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**6ème colloque Himalaya-Karakoram-Tibet = 6th
Himalaya-Karakoram-Tibet workshop : Auris en Oisans,
20 au 23 mars 1991**

Patrick Le Fort, Arnaud Pecher, Georges Mascle, Jean-Louis Mugnier

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GEOLOGIE ALPINE

**EDITE PAR LE LABORATOIRE DE GEOLOGIE
DE L'UNIVERSITE I DE GRENOBLE**

(Laboratoire de Géodynamique des Chaînes Alpines associé au CNRS)

MEMOIRE H.S. N° 16

**6ème COLLOQUE HIMALAYA - KARAKORUM
TIBET**

**6th HIMALAYA - KARAKORUM - TIBET
WORKSHOP**

Auris en Oisans, 20 au 23 Mars

1991

Ce sixième séminaire consacré à la géologie de l'ensemble Himalaya-Karakorum-Tibet est le premier à se dérouler au coeur de la chaîne alpine, dans un cadre qui n'est pas sans rappeler l'inconfort et la chaleur humaine des régions chères aux participants.

Les organisateurs tiennent à remercier ceux qui les ont aidé, soit moralement, soit matériellement, à mettre sur pied ce colloque. Leur gratitude va en particulier à Jean-François Dobremez, professeur à l'université de Chambéry directeur du Greco Himalaya-Karakorum du CNRS, et Pierre Béghin, ingénieur au CEMAGREF et alpiniste mondialement connu, qui ont accepté de venir participer à deux de nos soirées en nous présentant certains aspects de leurs expéditions en Himalaya. Thierry Grand, Responsable du centre de géologie alpine du Haut-Dauphiné, nous a fait connaître l'Auriençon et a été notre interprète auprès des autorités locales. Le professeur Jacques Debelmas a permis l'impression du volume de résumés dans la revue Géologie alpine qu'il dirige. Madame Revol nous a aidé à confectionner ce volume avec beaucoup de gentillesse. Nous ne saurions enfin oublier l'accueil chaleureux avec lequel Madame Paulette Thorelle nous a reçu dans son gîte de l'Auriençon, acceptant nos demandes variées.

Que ce colloque réussisse aussi bien que les précédents, et notre but aura été atteint !

Patrick Le Fort et Arnaud Pêcher
 Georges Mascle et Jean-Louis Mugnier
 Meriem Benharbit, Stéphane Guillot, Jean-Marie Léonard et Ingrid Reuber

*
 * *

This sixth workshop on the geology of the Himalaya-Karakorum-Tibet region is the first one to be held in the heart of the Alpine belt, in a place likely to remind the participants of the discomfort and convivial warmth of their beloved realm.

The organisers want to thank all those who, morally or materially, have helped them to build up the symposium. They are particularly grateful to Jean-François Dobremez, Professor at the university of Chambéry and Director of the Greco Himalaya-Karakorum (CNRS), and to Pierre Béghin, CEMAGREF ingéneer and world famous climber, for having accepted to deliver talks on some aspects of their experience of the Himalaya during two of our evening sessions. Thierry Grand, Head of the Haut-Dauphiné geological center, has introduced us to l'Auriençon and to the local authorities. Professeur Jacques Debelmas, chief editor of Géologie alpine, has enabled us to print the volume of abstract as a special issue of this publication. Mrs Revol has helped us with great kindness to make this volume. And finally, Mrs Paulette Thorelle has very cordially welcomed us and our many requests, at her lodge of l'Auriençon.

Be this workshop as successful as the previous ones, and our wishes will be fulfilled !

Patrick Le Fort et Arnaud Pêcher
 Georges Mascle et Jean-Louis Mugnier
 Meriem Benharbit, Stéphane Guillot, Jean-Marie Léonard et Ingrid Reuber

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Programme - Program

Mercredi 20 mars, Wednesday 20th march

après-midi, afternoon

Tectonique , Tectonics

- 17.15 - David A. Spencer: Different shortening histories between the 'syntaxial' and 'non-syntaxial' areas of the Himalayan belt.
- 17.35 - Laurent Spring, Henri Masson & Albrecht Steck: Tectonique et métamorphisme des séries sédimentaires dans la région de Sarchu (SE Zaskar - Haut Lahul).
- 17.55 - Mary S. Hubbard & David A. Spencer: Top-to-the-WSW displacement along the MMT, Babusar pass - Nanga Parbat region, Pakistan.
- 18.15 - Laurence Bourjot and Jean-Ph. Avouac: Cenozoic crustal shortening across the Kunlun.
- 18.35 - Maurizio Gaetani: The Karakorum fault in the Shaksgam area.
- 18.55 - Gerhard Fuchs: The term "nappe" in Himalayan geology.

soirée, evening

Himalaya of eastern Nepal

- 20.30 - Pierre Bordet: La région Everest-Makalu dans le contexte de la chaîne himalayenne.
- 21.30 - Pierre Béghin: Expéditions to Makalu and neighbouring mountains.

Jeudi 21 mars, Thursday 21st march.

matin, morning

Tectonique et métamorphisme, Tectonics

- 8.30 - George Mascle, Jean-Louis Mugnier & Thierry Faucher: La structure des Siwaliks de l'Ouest Népal: un prisme d'accrétion intracontinental.
- 8.50 - Chris Izatt: Tectonics of the Kirthar ranges of S. Pakistan: a comparison with offshore East Africa.
- 9.10 - M.N. Chaudhry, M. Ghanzafar, A. Meier, J.G. Ramsay, D. Spencer, Ch. Wahrenberger: New stratigraphic and fossil finds in the Higher Himalayas of the upper Kaghan valley, NE Pakistan.
- 9.30 - D.A. Spencer, J.G. Ramsay, U. Pognante, M. Ghazanfar & M.N. Chaudhry: The significance of eclogites in the Indian plate, NW Himalaya.
- 9.50 - Cinzia Spencer-Cervato & D.A. Spencer: Stable isotope analysis of the carbonates in the higher and lesser Tethyan Himalaya, north Pakistan.
- 10.10 - Steve Reddy: A microstructural and argon laserprobe study of fault rocks developed during Himalayan continental collision: a preliminary study.
- 10.30 - pause, break.
- 11.00 - Peter J. Treloar: P-T-t paths of metamorphism, Pakistan Himalaya: implications for crustal subduction and stacking.

- 11.20 - Daniel Schelling and Kazunori Arita: Tectono-metamorphic development of far-eastern Nepal.
 11.40 - Ugo Pognante: Different P-T-t paths along the High Himalayan crystallines: constraints on the formation and distribution of the Miocene leucogranites.
 12.00 - Philip England, Patrick Le Fort, Peter Molnar & Arnaud Pêcher: Heat sources for Tertiary metamorphism and anatexis in the Annapurna-Manaslu region, central Nepal.

après-midi, afternoon
 poster presentation

soirée, evening

(Soirée ouverte au public - public lecture).

Jean-François Dobremez: Environmental problems in the Himalaya-Karakorum-Tibet area
 Thierry Grand: Géologie de l'Oisans (Haut Dauphiné).

Vendredi 22 mars, Friday 22nd march

matin, morning

Thermochronométrie, thermochronometry

- 8.30 - Nicolas O. Arnaud & T.M. Harrison: New thermochronological studies on the Kunlun batholith and the thermal history of the Tibetan Plateau.
 8.50 - Joëlle Carpena: Last movements in the Biafo granite.
 9.10 - Meriem Benharbit, Arnaud Pêcher & Gérard Poupeau: Denudation rate in western Karakorum: apatite fission-tracks datation of the Yazghil dome section.
 9.30 - Michel G. Bonhomme & Eduardo Garzanti: Age of metamorphism in the Zaskar Tethys Himalaya (India).
 9.50 - Michael P. Searle: Uplift - erosion - exhumation rates across the NW Himalaya Karakorum and pressure, temperature and time constraints on the structural evolution of the India-Asia collision.
 10.10 - pause, break.

Magmatisme, magmatism

- 10.40 - Stéphane Guillot, Patrick Le Fort & Arnaud Pêcher: Contact metamorphism of the Manaslu leucogranite: an emplacement within a thickened crust.
 11.00 - Kazunori Arita, Saki Harutaka and Koide Yoshiyuki: Cretaceous alkaline magmatism in the Nepalese Lesser Himalayas.
 11.20 - Michael A. Sullivan and al.: Continental margin volcanism along the leading edge of Eurasia: the Dir volcanics.
 11.40 - Ingrid Reuber: Magmatic and plastic flow structures in the plutons intruding Dras arc and constituting the Ladakh batholith, Indus suture zone, Ladakh-Himalaya
 12.00 - Richard Oliver, Julian A. Pearce & Deng Wanming: Alkaline magmatism between 30 and 5 Ma on the Tibetan Plateau.

après-midi, afternoon
 poster presentation

soirée, evening

discussion générale, general discussion.

Samedi 23 mars, Saturday 23rd march

matin, morning

8.30 - John Wheeler, R. Murdie, G.J. Potte, D.J. Prior, P. Treloar, R.HW.H. Butler, M. George, N.B.W. Harris and C. Jones: Structure of the northern Nanga Parbat syntaxis and its relation to the Kohistan arc.

8.50 - Rob Butler, Chris Jones, Pete Treloar, John Wheeler and the 1988 Durham University Nanga Parbat Geological Expedition: Tectonic evolution of the Nanga-Parbat massif; insights from the central-southern segment.

Stratigraphie, stratigraphy

9.10 - Maurizio Gaetani & Eduardo Garzanti: Multirifting evolution of the Tethys Himalaya passive margin (Zaskar, northern India)

9.30 - Eduardo Garzanti, Alda Nicora & Andrea Tintori: Late Paleozoic to Triassic stratigraphy of Central Dolpo; preliminary results.

9.50 - Chris Izatt: Structure, stratigraphy and petroleum geology of the northern Sulaiman ranges, Pakistan.

10.10 - Salvatore Critelli & Eduardo Garzanti: Petrology of remnant ocean sandstones derived from the Himalayan suture belt

Cretaceous alkaline magmatism in the Nepalese Lesser Himalayas

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Whithin the Himalayan region reported occurrences of alkaline rocks are restricted to the northwest Pakistan and the Lesser Himalayas of central Nepal. However, alkaline igneous rocks are common in the Indian subcontinent where they are associated with the Gondwana sediments. Therefore, the presence of alkaline rocks in the Himalayas attracts attention with respect to Gondwana geology. This paper discusses the petrography, geochemistry, mineralogy, age and tectonic significance of the alkaline Aulis volcanics and Ampipal plutonic complex of the Nepalese Lesser Himalayas. We believe that the study of these alkaline rocks will help elucidate both the magmatic history and the mantle evolution of the frontal margin of the Indian subcontinent prior to its collision with Eurasia in the Eocene.

Aulis volcanic rocks - Gondwana sediments have recently been found north of the Main Boundary Thrust in the Tansen area of the central Nepal Lesser Himalayas (Sakai, 1983). These Gondwana sediments range from Permo-Carboniferous to probable Paleogene in age and are intercalated with sheets of alkaline volcanics rocks, the Aulis volcanics, of Upper Gondwana age. The Aulis volcanics are dark green to dark grey in color and are massive with occasional pillow structures. Although the volcanics are generally altered, under the microscope phenocrysts of sanidine (up to 7 mm in long), anorthoclase, and plagioclase (AN < 45), along with rare aegirine-augite, titano-augite (TiO₂: up to 4% , Al₂O₃ : up to 9%),

kaersutite (TiO₂:5 - 7% , XMg: 0.52 - 0.69, with a resorption border) and titano-biotite (TiO₂: up to 4%, Al₂O₃: up to 9%), are observed within a fluidal groundmass of subparallel sanidine and anorthoclase laths with accessory titanomagnetite and titanite. The bulk chemistry of the Aulis volcanics indicates that the rocks are phonotephrites, trachyandesites and trachytes belonging to alkaline rocks series field in the classification of Le Bias et al. (1986).

Ampipal plutonic complex : This unique plutonic complex of alkaline rocks, first described by Lasserre (1977), outcrops in the Lesser Himalayas of central Nepal 100 km northeast of the Aulis volcanic exposures. The rocks belonging to the Ampipal complex are olivine clinopyroxinites, shonkinites, malignites and nepheline syenites, along with minor two mica granites. Nepheline syenite makes up more than a half of the plutonic complex in volume. The Ampipal complex is in tectonic contact with the surrounding Kunchha Formation, metasediments of late Precambrian age, which were probably deposited in a continental-margin or island-arc environment. Both the Ampipal plutonic complex and the Kunchha Formation show a well-developed foliation and lineation formed as a result of ductile shear deformation and metamorphism related the shear-thrusting within the Main Central Thrust zone. Field and microscope observations suggest that the crystallization order of the Ampipal complex is as follows; olivine-clinopyroxenite shonkinite, nephe-line-syenite, two mica granite, the latter

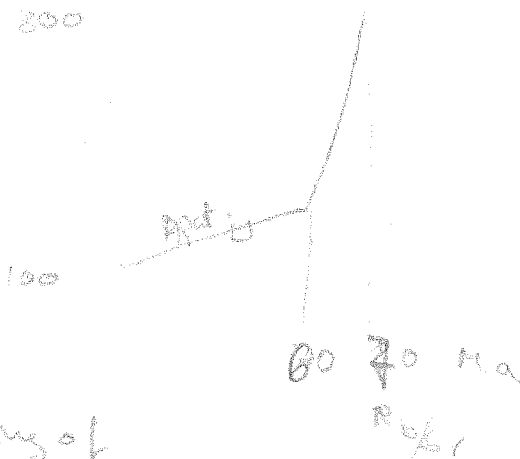
occurring in veins without a gneissose texture. The olivine clinopyroxenites, malignites, shonkinites and nepheline syenites all contain normative nepheline. The Ampipal plutonic rocks are characterized by enrichment of both light REE's and incompatible elements relative to subalkaline rocks. The rocks of the Ampipal complex are also enriched in high field strength elements such as Ta, Nb, Zr and Y. This geological and geochemical data leads us to the conclusion that the Ampipal plutonic rocks were derived from a single alkaline magma having modal and normative nepheline, and enriched in incompatible elements. Incompatible element enrichment especially of Ba (7200 ppm), differentiates the Ampipal plutonic magmatism from the alkaline magmatism of stable continent, continental

rift, island arc and ocean island environments.

