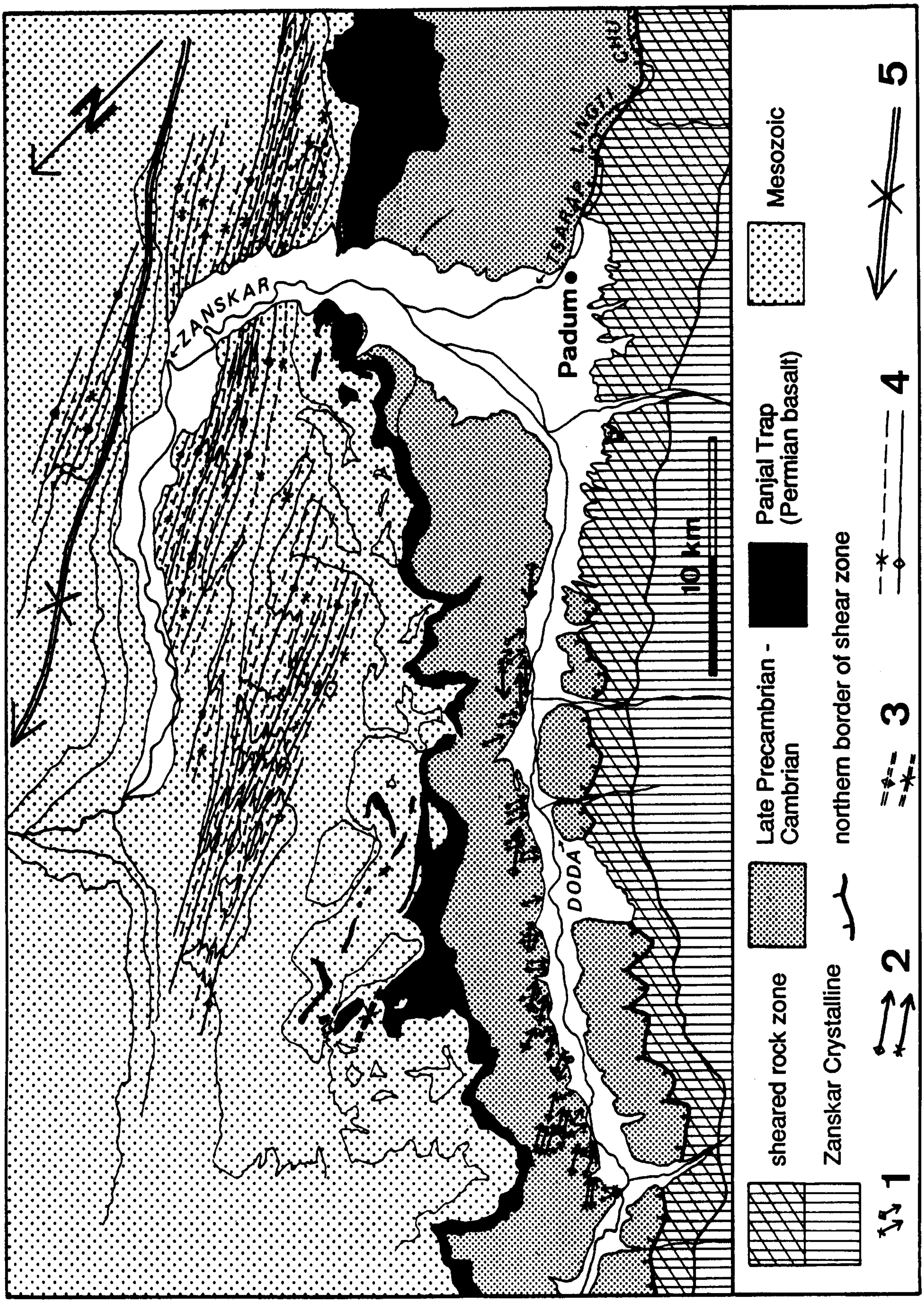


Figure 6.1: Geologic-tectonic map of the Zanskar area showing the different fold groups varying in their axial plane orientations and the lengths of the axial traces. 1 = Folds with short N-S trending axial traces (length of axial traces is tens of meters) within the Precambrian - Cambrian Phe and Karsha Formations. 2 = NW-SE trending folds with axial traces at most 3 km long, also within the Precambrian - Cambrian unit. 3 = A NW-SE trending syncline and anticline of slightly folded Panjal Trap sheet in the Ralakung region which can be followed over approximately 2 km. 4 = NW-SE trending folds within the Mesozoic unit with fold axial traces that are continous over tens of kilometers. 5 = The several km wide NW-SE trending Zangla Syncline which involves the Mesozoic Kioto Limestone, Spiti Shales, Giumal Sandstones and Chikkim Limestone.

orientation. After my own observations the trend of the pre-Himalayan folds is in general N-S but the major fold described by Srikantia et al. (1978) could not been verified.

The few fold axes which could be directly measured (Fig. 6.2) show an important feature. The plunge values of the fold axes of the Precambrian - Cambrian unit and of the Mesozoic unit show a great variation indicating probably the presence of axial culminations and depressions. E.g. the folds within the Mesozoic unit near Rinam (Fig. 3.1) plunge towards the southeast, whereas further northwest they plungs towards the northwest.

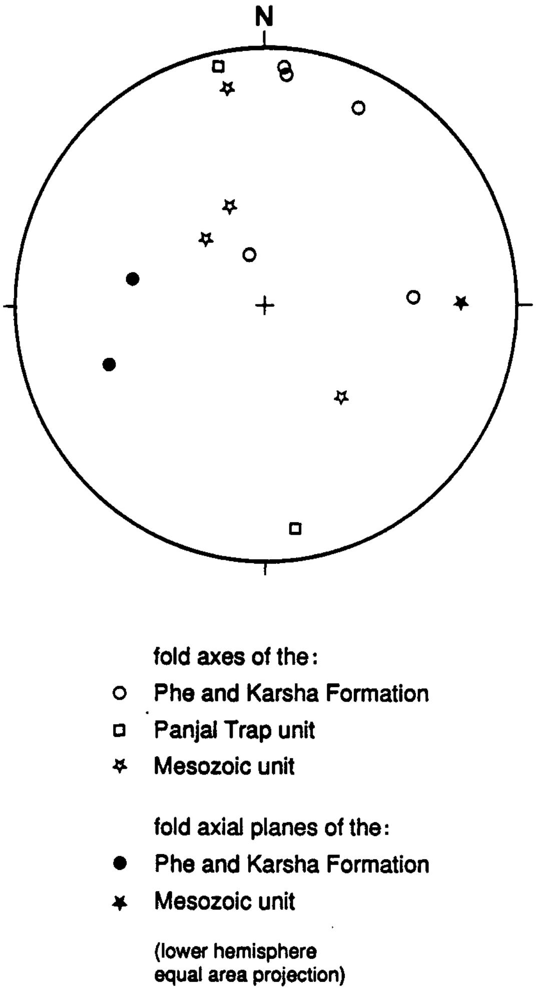


Figure 6.2: Equal area projection of the fold axes and fold axial planes within the Precambrian - Cambrian, Panjal Trap and Mesozoic units.

Schistosity

The schistosity within the Mesozoic unit and the Panjal Trap strikes 135° SE - 175° S and dips 40° - 80° NE (Fig. 6.3). This orientation is associated with the Himalayan NW-SE trending folding phase. The orientations within the Phe and Karsha Formations are more variable with strikes 110° E - 210° SW and dips 20° - 90° NE. The schistosity orientation within these two formations is more variable because of the superimposition of the N-S pre-Himalayan and the NW-SE Himalayan fold phases.

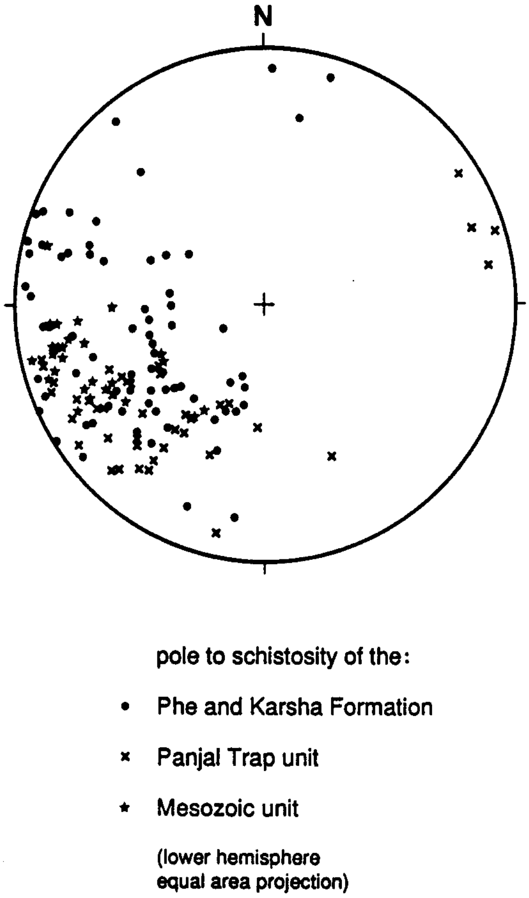


Figure 6.3: Equal area projection of the schistosity within the Precambrian - Cambrian, Panjal Trap and Mesoizoic units.

Lineations

All three units have similarly orientated stretching lineations with azimuths of 15° - 65° NE and plunges of 18° - 70° NE (Fig. 6.4) showing well the main Himalayan orientation. As expected, the Precambrian - Cambrian unit which was deformed during a pre-Himalayan event shows the largest scatter of the lineation orientations. The quartz lineation within this unit appears to be partly a pre-Himalayan feature, which was not completely overprinted and reoriented during the Himalayan orogenic event. In addition to the main lineation, the Panjal Trap shows stretching lineations with azimuths of 310° - 350° NW and plunges of 45° - 70° NW illustrating a local stretching event parallel to the strike of the Panjal Trap. It is important to notice that the main point maximum of the stretching lineations indicates a stretching oblique to the trend of the chain.

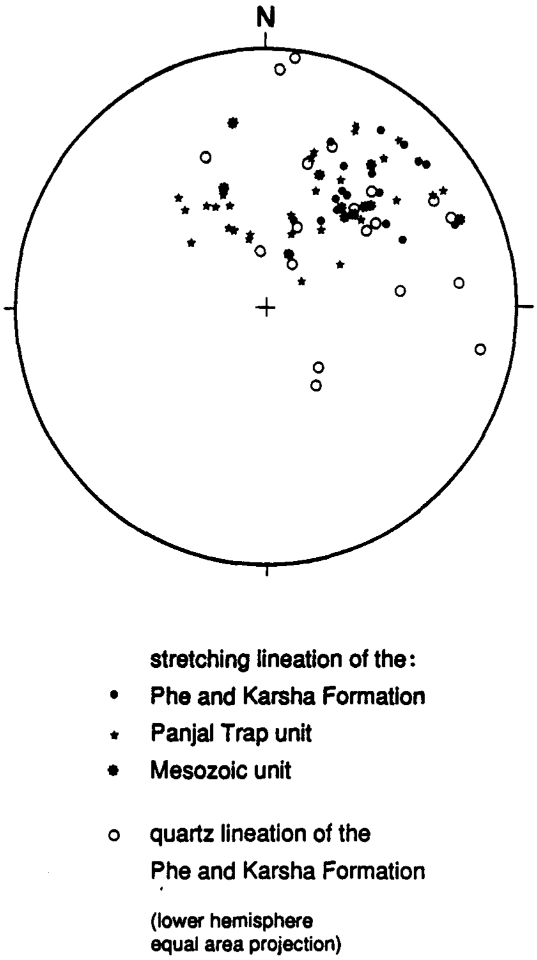


Figure 6.4: Equal area projection of the stretching lineation within the Precambrian - Cambrian, Panjal Trap and Mesozoic units.

Internal deformation of the units

The Precambrian - Cambrian unit shows a large internal deformation as a result of elongation and reorientation of the quartz grains within the greywackes. The orientation of the quartz grain long axes are subparallel to the schistosity, probably as a consequence of the great competence contrast between the matrix and the quartz grains. Locally a second schistosity is developed indicated by a second generation of small sericite flakes (Fig. 6.5). This schistosity is probably related to the backfolding event but is only visible in thin sections and not macroscopically on hand specimens.

In the Panjal Trap, only slight internal deformation is seen. Only the amygdaloidal-rich zones of the upper parts of the individual flows are deformed as indicated by the elongation of the vesicles. The interlayered sediments, especially the greywackes, show the same deformational features as the greywackes within the Precambrian - Cambrian unit. The degree of deformation, however, is greater. The observation of the strongly deformed interlayered sediments shows that the deformed vesicles within the basalts do not represent an igneous flow fabric, but a tectonic deformation. It should be emphasized that within the Panjal Trap the deformational profile is inhomogenous and dependant on the lithology. The Mesozoic formations show only minor internal deformation which is recognized by a ductile deformation of belemnites. Stretched belemnites, such as those described in European Alps (Daubrée, 1876 and Heim, 1878), were not observed. Solution - transfer appears not to have been an important deformation mechanism in this unit.

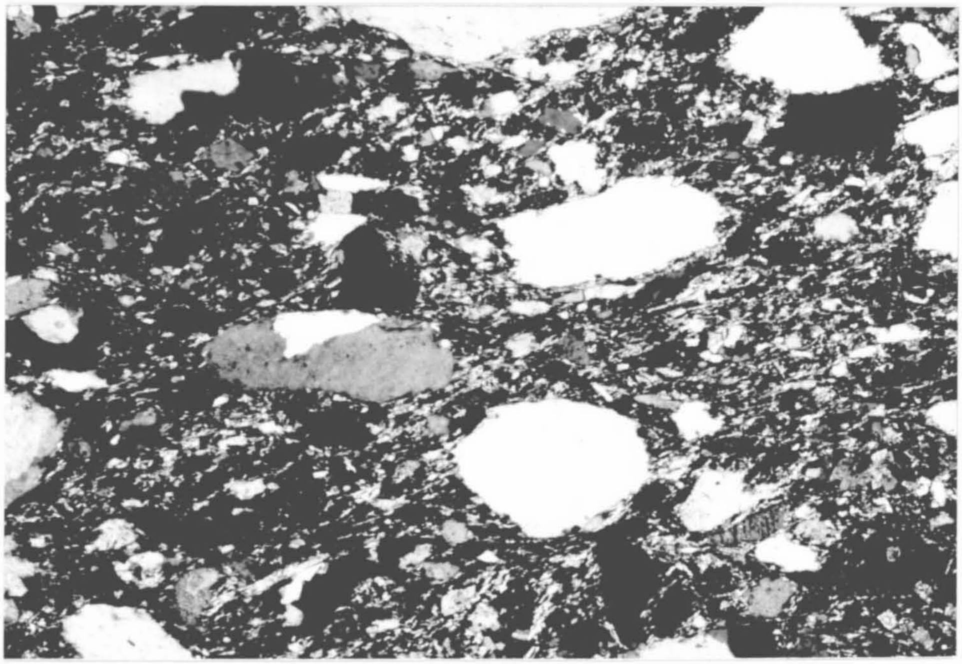


Figure 6.5: Thin section of a greywacke of the Phe Formation showing the quartz lineation associated with the schistosity defined by the orientation of small sericite flakes of a further generation with an inclined orientation to the previous one also within the matrix defined by the planar orientation of small sericitic flakes and a second schistosity.

Crenulation cleavage - Kink bands

Within the Mesozoic formations the crenulation cleavage represents the last deformational event. It can be related to the backfolding event (Fig. 6.6). In the highly anisotropic Precambrian - Cambrian unit, however, the crenulation cleavage related to the backfolding event best correlated with the second of two developed crenulation cleavages (Fig. 6.6). In the Panjal Trap unit only the sediments interlayered within the Panjal Trap unit show crenulation cleavage and kink bands. The basalts, do not show any late phase deformation.

Folding towards thrusting

The Precambrian - Cambrian, Panjal Trap and Mesozoic units consist of lithologies of very different competency. During the Himalayan deformation these units accomodated the tectonic shortening in different ways. The Precambrian - Cambrian and Mesozoic units show a predominantly ductile deformation style accomodating the shortening by folding and by internal deformation. The Panjal Trap, however, behaved in a more brittle manner because of the highly competent basalt lithology. The separate basalt sheets seen on the map are in fact individual thrust sheets. In the Ralakung area, Mesozoic sediments up to the Lilang Formation are thrust between two Panjal Trap thrust sheets (Fig. 3.21). This Mesozoic slice unusual in that it is extremely strongly folded. Décollement horizons and cross cutting thrusts appear to control the distribution of the individual units.