Tectonic significance - The Aulis volcanics have yielded a Rb/Sr biotite-feldspar isochron age of 96.7 ± 2.8 Ma ($^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio: 0.704842 ± 0.000031) and a K/Ar whole-rock age of 17.4 ± 0.9 Ma. The K/Ar age of the Miocene is likely to be the rejuvenated age due to heating caused by shear-thrusting within the Main Central Thrust zone. There are at present no isotopic age data from the Ampipal complex. Alkaline magmatism of the Aulis volcanics and the Ampipal plutonic complex as well as of the Rajmahal Traps of Cretaceous age in Indian Peninsulars thus is considered to be related to the rifting of the northern margin of the Indian subcontinent prior to its collision with Eurasia.

72 Tibeta plateau from 18 Ma onwards only

Pangong Suture



modeling of Rb/Sr patterns

New thermochronological studies on the Kun Lun batholith and the thermal history of the Tibetan plateau

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Key words : thermochronology, Kun Lun, Tibet, accomodation mechanisms.

During the summer 1989, a sino-french geotraverse went through the NW Kun Lun, the Tibetan Plateau, and reached the feet of the Karakorum range. The thermochronological study of these terranes is essential to the understanding of accomodation mechanisms and large scale movements since the India-Asia collision 65 Ma ago. Uplift in southern Tibet began only at 18 Ma (Copeland et al., 1987), but seems younger and still vigourous in the Pamir range (Zeitler, 1985) (Nanga Parbat). Recent progresses of the $^{40}\text{Ar}/^{39}\text{Ar}$ method on K-feldspars, the discovery of multi-domain structure and its bearing on diffusion mechanisms, now allow the reconstitution of complete thermal histories on one single sample. Coupled to fission tracks techniques, the complete range of temperatures between 350°C and 90 °C is studied. This yields numerous applications, especially on uplift rates, usually outlined by low temperature histories. These techniques were aimed to the reconstitution of the thermal history of the Kun Lun range and central part of the NW Tibetan Plateau. 0

The Kun Lun batholith, north of the Altyn-Tagh fault and Paleozoic in age, has seen rapid

erosion rates first in the Permian -perhaps an effect of accretion of Kunlun/Tarim and Qiantang microplates-, and in the Cretaceous. Then no trace of rapid erosion before 20 Ma is recorded. Fission tracks in apatites show that uplift occured between 20 Ma and present, and could be as recent as 4 Ma. The Rutog batholith, in central Tibet, proves that no more than 4 km of erosion occured since 50 Ma. Still there are two possibilities : either the erosion has been very slow, or uplift and erosion occured a short while ago, perhaps at the same time that uplift in the Kunlun terranes. The Karakorum belt is a recent feature, 12 to 15 Ma in age, and the Karakorum fault has been thermally, thus mechanically highly active until 9 Ma.

These new data confirm that crustal thickening, subsequent to India-Asia collision, was accomodated between 65 and 18 Ma by an other way than thickening of the lithosphere, probably continental escape (Tapponier et al., 1986). They also demonstrate that uplift in the Kun Lun and NW Tibet could be very recent, and that deformation could be propagating northward from the Himalayas.

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Denudation rate in western Karakorum : apatite fission-track dating of the Yasghil Dome section

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During an expedition to the Yasghil Dome (about 7450m), in western Karakorum, North to the Hispar Glacier, samples of granite have been collected, from the altitude of 4000 m up to 7200 m. This sampling has been used to determine the recent denudation rate in this part of Karakorum, using the fission track dating method on apatites.

On each sample, ages apparent as well as corrected (from the tracks recorded in the zone of complete stability) were measured (table). They correspond to closure temperature of 105°C and 65°C respectively. A fair linear correlation is observed between ages (apparent or corrected) and altitudes, allowing the

calculation of an apparent denudation/surrection rate : 0.76 ± 0.06 mm/y from 6.6 to 3.8 My (apparent ages), or 0.87 ± 0.16 mm/y from 3.8 to 0.8 My (corrected ages). Considering the analytical precision, these two values are not significantly different; we can consider in this part of the Karakorum a rather constant denudation rate, around 0.8 mm/y, from 6.6 to 0.8 My. This rate is not in contradiction with the others fission track data obtained on samples from the Karakorum batholith or its cover (Zeitler, Carpena); it also fits with the "global" denudation rate deduced from the datating of detrital minerals in the Bengal fan.

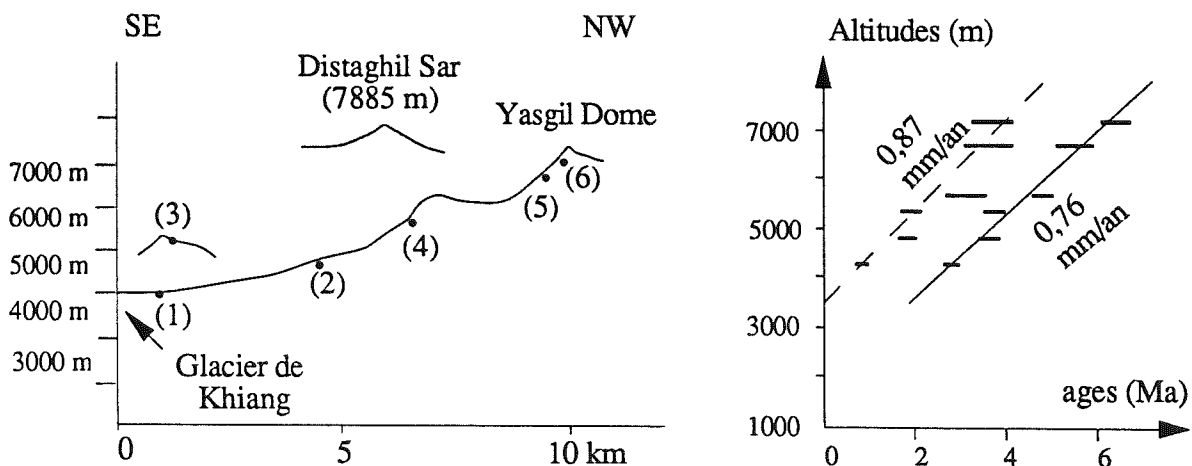


Figure - Left : schematic section of the Yasghil Dome section, with the location of the samples. Right : denudation rate deduced from apparent (plain line) and corrected (dotted line) ages.

Sample	Altitude	app. age (My)	corr. age (My)
1 (K36)	4280	2.8 ± 0.2	0.8 ± 0.06
2 (K3)	4810	3.6 ± 0.2	1.8 ± 0.1
3 (K6)	5350	3.8 ± 0.2	2.0 ± 0.1
4 (K10)	5700	4.9 ± 0.2	3.2 ± 0.2
5 (K30)	6700	5.8 ± 0.5	3.8 ± 0.4
6 (K34)	7200	6.6 ± 0.4	3.8 ± 0.3

Table - Apatites fission track ages from the Yasghuil Dome section

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Age of metamorphism in the Zaskar Tethys Himalaya (India)

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K-Ar dating of illites from Cambrian to Eocene sediments contained in five different tectonic units of the Zaskar Range has provided information about the age of the metamorphic event that affected the Indian passive margin succession during the first stages of the Himalayan Orogeny.

Himalayan metamorphism in the sedimentary zone was not always strong enough to reset the K-Ar clock of illites. In units with pre-anchizional "crystallinity" indexes, isotopic ages are usually older than deposition and give indication of detrital inheritance or possibly of Mesozoic thermal events, as for Jurassic ages characterizing the Cretaceous terrigenous deposits of the Zumlung Unit (149 to 210 My; I.C. = 0.46 to 0.68 Δ 28). The younger ages (77 to 118 My; I.C.= 0.22 to 0.66), locally recorded in the Khurna, Phugtal and Zumlung Units, may be ascribed either to higher crystallinity or to influence of the mid-Cretaceous extensional tectonism and associated magmatism (Gaetani & Garzanti, 1991). Early Tertiary ages (57 to 62 My; I.C.= 0.21 to 0.39) occur both in the Phugtal Unit and at the top of the Zaskar succession in the Zangla and Lingshed Units. Since collision between India and Eurasia began close to the Paleocene/Eocene boundary at about 54 My (zone P6), and sedimentation was still active in the early Eocene at around 50 My (zone P8; Garzanti et al. 1987), all of these ages predate the real age of Himalayan

metamorphism.

Only the middle Eocene ages (44 to 47 My; I.C.= 0.20 to 0.39) recorded in the Lower Zangla Unit both in easternmost and westernmost Zaskar, where epizonal conditions were reached (Garzanti & Brignoli, 1989), are geologically meaningful, and may approach the true age of metamorphic recrystallization.

The youngest age (27 My; I.C.= 0.15), obtained in medium grade Ordovician metaconglomerates near Sarchu, may be ascribed to loss of radiogenic argon during acid treatment, to delayed cooling in a deeper part of the nappe pile, or to a late high temperature metamorphic event.

Our results, which are consistent with the K/Ar ages obtained on detrital micas from central Nepal (Bordet et al. 1971, p.191) and with ³⁹Ar/⁴⁰Ar data on the High Himalayan Crystalline (Maluski & Matte 1984), indicate that the Tethys Himalaya Zone was affected by barrovian metamorphism shortly after collision and thrust stacking of the Indian passive margin succession (M1 phase of Searle et al. 1988, Staubli 1989), prior to tectonic transport along the MCT. Similar K/Ar data on illites have suggested that the metamorphic deformation of the Asian margin forearc basin succession took place slightly later, between 35 and 40 My (Van Haver et al. 1988).

Sample	Locality	Stratig. unit	Stratig age	Tectonic unit	I.C. $\Delta 2T$	Ro med	K-Ar ages (My \pm s)
ZD 9	Takh	Laptal	mid J	Khurna	0.29		88 \pm 5
ZD10	Takh	Laptal	mid J	Khurna			80 \pm 3
ZD 174	Sumdo	Spiti	up J	Zumlung	0.63		88 \pm 3
ZD156	Sumdo	Giumal	ea K	Zumlung	0.65		99 \pm 3
ZD 132	Ningri La	Giumal	ea K	Zumlung	0.63		149 \pm 5
ZD 111	Lari La	Giumal	ea K	Zumlung	0.56		160 \pm 4
ZD 102	Lari La	Giumal	ea K	Zumlung	0.46		199 \pm 5
ZD 94	Shade	Giumal	Alb	Zumlung	0.52		173 \pm 4
ZD 84	Shade	Spiti	up J	Zumlung	0.66		103 \pm 4
ZD 64	Takh	Giumal	Alb	Zumlung	0.68		210 \pm 5
ZD 59	Takh	Giumal	Alb	Zumlung	0.68		167 \pm 4
ZD 41	Takh	Giumal	ea K	Zumlung			171 \pm 6
ZD 39	Takh	Giumal	ea K	Zumlung			189 \pm 5
AZ 11	Takh	Giumal	Alb	Zumlung	0.57	3.7	201 \pm 7
E 1	Shinge La	Kong	Eoc	Lingshed	0.34-0.39		62 \pm 3
H 11+	Marpo	Chulung	Eoc	L. Zangla	0.57		47 \pm 3
H 15 +	Marpo	Chulung	Eoc	L. Zangla			47 \pm 3
H 18	Marpo	Chulung	Eoc	L. Zangla	0.22		57 \pm 3
H 19	Marpo	Chulung	Eoc	L. Zangla	0.39		57 \pm 2
ZD 4	Sarchu	QztSer	up T	L. Zangla	0.20		44 \pm 5
H 230 +	Tanze	Kurgiak	Cam	Phugtal			112 \pm 12
H 234+	Tanze	Kurgiak	Cam	Phugtal			77 \pm 5
H 246+	Tanze	Mauling	Cam	Phugtal			86 \pm 2
H 257+	Tanze	Phe	Cam	Phugtal			84 \pm 2
H 179+	Purne	Phe	Cam	Phugtal	0.22		118 \pm 3
ZD 3	Bara. La	Thaple	Ord	Phugtal	0.15		27 \pm 3
ZD 2	Bara. La	Mauling	Cam	Phugtal	0.26		117 \pm 4
ZD 1	Bara. La	Thaple	Ord	Phugtal	0.21		57 \pm 2

Figure 1 - K-Ar ages for the examined Zanskar illites.