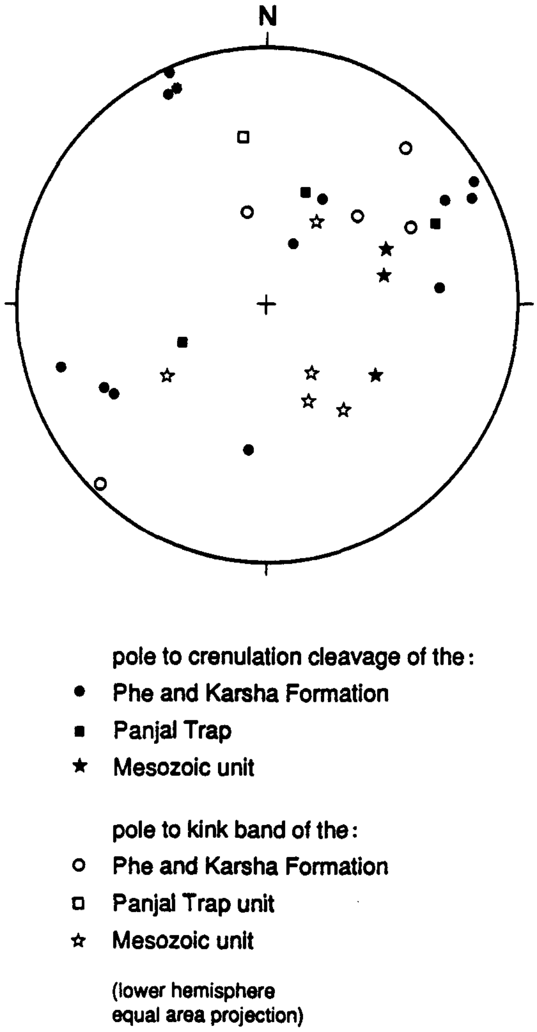


Figure 6.6: Equal area projection of the crenulation cleavage and kink bands within the Precambrian - Cambrian, Panjal Trap and Mesozoic units.

6.2 Comparison of the structures of the Tethys Himalaya with those of the Zanskar Crystalline unit

It is difficult to correlate the deformational styles of these two units. Although the Tethys Himalaya is the autochthonous cover of the crystalline unit the Zankar shear zone has displaced these two units so that they now occupy different tectonic levels. The Zanskar Crystalline unit is of amphibolite facies metamorphic grade, whereas the Tethys Himalaya is of lower greenschist facies. The transitional zone is so narrow and strongly overprinted by the Zanskar shear zone that within the shear zone a study of the early structures related to the main Himalayan deformational event is no longer possible.

Large scale folds related to the ***main deformation phase*** as in the sedimentary cover are not found in the Zanskar Crystalline unit. The observed small scale folds are related to an overprinting phase and are therefore not simply comparable with those observed in the sedimentary cover (Tethys Himalaya). Because the Zanskar Crystalline unit represents a deeper crustal level than that of the Tethys Himalaya, it is likely that superimposed folding developed during continous compressional activity.

The main deformational phase within both units is associated with a penetrative schistosity. The schistosity in the Zanskar Crystalline unit is associated with the synmetamorphic updoming of the crystalline unit. The local small scale superposed folds show only an embryonic schistosity. At the top of the Zanskar Crystalline unit, the schistosity is parallel to the overall strike of the tectonic units in the Zanskar area (strike 110° - 170° SE and dip 30° - 50° NE, Fig. 2.5: 1, 4, and 6). The strike of the schistosity within the Tethys Himalaya is more or less the same, but the dip is steeper (40° - 80° NE, Fig. 6.3).

Within the Zanskar Crystalline unit lineations also formed during the synmetamorphic updoming of the Zanskar Crystalline unit. The lineations combined with the schistosity define the form of the Haptal dome. Towards the top of the Zanskar Crystalline unit, a synmetamorphic lineation is locally developed (Tsarap Lingti Chu valley, Fig. 2.5, 6). Most of the measured lineations were stretching lineations related to straining within the Zanskar shear zone. The lineations within the Tethys Himalaya show such a great scattering that it is not possible to relate them with the lineations seen within the Zanskar Crystalline unit (azimuths of 15° - 65° NE and plunge of 18° - 70° NE, Fig. 6.4). The orientations of the stretching lineation within the Zanskar Crystalline unit (azimuth of 38° - 55° NE and plunge of 20° - 30°) do not coincide with those mapped in the Tethys Himalaya. The development of the Zanskar shear zone was related to a change in the orientation of the deformational field and in this zone the strikes were reoriented towards the ENE and the angle of plunge was decreased.

The ***backfolding event*** is represented within the Tethys Himalaya by crenulation cleavage and kink bands within shale horizons and within the Zanskar Crystalline unit by small scale folds especially well developed on top of the Zanskar Crystalline unit and which show an opposite sense of fold vergence to that the previous fold forming deformation.

6.3 Summary - Conclusion - Discussion

The ***pre-Himalayan structures*** related to the 500 Ma Kurgiakh Orogeny (Srikantia et al., 1978) are limited to the Karsha and Phe Formation and to the Zanskar Crystalline unit, and have been overprinted in the Zanskar Crystalline unit by structures developed during the period of Himalayan deformation and metamorphism. The orientation of the pre-Himalayan folds are predominantly N-S. These folds are often associated with a N-S schistosity indicated

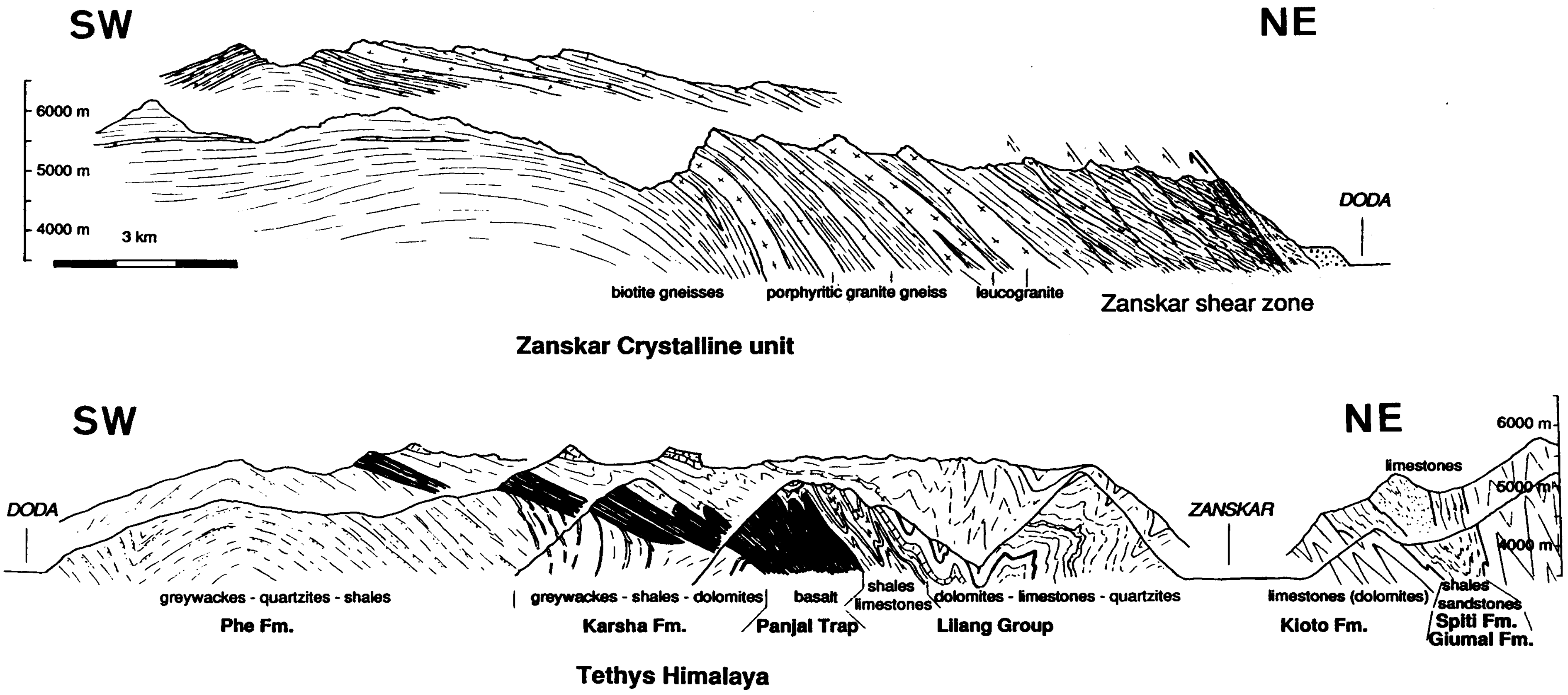


Figure 6.7: Cross-section through the Zanskar area.

within the greywackes by the planar orientation of the elongated quartz grains. The shales, however, are totally overprinted by the Himalayan structures.

The ***main Himalayan compressional tectonic activity***, accompanied by a prograde regional metamorphism, deformed the different lithologies in different ways. The deformation mechanisms depend on the differences in competence of the various rock lithologies.

The *Mesozoic formations* are folded into chevron, disharmonic and polyharmonic fold types as a direct consequence of the stratigraphic layering and a number of characteristic lithostructural units has been recognised. The fold axial traces of this limestone / shale sequence shows a constant NW-SE orientation independent of the fold type.

The *Panjal Trap* unit shows both brittle and competent behaviour during the deformation. The individual basaltic flows are welded together forming a rigid, competent, homogenous sheet which has resisted folding under the low metamorphic conditions accompanying the deformation. It generally deformed by thrust faulting. Further northwest, in the Suru region where the metamorphic grade reached amphibolite facies (Honegger et al., 1982), this same unit is folded in a ductile way together with the crystalline unit.

The *Phe and Karsha Formation*, with their greywackes, quartzites, shales and minor dolomites, show only locally developed Himalayan folds. The stratigraphical units show lateral variations in thickness and competence and individual layers are only possible to follow for some tens of meters. The fold styles are markedly irregular, and the folds are impersistent.

The *Zanskar Crystalline unit* was strongly overprinted by a prograde regional metamorphism. The Cambrian porphyritic granites were transformed into gneisses. A syn-metamorphic dome (Haptal dome) formed which is defined by the schistosity and lineation pattern. Three folding phases related to the Himalayan deformational event have been distinguished. The first one is simultanous with the peak of metamorphism. The second is related to the low P / high T phase and developed as small to mega scale folds that involve the Miocene leucogranites. The third one is only locally developed and appears to be related to backfolding; the vergence of the folds related to this event is opposite to that of the previous phase.

Folding within the Zanskar Crystalline unit, at relatively deep seated levels of the Himalayan orogeny (chapter 5), started at an earlier stage than it did within the Tethys Himalaya. Although the deformation lead to three geometrically distinguishable folding phases the folding history of the Zanskar Crystalline unit was probably a more or less continous process. The rather abrupt contact between the Zanskar Crystalline unit, affected by three Himalayan deformational phases, and the Tethys Himalaya, affected by only two Himalayan deformational phases, is due to shear decoupling taking place at the top of the Zanskar Crystalline at the level of the Zanskar shear zone (chapter 7). This shear zone juxtaposes different tectonic levels together so that there is no direct or simple structural transition between these two major units.

7. Extensional tectonics - the Zanskar shear zone

The Himalayan orogen is characterized by continous south-directed thrusting and piling up of tectonic units from the early Tertiary to the present. The Higher Himalaya unit in the north was thrust to the south over the Lower Himalaya unit along the Main Central Thrust (MCT, Figs. 1.3 and 1.5). Later, the Lower Himalaya unit was thrust over the Sub-Himalaya along the Main Boundary Thrust (MBT, Figs. 1.3 and 1.5). Finally, the still active Main Frontal Thrust (MFT) superimposed Pliocene Siwalik Formation on alluvial terraces. These features show that the active compression zone has progressively moved from north to south in time.

In contrast to the overall compressive tectonic pattern, an extensional event in the upper part of the Higher Himalaya tectonic unit is present in Zanskar. This paper describes the Zanskar shear zone (Figs. 1.3, 1.5, 5.1 and 7.1), a northeast-dipping normal fault similar to faults described by Burg et al. (1984) in Tibet. The shear zone separates the highly metamorphosed Zanskar Crystalline unit and a transitional zone from the overlying, slightly metamorphosed, late Precambrian-Early Cambrian sedimentary sequence (Tibetan zone, Tethys Himalaya). This shear zone, from observations of the morphology, lithology, structure, and metamorphism, is the dominant linear element in Zanskar, and has been interpreted differently by previous workers.

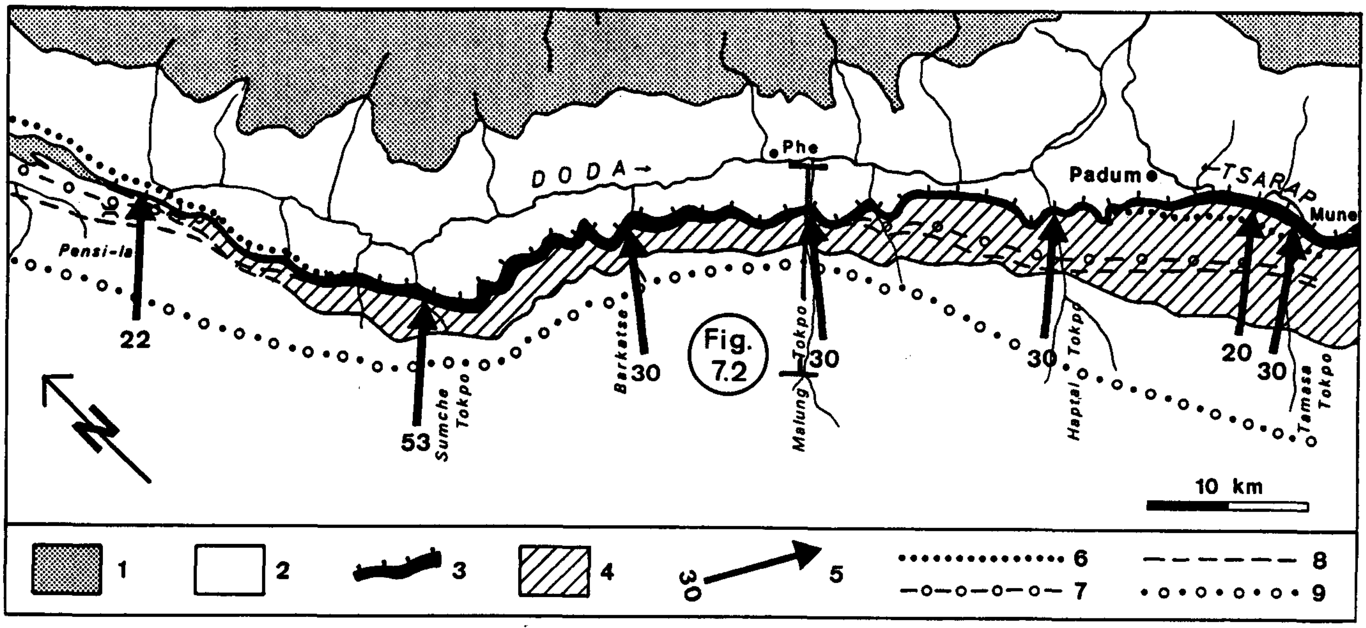


Figure 7.1: Detailed map of the Zanskar shear zone and line of cross section shown in Fig. 7.2. Lithologies: 1 = Panjal Trap and Zanskar Mesozoic, 2 = Zanskar Crystalline unit and late Precambrian-Cambrian sediments (Phe and Karsha Formation). Zanskar shear zone: 3 = Mylonitic belt, 4 = slightly sheared rock zone, 5 = stretching lineation. Metamorphic isograds in metapelites: 6 = garnet-biotite, 7 = staurolite, 8 = sillimanite and 9 = sillimanite-K-feldspar.

7.1 Geological setting

The Zanskar area is located in the north of the main Himalayan Range. In this area, the Zanskar Crystalline unit and its overlying sedimentary sequence, the Tibetan zone, is well exposed and strikes northwest-southeast. The Zanskar Crystalline unit consists mainly of biotite gneisses that contain 500 Ma layered intrusions of porphyritic granites (Honegger et al., 1982) and leucogranites of Himalayan age (chapter 4). This well-banded Zanskar Crystalline unit is highly metamorphosed and overlain by a weakly metamorphosed late Precambrian to Early Cambrian sedimentary sequence called the Phe Formation (Nanda and Singh, 1976; Baud et al., 1984). Nanda and Singh (1976), Srikantia et al. (1978), and Fuchs (1981, 1982) have agreed that the sedimentary sequence lies concordantly on the Zanskar Crystalline unit. However, according to Baud et al. (1984), the Tethys Himalayan unit was thrust over the crystalline unit, and therefore the sedimentary sequence represents a tectonic cover to the Zanskar Crystalline unit.

The boundary between the darker sedimentary sequence and the lighter, well-banded crystalline sequence and the transitional zone is readily visible in Landsat photos and corresponds in the field to a morphological depression. Detailed field investigations described below show that this contact zone is not stratigraphic but is a well-developed shear zone, herein called the Zanskar shear zone. Although metamorphic grade and structural style change rapidly across this zone, there is neither a large gap in the sedimentary sequence nor significant overthrusting.