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**Panorama de la rive gauche de la Kali
Gandaki vu de la haute Thini khola nord**

**Essai d'interprétation géologique d'après un
panorama photographique de l'esquisse
géologique de la Thakkhola, 1968**

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Cenozoic crustal shortening across the Kunlun

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The Kunlun mountains stretch East-West for nearly 350 km along the northern edge of Tibet, with peaks that tower to 5400m on average. Its width reaches 120 km in the West and decreases to 77 km in the East. It represents a narrow zone of transition between the Tarim basin, at a mean elevation of 1450 m, and the Tibet plateau, the elevation of which is between 5000m and 6000m. The Kunlun differs from the Himalayas which form a "great wall", higher than Tibet itself, or from the Qilian Shan where basins and ranges are arranged in steps of gradually increasing elevation. Topographic profiles across the range at different longitudes show an active morphology characteristic of continuing uplift. All along the foothills, in the Tarim basin, folds have formed within the Cenozoic piedmont. For example, at Yecheng, a Quaternary alluvial terrace is folded and perched by more than ten meters. Isopachs of the sedimentary filling, on top of the Paleozoic Tarim basement (1), suggest that the Kunlun overthrusts and flexes down the undeformed Tarim platform. The flexural basin is deepest at Hotien where the basement is covered by more than 11 km of sediments. About two thirds of the total filling are of Tertiary age(2). Thus, morphological as well as geological evidence shows that the Kunlun is actively deforming and suggests that this deformation and corresponding uplift started in the Tertiary.

We have balanced crustal cross-sections in order to estimate Cenozoic shortening across the Kunlun, which is related to crustal thickening under the range and the formation of a flexural basin. We chose the Altyn Tagh Fault as the southern limit of the zone where crustal area is balanced. Gravity anomalies (3)

show that the Tibet plateau is approximately locally compensated. By contrast, a deficit of mass is present under the Tarim and is coupled with an excess of mass under the Kunlun mountains. This pattern has previously been interpreted to be due to flexure of Tarim platform under the load of the range. The effect of flexural rigidity is to distribute thickening, as well as shortening, over a more or less wide area. The hypothesis of a ruptured plate yields a Moho which appears to be intermediate between the Moho which is obtained assuming local compensation and that obtained assuming regional compensation of the topographic load overlying a continuous elastic plate. Crustal areas computed for various flexural rigidities do not vary by more than 5%. We have supposed that the sedimentary filling overlies a crust originally 43 to 47 km thick. These values are consistent with the depth of the Moho under the Tarim proposed by Ma (4). We note that a flexural rigidity of 5.3 N/m yields a Moho which parallels the basement and dips about 3° to the South. A fraction of the sediments must have been deposited before the Tertiary or have been removed from the Tibet plateau (and not only from the Kunlun) and may thus be considered as of exogenetic origin. For simplicity we have computed crustal shortening assuming that all the sedimentary cover is exogenetic. Since we then neglect the amount of material eroded during Tertiary time, we obtain a lower bound to the shortening. To the East we find 70 km and to the West 81 km of shortening. The ante-tertiary sediments may represent only one third of the total filling (2). On the other hand the drainage pattern is roughly perpendicular to the

structures and the main rivers (Yarkand, Karakax and Yunrunkax) transport material eroded mainly from the Kunlun. The hypothesis of an endogenetic origin of the sediments may thus be more appropriate and yields a shortening of 102 +15 km (see table). It appears that the Kunlun has undergone a slightly heterogeneous shortening, which roughly correlates with the increasing width of the range to the west, and has absorbed about

102 km of convergence between Tibet and Tarim during the Cenozoic. Assuming that the reactivation occurred after the collision between India and Asia (55 Ma) a minimum rate of N-S shortening of 1.8 mm/yr and a minimum rate of vertical uplift of 0.1 mm/yr are obtained. We consider these values as lower bounds, since the onset of deformation is certainly younger than 55 Ma.

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Relationship between deep structure and surface tectonics in and around Tibet

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We have undertaken a tomographic study of the deep structure beneath the Tibet Plateau, using measured phase velocities of fundamental mode Rayleigh waves in the period range 30-120s. Phase velocities are obtained on source station paths for events located in Central Asia and observed at GDSN and GEOSCOPE stations at teleseismic distances, in such a way as to achieve optimal "criss-crossing" of paths inside Tibet. Whenever possible, paths are duplicated to verify repeatability of measurements, and generally analysed for consistency. The influence of the very specific slow crustal structure of Tibet is very clearly seen in the data, especially at periods less than 60sec (corresponding to a depth range reaching 70 to 80 km). At longer periods, this effect is less pronounced. There are also clear variations in

phase velocities along paths within the Plateau, implying lateral variations of structure and confirming earlier inferences by Brandon and Romanowicz (1986). The data are inverted using a tomographic method without a priori constraints on region boundaries, to obtain local estimates of phase velocities in and around Tibet. The limits of the anomalously slow zone corresponds well to the principal tectonic boundaries of Tibet, in particular the Altyn Tagh strike-slip fault and thrusts along the Lungmen Shan and the Qilian Shan. The data presently analysed are sufficient to establish the correspondence between surface features and deep structure with a fair degree of confidence north of 32°N. Additional paths, whose study is now in progress, are needed to obtain a reliable view of the deep lateral variations south of this limit.

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Tectonic evolution of the Nanga Parbat massif insights from the central-southern segment

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The Nanga Parbat massif represents the northern-most continuous outcrop of the Indian continent within the Himalayan collision belt, exhumed from beneath the over-riding Kohistan arc terrane by young thrust activity. Recent work has concentrated on the uplift neotectonics, effects which are concentrated on the western margin of the massif.

The internal structure of the Nanga Parbat massif is schematically represented as antiformal, with the early high strain contact between Kohistan-Ladakh and Indian continental material (a possible MMT analogue) defining this structure. However, recent studies of the internal structure of the massif (Wheeler, Potts and Treloar) along the accessible Indus transect suggest otherwise. This work defined two major antiformal structures in foliation of the Nanga Parbat basement. In this contribution we present new results arising from two expeditions into the Nanga Parbat massif, both of necessarily of a reconnaissance nature: the Durham University geological expedition in 1988 and a NERC-funded trip in 1990.

Our studies in the heart of the massif to the south attempted to trace the composite antiformal structure determined on the Indus section. Our more recent work suggests a rather more complex arrangement. Foliation on the western side of the massif is concordant to

the early high strain contact with Kohistan (subtracting the effects of local neotectonic faulting), consistent with the antiformal model. However, work along the Astor valley transect did not reveal a major antiformal closure. Rather the structure is of an asymmetric west-gaping synform with foliation on the eastern margin dipping steeply east, beneath Kohistan (Ladakh). The penetrative stretching lineation plunges N in the E and NE in the W with a gradual change in trend. Further insights from the Rupal transect allows a second major south-gaping closure to be mapped, with an apparently high strain upper limb (outcropping on the Rupal face and summit of Nanga Parbat). The lower, south-dipping limb, while also high strain, contains a south-plunging stretching lineation. We discuss the interpretation of these unexpected structures, specifically the relationship between position on large scale folds, shear criteria and orientation of lineations. However, the age of some fabrics in the massif, despite the "Himalayan" trend of stretching lineations, is not necessarily Tertiary. A suite of biotite granite bodies, mineralogically distinct to the late two-mica leucogranite veins of the massif, cross-cut fabric. Therefore we also discuss the problems of identifying Himalayan deformation from much earlier tectonics within basement of the Indian continent. Work is underway investigating these topics.

Last movements in the Biafo granite

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Surrounded by three major faults (Shyok suture, Karakorum Fault and Hispar-Sim Gang strike-slip fault), the Biafo granite forms part of the Miocene Karakorum batholith of the Northwest Himalaya. We present a geologic cross-section along the Biafo Glacier, from the Braldu River to the Hispar Pass (5400m). Typology of zircons from the Biafo granite confirms that it is an aluminous anatectic granite. At the contact of this granite, zircons contain inherited cores, probably of Precambrian age. These cores progressively disappear towards the middle of the batholith. Thus, the Biafo granite would have been produced by crustal fusion but at relatively low temperature,

and probably in relation with the surrounding major strike-slip faults. The contact of Biafo granite with the Dumordo Formation is intrusive. However, in some places as in Baintha valley, it is a tectonic contact, with ductile deformation.

The Fission track study of this granite indicates a late Miocene cooling and uplift history of this area, controlled by the late uplift history of the Nanga Parbat promontory. Apatite Fission track data indicates that active tectonics occurred along the Hispar-Sim Gang strike-slip fault 600 000 years ago.

ages \downarrow \rightarrow φ duct. 7.0 \rightarrow 4.00 $\sqrt{1.5}$, 0.6 on φ plane
 some 2x population 3.8, + 6.2
 ~ 18
 N 750 u/pb \rightarrow 350 100 N
 ~ 8.5 \rightarrow 7 S
 350 \rightarrow 130

The effect of stratigraphic variation on structural style : examples from the western limb of the Hazara-Kashmir Syntaxis, N. Pakistan.

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An attempt is made to integrate stratigraphic and structural data in order to generate an evolutionary model of the Lesser Himalaya and Subhimalaya of N. Pakistan. Field outcrops in the Potwar Plateau and Murree Hills and well data and seismic profiles from the Potwar Plateau constrain the stratigraphy. The regional stratigraphic variations are telescoped by Himalayan shortening, which exceeds 200km in the external zones of the Pakistani Himalaya. The true regional stratigraphy is evident only after the restoration of Himalayan structures.

Three stratigraphic cover series separated by major unconformities of base Permian and base Palaeocene age are represented in the Potwar region. The crystalline basement is overlain by a series of Eocambrian-Cambrian age that comprises the basal Salt Range Formation and the Jhelum Group clastics and carbonates. The Permian-Cretaceous series represent an essentially shallow marine shelf environment, although the cycles of sandstone, carbonate and occasional laterite indicate transgressive pulses throughout this period. Flexure and erosion is associated with the widespread basal Palaeocene unconformity. Erosion increases towards the southeast such that the Palaeocene overlies the Cambrian in the eastern Salt Range whilst in the north the unconformity is negligible. Shelf conditions were reestablished in the lower Tertiary before molasse deposition commenced in Miocene times. The thick,

but poorly-consolidated, alternating sands and shales of the Rawalpindi and Siwalik Groups form the youngest stratigraphic series.

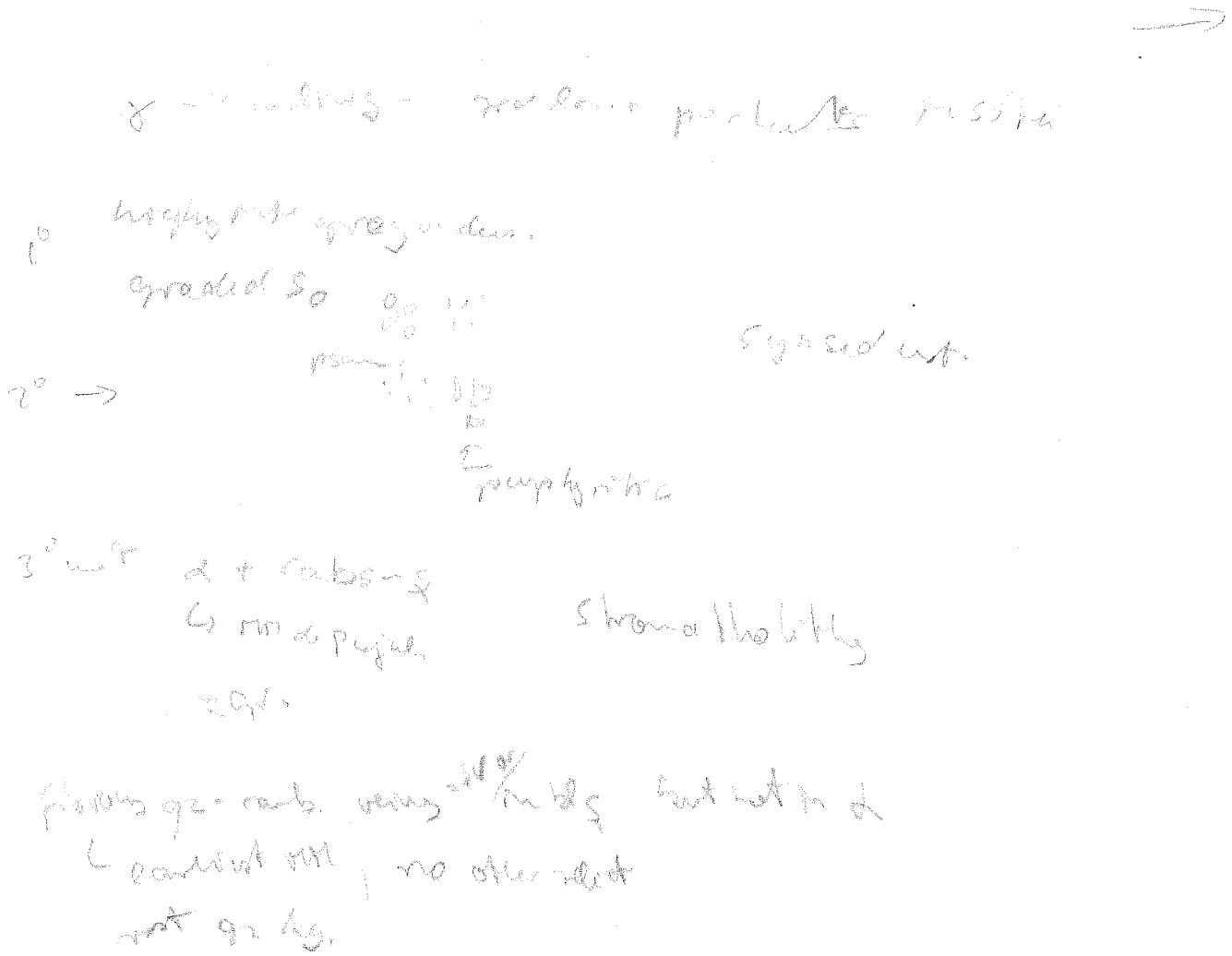
These stratigraphic series have distinct rheological properties. The weak evaporitic Salt Range Formation forms a major basement—cover decollement throughout the Potwar Plateau. The Permian-lower Tertiary carbonate carapace acts as a rheologically competent unit that deforms brittly. Where it is thick the carapace forms large thrust sheets. However the action of the Palaeocene unconformity reduces the carbonate carapace to approximately 100m thickness, effectively juxtaposing the Eocambrian salt and the Tertiary molasse. The molasse behaves incompetently and collapses to form a series of pop-ups, boxfolds and breaching thrusts above the salt decollement. The western and eastern Potwar therefore show different structural styles, the former being controlled by the carbonate carapace and the latter by the molasse.