7.2 Lithologies, structures and shear sense

The Zanskar Crystalline unit consists of fine-grained dark biotite gneisses and sills of two-mica porphyritic granite gneisses and fine-grained garnet- or tourmaline- bearing leucogranites. The thicknesses of the individual layers gradually decrease toward the shear zone from a maximum of about 600 m to only 0.1 m. It is uncertain whether this change is original or the result of tectonic thinning. Toward the northeast there is a transitional zone of pelitic-psammitic intercalations and porphyritic granite gneisses. The pelitic-psammitic layers of the transitional zone represent a transition from the crystalline basement rocks to the overlying late Precambrian-Early Cambrian sedimentary sequence of the Phe Formation. Petrographically, these sediments are indistinguishable from the Phe Formation and are here regarded as part of the same Formation. The sill-like intrusions of porphyritic granite gneisses are petrographically similar to those found in the underlying gneissic formations. An uppermost 50-150-m-thick two-mica porphyritic granite gneiss sill of probable age 500 Ma (chapter 2.1) is continuous from northwest to southeast and marks the boundary of the transitional zone of the Phe Formation. The transitional zone of the Phe Formation varies in width from 500 m (Sumche Tokpo, Fig. 7.1) to 150 m (Tsarap Lingti Chu Valley, Fig. 7.1).

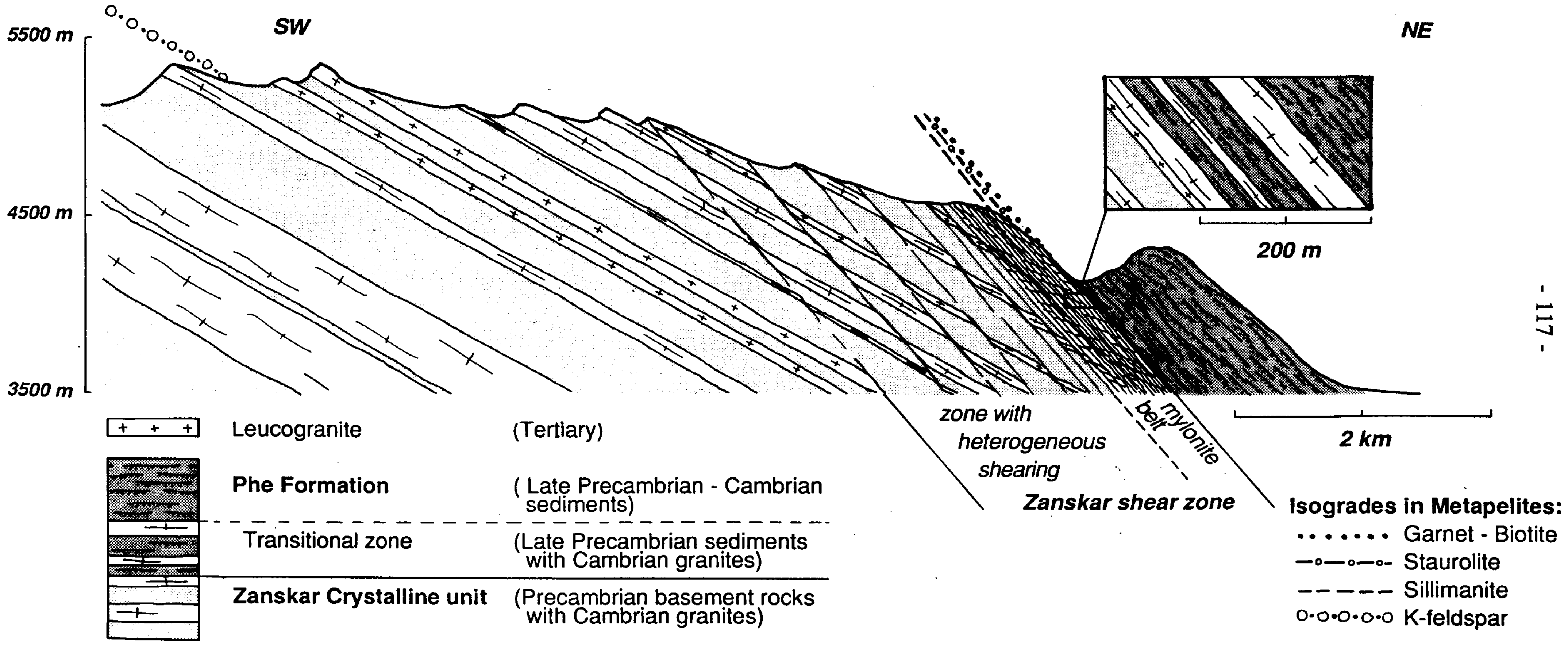


Figure 7.2: Generalized cross section through Zanskar shear zone (Malung Tokpo, Fig. 2) showing geometric features of shear zone (slight vertical exaggeration).

The contact between the Zanskar Crystalline unit and the Phe Formation is therefore farther south than where previous workers placed it (e.g., Nanda and Singh, 1976; Srikantia et al., 1978; Baud et al., 1984). From these new observations, I conclude that the Phe Formation is not a different sedimentary sequence from the Zanskar Crystalline unit as Baud et al. (1984) have stated.

In the south of the study area a well-developed foliation, especially within the fine-grained biotite gneisses, varies as a result of doming but near the shear zone it has an overall strike of 90^o - 150^o and dips of 30^o - 40^o NE. This foliation appears to be genetically related to the main deformation event and to the peak of the metamorphism (chapter 2). Toward the northeast, the different rock types become progressively sheared (Fig. 7.2). The southwestern boundary of the shear zone is defined by the first appearence of sheared rocks. S and C surfaces (Fig. 7.3a) (Berthé et al., 1979a, 1979b) and asymmetric K-feldspar augen (Fig. 7.3b) are developed locally, especially within the porphyritic coarse-grained granite gneisses. The intensity of shear increases gradually toward the northeast, and the rocks pass into protomylonites, mylonites, and cataclasites associated with brittle faults. Shear deformation affects all lithologies, but the intensity of shear changes from one lithology to another. With increasing shear strain, the S surfaces become more deflected into parallelism with the C surfaces, and a mylonite with parallel mylonitic foliation and shear bands develops. This gradual transition from slightly sheared rocks in the southwest to mylonite in the northeast is similar to strain variations described by Berthé et al. (1979) in the South Armorican shear zone of France. Individual mylonite zones have the same orientation as the C surfaces within the sheared rock sequence and generally dip to the northeast at 50^o. The shear zone boundary is parallel to the C surfaces. Microscopically, the quartz grains show several stages of dynamic deformation (Fig. 7.3c). Feldspar, tourmaline, staurolite, and kyanite deform brittlely within a more ductile matrix (Fig. 7.3d).

The Zanskar shear zone varies in width from 2.25 km (Malung Tokpo) to 6.75 km (Tamasa Tokpo, Fig. 7.1) in the southeast and can be divided into (1) a sheared-rock zone, defined by the first appearance of sheared rocks, and (2) a mylonite belt, defined by the first appearance of mylonite (Fig.7.1), that varies in width from 350 m (Haptal Tokpo) to 625 m (Tamasa Tokpo).

The development of the shear fabric is associated with a stretching lineation (Figs. 5.1 and 7.1), defined by the long axes of elongated quartz and stretched tourmaline, staurolite, and kyanite grains. The lineations have azimuths varying from 38^o to 55^o NE, trend predominantly normal to the shear zone border, and are interpreted as X directions formed nearly parallel to the transport direction. The lineation plunge changes slightly from one valley to the next (between 53^o NE, Sumche Tokpo, and 20^o NE, Tsarap Lingti Chu Valley; Fig. 7.1), and it generally becomes less toward the southeast. The strike of the associated foliation generally follows the orientation of the lithologies (Figs. 2.4 and 7.1, strike E-W to NNW-SSE, dip 55^o - 25^o NE).

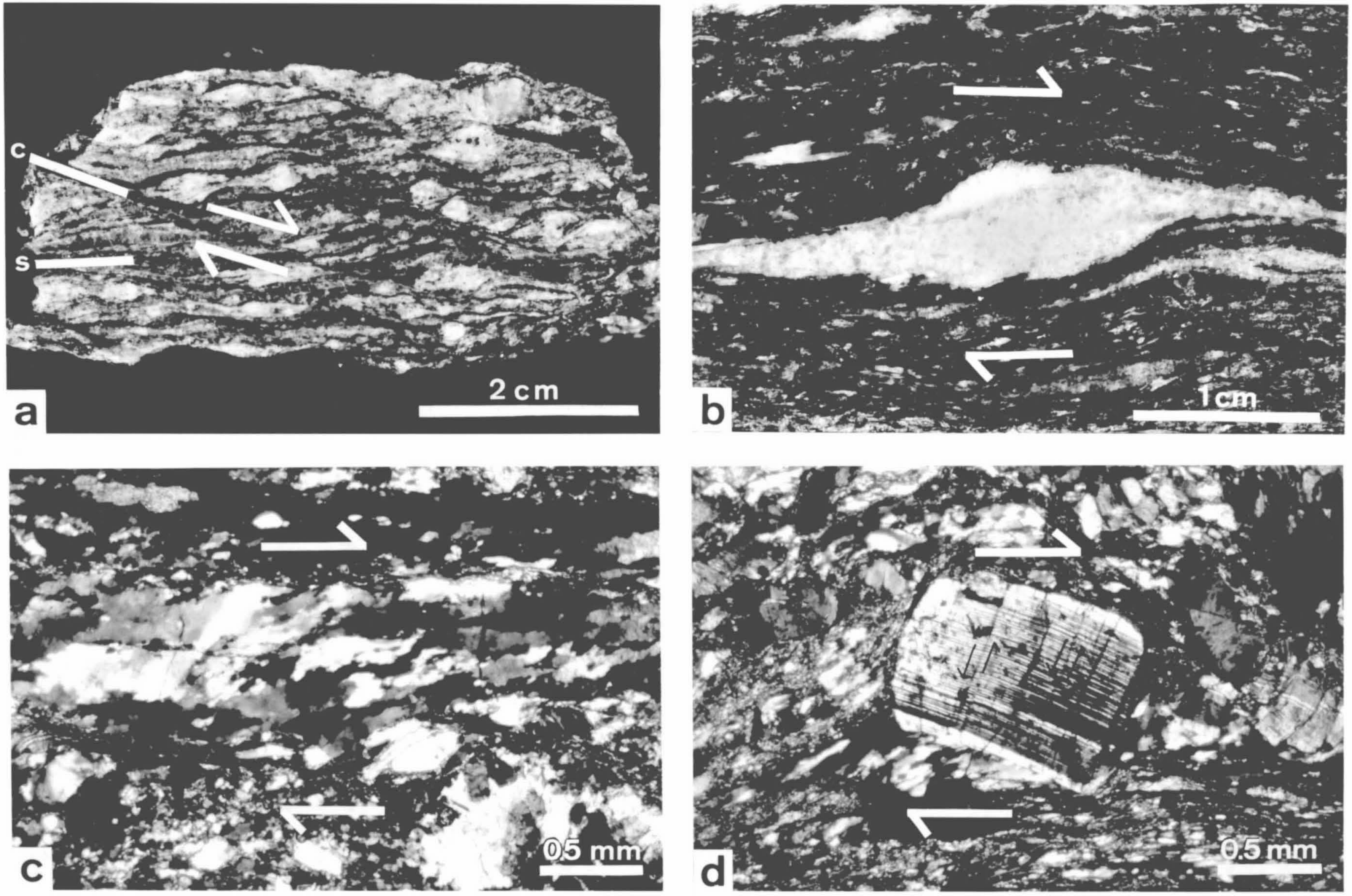


Figure 7.3a: Sheared augen granitic gneiss; S and C surfaces indicate dextral shear. **7.3b**: Asymmetric feldspar augen in granitic gneiss. **7.3c**: Subgrains and recrystallized grains with their flattening plane oblique to macroscopically visible foliation plane; crossed nicols. **7.3d**: Broken and displaced hard grain of feldspar in ductile matrix; crossed nicols.

The boundary between the uppermost granite gneiss sill of the transitional zone of the Phe Formation and the overlaying pelitic-psammitic rocks represents the northeastern boundary of the shear zone and is marked by a sudden decrease in intensity of the strong shear fabric, so the overall shear profile through the zone is asymmetric. In the literature, only the low-grade and unsheared pelites and psammites above the Zanskar shear zone are referred to the Phe Formation.

Within the different lithologies we find many different indicators for the shear sense (Simpson and Schmid, 1983): S and C surfaces (Fig. 7.3a); the orientation of individual mylonite zones; asymmetric pressure shadows around garnet, feldspar, and quartz clasts; asymmetric K-feldspar augen (Fig. 7.3b) and boudins of pegmatites; oblique, elongate, and recrystallized grains and subgrains; grain-shape fabric asymmetry (Fig. 7.3c); and displaced broken grains (Fig. 7.3d). All of these indicators are consistent in recording a normal (northeast-side down) displacement sense. Brittle faults, where present, have a similar displacement sense to the mylonites.

7.3 Regional metamorphism and development of the shear zone

In the Suru Valley (Figs. 1.5 and 5.1, left), there is a continuous decrease in metamorphic grade from the Zanskar Crystalline unit in the southwest to the Tibetan zone in the northeast. Permian - Triassic rocks are strongly and recumbently folded within the Zanskar Crystalline unit, and crosscutting isograds indicate a Himalayan age for the metamorphism (Honegger et al., 1982). The peaks of fabric development and metamorphism coincide (Honegger et al., 1982; Gilbert, 1986). As shown in Figures 5.1 and 7.1, the metamorphic isograds of the metapelites in the shear zone of the Zanskar area, however, come closer together. From Sumche Tokpo to Malung Tokpo, the isograds of biotite - garnet, staurolite, and sillimanite are condensed to a 200 - 250 m wide zone. The closeing together of the isograds is interpreted as a direct consequence of the shearing.

One of these narrow Permian-Triassic wedges (Figs. 5.1 and 7.1, southwest of Rangdum) thins toward the southeast and trends directly into the shear zone (R. Kündig, personal commun.). In the Zanskar area, however, such sedimentary rocks are not present within the Zanskar Crystalline unit. The Zanskar area is therefore interpreted as representing a deeper erosional level of the orogen.

Metamorphic minerals such as staurolite and kyanite are kinked and partly boudinaged in the shear zone. The leucogranites have a Miocene age (chapter 4) and their constituent minerals are partly affected by deformation in the shear zone. Retrograde formation of chlorite on C surfaces (Fig. 7.4), which are related to the shear zone, within amphibolite facies rocks indicates greenschist conditions during the formation of the shear zone. In the hanging wall of the shear zone, the presence of cataclasites and small brittle faults shows that the shear deformation occurred at temperatures lower than greenschist facies. These features indicate that the shear zone began to form during a late stage in the Himalayan metamorphism, after the intrusion of leucogranites.

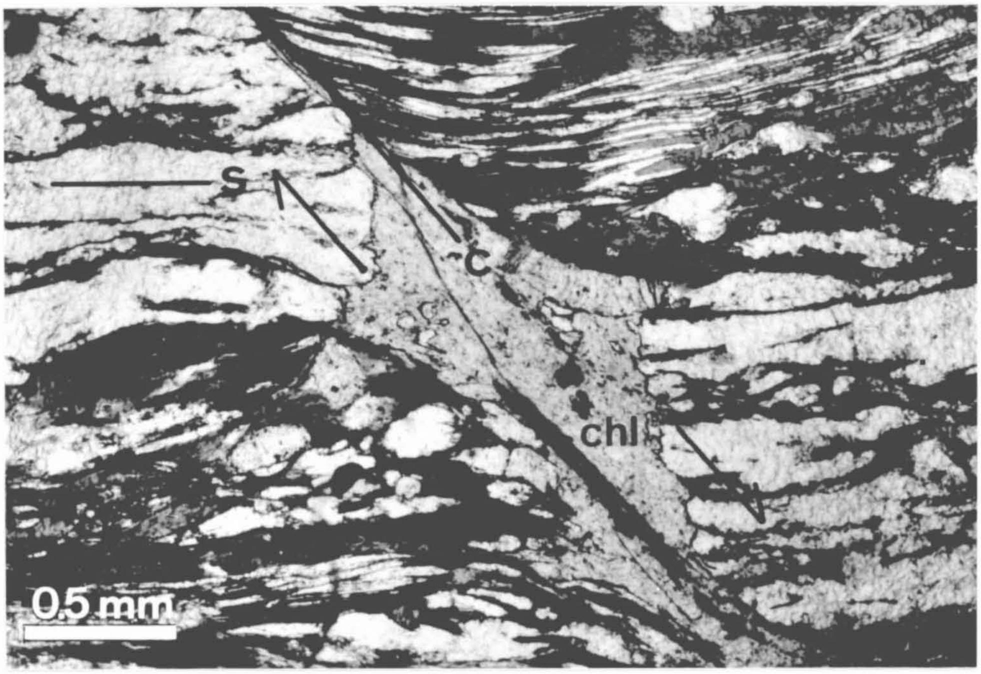


Figure 7.4: Retrograde growth of chlorite on C surface in sheared high amphibolite facies metasemipelite; crossed nicols.