During the south-southeastward propagation of the Pakistani thrust wedge two major detachments have been exploited, the Hazara Detachment (or MBT) and the Salt Range Detachment (or MFT). The strongly deformed strata of the Murree Hills lie in the hangingwall of the Hazara Detachment. This thrust has been carried more than 80km across the molasse basin, a process assisted by the presence of talcs and evaporites in the Hazara Slate Formation.

Further displacement occurred by duplexing in the footwall of the Hazara Detachment, the floorthrust following the basement-cover contact until the Salt Range Formation was encountered. This decollement is still active today.

using palaeomagnetic reversal methods in the molasse sediments of the Potwar Plateau. Dating of events in the Murree Hills is more loosely constrained by metamorphic cooling ages in the internal zones and thrust interference with the southwest-directed Kashmir thrust wedge.

The timing of deformation can be dated



New stratigraphic and fossil finds in the Higher Himalayas of the upper Kaghan valley, NE Pakistan

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A collaborative project between the EHT and Punjab University during the summer of 1990 has led to important new discoveries bearing on the stratigraphic and structural relationships of the various rock groups marking up the Higher Himalaya Unit of N.E. Pakistan.

A coherent three unit stratigraphic subdivision appears to hold over most of the region. A basement consists of granitic gneiss which is overlain by a group of meta-pelitic to semipelitic sediments of original greywacke aspect which, although strongly recrystallised and locally granitised, still show traces of graded bedding with consistent younging directions away from the granitic basement. Although the relationships between these units is clear, suggesting that the granitic gneisses were metamorphic basement to a regionally overlapping group of sediments, no clear angular discordance has yet been discovered on outcrop scale.

The two basement groups are overlain by a thick series of calcareous pelites lithologically similar to the "schistes lustrés" of the European Alps, and interpreted as a sedimentary cover. These rocks locally contain good sedimentary "way up" structures, synsedimentary

extension faults and fossils (stromatolites, trace fossils). Considering the amphibolites metamorphic grade of these rocks, the preservation of fossils is remarkable. The base of the cover succession is marked by extensive thick sheets of amphibolite locally showing deformed amygdalites suggesting that they were initially basaltic lavas, and thinner sheets of amphibolite of similar petrographic aspect are found throughout the succession.

As yet no firm ages have been placed on these stratigraphic units. However, lithological correlations with rocks of Swat, the Srinagar Basin and Ladakh suggest that the granitic gneisses are probably of Pre-Cambrian age. The metapelites are of Lower Paleozoic age and the calc-schists and associated basaltic lavas may be correlated with various basic volcanic rocks of Paleozoic and younger age (perhaps some being equivalent to the Punjal Traps).

The overall distribution of these three units is suggestive of the presence of large scale recumbent fold nappes, but this pattern is complicated by the intensive development of later superposed fold phases and the formation of regional tectonic dome and basin structures.

Petrology of remnant ocean sandstones derived from the Himalayan suture belt

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After the India-Eurasia collision, which determined the final closure of the Neotethys Ocean in the early Eocene, "recycled orogenic" arenites began to be deposited in remnant oceanic basins at both sides of the Indian Peninsula. These sediments, of late Oligocene to early Pliocene age, were progressively incorporated in accretionary prisms formed at subduction zones both to the east (Andaman - Mentawi islands : Moore 1979) and west (Makran : Critelli et al. 1990) of the collision zone. Detritus derived from the elevated Himalayan chain is still being accumulated today in the two greatest turbiditic cones of the world, floored by remnant oceanic crust (Bengal and Indus Fans: Ingersoll and Suczek, 1979; Suczek and Ingersoll 1985).

Detrital modes of these "recycled orogen" clastic wedges are all comparable,

and testify to a predominant contribution from the Himalayas. They thus represent the distal "flysch" equivalent of ancient and recent "molasses" (Siwaliks : Prakash et al. 1980, Indo-Gangetic Plain, Potter, 1978), deposited in subaerial foreland basins floored by Indian continental crust.

A major difference in detrital modes among these deposits is represented by the significant volcanic contribution from active magmatic arcs to the subduction complex sandstones (Nias and Makran). Both the Indus and Bengal turbiditic cones and the ancient and recent foredeep deposits were instead entirely derived from the uplifted Himalayan Chain. While volcanic detritus is absent in the Siwaliks and Ganges sands, recycled volcanoclastics derived from the Transhimalayan arc and Indus-Tsangpo suture zone are transported by the Indus and Brahmaputra rivers up to the turbiditic cones of the Indian Ocean.

Indus	61	7	32	--	--	35	11	54
Ganges	74	10	16	--	--	64	0	36
Brahmaputra	51	26	24	--	--	40	27	33
Indus Fan	43	30	27	.03	.66	52	11	37
Bengal Fan	57	28	14	.01	.68	87	4	9
Siwaliks	57	7	36	.10	--	63	tr	37
Nias	70	11	19	.05	.70	35	29	36
Makran	56	10	34	.04	.68	31	37	32

Figure 1 - Detrital modes of modern sands and Tertiary sandstones derived from the Himalayan Chain. Available data for modern river sands are in QFR rather than QFL mode.

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coll. v. 100 SS

M1 nappes section

analysis M2 MCT

M3 section →

Heat sources for Tertiary metamorphism and anatexis in the Annapurna-Manaslu region, Central Nepal

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Following the collision of India with southern Tibet, the crustal rocks of the leading edge of India (1) underwent regional metamorphism to upper amphibolite grade, (2) were locally melted to produce anatectic granitoids, and (3) were sheared and thrust onto lower grade rock along the Main Central Thrust, yielding an inverted metamorphic sequence. This sequence is exemplified in the Annapurna-Manaslu region. We use simple physical calculations to examine the heat sources involved in the different phases of metamorphism. The regional metamorphism is apparently due to the burial of the northern edge of India by the overthrusting of the accretionary prism along the southern edge of Tibet. The observed temperatures and pressures of this first phase of metamorphism are consistent with the thermal relaxation, in the 10-30 Myr before slip on the Main Central Thrust began, of thickened continental lithosphere whose original surface heat flux was between 60 and 70 mW m⁻². The release of water from the block thrust beneath the Main Central Thrust apparently facilitated melting of crust in the second phase. Such melting could have occurred in the first million years or so of thrusting, if warm (550-650° C) crust in the lower block was wet. If

melting did not occur in the earliest stages of slip on the Main Central Thrust, dissipative heating, with shear stresses of 10 to 100 MPa, is required in order that the temperatures near the Main Central Thrust should have remained high enough, during the underthrusting of cold material to generate melting above the fault. The thickness (6-8 km) of the zone of inverted isograds below the fault implies that the time required to carry the rocks preserving the metamorphism from the surface to their present position was 4-8 Myr. The apparent inverted temperature gradients (about 10-25 °C/km) in this zone can be understood as the combined result of two processes. Thrusting of cold rocks over hot rocks for roughly 5-10 Myr expunged the original temperature gradient near fault, and could have created an inverse gradient of 10-20 °C/km. The peak temperatures in such a zone, however, would not have exceeded about 350 °C, and therefore an additional source of heat is required to explain peak temperatures in excess of 600 °C during slip on the fault. Dissipative heating at shear stresses of about 100 MPa can account for these peak temperatures, and would have contributed as much as 13° C/km to the inverse gradient.

Pétroglyphes archaïques du Ladakh et du Zanskar

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De très nombreux pétroglyphes sont présents dans la haute vallée de l'Indus. Grâce à quelques représentations caractéristiques comparées à des figurations et objets provenant de Chine, Mongolie, Tuwa, Tien Shan, Altaï et Kazagstan, il est possible de

dater certains sites de l'âge du bronze (IIIème à IIème millénaire) et de l'âge du fer (Ier millénaire au IVème siècle). L'art steppique ainsi caractérisé suggère que les tribus qui l'ont produit étaient en contact avec les empires de Chine et de Perse.

Remarque

Pour développer ce travail nous souhaitons obtenir des informations sur les trouvailles éventuelles (situation, relevés et/ou photographies), à adresser à H.P. Francfort.

The term "nappe" in Himalayan geology

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In the last decade the term "nappe" was rather loosely used in the Himalayas, which makes a redefinition necessary. This is aimed by analysing the structural units of the Himalaya, beginning in the S.

At present the young foreland sediments are sheared off from their basement by a developing detachment thrust. Series of listric planes in the Siwaliks probably are related to this decollement. The thrust S of the MBT led to imbricate structure (schuppen). The Siwalik Molasse was deposited after the Lesser Himalayan pile of nappes was formed in the Miocene. Continued compression forced the Lesser Himalayan units to override the Siwalik Belt along the MBT in the well-known windows of Solon, Bidhalna-Pharat etc. Simla Slates and Subathus are exposed but not the Siwaliks. Thus it is a basal scale of the Krol Belt exposed in these windows are not the Siwaliks and MBT, which is rather a reversed fault. The Krol Belt was accepted as "Kroll Nappe", but its rocks were deposited in the southern part of the Lesser Himalayan and were thrust onto the Siwaliks only marginally, therefore the name Parautochthonous Unit is appropriate.

The Simla Nappe and the Rukum Nappe show upright stratigraphic sequences, slight metamorphism and rest on younger rocks. Their allochthony is proved by windows indicating a displacement of at least 50 km.

The Chail Units were deposited in the Lesser Himalaya N of the Krol Belt. Lowest units are autochthonous or

parautochthonous, whereas the higher units are nappes. All the units consist of upright series and the grade of metamorphism increases upwards, mainly it is of greenschist grade. Outliers and windows document a horizontal transport of the Chail Nappes of ca. 100 km.

The Crystalline Nappes, which have their roots in the Central Crystalline Zone, were thrust towards the S also for about 100 km. The Lower Crystalline Nappe is generally thin and of lower amphibolite facies grade. The thick Upper Crystalline Nappe is composed of high grade amphibolite facies rocks frequently migmatitic. Upwards the metamorphism decreases and dies away in the sedimentaries of the Tethys Zone. The sedimentary sequences of Kashmir, Chamba, Kathmandu or Thang Chu are autochthonous in respect to the underlying Crystallines, however, allochthonous in relation to the Lesser Himalayan units.

N of the Central Crystalline the Tibetan Zone represents a Jura-type fold belt. Folding was accompanied by reversed faulting, wedges, etc. The direction of these movements varies frequently S or N; only where thrust masses are overlying the vergency is uniform S (e.g. Kumaun, Spongtang). The Jungbwa and Spongtang outliers are composed of 2-3 allochthonous units. As they represent isolated thrust-masses I do not use the term nappe, which suggests a unit having been continuous over a wider region.

The counter thrusts disturbed the older

nappe structures along the Indus Zone. Though transport over 12 km is documented E of Kargil, I do not support the use of the term nappe.

From the above consideration it is deduced that a nappe is a major rock mass thrust over a considerable primarily horizontal distance. By later folding the thrust plane may be inclined in various directions. The transport should have been at least over 10 km. Imbrications also may reach this amount, but there the movement was directed upwards obliquely to the earth surface and not tangential to it. A unit which only marginally overrides the adjacent unit should not be called a nappe.

A nappe may consist of an upright rock sequence as a sheet or it developed from a huge fold (+/- inverse limb.) . A nappe is indicated by older beds resting on younger ones, high grade rocks on less or non metamorphosed series. Frequently there is

also a difference in facies between the nappe and the underlying unit. Outliers and windows document the amount of displacements. The internal deformation of a nappe is not significant for its definition. A fold belt may show large shortening too, but it is the displacement of the thrust sheet in relation to the unit immediately underlying which is important.

Regarding the mechanism of transport there may be overfolding, active thrusting or passive gravitational gliding of a nappe. Along the strike it should be continuous over a larger area, otherwise it represents an isolated thrust mass.

Last not least the allochthony of a rock mass must be documented, mere disturbance of formation boundaries or intensive folding do not justify the use of the term nappe.

Rings Shapita ppt → Rang shikha of ~ 10 km
 Several small folds of but not -25
 ~ medium distance
 + position within major folds
 argues small, almost sheets for ppt & gneiss

The Karakorum fault in the Shaksgam area

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The following elements seem to characterize the Karakorum Fault Zone (KFZ) in the Shaksgam area (see geological map).

1) Several subparallel faults disrupt the Shaksgam Sedimentary Belt. However, the fault running from the Indira Pass to the lower Sarpo Laggo valley and then along the lower Shaksgam valley is the more continuous and may be considered as the main alignment of the KFZ. (see cross-sections).

2) Unmetamorphosed sedimentary and magmatic rocks are located on both side of the fault zone.

3) The Shaksgam sediments are arranged in wide folds, crossed by a younger fault pattern aligned with the main KF or forming a very small angle against it. Vertical throw may reach 1 km.

4) Vertical or steeply dipping faults, with cataclasites and no mylonites associated with metamorphic recrystallization are situated at the contacts.

5) The Permo-Triassic sediments of Shaksgam may be correlated with the equivalent SE Pamir sediments. Thus the KF system crosses a zone palaeogeographically unitarian during the Permo-Triassic and, consequently, it seems not to coincide with a plate boundary.

6) Several Cretaceous calcaline granitoid

bodies are cropping out around the Shaksgam Valley, on both sides of the KFZ. They form bodies elongated along the structural discontinuities trending NW-SE and which, except for the Sarpo Laggo-K2 orthogneisses, do not show either pervasive internal deformations, or obvious intrusive relations, but only faulted contacts with the adjacent rocks. Uplift of the granitoids should have occurred in response to the active tectonism along the Karakorum Fault Zone.

7) The lamprophyric dyke system (Pognante, 1991) is faulted along the KFZ. Their equivalent in Baltoro area are Neogene in age (Rex et al., 1988).

8) The gravimetric profiles (Palmieri, 1991) might indicate a deepening of the Shaksgam Sediments slab below the main Karakorum Range.

9) Zircon fission tracks (Cervený et al., 1989; Carpena & Rutkiewicz, 1989) indicate a latest episode of very recent and rapid uplift in the last 5 MY in the magmatic bodies along the alignment K2-Gasherbrum IV, which is parallel to the KFZ.

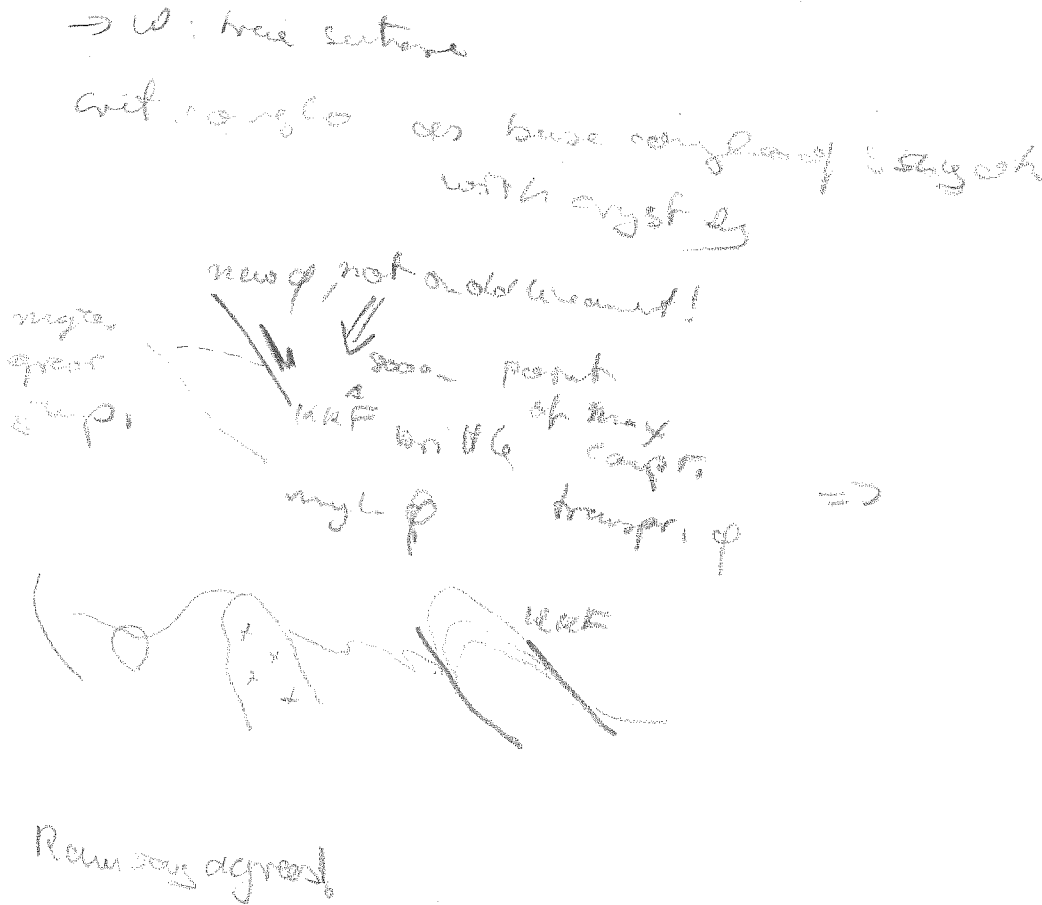
10) The main Karakorum Range corresponds to a geoid anomaly (Marussi, 1964; Caporali et al., 1990; Caporali, 1991), that could be interpreted as a bulge connected with the thrusting of the Main Karakorum Ridge over the Shaksgam.

11) All the 8000 m peaks of the

Karakorum are aligned with the KFZ and lies within 15-20 km in distance from it.

These observations indicate a multiphase deformation history of the Karakorum Fault Zone. Vertical faulting and dextral shearing were superimposed on the previous folding. Additionally, the existence of Neogene lamprophyres, trending more or less parallel to the KFZ, suggest that the KFZ transiently worked as an extensional fault system, triggering ascent and emplacement of the K-rich magma. A normal fault, parallel to the Karakorum Fault, was also suggested by Rex et al. (1988); Searle et al. (1989, 1990a); and by Parrish & Tirrul (1989) to explain the emplacement of the Baltoro granitoids. The KF is mostly known as a strike-slip fault system. This regime should have more effective to the south (Molnar & Tapponnier, 1975; Liu et al.,

1990), whilst north of Karakorum Range its effects appear to be confined to smaller amplitudes of one or two orders of magnitude (i.e the Misgar Fault in Gaetani et al., 1990a). The present picture for the area here considered is that of a shear-zone, with a certain amount of transpression. After emplacement of the lamprophyric magma, the continuous compression of the Indian Plate should have (re)activated a transpressional regime along this tectonic zone with recent uplift to the highest altitudes of the Main Karakorum Range and its thrusting over the rocks units of the Shaksgam Valley. The highest altitudes are reached also on the western side of the Karakorum indenter, because the Hindu Kush highest peaks (i.e. Tirich Mir and Noshaq) are positioned near the western shear- zone.



Multirifting evolution of the Tethys Himalaya passive margin (Zaskar, Northern India)

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The opening and closure of Neo-tethys is recorded in the Late Paleozoic to Early Tertiary stratigraphic succession of the Zaskar Range (Northern India), which represents the most complete transect through the passive northern margin of the Indian sub-continent.

Following a prolonged period of epicontinental sedimentation in shallow seas linked to Palaeo-Tethys, Neo-tethyan history began in the Late Paleozoic, when a rift arm opened between Palaeoindia and the Cimmerian microcontinents. The subsequent passive margin evolution may be subdivided into two megacycles. The first one started with break-up in the latest Permian and lasted until the end of the Jurassic. The second one began in the Early Cretaceous, with the final detachment of India from Gondwana-Land and the opening of the Indian Ocean, and ended with the India-Eurasia collision in the early Eocene.

Six transgressive-regressive super sequences,

bounded by tectonically enhanced unconformities and representing each periods of time from 15 to 65 My, were recognized in the Neo-tethyan succession. Basal sandstone units of Early Permian, Late Permian, Norian, Callovian, Early-Cretaceous and Paleocene age, invariably associated with oolitic ironstones or reworked glauco-phosphorites and commonly containing volcanic detritus from penecontemporaneous active sources, mark the transgressive part of each supersequence. Next, condensed nodular carbonates or shales with pelagic fauna are typically overlain by thick shallowing-upward marly units capped by regressive platformal carbonates. These six tectono-eustatic supercycles may reflect successive rifting episodes which punctuated the progressive separation of India from the rest of Gondwana-Land, and document the combination of plate/microplate reorganizations and eustatic, climatic and oceanographic changes in the Tethyan domain.

Preliminary notes on the High Chitral Geology

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The High Chitral area, from Mastuj to Tirich Gol and Morich Gol valleys, i.e. from SE to NW, consists of the following units.

- 1) Lavas and volcanoclastics of the topmost Kohistan arc.
- 2) Chitral Slates (grey phyllitic slates) and marbles, possibly covered with angular unconformity by 500 m thick polymict conglomerate, including abundant volcanic pebbles.
- 3) Shogram-Kuragh Unit. It includes the classical Silurian to Cretaceous succession, sealed by the Reshun Conglomerate, described by Hayden (1915), Desio (1959) and Talent et al. (1981). Disrupted in several blocks, the more complete successions lies northwestwards. It is separated of the following units by the Mt. Shogram Fault.
- 4) Lun Slate Unit. Extremely thick unit of grey dark slates, with subordinated marls and marly limestones, with metamorphic grade increasing from SE to NW. In the Morich Valley, it reaches the low-grade with phyllites and micascists. This belt, wide 15-20 km, was formerly considered as Carboniferous, but Talent et al. discovered in several places Devonian Conodonts.
- 5) Uzhnu Gol Metavolcanics. Bounded by regional faults, a metavolcanic body (amphibolites according to Buchroithner, 1980), some 20 km long and up to 1 km wide, has been observed. It disappears westwards.
- 6) Attak Sedimentary Unit. The term was introduced by the Austrian authors, Gamerith and Buchroithner. It forms a carbonate belt, from the upper reaches of the Rich Gol to just south of the Tirich Mir. Its contact with unit 4 and 5 is due to a regional fault with significant sinistral component. The metamorphic deformation mostly hampers any detailed stratigraphy. However, in the Zundrangram area, along the Rosh Gol, a Permian sequence of about 600 m was measured. It consists of an arenite-carbonate to claystones sequence, very rich in Fusulinids in the central part, that may be interpreted as a passive margin succession, drowning during the Middle Permian. Moreover very thick shallow-water carbonates are testified by the presence of Megalodontids and Rudists. Previously considered only as Paleozoic, the age of this unit should be extended up to most of Mesozoic. The sedimentary sequence is crosscut by sills oriented NE-SW, subsequently penetrated by rarer NW-SE dykes.
- 7) Whakhan Slates. Separated from the previous unit by another regional fault, dark grey or black slates follow, with subordinated arenites, microconglomerates and rarer pebbly mudstones. Sure turbiditic sequences have not been observed. Along the Rosh Gol an horizon packed with Bryozoan possibly of Palaeozoic age has been sampled, together with poorly preserved Brachiopods. The slates may be intruded by granitoid bodies.

Late Paleozoic to Trias stratigraphy of Central Dolpo: preliminary results

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The stratigraphic succession of central Dolpo (Tarap area) begins with thick highly metamorphosed Early Paleozoic carbonates injected by pegmatitic dykes. The strongly deformed mid-Paleozoic sequence, largely ascribed to the Devonian (Fuchs 1977), comprises shallow-water fossiliferous marls, hybrid arenites, limestones and dolomites in the upper part. In the western part of the surveyed area, the dolomitic interval is unconformably followed by 20 m of highly fossiliferous limestones yielding abundant bryozoans and corals ascribed to the middle Devonian (H. Flugel, pers. comm.). After a prominent ironstone layer (up to 2.5 m thick), a dark pelitic unit (300 to 350 m thick) contains quartzose sandstones and thin to medium-bedded bioclastic limestones at several intervals.

The overlying unit, unconformably overlying a 7 m thick interval of fenestellid-rich biocalcarenes at Tarap, is 60 to 100 m thick and consists of thick-bedded quartzarenites intercalated with dark pelites. A fossiliferous marker horizon (18 to 27 m thick) follows with sharp unconformable base. This interval yielded a rich large brachiopod fauna of mid-Permian age, characterized by *Costiferina alata* and *Fusispirifer nitiensis*. The overlying sparsely fossiliferous shelfal pelites (39 to 47 m thick) contain *Spiriferella rajah* in the lower part and *Neospirifer ravaniformis* in the upper part. They are unconformably overlain by a 37 to 41 m thick quartzarenite interval displaying spectacular sigmoidal cross-bedding, which testifies to deposition

in estuarine environments. Next, another disconformity is overlain by conglomeratic to glauconitic arenites (up to 13 m thick), ochre-weathering pelites (16 to 28 m thick) and dark shales with a few quartzose siltstones (18 m thick). These only locally fossiliferous intervals are ascribed to the late Permian.

The Triassic Tamba Kurkur Fm. (about 30 m thick) starts with a thin horizon of orange-weathering nodular carbonates yielding bivalves, ammonites (*Koninckites*) and conodonts (*Neospathodus kummeli*, *N. pakistanensis*, *N. cristagalli*) of Dienerian age, followed by dark pelites in turn overlain by nodular limestones and marls yielding conodont and ammonite faunas of Smithian (*Anasibirites*, *N. waageni*) to latest Spathian/earliest Anisian (*Gondolella timorensis*) age.

In the Anisian, Ladinian and Carnian, some 250 m of marls and subordinate marly limestones, yielding lower Bithynian conodonts 15 m above the base and locally containing ammonites, were deposited (Mukut Fm.). They are followed by the very thick Tarap Shale (about 500 m), consisting of dark pelites with early Norian ammonites in the lower part (*Griesbachites*, *Palicites*) and interbedded with orange-weathering siltstones containing large Zoophycos-type burrows in the upper 150 m. In the Rhaetian?, quartzo-feldspathic sandstones and siltstones interbedded with nodular to marly limestones (92 to 128 m) are followed by thick quartzarenites (73 to 90 m thick)

displaying spectacular herringbone structures, which indicate deposition by tidal currents ("Quartzite Series"). The latter unit is overlain by the shallow-water carbonate platform of the Kyoto Limestone, represented by mudstones/wackestones and

subordinate co- and bio-calcarenes. A Dogger unit (Laptal Fm. or "Lumachelle") is preserved only in the deformed core of a few synclines located at high altitudes. Younger terms of the succession are not exposed in the investigated area.