7.4 Regional situation

The shear zone is well defined only in the Zanskar area. To the northwest (Suru Valley), in the area around Rangdum (Figs. 1.5 and 5.1), only slightly sheared granites with C surfaces are observed (Gilbert, 1986). A 50-m-wide shear zone can be recognized at the Pensi La (Figs. 1.8, 5.1 and 7.1). This zone widens, becomes better defined, and shows increasing shear displacement toward the southeast. The shear intensity of the zone reaches a maximum southwest of Phe and then decreases southeast of Padum in the Tsarap Lingti Chu Valley (Fig. 7.1). Baud et al. (1984) have described a sharp contact between the Zanskar Crystalline unit and the Phe Formation extending the Chandra and Bagha Valleys in the northern Lahul area which might represent the continuation of the Zanskar shear zone.

The pattern of the metamorphic isograds (Figs. 5.1 and 7.1) and the variation in geometric features of the shear zone indicate that the shear zone shows marked lateral changes in shear intensity. In the northwest, in the Malung Tokpo, for example, the sillimanite - K-feldspar isograd lies close to the shear zone and is only 3 km southwest of the sillimanite isograd. In the southeast (Tamasa Tokpo) this same isograd is not affected by shear and is about 9 km southwest of the sillimanite isograd.

7.5 Amount of shear

A simple model has been developed to estimate the approximate minimal amount of shear. The difference in distance between the metamorphic isograds from the unsheared (or less sheared) western Suru area and the strongly sheared Zanskar area (Fig. 5.1) has been used to calculate the approximate amount of shear in the Zanskar region.

The shear zone is assumed to be a zone of homogeneous simple shear. The width of the shear zone is known. The metamorphic isograd planes are known to be sub-parallel to the foliation of the gneisses of the Zanskar Crystalline unit (Fig. 7.5) (Honegger, 1983).

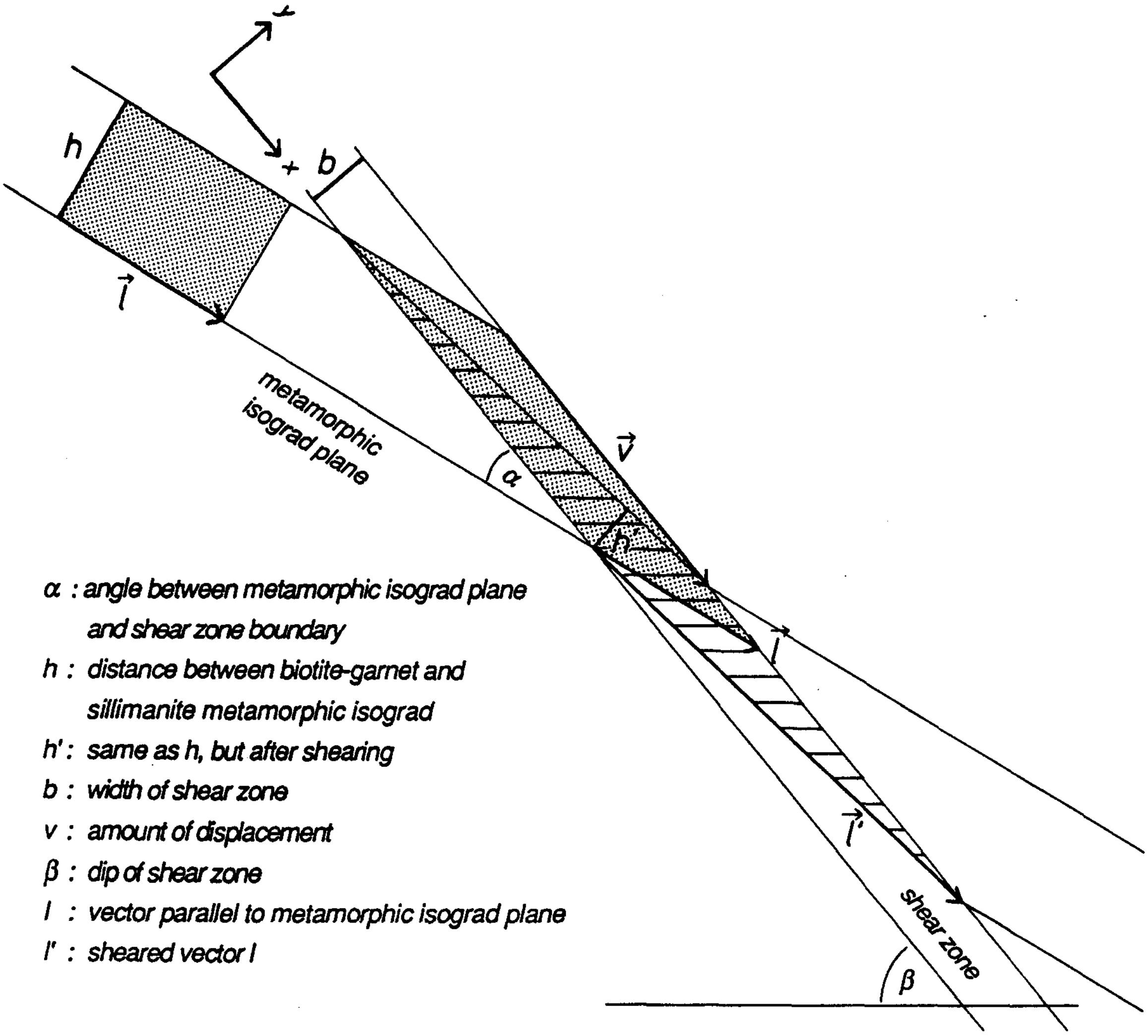


Figure 7.5: Simple shear model to deduce minimal amount of shear.

A simple shear of shear strain γ parallel to the x-axis is given by the deformation gradient matrix

$$\begin{bmatrix} 1 & \gamma \\ 0 & 1 \end{bmatrix} = A.$$

The deformed length l' of the vector l is given by

$$l' = A\,l. \qquad (1)$$

From the trigonometrical relationships indicated in Figure 6, the components of the vector l are

$$lx = l \cos \alpha$$

$$ly = l \sin \alpha$$

Substituting these into equation (1) we obtain

$$lx' = l \cos \alpha + \gamma\, l \sin \alpha$$

$$ly' = l \sin \alpha$$

Using the relationship $l'^2 = l_x'^2 + l_y'^2$ we obtain

$$l'^2 = l^2 \,(\gamma^2 \sin^2 \alpha + 2\gamma \cos \alpha \sin \alpha + 1).$$

The three patterned fields in Figure 7.5 have the same area. Using the relationship hl = h'l', we can replace l'^2 / l^2 by h^2 / h'^2 and we get the following quatratic equation:

$$0 = \gamma^2 + (2 / \tan \alpha)\gamma + (1 / \sin^2 \alpha)(1 - h^2 / h'^2). \qquad (2)$$

We are not intrested in the negative result because it would indicate an opposite shear sense. The discriminant of equation (2) is $(2 / \sin \alpha) \sqrt{(h^2 / h'^2) - \sin{}^2\alpha}$. $\sin^2 \alpha$ is negligible in comparison to h^2 / h'^2, so we can omit it, giving

$$\gamma \approx (1 / \sin \alpha)(h / h' - \cos \alpha). \qquad (3)$$

The displacement vector v is γb

$$\underline{v \approx (b / \sin \alpha)(h / h' - \cos \alpha).} \qquad (4)$$

From field evidence the values of α and h' are 20° and 250 m respectively. Because the model is based on homogeneous shear and because within the marginal sheared rock zone the rocks are only partially sheared, it seems reasonable to use a value of b as the width of the mylonite belt, that is, 350 m. The α, h' and b values were those measured in the Malung Tokpo (Figs. 7.1 and 7.2). Estimating the value of h is more difficult. Northwest of Rangdum, the strike of the Zanskar Crystalline unit is about the same as in Zanskar; the average dip is 30°. Given a dip of 30° and a horizontal distance between the biotite - garnet isograd and the sillimanite isograd of 12.6 km, we obtain 6.3 km for h. The dip, β, of the shear zone is constant: 50°. Therefore, $\alpha = 20^{\circ}$, $h = 6.3$ km, $h' = 0.25$ km, $b = 0.35$ km, $\beta = 50^{\circ}$, and this gives the minimum displacement amount of 25 km.

The metamorphic isograds form smooth curves, and no offsets are mappable. If fault discontinuities exist, they are on a sufficently fine scale (finely distributed shear bands) to still allow this calculation to produce a realistic approximation for the total displacement.

7.6 Discussion

From its tectonic position, shear sense, amount of displacement, and age, the Zanskar shear zone is directly comparable with normal fault zones from southern Tibet some 1200 km east-southeast from Zanskar, described by Burg et al. (1984) and Burg and Chen (1984).

Burchfiel and Royden (1985) have presented a model developing the results of Burg et al. (1984) to explain qualitatively the apparently incompatible juxtaposition of contemporaneous north-south shortening by thrusting in the Lower Himalayas and north-south extension by normal faulting in the Higher Himalayas. The subhorizontal extensional stresses produced in southern Tibet and the Higher Himalayas can be interpreted as the direct result of gravity acting on the highstanding plateau, and the extensional faulting can be considered as a type of gravitational collapse of the Himalayan topographic front. This gravity spreading or gravitational collapse is a secondary effect superposed on regional north-south compression.

The results presented here suggest that such interlinked compression and extension tectonics extent widely through the northwest Himalayan region as well as in the central Himalayas and Tibet.

8. Discussion

Within this chapter some additional problems of the Zanskar area, Ladakh and NW Himalaya will be dicussed in more detail and the deformational style of the Zanskar area will be compared and contrasted with other regions of Ladakh using data from previous publications. The problem of the nature of the angular discordance between the Panjal Trap unit and the Precambrian - Cambrian unit will be briefly discussed, for many of the problems, especially those concerning the paleogeography in Precambrian - Paleozoic time, remain unresolved. The discussion about interrelationships between the backfolding and the Zanskar shear zone presents some speculative conclusions, and it is hoped that these will lead to further discussions and give ideas on what observations need to be made in future research. In general this work should be a starting base for further studies, as many points remain unresolved.

8.1 Deformational style in the Zanskar area compared with the literature. Is the Tethys Himalaya Allochthonous?

The Spongtang Allochthon, west of the Zanskar river, is accepted by all previous workers to be a nappe lying on top of Tethyan sediments (e.g. Frank et al., 1976; Fuchs, 1979, 1982 and Kelemen and Sonnenfeld, 1983). The surrounding series of the "Zanskar Synclinorium" (Kelemen and Sonnenfeld, 1983) are authochthonous or para-autochthonous rocks (Fuchs, 1979, 1982, 1986). In contrast, Bassoullet et al. (1980, 1983) take the northern carbonate belt of Ladakh, which they call Zanskar - Shillakong Nappe, to be allochthonous. Baud et al. (1982, 1984) and Gaetani et al. (1985) accept this northern carbonate unit as allochthonous, also in the region east of the Zanskar river, and extend the allochthon concept to the whole of the Tethys Zone. According to these authors the Tethys Himalaya consists of a pile of nappes resting tectonically on the Zanskar Crystalline unit. I will now discuss the results of previous workers in relation to the zones investigated in this study.

In the studied Zanskar area my data does not accord with the nappe concept of Baud et al. (1982 and 1984) and Gaetani et al. (1985). They describe a tectonic contact of the so-called "**Phuctal nappe**" (Phe and Karsha Formation) with the underlying Zanskar Crystalline unit. The new investigations of this dissertation show that, in reality, this contact is a zone of extensional ductile shear, the Zanskar shear zone (Herren, 1987). The movement direction on an extension shear zone is opposite to that which would be found on a thrust contact of a nappe. This large scale normal fault separates the high grade metamorphic rocks of the Zanskar Crystalline unit from its overlaying low metamorphic sedimentary rocks of the Tethys

Himalaya (chapter 7). Further to the northeast, the base of the "**Zangla nappe**" (Permian to Paleogene rocks) of Baud et al. (1982, 1984) and Gaetani et al. (1985) corresponds to the base of the Panjal Trap unit. This unit is in some places in tectonic contact with the Phe, respectively Karsha Formation. The tectonic effects are those of local décollement horizons rather than major thrust contacts. These structural features represent differences in the deformational behaviour of the rigid Panjal Trap unit in relation to the various rock types in the overlying and underlying sedimentary sequences (chapter 3.2).

To the northeast, the Upper Triassic to Cretaceous "**Zumlung nappe**" (Baud et al., 1982, 1984 and Gaetani et al., 1985) is separated from the "Zangla nappe" by the *Kangi-Naerung-Zangla Fault* (Kelemen and Sonnenfeld, 1983), which is also considered by Kelemen and Sonnenfeld (1983), Fuchs (1982) and Bassoullet et al. (1980, 1983) to form the southern border to the northern carbonate belt of Ladakh. Gaetani et al. (1985) describe this contact zone as a ramp anticline of Kioto Limestone overhanging the overturned Zangla syncline of the Zangla nappe and follow the fault plane until Shade (50 km east of Tongde, Fig. 3.1). This fault contact zone seems to be well developed in the Kangi-Naerung area northwest of the Zanskar river (Kelemen and Sonnenfeld, 1983, Fuchs, 1982), and according to Fuchs (1985) was only active near the Spongtang allochthon. In the studied Zangla area such a thrust contact could not be established. The geological mapping of this study is in broad agreement with that of Baud et al. (1982) and that of Kelemen and Sonnenfeld (1983). Also the observations of Gaetani et al. (1985) fit well with my own observations, although we differ in interpretation. Because I do not agree with their interpretation I did not indicate the so-called Kangi-Naerung-Zangla Fault neither on my tectonic nor on my geologic maps (Figs. 3.1 and 3.3). This so-called fault seems to be the upper limb of the Zangla syncline or, in other words, the inverted limb of the northeastern following anticline within the Kioto Limestone (Fig. 6.1). Locally, late shearing along the probably thinned limb of these folds may have occured but in the region I have mapped it does not appear to have regional significance and is not associated with significant thrusting. Evidence for large scale overthrusting are totally missing and the stratigraphic sequence of formations is not disturbed. In addition, there are no facial changes occuring, for example, in the Kioto Limestone on either sides of the Zangla Synlicline within the "Zangla" and "Zumlung nappes" (Baud et al., 1984). Such as would be expected if a thrust fault had juxtaposed together originally widely separated depositional zones.

Thus, it appears that stratigraphic boundaries have been misinterpreted as nappe boundaries because they are locally tectonized due to differences of different parts of the sedimentary succession.

Searle (1983) gives a general description of the tectonic evolution of Ladakh. In his first paper about Ladakh, he recognises only one major deformational phase, with an additional backfolding event and the emplacement of the Spongtang Allochthon. In Searle (1986), however, the major phase of crustal shortening in the Tethys Himalaya and in the Indus Suture zone are desribed by polyphase thrusting and intense tight to isoclinal folding. His proposed tectonic concept, supported with balanced cross sections, does not seem to be applicable in the Zanskar area. Searle (1986) regards the Phe and Karsha Formation, the Panjal Trap and the Mesozoic unit as one mechanically linked rock sequence which deforms more or less homogeneously independant of lithology. He draws thrust planes extending from the Phe Formation to the Triassic lithologies (Searle, 1986: Figs. 6 and 7) and shows thrusting associated with folding. The harmonic and polyharmonic folds (Searle, 1986: Fig. 10a) located east of Zosar between Tongde and Zangla (Fig. 3.1) have been developed in the Lilang group and the overlying Kioto limestones. I have not been able to find evidence that indicated that thrust planes cut the folds as described and illustrated by Searle (1986).

8.2 Deformational style in the Zanskar area compared with other regions in Ladakh.

Bassoullet et al. (1980, 1983) suggested a very complicated structural evolution of the Tethys Himalaya to explain the present geological relations. In their view repeated thrusting both towards the south and north is necessary to develop a complex system of nappes and wedges, with all units of northern Zanskar ending up as rootless Allochthonous masses.

Kelemen and Sonnenfeld (1983) distinguished the "Honupattah Anticlinorium" north of the Kangi-Naerung Fault and the "Zanskar Synclinorium" south of it. Three major phases of deformation are distingished: Late Cretaceous insoclinal folding with SW verging axial planes contemporaneous with deposition of the Kangi La Flysch (upper Cretaceous), post-Lower Eocene open folding about almost vertical axial planes, and brittle deformation of this later structure during emplacement of the Spongthang Allochthon. They interpret the deformation in the greater Ladakh region to be continous from at least late Cretaceous through to the Miocene.