Contact metamorphism of the Manaslu leucogranite : an emplacement within a thickened upper crust

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P-T conditions of the upper metamorphic contact of the Manaslu pluton with the Triassic series has been inferred using metamorphic mineral assemblages and electron microprobe data on some ten samples. Samples were collected by one of us on two outcrops and morainic boulders around the 50m. thick contact auréole. They belong either to metamorphic calcareous sandstones or to pelitic micaschists.

The pelitic schists present four mineral assemblages :

- (A1) Garnet + biotite + chlorite 1.
- (A2) Garnet + biotite.
- (A3) Garnet + biotite + staurolite 1.
- (A4) Biotite + staurolite 1.

Muscovite, plagioclase, tourmaline, quartz and ilmenite associated with these assemblages, define the main cleavage. In some garnets and staurolites remnants of an earlier cleavage are still visible. Thus, we will consider the main cleavage as an S2 cleavage. A strain-slip S3 oblique on S2 is associated with the growth of chlorite 2 in A1 and A2, and with the last increment of staurolite 1-2 growth in A3.

Thermometrical investigations based on

the partitioning of Fe and Mg between garnet and chlorite, and garnet and biotite give :

- * 500-540°C for A1
- * 520-550°C for A2
- * 550-600°C for A3

Pressure is estimated between 2.5 and 4 Kbars using the plagioclase-biotite-garnet-muscovite association. A4 gives minimal P-T conditions of 570°C and 3.2 Kbars using (i) the prograde metamorphic reaction :

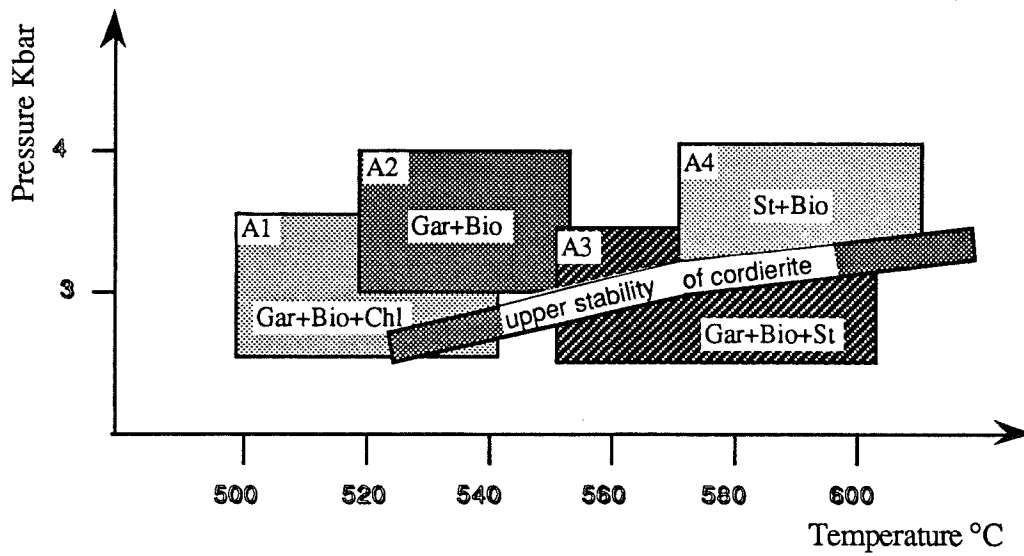
$$\text{gar} + \text{chl} + \text{mu} = \text{st} + \text{bio} + \text{qtz} + \text{H}_2\text{O}$$
 and (ii) the absence of cordierite.

The minimum pressure conditions at the time of granite emplacement require a cover of some 12 km, i.e. much thicker than the known thickness of the sedimentary pile above the Triassic (some 3km). It implies large refolding of this cover and/or nappe emplacement on top of it.

S2 cleavage and S3 strain-slip have grown at the time of granite emplacement and could be related to the northward extension movements already evidenced at the boundary between the High Himalayan Crystalline Formations and the Tibetan Sedimentary Series.

Tectonic event	Pre - S2	S2	S3
Mineral phases			
Quartz	Present	Present	Present
Plagioclase	Present	Present	Present
Garnet	Absent	Present	Present
Staurolite	Absent	Present	Present
Chlorite	Present	Present	Present
Biotite	Present	Present	Present
Muscovite	Present	Present	Present
Ilmenite	Present	Present	Absent
Tourmaline	Absent	Present	Present

Relationships between crystallisation and deformation in the pelitic micaschists



P-T conditions of the pelitic mineral assemblages upper stability of cordierite modified after Thomson, (1976)

Top to the WSW displacement along the MMT, Babusar Pass - Nanga Parbat region, Pakistan

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The Himalaya/Karakoram mountains of northern Pakistan are the product of multiple deformational phases from continental collision events that trapped the Kohistan island arc between the Asian and Indian plates, to the development and emergence of the Nanga Parbat syntaxis. Field work along the Main Mantle Thrust (MMT) and within Indian plate rocks in the area between Babusar Pass and Toshe Gali was aimed at an understanding of the kinematic and temporal relationship between these deformational phases. The MMT is the suture between the Indian plate rocks and rocks of the Kohistan sequence. Workers in adjacent areas have found evidence that the MMT had southeast directed transport of the Kohistan rocks over the Indian plate. In the study area, that deformation has been overprinted by a ductile fabric with a

shallowly WSW-plunging stretching lineation. Quartz grain shapes, asymmetric augen, and shear bands suggest a top-to-the-WSW sense of shear. This ductile fabric is pervasive at the MMT contact, within the Indian plate cover sequence below the MMT, but decreases in intensity in the Indian plate basement rocks and the Nanga Parbat gneiss. This top-to-the WSW sense of shear represents normal, or extensional, shear relative to the Nanga Parbat massif. If there has been sufficient displacement across this zone then the WSW-trending deformational phase may have been responsible, in part, for the exhumation of the Nanga Parbat massif. Shallowly WSW-plunging stretching lineations have been reported in the adjacent areas to the northeast by Butler et al., 1989 and to the west by Greco, 1989

Metamorphism and granite genesis in the Langtang valley section, north-central Nepal

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The valley of the Langtang Khola exposes a ≈ 15 km thick section from the Main Central Thrust zone (MCT) to the Tethyan Sedimentary Series (TSS). The MCT is a ≈ 4 km thick shear zone with a number of discrete high-strain horizons, and emplaces kyanite-grade micaschists of the High Himalayan sequence onto the chlorite-grade Lesser Himalayan formations. The High Himalayan Crystalline sequence is a pelite-dominated metasedimentary pile which exhibits inverted metamorphism; the kyanite grade schists pass up into a thick sillimanite zone which shows extensive migmatitisation and is cut by a series of subvertical leucogranitic dykes. The low-grade psammites and semipelites of the TSS are emplaced onto the upper-amphibolite facies rocks of the High Himalaya by a north-dipping normal fault zone. A substantial body of leucogranite is intruded into the TSS as a series of sills and subconcordant sheets, associated with a large network of pegmatitic veins. Textural and thermobarometric constraints suggest that the metamorphic inversion is an artefact of a polymetamorphic history. The lower part of the section records P-T conditions of 620-750°C, 7-11 kb (M1), and preliminary Rb-Sr ages are 22 Ma for muscovite ($T_c \approx 550^\circ\text{C}$), 4.4 Ma for biotite ($T_c \approx 350^\circ\text{C}$). The sillimanite zone gives estimates of 650-790°C, 3-6 kb (M2), as well as petrographic indications of a sillimanite-grade event overprinting kyanite-

staurolite assemblages, and a biotite Rb-Sr age of 17 Ma. The most likely cause of this low-P, high-T event is heat refraction at the interface between the high conductivity, high radioactive heat production crystallines and the low conductivity, low heat production sediments. This implies that most of the normal faulting occurred prior to M2. The highly mobilised sillimanite zone offers an obvious source for the leucogranites, which are virtually undeformed and mostly post-kinematic. However, isotopic data preclude the migmatites as the granite's source region. The whole section records an isotopic homogenisation event at c. 505 Ma, but the micaschists (unmelted where exposed in Langtang) are isotopically distinct from the higher grade rocks, and represent the probable protoliths to the anatexitic granites. Trace element modelling suggests that a small-degree ($\approx 12\%$) partial melt of these metapelites, dominantly by fluid-absent dehydration melting of muscovite, could produce the observed magma compositions, but this melt fraction could only migrate efficiently if some deformation-enhanced segregation mechanism prevailed. Since the actual root-zone of the granite is not observed, it is still not possible to relate the generation of the anatexitic melt directly to the observed thermal evolution of the crystalline sequence.

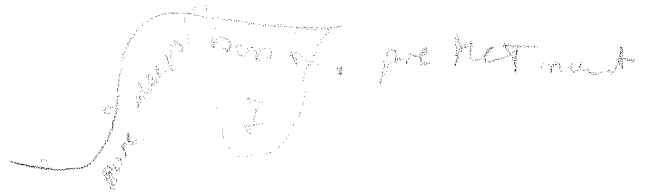
the skinned the sets \rightarrow ~~EF-100~~, F of open's held + another range
passed + smooth.

but

Over front, N of ridge deformed off set in some
of the north however.

S of ridge also does
ridge effect does \rightarrow 8m pl₂

transpiration to E. end of \rightarrow max related.



Tectonics of the Kirthar ranges of S. Pakistan : a comparison with offshore East Africa

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The Kirthar Ranges of Southern Pakistan strike N-S and connect E-W trending Makran accretionary prism to the south with the NW-SE trending Himalayan mountain belt of N Pakistan and India. Outcrop of the Kirthar Ranges comprises Triassic to Recent strata, these ranges being the uplifted and shortened elements of the NW Indian Mesozoic-Cenozoic continental shelf edge.

The geometry of the E-W shortening across the Kirthar Ranges, and the Sulaiman Ranges to the North has largely been described in terms of thin-skinned tectonics, namely fault termination folds, and passive-roof duplexes. However, problems exist in accounting for large amounts of lateral shortening since neither fold belt has an internal zone of crystalline basement, neither does good evidence exist for a N-S trending late Pliocene subduction zone west of these ranges.

Instead, major facies variations are noted within the Triassic-Oligocene sequence, some of which are aligned along later Pliocene

compressive features. Could the Kirthar Ranges be caused by basement inversion ?

Cross-sections drawn across the low-amplitude structures of the S Kirthar Ranges and offshore Indus Basin using seismic reflection, well and field data suggest that anticlines are a result of basement inversion and reactivation of strike slip faults, inversion being of late Pliocene age.

Seismic reflection data shot along the East Coast of Africa also show similar geometries, good evidence of extensional offset at depth, with inversion anticlines higher up. The inversion here is of Middle Eocene age but the structures formed are of similar geometry.

Are the fold belts of offshore E. Africa and Southern Pakistan genetically related to earlier passive margin extensional geometries ?

How much of the uplift of the Kirthar Ranges is due to Himalayan tectonics at all ?

Structure, stratigraphy and petroleum geology of the Northern Sulaiman Ranges, Pakistan

C. IZATT

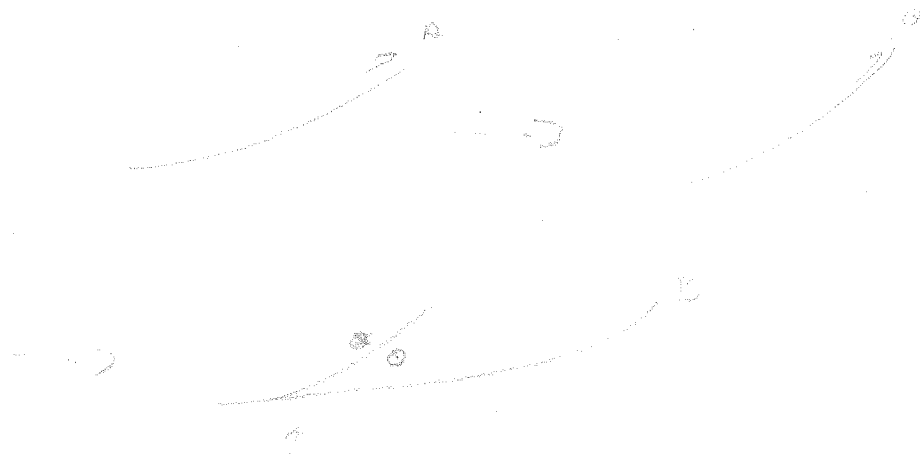
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Rocks of Middle Jurassic to Recent age outcrop along the strike of the Sulaiman Ranges in Central Pakistan. The eastern margin of the Sulaiman Ranges is represented by a major structural culmination or frontal monocline as uplifted strata of the Sulaiman Ranges dip eastwards under the undeformed Indus foredeep basin (late Tertiary age).

The Jurassic-Oligocene strata represent a record of the sea level changes and facies

variations that took place along this part of the Indian craton.

This paper explains the major patterns seen in the stratigraphic record. An evaluation is made of the Mesozoic-Cenozoic stratigraphy in terms of hydrocarbon source and reservoir potential, and attention is drawn to the late Pliocene shortening event and structures that result.



* Kest → strike slip with
local transverse / transverse → 1.5 m units

La structure des Siwaliks du Népal de l'Ouest: un prisme d'accrétion continental

Structure of the western Nepal Siwaliks: a continental accretion prism

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The Siwaliks are the actually active foothills of the Southern Himalaya. Erosion, sedimentation and faulting act simultaneously in the zone. Cross-sections across the West ranges of Siwaliks of Nepal show the succession of at least 3 North dipping main thrust zones. Displacement is transferred laterally from one thrust to another one, and anticlines are observed at the lateral tip of the faults. Erosion is very active at the frontal part of the thrust sheets, and results in monocline hanging wall structures, parallel to the thrust. Sedimentation acts in the Dune zones located in the trough between two hanging wall structures. Present-day breccic sediments are located beneath the thrust surfaces. They show that several faults are simultaneously active along a same traverse.

Close to the main faults, mesostructures have been observed. At the footwall, slickensides and fractures in pebbles of the upper Siwaliks formations show a shearing parallel to the bedding and a stretching perpendicular to the displacement plane.

Minor faults with a ramp-flat trajectory and duplexes are present in the hanging-wall blocks, mainly constituted of interbedded sandstones and mudstones (lower Siwaliks formations).

An intra-continental accretionary prism model is proposed to describe the evolution

of the Siwaliks. All the thrust structures seen in the field would be linked to a major decollement. The later would be located close to the top of the foreland basement, would branch to the main Boundary thrust and would root beneath the Mahabarat. The main frontal structure would be in most places a fold linked to a fault propagation, while the others thrusts have widely transported the frontal fold, presently eroded. If the displacement along a thrust exceeds the length of the hanging-wall thrust sheet, it results in back-tilting of the inner structures. Back-thrusting and back-folding are observed close to back-tilted steep faults and could be linked to difficulties in reactivating steep faults as thrusts. The faults show presently dextral strike-slip movements, and even locally down dip displacement. The bulk shortening velocity in the Siwaliks area, estimated from uplift effects ranges from 5 to 10 mm/years, -i.e.- is less than 1/5 of the plate convergence between India and Asia.

Les Siwaliks constituent le piedmont sud de l'Himalaya. Des phénomènes tectoniques, érosifs, et sédimentaires s'y produisent simultanément. Les structures de l'Ouest Népal montrent au moins 3 chevauchements majeurs à vergence sud affectant les sédiments de la fosse d'avant-pays. Ces accidents se relaient pour

absorber le déplacement, et peuvent s'amortir latéralement dans des anticlinaux liés à la propagation latérale des chevauchements. Des failles de décrochement interviennent également pour transférer le déplacement d'un système chevauchant à l'autre. Dans les zones frontales, l'érosion intense qui affecte les zones de chevauchements actifs permet l'affleurement des structures monoclinales, sub-parallèles aux chevauchements. Entre les culminations situées à l'aplomb des différents chevauchements se déposent des sédiments qui forment de petits bassins transportés, couramment appelés "duns". Les sédiments actuels, parfois bréchiques, situés sous les chevauchements montrent que plusieurs failles sont simultanément actives.

Au voisinage des grands accidents, les micro- et méso-structures ont été étudiées. L'analyse des stries et des galets éclatés situés dans les formations des Siwaliks supérieurs, sous les chevauchements majeurs, montre à la fois un cisaillement dans le plan de mouvement et un étirement perpendiculaire. Au-dessus des plans de chevauchement, dans la lame en mouvement constituée le plus souvent par l'alternance de marnes et grès des formations des Siwaliks inférieurs, de nombreux glissements sur les couches induisent des structures en plats et rampes et parfois en duplex.

Un modèle de prisme d'accrétion intracontinental est proposé pour rendre compte des structures observées dans ce domaine. Dans ce modèle tous les chevauchement majeurs observés se raccordent en profondeur à un grand décollement situé au toit du socle du craton indien. Les structures rencontrées sur le terrain correspondent à 3 stades d'évolution d'une structure chevauchante. Le premier stade est lié à la propagation d'un chevauchement, avec développement d'un pli de propagation. C'est celui que l'on rencontre très fréquemment le long du chevauchement frontal mettant en contact les Siwaliks avec la plaine du Gange. Le deuxième stade, plus évolué, est consécutif à un déplacement important. Les plis de propagation sont alors transportés et érodés.

Dans le troisième et dernier stade, lorsque le déplacement d'une écaille excède sa longueur, le mouvement sur l'accident externe redresse ceux situés en arrière de l'écaille. Des plis et des chevauchements à vergence interne sont observés à proximité de ces accidents très redressés et sont probablement liés à la difficulté de les réactiver en chevauchement. Cependant ces accidents redressés montrent encore une activité actuelle essentiellement en décrochement, parfois même en faille normale. C'est le cas de certaines portions des différentes branches du "Main Dun Thrust" (M.D.T.), ainsi que du M.B.T. (Main Boundary Thrust).

The stratigraphy of the Higher Himalaya at upper Kaghan valley, NE-Pakistan

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As a part of the Himalayan research programme of the ETH we had the opportunity to do the fieldwork for our diploma thesis in summer 1990 in Pakistan. During the fieldwork a stratigraphic profile of a total measured length of about 1400 m was taken. The effect of deformation on the original bed thickness has not yet been considered.

Three major lithological groups can be defined : a group of metagranitoid rocks overlain by metapelites form a "basement" overlain by a series of metamorphic calcpelites, which have been interpreted as a cover to this basement. (Greco et al., 1989).

The stratigraphically lowermost group is represented by a leucocratic-mesocratic garnetiferous two mica-gneiss. A banding with dark mica dominated schist layers takes place at 10 cm scale.

The transitional contact with a stratigraphically overlying group of

micaschists takes place within about 2 m. No angular discordance was observed. These rocks are garnet-two micas gneisses characterized by porphyroblastic felspar and an abundance of biotite. The aluminium rich nature of these rocks and the preservation of sedimentary structures shows that the original material was pelitic to semipelitic sediment. The group also comprises occasional quartzitic layers and rare marbles. The contact to the uppermost group is also transitional over a distance of about 15 to 20 m. This group consists mostly of metamorphic calcpelites which vary from pure marbles to garnet-micaschists together with more psammitic layers. At the top of the profile stromatolitic layers are associated with structures indicating synsedimentary extension.

Amphibolites are present in all groups. These being interpreted associated with the Panjal Trap Basalts (Papritz and Rey, 1989). They are probably of both extrusive and intrusive origin.

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The Lower Triassic sequence of Central Dolpo, Nepal.

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The Lower Triassic sequence of Central Dolpo is represented by the Tamba Kurkur Formation, a characteristic carbonatic unit that has been recognized also in Zanskar (India), Thakkhola and Manang area (Nepal). This unit shows slightly different lithologic successions in the Tarap and Atali areas, where our 1990's researches have been concentrated. At Tarap, the formation consists of:

1) A lower part characterized by orange-weathering nodular carbonates (mudstones-wackestones in 1-10 cm thick beds) in amalgamated beds or with thin shaly interlayers (totally 2.60 m) resting on the black shales of the upper Thini Chu Formation.

2) Grey-green, brown-weathering, silty marls and subordinated grey, planar (5-10 cm thick beds) marly limestones, locally with ammonites (12.25 m). At Atali, the formation, that has been investigated in two different sections (Atali Campo, Atali Alta) consists of:

a - planar black, yellow-weathering marly limestones in 3-10 cm thick beds

extremely rich in ammonites, and bivalves, with thin black marly intercalations, but locally up to 3.10 m, resting on the black shales of the upper Thini Chu Formation (total thickness 1.7 m),

b - black shales (12 m at Atali Campo; 22 m at Atali Alta);

c - planar black, yellow-weathering limestones (3-10 cm thick beds) with thin marly intercalations followed by grey, planar, laminated limestones (5-20 cm thick beds) and higher up, thicker (10-15 cm) marly interlayers (17 m at Atali Campo; 6.30 at Atali Alta). Toward the top ammonites and bivalves can be present.

The Mukut Formation (dark grey to black shales and subordinated dark grey limestones, marly limestones in 20-30 cm thick planar beds) unconformably follows in both areas.

Conodont and ammonite faunas

In the Tamba Kurkur Formation the following assemblages (bottom to top) are reported.

1.	Neospathodus kummeli		E.Dienerian
2.	N.dieneri, N.cristagalli, N.pakistanensis, Proptychites sp.	Hemiprionites typus Clypeoceras yudishthira Gyronites frequens	L.Dienerian
3.	N.waageni N.pakistanensis		Smithian
4.	N.waageni		L.Smithian

5.	N.waageni Gondolella mosheri G.milleri G.cf.elongata	Anasibirites kingianus Flemingites sp.	1.L.Smithian
6.	N.homeri G.timorensis		1.L.Spathian

In the Mukut Formation, that has been only partially investigated, *Gondolella timorensis* (Scythian/Anisian) is still present 2 m above the base of the unit at Tarap, while a conodont fauna characterized by the presence of *Gondolella regale* along with *G.bulgarica* (Lower Bithynian) is present at 14.60 m above the base at Atali Campo section.

Remarks

In Central Dolpo, the Tamba Kurkur Formation and consequently the limestone deposition, occurred in the Dienerian, as in the Manang area (Fuchs & al., 1988), while in Zanskar it took place in the Griesbachian (Nicora & al., 1985). Missing of most of the Spathian is only due to lacking of sampling.

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The geochemistry of 30 Ma to recent alkali magmatism on the Tibetan Plateau

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The Palaeogene (c.45 Ma) collision between India and Eurasia was followed by at least three episodes of volcanic activity within what is now the Tibetan Plateau. The first episode (from 32 to 27 Ma) forms a narrow E-W running province in central Tibet which contains a range of highly alkaline rock types with variable potassium content. The second episode from 15 to 10 Ma has been identified in both northern and southern Tibet and is dominated by high-K calc-alkaline andesite to rhyolite rocks as well as subordinate rocks with shoshonitic affinities. A third Pliocene to Recent episode is restricted to NW Tibet, where olivine basalts and pyroxene andesites are the main eruptive products. Isotope and trace element data for the Oligocene episode, indicate low degrees of melting of a continental lithospheric mantle source with subsequent crustal contamination. For the Miocene episode the northern province closely resembles to Oligocene episode in its

chemistry but with a greater crustal component, whereas the southern province chemically resembles some of the pre-collision volcanic arc lavas, and may result from a reactivation of the Paleogene mantle wedge. The Pliocene to Recent episode is slightly less alkaline in character, indicating a greater degree of melting, and the source appears to be somewhat less enriched in terms of its trace elements. Although the geographic coverage is very poor, the above data could be interpreted as suggesting that 10 to 15 Ma after the onset of collision, strike slip faulting gave rise to a first volcanic episode. The second episode 25 to 30 Ma after the start of collision, was related to mantle and crustal melting accompanying the crustal thickening, and the most recent episode, 40 to 45 Ma after collision, results from upwelling in the asthenosphere, after post thickening delamination of the sub-continental lithosphere.

30 Ma old → melting ~ crustal contamination - art + ascending mantle + crust - alk.

15 Ma old N side
S side. mantle sandwich?

recent thinning of lithosphere by mantle ↑

ENepal.

rustic

Khagben.

± rmp paths in west coast

+ h E-W

3 MM stages M1 Bayon. low obs

M2 decompr. Uplift

M3 in situ

→ eclog. M1

pre-Karoo cooling during T1

rustic. ga granite
PT →

30-25 Ma.

ht p. in total

heating & dens ↑

~ 16 Ma

pressure

grat gran ~ heating during T1

16-5 Ma

E-W. 1° folded

2° low-angle fold

extension unroofing

continues until low P

late low angle of NW Pak

rare in Z + abundant in W

fluids required are more and HP (low) -

→ subd. at ophiolite levels in W

India - AS collis. began in W - conti subd. of India. in
while still occ. subd. in E - of India.

→ Syntaxis of Pak related + more rapid uplift / lower str. level

Different P-T-t paths along the High Himalayan Crystallines: constraints on the formation and distribution of Miocene leucogranites

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On the ground of previous studies of the P-T metamorphic conditions and of new data emerged recently on the High Himalayan Crystallines (HHC), this paper suggest that different P-T-t paths exist not only in N-S cross sections, as usually described, but also along the belt from western to eastern Himalayas.

In the Kaghan nappe of northern Pakistan, the P-T-t path with an early (M1) eclogite-facies metamorphism ($P > 13$ kbar, $T = 650 \pm 50^\circ \text{C}$; Pognante and Spencer, in prep.) and a later exhumation at decreasing temperatures (Greco, 1989), are typical of subducted and collided tectonic sheets with low initial heat supply which were uplifted very rapidly and/or were imbricated with other nappes. In northern Pakistan the minerals give prevalent pre-Miocene cooling ages (Treloar et al. 1989).

East of Pakistan, occasional granulites formed during stage M1 (Burg et al. 1987; Pognante and Lombardo, 1989) instead of eclogites and relatively slow uplift rates are suggested by the prevalent Miocene cooling ages of the minerals. The decompression path occurred at uniform or increasing temperatures which produced anatexis and formation of leucogranitic melts during stage M2 (e.g. Caby et al., 1983; Staubli, 1989; Pognante et al., 1990; $P = 4-7$ kbar, $T = 600-750^\circ \text{C}$). This is typical of rocks involved in a continental collision event and derived from crust with normal or high initial heat supply (Thompson and England, 1984). The stage M3 produced an incipient retrograde

recrystallization in Zaskar. In contrast, anatexis continued during stage M3 in Buthan and Nepal where leucogranite melts were produced also in the cordierite-andalusite field (Brunel and Kienast, 1986; personal observations in the Everest-Makalu area; $P = 3-5$ Kbar, $T = 600-650^\circ \text{C}$).

From the available data along the HHC also emerges that close relations exists between P-T-t paths and distribution and characters of the Miocene crustally derived leucogranites.