Stutz and Steck (1986) and Stutz (1988, in prep) also describe several deformational phases from the investigated northwestern end of the Tso Morari culmination adjacent the Indus Suture zone. The Langtang Nappe (Carboniferous to lower Tertiary rocks) overlying the Nyimaling unit (Cambrian metasedimentary sequence and Ordovician granites) is folded by several later phases. Isoclinal phase 1 folds predate southwest vergent megascopic recumbent folds (phase 2) within this fold nappe. The associated schistosity is the main regional deformational structure. Phase 3 can be correlated with the main schistosity within the underlying Nyimaling unit which has a structural form resulting from the updoming of this area. Therefore within this region, facily close the Indus Suture zone, two folding phases have been distinguished predating the first backvergent deformation.

In the view of Fuchs (1985) all units form one stratigraphic complex and he concluded that it is not possible to differentiate different structural units as previously suggested by Bassoullet et al. (1983). In a later publication (Fuchs, 1986) he cleary disagrees with the structural evolution drawn by the French group. Although he agreed that in a first tectonic phase nappes were thrust from the Indus Suture zone towards the south he deduces from the presence of Early Tertiary formations at the base of the Spongtang Allochthon that the nappes took their place not in Upper Cretaceous but in post-Lower Eocene time. These Tertiary rocks are not taken into account in the chronology of tectonic events by the French team. Further more there is no evidence to back the assumption that in phase 1 a Zanskar - Shillakong Nappe moved onto the Tethyan series. Phases 2 and 3 of the French group probably formed during a single phase of compression, in which northern Zanskar in the area N of the Spongtang Allochthon attained its fan structure. At the same time, when the Indus Suture zone was overturned towards the N and deformed with northern vergence (phase 2 of the French), the "phase 3" movements affected central Zanskar. This is suggested by the gradual change from south dipping structures in the Indus zone to vertical tight folding in northern Zanskar and to north dipping structures in central Zanskar. He concluded that the geology of Ladakh can be explained in an easier way.

In the studied Zanskar area I have recognised only two deformational phases, namely a major folding and thrusting phase and a slightly developed backfolding phase. Thrusting of the Panjal Trap unit is simultanous with folding of the overlying (Mesozoic units) and underlying formations (Phe and Karsha Formation). Because no Tertiary and no undeformed sediments are exposed in the studied Zanskar area it is not possible to date the main folding phase exactly. However, comparisons with other regions and, in particular, correlations of the deformation mechanisms and evolution within the individual units allow some possible interpretations to be made. The main folding and thrusting phase of the Himalayan orogeny is correlatable, in the Zanskar area, within all units from the Zanskar Crystalline unit through to the Mesozoic formations of the Tethys Himalaya and no nappes are present. The well developed schistosity within all units is related to this main deformational phase. The northern part of the Tethys Himalaya and the Suture zone show, in opposition to the Zanskar area, several deformational phases (Stutz, in prep.; Kelemen and Sonnenfeld, 1983; Bassoullet et al., 1980, 1983). The second phase of Stutz (in prep.) and the third phase of Kelemen and Sonnenfeld (1983) are probably correlatable with the main folding phase in the Zanskar area. Folding started in the units near the Indus Suture zone in the north probably at an earlier time than in the more southern lying Zanskar area. It is not yet resolved whether deformation started at Cretaceous time, as interpreted by Kelemen and Sonnenfeld (1983), or post-Cretaceous (Bassoullet et al., 1980, 1983) or later in Eocene time (Fuchs,1982; Searle 1986). No features were found which enabled the main deformation phase to be dated (chapters 2 and 3). I tend more towards the interpretation given by Fuchs (1982) and Searle

(1986) that the major tectonic phase, developing folding and thrusting, started immediately after the continental collision and closure of the Tethys (post - Eocene) and not as early as Cretaceous time, as postulated by Kelemen and Sonnenfeld (1983) and Bassoullet et al. (1980, 1983).

8.3 The angular discordance between the Panjal Trap unit and the Phe respectively Karsha Formation

In the Zanskar area, the Cambrian Karsha Formation is the highest exposed Paleozoic formation, whereas to the southeast a more complet Paleozoic succession is present, forming the Zanskar - Lahaul - Spiti basin (Nanda and Singh, 1976). To the west, a similar complete Paleozoic succession is exposed in the Kashmir area (Fig. 8.1).

In the high grade metamorphic Suru region as well as in the western part of the Zanskar area, the Phe Formation is the only Precambrian - Cambrian formation exposed and is the oldest member of the Tethys sedimentary sequence. This formation is sometimes reduced in thickness (Fig. 8.1). Compared with the thick and more complete successions of Paleozoic basin of Kashmir and of Lahaul - Spiti, the Paleozoic units thin out gradually towards the Suru region from both sides. By comparing different lithological profiles Honegger (1983) has clearly demonstrated that the characteristic Paleozoic lithological sequence is not present in the Suru region.

My own investigations support the conclusions of Honegger (1983), that the Suru as well as the Zanskar regions were either areas of no or little sedimentation, or were areas of erosion during Paleozoic time. Because the stratigraphically lowest unit of the Tethys Himalaya, the Phe Formation, is present only in reduced form, and because the younger formations gradually crop out towards the southeast and the northwest, the Suru and the W Zanskar are considered to be regions which were stable or which showed uplift (with sediment regression) during Paleozoic time. During Permian time great basaltic flows erupted and covered the incomplete late Precambrian - Paleozoic sedimentary succession as is evident by the Panjal Trap unit. The angular discordance between the Panjal Trap unit and the underlying Phe and Karsha Formations, respectively (Fig. 1.4), is an angular unconformity representing a sedimentary gap.

Two interpretations of this hiatus can be suggested. One interpretation could be that all of the Paleozoic sediments were present, as in the adjacent Kashmir and Lahaul - Spiti basin, but that they were eroded before the extrusion of the Panjal Trap volcanics. Such a great erosion phase would require major tectonic activity prior to Permian time. There is, however, no evidence to suggest large scale regional tectonic activity at pre-Permian time. In addition, the large volumes of sediments which might represent the erosion products of these Paleozoic lithologies have to my knowledge not as yet been observed.

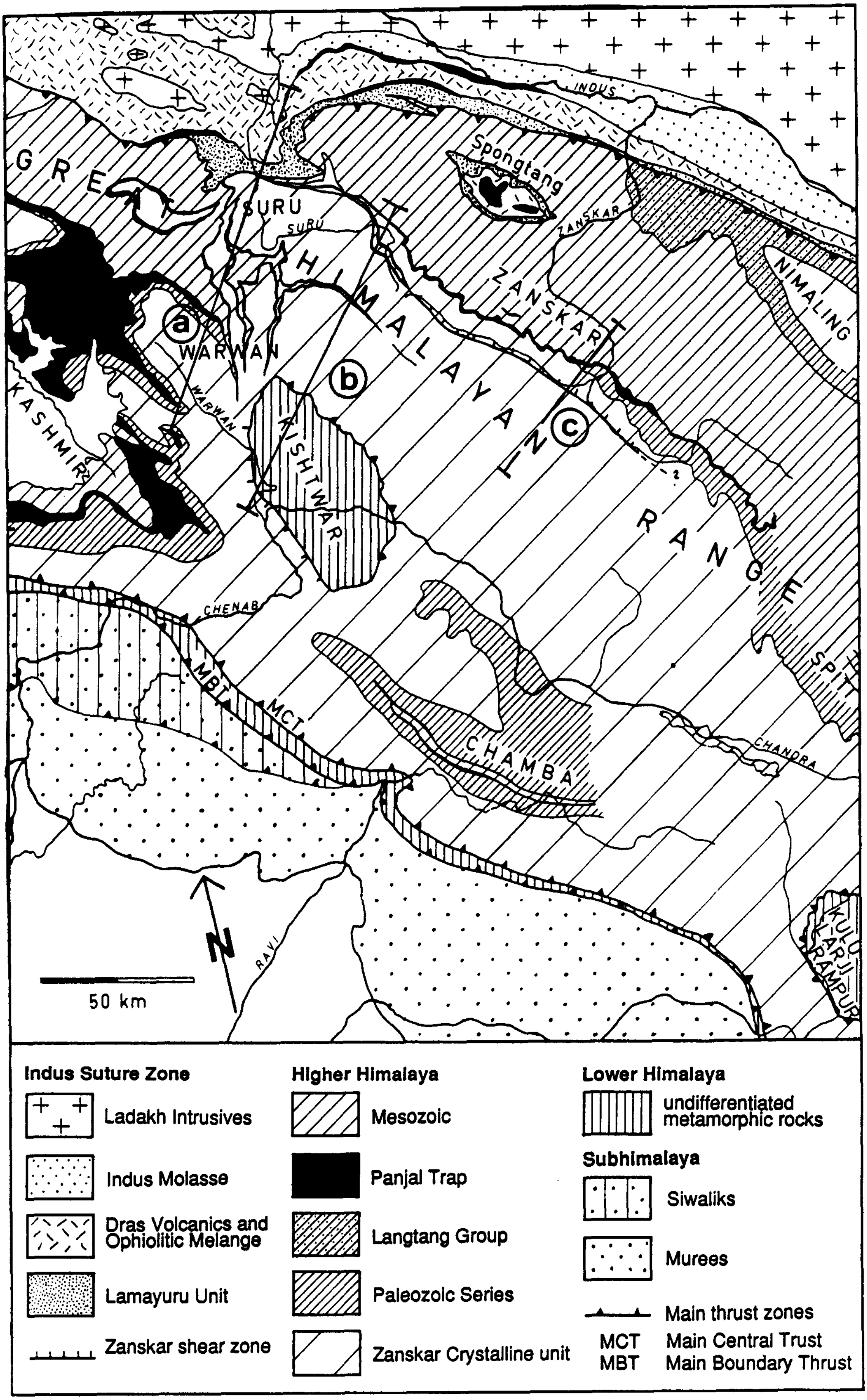


Figure 8.1: Tectonic - geologic map of Kashmir - Ladakh and line of cross sections shown in Fig. 8.2 (after Honegger, 1983 and Frank et al., 1987, modified). (Black within the Indus Suture zone are Ophiolites; the age of the Langtang Group is Pelaozoic - Tertiary)

The second possibility is that the original Paleozoic - Mesozoic sedimentary cover of the Zanskar Crystalline unit was thrust away on a décollement thrust and replaced by an allochthonous Permo - Mesozoic sequence (Baud et al., 1984; Gaetani et al., 1985) (substitution de couverture, Trümpy, 1960). Structural and metamorphic investigations, have shown a clear and gradual transition from the characteristic fold - nappe structure from the Zanskar Crystalline unit in the Suru region to the fold - thrust structure in the Zanskar region (chapters 2, 5 and 7). The recognition of Himalayan age of the main metamorphism made by Honegger et al. (1982) and Honegger (1983) is also valid for the Zanskar region. As Mesozoic lithologies have been folded within the Zanskar Crystalline unit in the Suru region (Honegger et al., 1982), the uppermost part of the sedimentary sequence might have been thrust off from its substratum. Several arguments can be mentioned against this idea:

- There is no field evidence for a "cool" thrusting event before ductile folding of the Zanskar Crystalline unit and overlying Permo - Mesozoic units in the Suru region - a region where Paleozoic formations are mostly missing.
- There is no evidence at the base of the Panjal Trap to suggest the presence of a great overthrust plane (chapter 3.2.2).
- No nappes of Paleozoic and Mesozoic units are found further southwest, a region which would have been the probable place of their emplacement.

8.4 Backfolding - Zanskar shear zone

The deformation style changes markedly from the Suru to the Zanskar region. The Suru region is strongly affected by a backfolding event which steepens the units of the Zanskar Crystalline unit and turns the formations of the Indus Suture zone so that they dip towards south (Fig. 8.2a). Towards the southeast (Zanskar region) the backfolding decreases in intensity. The individual formations no longer dip towards north or northeast. Backfolding structures are only represented as small scale developments of crenulation cleavage in the shales of the Phe, Karsha and Mesozoic formations and as small scale folds, especially on top of the Zanskar Crystalline unit, with a fold vergence opposed to the vergence of those folds related the earlier main deformation phase (Fig. 8.2b,c).

The development of the backfolding occurred late in the metamorphic history after the peaks of fabric development and metamophism. Honegger (1983) could clearly demonstrate that not only the formations but also the metamorphic mineral zones in the Suru region are steepened or even overturned to the north (Fig. 8.3). In the Zanskar region, however, such a steepening and an overturning of the formations and of the mineral zones does not occur (Fig. 8.2).

On the other hand the amount of shear movements on top of the Zanskar Crystalline unit in the Zanskar region was enormous and led to the formation of the extensional Zanskar

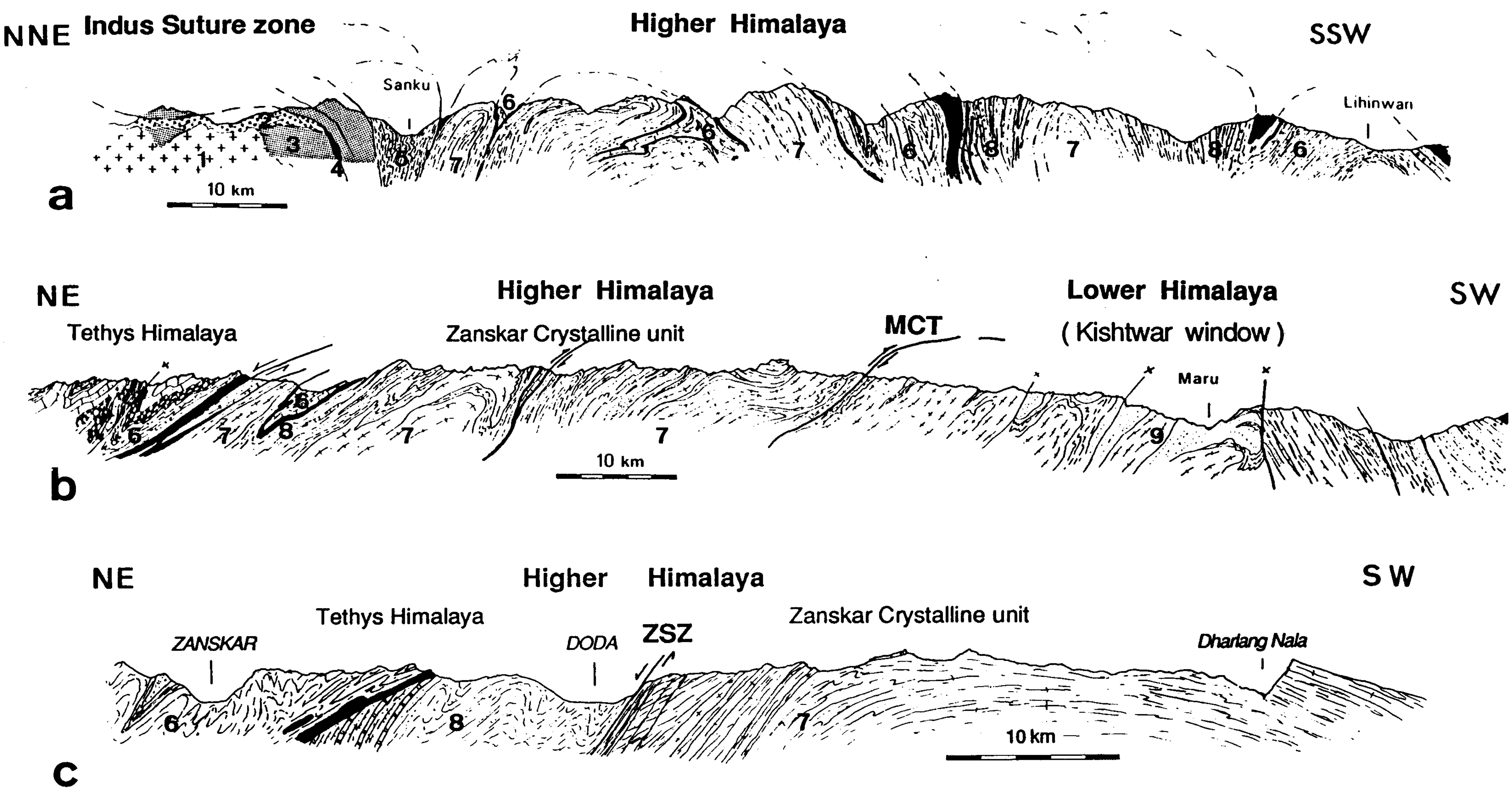


Figure 8.2: Cross sections through the Suru region (after Honegger, 1983) and the Zanskar area. Line of cross sections on Fig. 8.1. Lithologies: 1 = Ladakh Batholith; 2 = Indus Molasse; 3 = Dras Volcanics; 4 = Ophiolitic Mélange; 5 = Lamayuru unit; 6 = Panjal Trap and Mesozoic formations; 7 = Zanskar Crystalline unit (gneisses, granite gneisses and leucogranites); 8 = Precambrian - Cambrian formations and 9 = Lower Himalaya (crystalline rocks). **a:** from Kargil to the Kashmir valley; **b:** from Rangdum to the Warwan area; **c:** from Zanskar to the Dharlang Nala.

shear zone (chapter 7), well defined only in the Zanskar area. To the northwest (Suru region), no sheared lithologies are present. Further southeast of the Suru region, in the area around Rangdum (Fig. 5.1), only slightly sheared granites with C surfaces have been observed (Gilbert, 1986). A 50-m-wide shear zone can be recognized at the Pensi La (Figs. 5.1 and 7.1). This zone widens, becomes better defined, and shows increasing shear displacement toward the southeast. The shear intensity of the zone reaches a maximum southwest of Phe and then decreases southeast of Padum in the Tsarap Lingti Chu (Figs. 5.1 and 7.1).

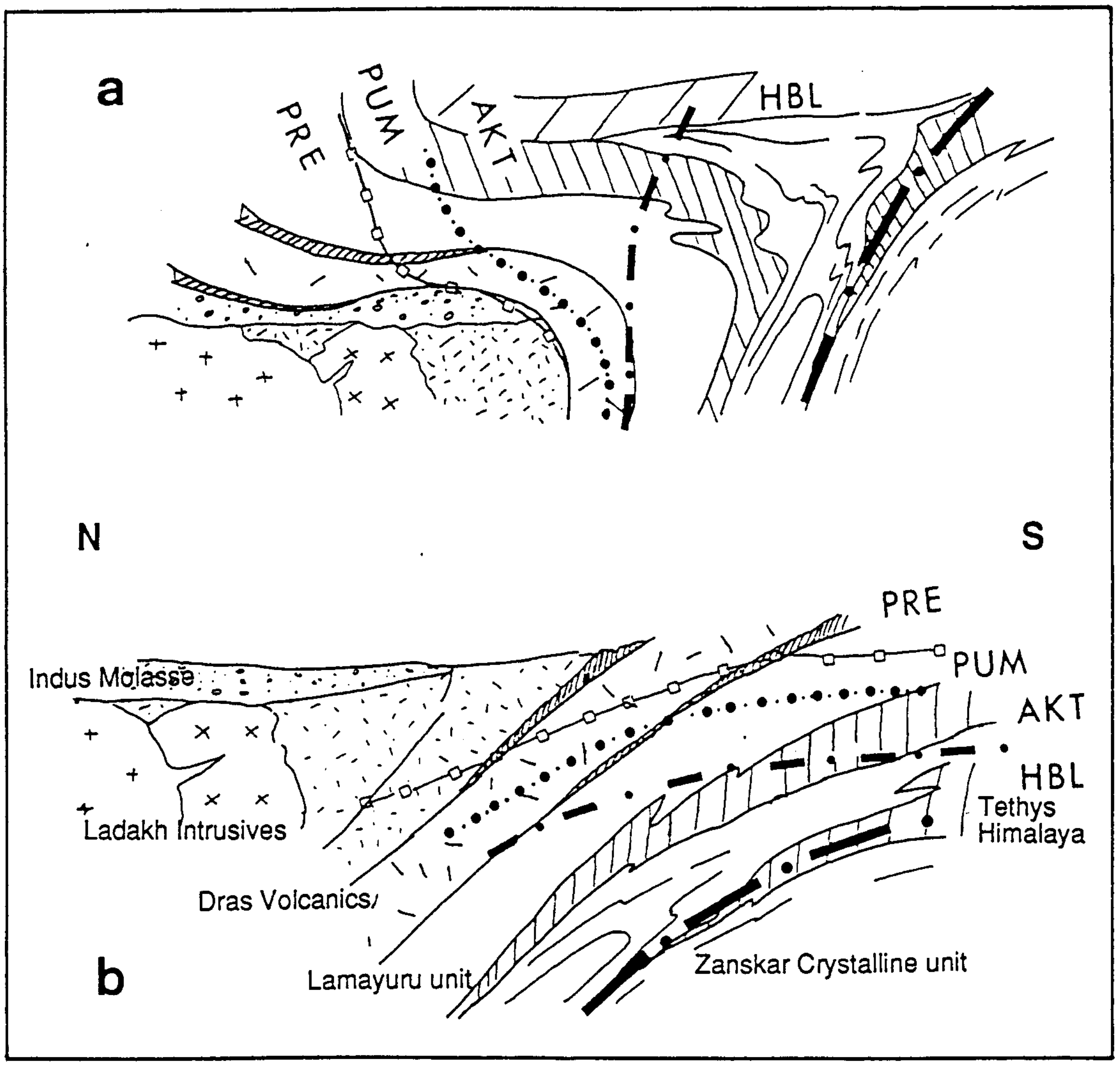


Figure 8.3: The relation metamorphic isograds (of the Meta-basica) - structures along a N-S cross-section in the Suru region (after Honegger, 1983). PRE = prehnite - pumpellyite mineral zone, PUM = actinolite - pumpellyite mineral zone, AKT = actinolite - albite - epidote - chlorite mineral zone and HBL = hornblende - albite - epidote - chlorite mineral zone. **a:** By the backfolding event overturned mineral zones. **b:** Reconstruction of the orientation of the mineral zones and the tectonic units before backfolding.

Lithological, structural, metamorphic, macroscopic and microscopic studies lead to the suggestion that backfolding as well as extensional shearing might have the same origin, namely the continuous crustal shortening of the northern margin of the Indian continent due to the continuous northward migration of the Indian continent towards Asia. The difference between the Suru and Zanskar region which leads to different predominant deformation features lies (1) in different lithological successions and (2) in a different metamorphic grade. These two suggestions will be explained in more detail in the following paragraph:

(1) Suru region:

- Between the Zanskar Crystalline unit and the Indus Suture zone the Tethyan sedimentary sequence is not well developed (Fig. 8.1). The Phe Formation is stratigraphically reduced (compare 8.3), the Panjal Trap is tectonically thinned to some meters (Honegger, 1983) and the Mesozoic formations are reduced or eroded because of late updoming of this region (Honegger, 1983).
- The distance between the Zanskar Crystalline unit and the rigid Ladakh Batholith is very small, locally only 20 km (Figs. 1.5 and 5.1).

Zanskar region:

- The Tethyan sedimentary formations are well developed. A thick (several km) Precambrian - Cambrian sequence is exposed (Fig. 8.1).
- The distance from the Zanskar Crystalline unit to the Ladakh Batholith is at least 70 km.

(2) Suru region:

- The regional metamorphism reaches high into the sedimentary sequence (Honegger, 1983). E.g. the biotite - garnet mineral zone reaches the Indus Suture zone. The Mesozoic rocks near Rangdum are of upper greenschist metamorphic grade (Fig. 5.1).
- Permo - Mesozoic rocks are strongly and recumbently folded within the Zanskar Crystalline unit.
- The Panjal Trap unit shows ductile deformation (Honegger, 1983).

Zanskar region:

- The garnet - biotite mineral zone can be found on top of the Zanskar Crystalline unit or lies within this unit (Fig. 5.1).
- The Tethyan sediments are of lower greenschist or even lower metamorphic grade (chapter 5).

Tectonic evolution in the Suru region:

Permo - Mesozoic lithologies are strongly and recumbently folded within the Zanskar Crystalline unit forming a complicated fold and nappe region (Honegger, 1983) enduced by the collision of the Indian and Asian continent. These fold and nappe structures may be compared with the Lepontin region of Swiss Alps where Mesozoic sediments can be used to separate individual nappes (e.g. Heim, 1921 and Blattner, 1965). Continuous further crustal shortening of the northern margin of the Indian continent squeezed all the units together and backfolding started. The relatively high grade metamorphic Mesozoic rocks, the shales and flysch of the Lamayuru unit and the Dras volcanics show a very ductile behaviour and were thrust as inverted limbs of fold nappes over the Indus Molasse and the Ladakh Batholith (Honegger, 1983). The Indus Suture zone changes its dip direction from south to north.

Tectonic evolution of the Zanskar region:

Permo - Mesozoic rocks are not folded within the Zanskar Crystalline unit (Figs. 1.5 and 5.1) because between these units lie on the thick (some km) Precambrian - Cambrian sedimentary sequence. Backfolding developed within all units as a consequence of continous shortening after the main deformational phase illustrated by folding and thrusting. Crenulation cleavage with a south dipping axial plane in the Tethys Himalaya (Fig. 8.2) and small scale folds with a fold vergence opposed to that of the folds related to the main deformational phase (Fig. 8.4) in the Zanskar Crystalline unit appear to be related to the backfolding.

Figure 8.4: Small scale fold within the Zanskar Crystalline unit, related to the backfolding event by its fold vergence. The scale in the lower left has 10 mm major devision.

When the continuous shortening could not be accommodated any longer by backfolding, and where the lithologies do not allow the formation of overturned folds as in the joining Suru region other types of deformation ensued. The mostly terrigenous sediments of the Phe and Karsha Formations appear to have become locked and unable to take up further deformation and therefore behaved in a less ductile manner as a consequence of continuing deformation. Therefore the Zanskar shear zone (chapter 7) started to develop. Shearing within the well banded crystalline rocks seems to have accommodated the shortening deformation easier than backfolding.

The following two facts support these suggestive ideas presented above:

1) Microscopic investigations has demonstrated that shearing as well as backfolding developed in the Zanskar area but at a later period in time.
2) The geometric features of the shear zone show that the Zanskar Crystalline unit has moved upwards relative to the Tethys Himalaya.

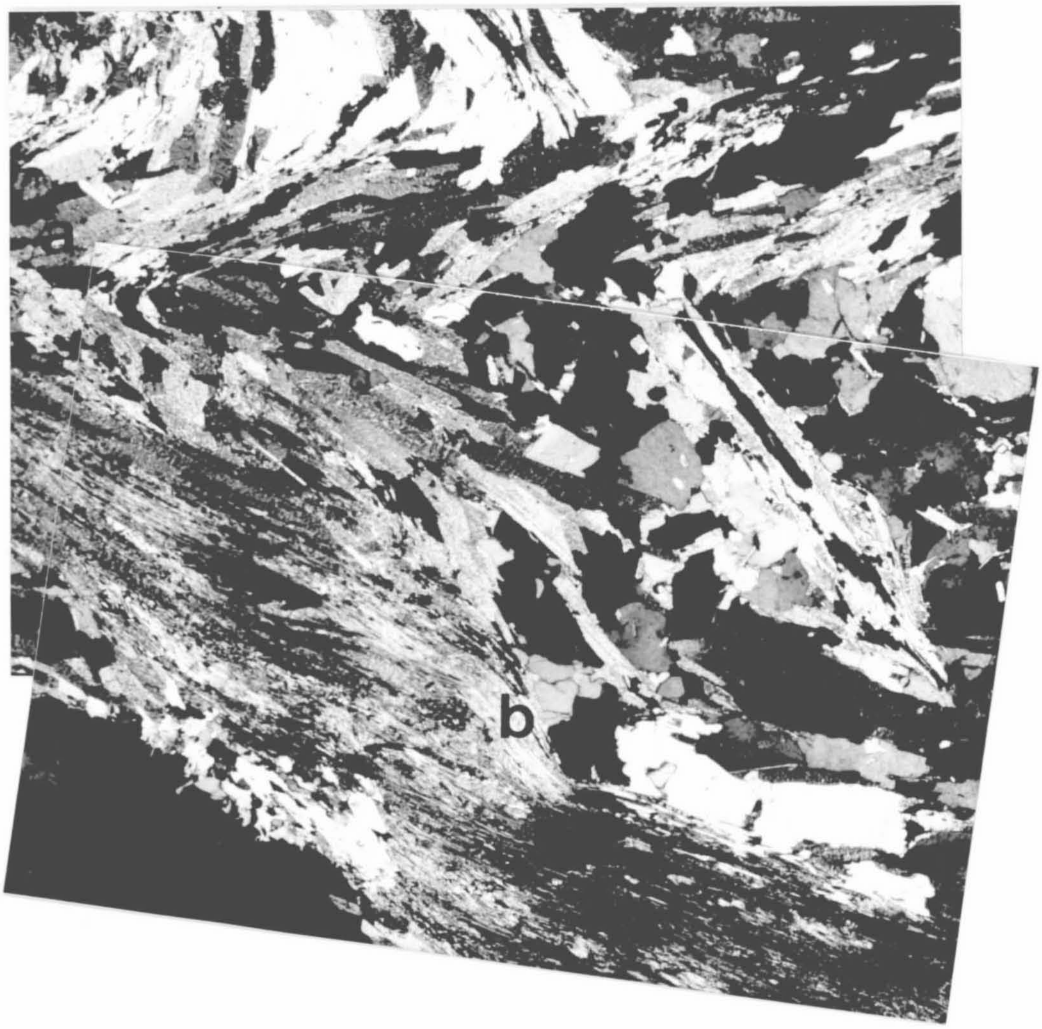


Figure 8.5: Thin sections of a rock specismen showing small scale folds as well as C - S shear texture. The development of the shear planes seems to be later in time than folding. The width of the figures correspond to 3 mm, crossed nicols. **a:** Hinge of a small scale fold, note the biotite flakes which are neither kinked nor bend. **b:** Slightly developed shear plane (C - surface) inducing a bending of the biotite flakes and locally biotite flakes are stretched.

1) In the Tamasa Tokpo, shearing is not as strongly developed as in the Malung Tokpo. Mineral and stretching lineations are locally developed next each other. Small scale folds related to backfolding as S - C shear fabrics are present in the same rock specimens. Microscopic investigations of two samples from the Tamasa Tokpo with folds (Fig. 8.4) and a slightly sheared fabric shows a clear relationship between backfolding and shearing. In Figure 8.5 (a) mm to cm sized folds are illustrated by biotite flakes which are neither kinked nor broken. The angular relationships between fold axial planes and rock banding in these folds shows that the folds are related to the backfolding. The biotite flakes are locally deflected by C planes (Fig. 8.5 (b)) indicating the development of C planes later in time than folding.

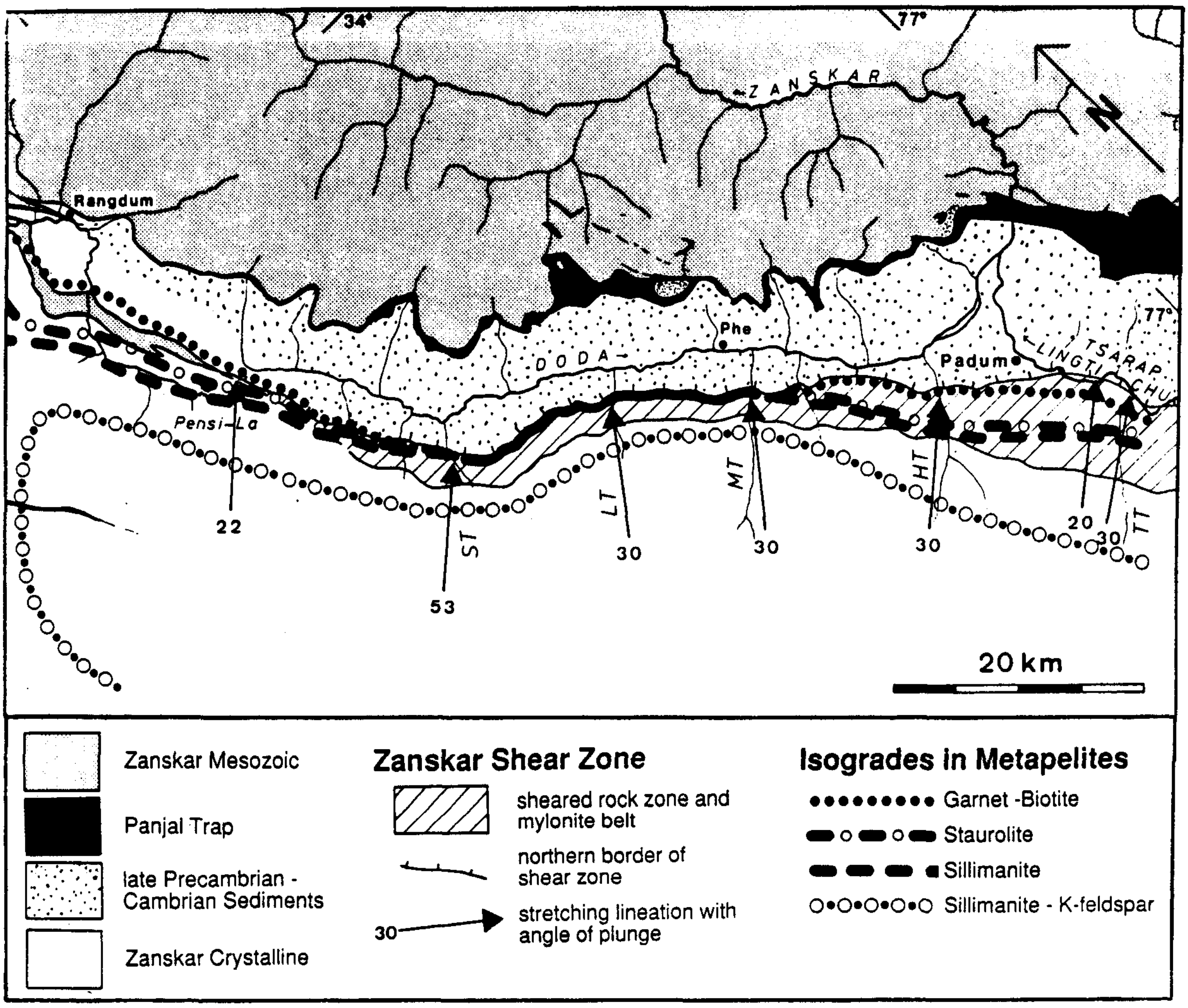


Figure 8.6: Metamorphic map of the Zanskar area showing the closeness of the metamorphic isograds within the Zanskar shear zone (detail from Figure 5.1). In the region of the Sumche Tokpo, Lechan Tokpo and Malung Tokpo the closeness of the metamorphic isograds indicates the greatest amount of shearing within the Zanskar shear zone, therefore in this region lies the largest amount of uplift of the Zanskar Crystalline unit relative to the sedimentary cover. Abbreviations: ST = Sumche Tokpo; LT = Lechan Tokpo; MT = Malung Tokpo; HT = Haptal Tokpo and TT = Tamasa Tokpo.

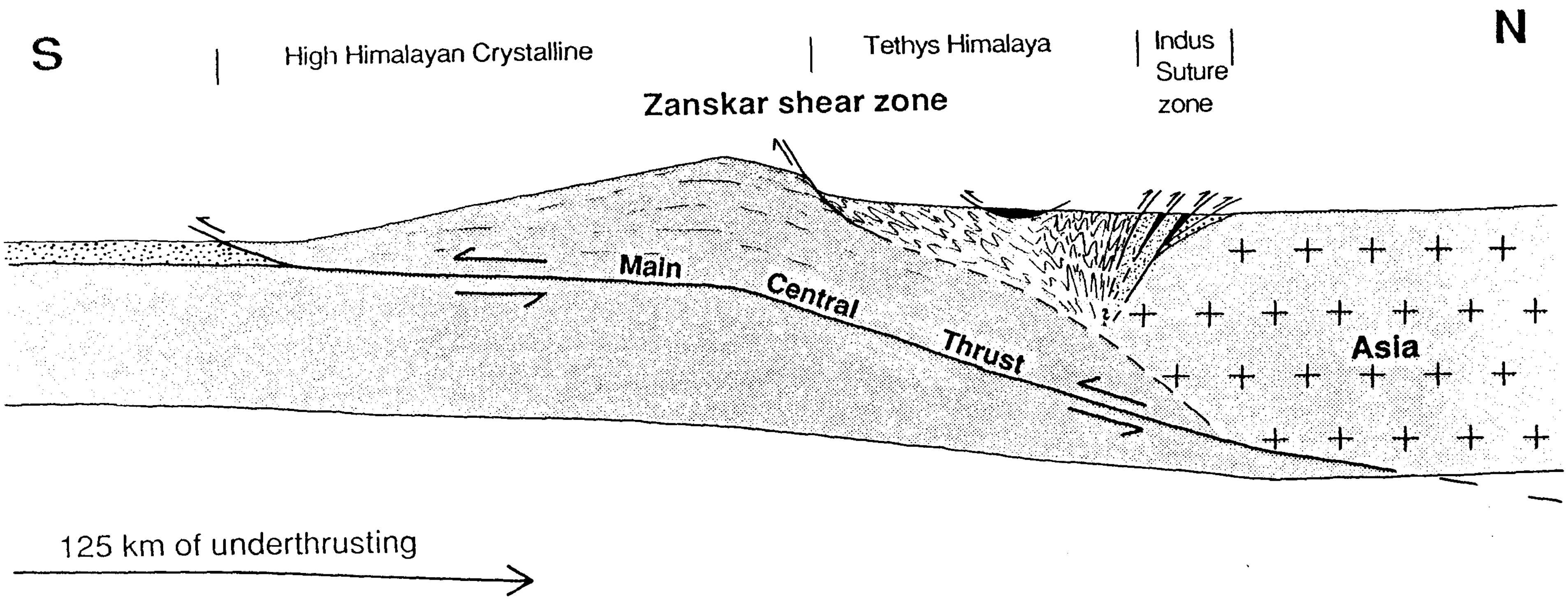


Figure 8.7: Schematic and idealized cross-section through the Himalayas after 125 km of underthrusting of India along the Main Central Thrust (MCT). Note the marked uplift of material over the MCT. The gross features are after Lyon - Caen and Molnar (1983) (compare also Fig. 2.10), adapted and modified to the situation in Ladakh - Kashmir. The Zanskar shear zone, the counterthrusts within the Indus suture zone and the MCT have been active contemporaneous. The folds within the Tethys Himalaya, however, formed at an earlier time.

2) Within the Zanskar shear zone the relative shear sense can be determinated using micro and macro structures (chapter 7) indicating a normal (northeast-side-down) displacement sense. The absolute movements on the units (Tethys sedimentary sequence gliding downwards or Zanskar Crystalline unit moving upwards), can not be firmely established, because the shear sense determination gives only the relative movement sense. The geological map (Fig. 8.6), however, shows evidence that the crystalline part was moving upwards. The pattern of the metamorphic isograds (Fig. 8.6) and the variation in geometric features of the shear zone indicate that the shear zone shows marked lateral changes in shear intensity. In the northwest, in the Malung Tokpo, for example, the sillimanite - K-feldspar isograd lies close to the shear zone and is only 3 km southwest of the sillimanite isograd. In the southeast (Tamasa Tokpo) this same isograd is not affected by shear and is about 9 km southwest of the sillimanite isograd. Therefore, if the Tethys sedimentary sequence would have moved downwards, a structural depression would be expected where the shear intensity was largest, that is, in the area near Phe opposite to the Malung Tokpo. Figure 8.6), however, shows that the base of the Permo - Mesozoic unit strikes more or less parallel the top of the Zanskar shear zone. The geometric feature of this unit shows that it appears not to be affected by the variation of amount of shear within the shear zone.

The apparent paradoxical juxtaposition of extension (Zanskar shear zone) and compression (general deformational field) in the Zanskar area can be explained in the following way: Local extension in the Zanskar area is assumed to have been contemporaneous with late overthrusting along the Main Central Thrust (MCT) further southeast (at least 50 km southeast of Zanskar). The movements on the MCT must have been active for a long time because the intrusion of the Zanskar leucogranites was contemporaneous with the movements on this major thrust plane (chapter 4) yet these intrusions were deformed along the Zanskar shear zone (chapter 7). The coincidence of overthrusting due to compression on the MCT and of extension by the Zanskar shear zone can be explained by a sort of "escape" of the wedge shaped Zanskar Crystalline unit on fault planes (thrusting along the MCT is more or less parallel the schistosity, whereas the shear planes of the Zanskar shear zone dip 20^{o} more than the schistosity (chapter 7) giving the Zanskar Crystalline unit a wedge shaped structure). These escape movements accomodated the shortening whilst in the Suru region backfolding continued. This speculative interpretation is shown in Figure 8.7.

Bibliography

Allègre, C.J., and Othman, D.B., 1980: Nd-Sr isotopic relationship in granitoid rocks and continental crust development: a chemical approach to orogenesis. - Nature, 286, 335-346.

Auden, J.B., 1933: On the age of certain Himalayan granites. - Rec. Geol. Surv. India, 66(4), 461-471.

———, 1935: Traverses in the Himalaya. - Rec. Geol. Surv. India.

Bassoullet, J.P., Colchen, M., Juteau, Th., Marcoux, J., et Mascle, G., 1980: L'édifice de nappes du Zanskar (Ladakh, Himalaya). - C.R. Acad. Sc. Paris, 290 (Série D), 389-392.

Bassoullet, J.P., Colchen, M., Juteau, Th., Marcoux, J., Mascle, G., and Reibel, G., 1983: Geological studies in the Indus Suture zone of Ladakh (Himalayas) - Contr. Himal. Geol. (ed. Gupta, V.J.), 2, 96-124.

Baud, A., Gaetani, M., Garzanti, E., Fois, E., Nicora, A., and Tintori, A., 1984: Geological observations in southeastern Zanskar and adjacent Lahul area (northwestern Himalaya). - Eclog. Geol. Helv., 77(1), 171-197.

Berthé, D., Choukroune , P., and Jegouzo, P., 1979a: Orthogneiss, mylonite and non coaxial deformation of granites: the example of the South Armorican Shear Zone. - J. Struct. Geol., 1, 31-34.

Berthé, D., Choukroune, P., and Gapais, D., 1979b: Orientation preferentielles du quartz et orthogneissification progressive en regime cisaillant: l'example du cisaillement sud-armoricain. - Bull. Minéral., 102, 265-272.

Berthelsen, A., 1953: On the geology of the Rupshu district NW Himalaya. - Medd. Dansk Geol. Foren., 12(3), 350-414.

Bhanot, V.B., Bhandari, A.K., Singh, V., and Ashok, K.K., 1970: Geochronological and geological studies on a granite of Higher Himalaya, NE of Manikaran, Himachal Pradesh. - J. Geol. Soc. India, 20, 90-94.

Bhat, M.I., and Zainuddin, S.M., 1978: Geochemistry of the Panjal Traps of Mount Kayol, Lidderwat, Pahalgam, Kashmir. - J. Geol. Soc. India, 19, 403-410.

———, 1979: Origin and evolution of the Panjal Volcanics. - Himal. Geol., 9(2), 421-461.

Blattner, P., 1965: Ein anatektisches Gneissmassiv zwischen Val Bodengo und Valle di Livio (Prov. Sondrio und Como). - Schweiz. Mineral. Petrogr. Mitt., 45 (2), 973-1071.

Blattner, P., Dietrich, V., and Gansser, A., 1983: Contrasting ^{18}O enrichment and origins of High Himalayan and Transhimalayan intrusives. - Earth Planet. Sci. Lett., 65, 276-286.

Bordet, P., Colchen, M., Krummenacher, D., Le Fort, P., Monterde, R., and Rémy, J.M., 1971: Recherches géologiques dans l'Himalaya du Népal, région de la Thakkhola. - Ed. Cent. Nat. Rech. Sci., Paris, 279p.

Bortolami, G.C., Lombardo, B., and Polino, R., 1976: The Higher Himalaya and the Tibetan series in the Lhotse area, eastern Nepal. - Boll. Soc. Geol. Ital., 95, 489-499.

Bühl, H., 1981: Zur Sillimanitbildung in den Gneisen der Zone von Bellinzona. - Schweiz. Mineral. Petrogr. Mitt., 61, 275-295.

Burchfiel, B.C., and Royden, L.H., 1985: North - south extension within the convergent Himalayan region. - Geology, 13, 679-682.

Burg, J.P., and Chen, G.M., 1984: Tectonics and structural zonation of southern Tibet, China. - Nature, 311, 219-223.

Burg, J.P., Brunel, M., Gapais, D., Chen, G.M., and Liu, G.H., 1984: Deformation of leucogranites of the crystalline Main Central thrust sheet in southern Tibet (China). - J. Struct. Geol., 6(5), 535-542.

Caby, R., Pêcher, A., and Le Fort, P., 1983: Le grand chevauchement central himalayan; nouvelles données sur le metamorphisme inverse a la base de la Dalle du Tibet - Rev. Géol. Dynamique Géogr. Phys., 24, 89-100.

Cuney, M., Le Fort, P., and Wang, Z.X., 1984: Uranium and thorium geochemistry and mineralogy in the Manaslu leucogranite (Nepal, Himalaya). - In: Xu, K., and Tu, G. (eds.), Proc. Symp. Geology of granites and their Metallogenic Relations, Nanjing Univ. 1982, Science Press, Beijing, 853-873.

Dainelli, G. 1933-1934: La Serie dei Terreni, I and II. - Sped. ital. De Filippi nell'Himalaya, Caracorum e Turchestan Chinese (1913-1914) II/2, Zanichelli, Bologna, 1096p.

Daubrée, G.A., 1876: Expériences sur la schistosité des roches et sur les déformations des fossiles, corrélatives de ce phénomene. - Compt. Rend. Acad. Sci. Paris 82.

De Terra, H., 1935: Geological studies in the North-West Himalaya between the Kashmir and the Indus Valleys. - Mem. Connecticut Acad. Arts, Sci., 8, 18-76.

Debon, F., and Le Fort, P., 1983: A chemical - mineralogical classification of common plutonic rocks and associations. - Earth Sci., 73, 135-149.

Debon, F., Le Fort, P., Sheppard, S.M.F., and Sonet, J., 1986: The four plutonic belts of the Transhimalaya - Himalaya: a chronological synthesis along a Tibet - Nepal section. - J. Petrol., 27(1), 219-250.

Debon, F., Sonet, J., Liu, G., Jin, C., and Xu, R., 1984: Caractères chimico-minéralogiques et datations par Rb-Sr des trois ceintures plutoniques du Tibet méridional. - In: Mercier, J.L., and Li. G.C. (eds.), Mission Franco - Chinoise on Tibet 1980, CNRS, Paris, 309-317.

Deniel, C., 1985: Appart des isotopes du Sr, Nd et du Pb à la connaissance de l'âge et de l'origine des leucogranites himalayennes. Exemple du Manaslu (Himalaya, Népal). - Thèse de 3ème cycle, Clermont-Ferrand, 151p.

Deniel, C., Vidal, Ph., and Le Fort, P., 1983: The Manaslu granite (Himalaya, Nepal): new Sr and Nd isotopic data. - Terra Cognita, 3(2-3), 266.

Deniel, C., Vidal, Ph., Dietrich, V., and Le Fort, P., 1985: Origin of the leucogranites of the High Himalaya. - Terra Cognita, 5, 292.

Dietrich, V., and Gansser, A., 1981: The leucogranites of the Bhutan Himalaya (Crystal anatexis versus mantle melting). - Schweiz. Mineral. Petrogr. Mitt., 61, 177-202.

Dietrich, V.J., Frank, W., and Honegger, K., 1983: A Jurassic - Cretaceous island arc in the Ladakh - Himalayas. - J. Volc. Geotherm. Res., 18, 405-433.

Ferrara, G., Lombardo, B., and Tonarini, S., 1983: Rb/Sr geochronology of granites and gneisses from the Mount Everest region, Nepal Himalaya. - Geol. Rdsch., 72, 119-136.

Ferrara, G., Lombardo, B., Tonarini, S., and Turi, B., 1985: Miocene anatexis in the Higher Himalaya basement nappes: 87Sr / 86Sr and ^{18}O / ^{16}O evidence from the Gophu La leucogranite of Bhutan. - Terra Cognita, 5, 228.

France-Lanord, C., 1987: Chevauchement, métamorphisme et magmatisme en Himalaya du Népal central. Etude isotopique H, C, O. - Thèse de 3ème cycle, Nancy, France, 226p.

Frank, W., Thoeni, M., and Purtscheller, F., 1977: Geology and petrography of Kulu - South Lahul area. - In: Colloq. Int. C.N.R.S., 268, Ecologie et Géologie de l'Himalaya, 147-172.

Frank, W., Baud, A., Honegger, K., and Trommsdorff, V., 1987: Comparative studies on profiles across the Northwest Himalayas. - In: Rodgers, J., and Schaer, J.P. (eds.): Material for comparative Anatomy of Mountains Ranges, Princeton University press, New York.

Frank, W., Gansser, A., and Trommsdorff, V., 1977: Geological observations in the Ladakh Area (Himalayas). A preliminary Report. - Schweiz. Mineral. Petrogr. Mitt., 57, 89-113.

Fuchs, G., 1977: Traverse of Zanskar from the Indus to the valley of Kashmir - a preliminary note. - Jb. Geol. B.-A., 120(2), 219-229.

———, 1979: On the geology of Western Ladakh. - Jb. Geol. B.-A., 122(2), 513-540.

———, 1981: Outline of the geology of the Himalaya. - Mitt. Öesterr. Geol. Ges., 74/75, 101-127.

———, 1982: The geology of Western Zanskar. - Jb. Geol. B.-A., 125(2), 513-540.

———, 1985: The Tibetan (Tethys) Zone - is it Allochthonous ? - Contr. Himal. Geol. (ed. Gupta, V.J.), 3, 67-77.

———, 1986: The Geology of the Markha - Khurnak Region in Ladakh. - Jb. Geol. B.-A., 128(3/4), 403-437.

Gaetani, M., Casnedi, R., Fois, E., Garzanti, E., Jadoul, F., Nicora, A., and Tintori, A., 1985a: Stratigraphy on the Tethys Himalaya in Zanskar, Ladakh. - Riv. It. Paleont. Strat., 91(4), 443-478.

Gaetani, M., Garzanti, E., and Jadoul, F., 1985b: Main structural elements of Zanskar, NW Himalaya (India). - Rend. Soc. Geol. It., 8, 3-8.

Gaetani, M., Nicora, A., Silva, J.P., Fois, E., Garzanti, E., and Tintori, A., 1983: Upper Cretaceous and Paleocene in Zanskar Range NW (Himalaya). - Riv. It. Paleont. Strat., 89(1), 81-118.

Gansser, A., 1964: Geology of the Himalayas. - Wiley Interscience, London, 289p.

———, 1977: The great suture zone between Himalaya and Tibet - a preliminary account. - Colloqu. Int. C. N. R. S., 268, Ecologie et Géologie de l'Himalaya, 181-192.

———, 1983: Geology of the Bhutan Himalaya. - Mém. Soc. Helv. Sci. Nat., Birkhäuser Verlag, Basel, 96, 181p.

Gapais, D., Gilbert, E., and Pécher, A., 1984: Tectonique. - Structures et trajectoires de déformation dans la zone de suture de l'Indus - Tsangpo en Himalaya du Ladakh, région de la Suru. - C. R. Acad. Sc. Paris, 299 II(4), 179-182.

Garzanti, E., Casnedi, R., and Jadoul, F., 1986: Sedimentary evidence of a Cambro-Ordovician orogenic event in the NW Himalaya. - Sedim. Geol., 48, 237-265.

Gilbert, E., 1986: Structures et déformation dans le nord de la plaque indienne en Himalaya du Ladakh (crystallin du Haut Himalaya et Séries Téthysiennes). - Thèse de 3ème cycle, Universtité de Poitier, France, 225p.

Gupta, V.J., 1976: Triassic Conodonts from Nepal. - J. Geol. Soc. India, 17, 562.

———, 1977: Conodont biostratigraphy of the Middle and Upper Triassic rocks of Kashmir and Ladakh. - Him. Geol., 6, 314-322.

Gupta, V.J., and Kumar, S., 1975: Geology of Ladakh, Lahaul and Spiti regions of Himalaya with special reference to the stratigraphic position of flysch deposits. - Geol. Rdsch., 64, 540-563.

Hayden, H.H., 1904: The geology of Spiti, with part of Bashahr and Rupshu. - Mem. Geol. Surv. India, 36(1), 1-129.

———, 1908: Geography and Geology of the Himalaya. - Geol. Surv. India (ed.), Calcutta, Part 4, 233-236.

Heim, A., 1878: Untersuchungen über den Mechanismus der Gebirgsbildung im Anschluss an die geologische Monographie der Tödi - Windgällen - Gruppe. - 2 Bände und 1 Atlas, Basel.

Heim, A., 1921: Geologie der Schweiz (3 vols.). - Tauchnitz, Leipzig.

Heim, A., and Gansser, A., 1939: Central Himalaya. Geological observations of the Swiss Expedition 1936. - Kommisionsverlag Geb. Fretz AG, Zürich, Denkschr. der Schweiz. Naturf. Gesell., 73(1), 243p.

Herren, E., 1987: The Zanskar shear zone: Northeast - southeast extension within the Higher Himalayas (Ladakh, India). - Geology, 15, 409-419.

Honegger, K., 1983: Strukturen und Metamorphose im Zanskar Kristallin (Ladakh - Kashmir, Indien). - Ph. D. Thesis, ETH, Zürich, No. 7456, 117p.

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

Jadoul, F., Fois, E., Tintori, A., and Garzanti, E., 1985: Preliminary results on Jurassic stratigraphy in Zanskar (NW Himalaya). - Rend. Soc. Geol. It., 8, 9-13.

Jäger, E., Bhandari, A.K., and Bhanot, V.B., 1971: Rb-Sr age determinations on biotites and whole rock samples from the Mandi and Chor granites, Himachal Pradesh, India. - Eclog. Geol. Helv., 64(3), 521-527.

Jaupart, C., and Provost, A., 1985: Heat focussing, granite genesis and inverted metamorphic gradients in continental collision zones. - Earth Planet. Sci. Lett., 73, 385-397.

Kelemen, P.B., and Sonnenfeld, M.D., 1983: Stratigraphy, Structure, Petrology and local Tectonics, Central Ladakh, NW Himalaya. - Schweiz. Mineral. Petrogr. Mitt., 63, 267-287.

Klootwijk, C., Sharma, M.L., Gergan, J., Tirkey, B., Shah, S.K., and Agarwal, V., 1979: The Extent of Greater India, II. Palaeomagnetic data from the Ladakh Intrusives at Kargil, Northwestern Himalayas. - Earth Planet. Sci. Letters, 44, 47-64.

Klootwijk, C.T., 1980: A summary of palaeomagnetic data from Extrapeninsular Indo - Pakistan and south Central Asia: implications for collision tectonics. - In: Saklani, P.S. (ed.): Structural Geology of the Himalaya, New Delhi (Today and Tomorrow's Printers & Publ.), 307-360.

Kündig, R., (in review) a: Domal structures and high-grade metamorphism in the Zanskar region (NW - India). - J. Metam. Geol., Spec. issue on Himalayan metamorphism.

———, (in prep.) b: Kristallisation / Deformation in der tektonischen Einheit des Higher Himalaya, Zanskar, Ladakh (NW - Indien). - Ph. D. Thesis, ETH Zürich.

Le Fort., P., 1973: Les leucogranites à tourmaline de l'Himalaya sur l'example du granite du Manaslu (Nepal central). - Soc. Geol. Fr. Bull., 7(15), 555-561.

———, 1975: Himalayas: the collided range. Present knowledge of the continental arc. - Am. J. Sci., 275A, 1-44.

———, 1981: Manaslu leucogranite: a collision signature of the Himalaya, a model for its genesis and emplacement. - J. Geophys. Res., 86, 10545-10568.

———, 1986: Metamorphism and magmatism during the Himalayan collision. - In: Coward, M.P., and Ries, A.C. (eds.), Collision Tectonics, Geological Society Special Publication, 19, 159-172.

Le Fort, P., Cuney, M., Deniel, C., France-Lanord, C., Sheppard, S.M.F., Upreti, B.N., and Vidal, P., 1987: Crystal generation of the Himalayan leucogranites. - Tectonophysics, 134, 39-57.

Le Fort, P., Debon, F., and Sonet, J., 1980: The "Lesser Himalayan" cordierite granite belt. Typology and age of the Pluton of Manserah (Pakistan). - Proc. Int. Geodyn. Conf., Peshawar, Nov. - Dec. 1979, Geol. Bull. Univ. Peshawar (Pakistan), 13, 51-61.

Lydekker, R., 1883: The geology of the Kashmir and Chamba territories and the British district of Khagan. - Mem. Geol. Surv. India, 22, 1-344.

Lyon-Caen, H., and Molnar, P., 1983: Constraints on the structure of the Himalaya from an analysis of gravity anomalies and a flexural model of the lithosphere. - J. Geophys. Res., 88(10), 8171-8191.

Mehta, P.K., 1977: Rb/Sr Geochronology of the Kulu - Mandi Belt: Its implications for the Himalayan Tectonogenesis. - Geol. Rdsch., 66, 156-174.

Misch, P., 1949: Metasomatic granitization of batholitic dimensions. - Am. J. Sci., 247, 209-245, 372-406, 673-705.

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

Molnar, P., Chen, W.P., and Padovani, E., 1983: Calculated temperatures in overthrust terrains and possible combinations of heat sources responsible for the Tertiary granites in the Greater Himalaya. - J. Geophys. Res., 88, 6415-6429.

Nakazawa, K., and Kapoor, H.M., 1973: Spilitic pillow lava in Panjal. - Mem. Fac. Sci., Kyoto Univ., Ser. Geol. Mineral., 39, 83-98.

Nanda, M.M., and Singh, M.P., 1976: Stratigraphy and Sedimentation of the Zanskar area, Ladakh and adjoining parts of Lahaul region of Himachal Pradesh. - Himal. Geol., 6, 365-388.

Nanda, M.M., Singh, M.P., and Sinha, P.K., 1978: On the volcanics of the Zanskar valley, Ladakh, Z & K. - J. K. Rec. Geol. Surv. India, 110(2), 194-202.

Nautiyal, S.P., Jangpangi, B.S., Singh, P., Guhusarkar, T.K., Bhate, V.D., Raghavan, M.R., and Sahai, T.N., 1969: A preliminary note on the geology of Bhutan Himalaya. - Int. Geol. Congr. Rep. Sess. 22nd 1964, part II, 1-14.

Nicora, A., Gaetani, M., and Garzanti, E., 1984: Late Permian to Anisian in Zanskar (Ladakh, Himalaya). - Rend. Soc. Geol. It., 7, 27-30.

Norin, E., 1946: Geological explorations in western Tibet. - Rept. Sino - Swedish Expedition, 29, Aktiebolaget Thule, Stockholm, 214p.

Pareek, H.S., 1976: On studies of the agglomeratic slate and Panjal Trap in the Jhelum, Liddar and Sind Valleys, Kashmir. - Rec. Geol. Surv. India, 107(2), 12-37.

Pêcher, A., and Le Fort, P., 1986: The metamorphism in Central Himalaya, its relations with the thrust tectonic. - Sciences de la Terre, Memoire 47, 285-309.

Pettijohn, E.J., 1975: Sedimentary Rocks. - Harper & Row, New York, 3rd ed., 628p.

Pognante, U., Genovese, G., Lombardo, B., and Rosetti, P., 1987: Preliminary data on the High Himalayan Crystallines along the Padum - Darcha traverse (south eastern Zanskar, India). - Rend. Soc. It. Min. Petr., 42, 95-102.

Powell, C.Mc A., and Conaghan, P.J., 1978: Rb-Sr Geochronology of the Kulu - Mandi Belt: Its implications for the Himalayan Tectogenesis - Discussion. - Geol. Rdsch., 68(1), 380-383.

Ramsay, J.G., 1967: Folding and fracturing of rocks. - Mc Graw Hill, New York, 568p.

Ramsay, J.G., and Huber, M.I., 1983: Modern structural geology Volume 1: Strain analysis. - Academic Press, London, 307p.

Ramsay, J.G., and Huber, M.I., 1987: Modern structural geology Volume 2: Folds and fractures. - Academic Press, London, 700p.

Searle, M.P., 1983: Stratigraphy, structure and evolution of the Tibetan - Tethys zone in Zanskar and the Indus Suture zone in the Ladakh Himalaya. - Trans. Roy. Soc. Edinburgh: Earth Sci., 73, 205-219.

———, 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(8), 923-936.

Searle, M.P., and Fryer, B.J., 1986: Garnet tourmaline and muscovite-bearing leucogranites, gneisses and migmatites of the Higher Himalayas from Zanskar, Kulu, Lahore and Kashmir. - In: Coward, M.P., and Ries, A.C,. (eds), Collision Tectonics, Geol. Soc. Special Publ., 19, 185-201.

Seitz, J.F., Tewari, A.P., and Obradovich, J., 1976: A note on the absolute age of the tourmaline granite, Arwa valley, Garhwal Himalaya. - Geol. Surv. India, Misc. Publ., 24(2), 332-337.

Shah, S.K., Sharma, M.L., Gergan J.T., and Tara, C.S., 1976: Stratigraphy and structure of the western part of the Indus Suture belt, Ladakh, Northwest - Himalaya. - Himal. Geol., 6, 534-556.

Sheppard, S.M.F., Debon, F., Liu, G., Jin, C., and Xu, R., 1983: Oxygen isotope relationships in three plutonic belts in Southern Tibet. - Terra Cognita, 3(2-3), 272.

Simpson, C., and Schmid, St.M., 1983: An evaluation of criteria to deduce the sense of movement in sheared rocks. - Geol. Soc. Amer. Bull., 94, 1281-1288.

Srikantia, S.V., Ganesan, T.M., Rao, P.N., Sinha, P.K., and Tirkey, B., 1978: Geology of Zanskar area, Ladakh Himalaya. - Himal. Geol., 8, 1009-1033.

Stäubli, A., (in review) a: Polyphase metamorphism and the development of the Main Central Thrust (M.C.T.) at the Kishtwar window, NW - India. - J. Metam. Geol., Spec. issue on Himalayan metamorphism.

———, (in prep.) b: Polyphase Metamorphose im Himalaya und die Entwicklung des Main Central Thrust (M.C.T.) beim Kishtwar - Fenster, NW - Indien. - Ph. D. Thesis, ETH Zürich.

Stöcklin, J., 1980: Geology of Nepal and its regional frame. - J. Geol. Soc. London, 137, 1-34.

Stoliczka, F., 1865: Geological sections across the Himalayan mountains, from Wantu Bridge on the River Sutlej to Sungdo on the Indus, with an account of the formations in Spiti, accompanied by a revision of all known fossils from that district. - Mem. Geol. Surv. India, 5(1), 1-154.

———, 1866: Summary of the geological observations during a visit to the provinces Rupshu Karnag, South Ladakh, Zanskar and Dras of Western Tibet. - Mem. Geol. Surv. India, 5(5), 337-354.

Stutz, E., (in prep.): Géologie du Massif de Nyimaling. - Thèse Université Lausanne.

Stutz, E., and Steck, A., 1986: La terminaison occidentale du Cristallin du Tso Morari (Haut - Himalaya; Ladakh méridional, Inde): Subdivision et tectonique de nappe. - Eclog. Geol. Helv., 79(2), 253-269.

Stutz, E., and Thöni, M., 1987: The Lower Paleozoic Nyimaling granite in the Indian Himalaya (Ladakh): new Rb/Sr data versus zircon typology. - Geol. Rdsch., 76(2), 307 - 315.

Tewari, A.P., 1964: On the upper Tertiary deposits of Ladakh Himalayas and correlation of various geotectonic units of Ladakh with those of the Kumaon - Tibet region. - Geol. Congr. XXII Sess., Part XI, 37-58.

Thakur, V.C., 1980: Tectonics of the central crystallines of western Himalaya. - Tectonophysics, 62, 141-154.

Trommsdorff, V., Dietrich, V., and Honegger, K., 1982: The Indus Suture Zone: paleotectonic and igneous evolution in the Ladakh - Himalayas. - In: Hsu, K.J. (ed.), Mountain Building Processes, Accademic Press, London, 213-219.

Trümpy, R., 1960: Paleotectonic Evolution of the Central and Western Alps - Bull. geol. Soc. Amer., 71, 843-908.

Turner, F.J., and Weiss, L.E., 1963: Structural analysis of metamorphic tectonites. - Mc Graw - Hill, New York, 545p.

Vidal, Ph., Bernhard-Griffiths, J., Cocheril, A., Le Fort, P., Peucat, J.J., and Sheppard, S.M.F., 1984: Geochemical comparison between Himalayan and Hercynian leucogranites. - Phys. Earth Planet. Inter., 35 (spec. Issue), 179-190.

Vidal, Ph., Cocherie, A., and Le Fort, P., 1982: Geochemical investigations of the origin of the Manaslu leucogranite (Himalaya, Nepal). - Geochim. Cosmochim. Acta, 46, 2279-2292.

Wadia, D.N., 1928: The geology of Poonch State (Kashmir) and adjacent portions of the Punjab. - Mem. Geol. Surv. India, 51(2), 185-370.

———, 1937: The Cretaceous volcanic series of Astor - Deosai, Kashmir, and its intrusions. - Rec. Geol. Surv. India, 72(2), 151-161.

———, 1961: Geology of India. - Macmillan, London.

Wang, J., Chen, Z., Gui, X., Xu, R., and Zhang, Y., 1981: Rb-Sr isotopic studies on the same intermediate-acid plutons in southern Xizang. - In: Geological and Ecological Studies of Qinghai - Xizang Plateau, 1, Beijing, Science Press, 515-520.

Curriculum vitae of Eveline Herren (origin of Mühleberg BE)

I was born on 11 th march 1955, the daughter of Georges and Cécile Herren - Knecht. After six year primary school in Stäfa (ZH) I attended secondary school in Stäfa for three years. 1971 - 1975 I attended high school in Wetzikon (ZH) which I finished with the school - leaving examination type C. After one year at the University Zürich I decided to change the subject of my studies from secondary school teacher to geology. During the years 1976 - 1981 I studied geology at the ETH Zürich and finished with a diploma under the supervision of Prof. J.G. Ramsay and Prof. G. Milness.

In the Autumn 1980, still during my studies, I participated in a geological excursion to Ladakh. This was my first visit of Ladakh (India). After my university education I spend three month in Ladakh together with K. Honegger as his field assistance. Afterwards I continued travelling and visited Nepal for mountainiering reasons and South-India for relaxation. The last three months of my "intermediate year" I worked in the geological office of Dr. H. Wanner in St. Gallen.

In the early summer 1982 I started work on my doctoral dissertation over a region in southeastern Ladakh (Zanskar) and spent again several month in India (summer 1982 three month, summer 1983 four month). From june 1982 until may 1986 I worked as an assistant for research and teaching at the Geological Institute of the ETH Zürich with Prof. J.G Ramsay.