Intrusive leucogranite bodies are subordinate in western Himalayas. In the Khagan nappe, the lack of a heating stage during uplift and the crossing of the granite melting field only at medium-/high pressures, all should be responsible for the formation of small amounts of melt.

In Zankar, extensive anatexis occurred during stage M2 (in the sillimanite +/- kyanite field) but relatively small amounts of melt were produced. In the middle structural levels, collection and ascent may have been partly inhibited by high, viscosity of the dispersed melt which chiefly froze "in situ" as migmatites and anatectic leucogranites (Pognante, in prep.).

In Buthan and Nepal, anatexis continued after stage M2 with the production of more significant amounts of melt. In fact relatively low amounts of H_2O (or micas in case of deshydration melting) are required to produce a granitic melt at the low-pressure conditions

of stage M3. Large portions of this melt were extracted and intruded to high structural levels (Le Fort et al., 1987) where

they coalesced to form the large lens-shaped leucogranite bodies.

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A microstructural and argon laserprobe study of fault rocks developed during Himalayan continental collision: a preliminary study

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Areas of NW Pakistan and Nepal have been selected to investigate the processes and timing of microstructural development associated with fault and shear zone development. In NW Pakistan, a series of ductile-brittle thrust faults associated with the collision of India with the Asian plate, are developed within the Indian plate in the footwall of the Main Mantle Thrust (MMT). These range from synmetamorphic to postmetamorphic in origin, developed at a series of metamorphic grades and are thought to have given rise to the apparent metamorphic inversion observed in the footwall of the MMT (Treloar et al 1989a, Williams 1989). The MMT itself records a complex deformation history involving thrusting and emplacement of the Indian plate onto Kohistan arc material and subsequent normal reactivation and overprinting (Williams, 1989).

Recent studies have illustrated that the late normal faults are important structural features throughout the Himalayas and show displacements up to about 20 km (Burg et al, 1984). Within the Langtang area of Nepal the North Himalayan Fault is recognised as a large normal fault which places basement gneisses of the Higher Himalayan Group against low grade Tethyan metasediments (Burchfiel and Royden 1985; Herren 1987). Metamorphic grades across the normal shear zone are variable and decrease within the footwall towards the contact with the hangingwall sediments. Within the hangingwall itself, cataclasites associated with the extension developed below greenschist

conditions. Beneath the normal fault, high strain rocks of the MCT record inverted metamorphism, but in this case the inversion is considered to be the result of high heat production in the footwall and the insulation effect of the low thermal conductivity sediments in the hangingwall.

Previous studies which have attempted to date deformation within Himalayan fault and shear zones have largely relied on indirect dating methods. These methods have included bracketing deformation by dating pre- or post-deformational intrusions, dating metamorphic recrystallization at temperatures close to individual mineral cooling temperatures and by relating deformation to the rapid cooling established by analysing a suite of minerals with different isotope blocking temperatures. However, the recent advances in the geochemical investigation of argon isotopes, utilising the laser microprobe system, provide a powerful tool which is capable of analysing minerals of different generations with different textural relationships. This enables mapping of mineral grain age contours ("chrontours") and the characterization of argon diffusion profiles across single grains which in turn may be used to constrain the complexities of mineral growth and/or the thermal histories of mineral phases within a rock. The technique can therefore provide valuable information on timing and understanding of processes taking place in fault zones which record protracted deformation histories characterized by multi-stage mineral growth, dissolution and fracturing.

This study focusses on the application of the laserprobe to the investigation of the temporal variations of deformation processes and development of fault zones and integrates detailed microstructural observations, utilizing the SEM, with laserprobe dating techniques.

This work represents a research program which has only recently been started. At this workshop meeting, the specific problems associated with these fault zones, and the methodology by which they are hoped to be solved, are presented.

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Magmatic and plastic flow structures in the plutons intruding Dras arc and constituting the Ladakh batholith, Indus suture zone, Ladakh-Himalaya

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In Ladakh, the Indus suture zone, representing the main Himalayan suture, separates formations of the Indian plate's passive margin ("Zaskar", fig. 1), from those formed in the environment of a subduction related magmatic arc. Volcano-sedimentary series often associated with ophiolitic remnants, are intruded by gabbro-norites, diorites and granitoids. These plutons converge to form the Ladakh batholith, in which remnants of the host rock series are preserved as enclaves generally pervasively recrystallized. The successive generations of different plutons can be traced under favorable conditions by intersection and xenolith relationships as in the Kargil plutonic complex : wehrlites evolving into gabbros, related with serpentinites = ophiolitic remnants; norites; diorites; and leucocratic granodiorites constitute four successive generations of plutonic rocks.

Plutons and their host rocks are affected by a foliation of locally variable intensity and geometry, that traces flow during and following intrusion of the magma. Weak structures are found in any direction and commonly in near to horizontal ones. They appear to be related with the primary geometry of the corresponding pluton. Near to vertical shear zones of stronger intensity are probably dependant on the accommodation of regional stress. They are well developed in directions parallel to the arc and suture, i.e. WNW-ESE, and transverse, i.e. NNW-SSE. Associated lineations are of variable plunge between dip-parallel to strike-parallel, though a NW-plunge

is predominant for both families of foliations.

In the **Kargil plutonic complex** the diorites and the volcano-sedimentary host rock, the metamorphic degree of which increases towards the contact with the plutonic rocks, present the same orientation of foliations: a major WNW-ESE striking shear is developed across Mt. Somau (fig. 2), from which a NNW-SSE shear zone branches off southwards. Plutons further south show little or no anisotropic structure. The wehrlites and gabbros appear to have preserved their own structure, and the norites present the least intense foliation. The two units may have reacted as more solid than the rest, or simply were located north of the main couloir (fig. 2).

In the **batholith around Leh**, WNW-ESE foliations are common, but generally weak. More intense are those following NNW-SSE directions, predominant in the SE part of the investigated sector, where they indicate the early origin of a later fault (fig. 3). Also here, mafic enclaves often preserved their own structure or none at all, and volcano-sedimentary host rock has not been observed in connection with intensely deformed plutons.

The kinematics of the arc complex of Ladakh appear to have followed similar tectonic conditions during a long span of time. These result however in a heterogeneous deformation pattern, with the development of shear zones, broad during plastic flow, getting continuously localised as conditions become colder.

Tectono-metamorphic development of far-eastern Nepal

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The far eastern Nepal Himalayas are made up of three distinct thrust-bound tectonic packages: from north to south the Higher Himalayan (crystalline) thrust sheet, the Lesser Himalayan (metasediment) thrust package and Sub-Himalayan imbricate fan. The Higher Himalayan crystallines, consisting of kyanite- and sillimanite-bearing gneisses intruded by the late-tectonic leucogranites probably of Miocene age, have been thrust over the Lesser Himalayan metasediments along the Main Central Thrust (MCT) for a distance of 140 km to 175 km. The Lesser Himalayan metasediments are a 12 km thick unit composed of phyllites, quartz gritty phyllites, metaquartzite, and mylonitic augen gneisses in which garnet-, biotite- and chlorite-metamorphic zones are exposed in progressively deeper structural levels. Older intrusive granites occur in the lower part of the metasediments. The Lesser Himalayan thrust package has an internal structure approximating

a hinterland-dipping duplex, with the MCT and the Main Detachment Fault (MDF) corresponding to the roof and floor thrusts, respectively. The MDF is a decollement, a calculated depth of which is changed from between 6 to 10 km underneath the Mahabharat Lekh to between 20 to 25 km north of the Tamar Khola Dome. Folding and thrusting within the Lesser Himalayan thrust package and thrusting along the Main Detachment Fault has resulted in the formation of the Tamar Khola ramp-anticline and in the folding and faulting of the MCT roof thrust. The MDF continues southward and beneath the Siwalik (Churia) Hills at a depth of 5.5 km to 6 km and, splays off the MBT, the Main Frontal Thrust and other thrusts. These thrusts have been activated from north to south with time with the exception of the Tamar Khola Thrust, an out-of-sequence branch thrust.

16-25 Ma MCT 7.9 - 15.3 mm/a.

Uplift-erosion rates across the N-W Himalaya Karakorum and pressure, temperature and time constraints on the structural evolution of the India - Asia collision

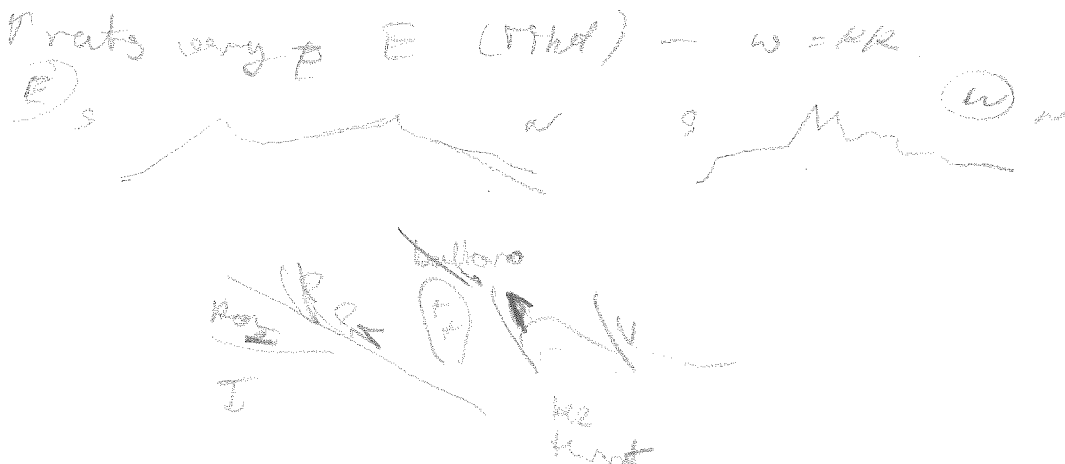
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The thermal evolution of the NW Himalaya (Zaskar, Kishtwar, Kashmir) south of the Indus suture and the Karakoram, north of the Indus suture has been inferred using regional structural constraints combined with cooling histories from multi system radiometric dating. U-Pb zircon, monazite and allanite, ^{40}Ar - ^{39}Ar and K-Ar dating on amphiboles and micas give cooling histories of rocks over the span 750°C to 300°C . Cooling curves can be used to calculate exhumation rates assuming an average continental geothermal gradient of $30^\circ\text{C}/\text{km}$ and a lithostatic gradient of $0.285 \text{ kbar}/\text{km}$ (or 3.5 - $3.7 \text{ km}/\text{kbar}$). Processes involved in exhumation include both uplift relative to the geoid, climatic erosion and tectonic erosion (eg: extensional faulting, underplating etc..).

P-T conditions, timing of metamorphism, uplift, erosion and exhumation rates vary dramatically across the Himalaya - Karakoram. In the Zaskar Himalaya P-T

conditions of 750°C and 5 - 12 kbars were attained ca. 20 - 30 Ma ago, giving a time-averaged exhumation rate of 2.1 - $1.4 \text{ mm}/\text{year}$. In the southern Karakoram pressures up to 10 kbars were attained by 37 Ma , meaning that roughly 35 km of overburden has been eroded since the Eocene-Oligocene boundary, giving a time-averaged exhumation rate of $0.95 \text{ mm}/\text{year}$. The 21 Ma Baltoro granite batholith crystallised at temperatures above 750°C at pressures over 10 kbars equating to depths between 26 and 35 km . Because the timing of crystallisation was much younger than the age of regional metamorphism the exhumation rate (unroofing) is greater at around 1.2 - $1.6 \text{ mm}/\text{year}$. Exhumation rates north of the Himalaya in the Zaskar and Ladakh terranes and north of the Karakoram batholith are much lower because both are affected by massive (15 - 20 km throw) culmination collapse north-dipping normal faults.



**A new geological map of the
Central Karakoram at 1/250000
scale**

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A new geological map of the central Karakoram based largely on the last five field seasons mapping is presented. The map covers the area from the Hunza valley in the west to the Baltoro-Siachen glacier divide in the east, and from the Shimshal valley and Skamri glacier in the north to the Nanga Parbat massif and the Deosai plains in the south. The High Himalayan terrane of the Nanga Parbat-Haramosh massif forms part of the northwestern syntaxis of the Himalaya. The Kohistan terrane to the west and the Ladakh terrane to the east of Nanga Parbat are continuous eastwards with the Trans-Himalayan batholith in southern Tibet. These terranes are bounded along the south by the Indus suture zone or Main Mantle Thrust, and

along the north by the Shyok suture zone or Main Karakoram Thrust.

The Karakoram terrane is continuous eastwards to the Lhasa Block in south Tibet, and is made up of three domains: the Karakoram metamorphic complex in the south, the Karakoram batholith and the northern Karakoram domain composed mainly of sedimentary rocks with structural culminations of high-grade gneisses along the K2 - Broad Peak Range.

The map will be published in the back of the forthcoming book "Geology and tectonics of the Karakoram Mountains" (J. Wiley and Sons), due in 1991.

Tectonics of the western Kuen-Lun as a key to the tectonics of the Altaid collage accretion tectonics and continental growth

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Geology of the western Kuen-Lun is plotted on a 1/1.000.000 scale geological map on the basis of data provided by the expeditions of Stoliczka, Trinkler, Hedin, and Visser plus all other expeditions that went through the area and made passing observations on the geology and physical geography. We also used the available satellite coverage to complete the map between expedition traverses. The resulting map was then compared with existing geological maps produced by the various geological institutions in the People's Republic.

The dominant tectonic unit in the western Kuen-Lun is a ? late Proterozoic to Silurian subduction-accretion complex that accumulated at the foot of a northern "backstop" (not necessarily cratonic !). This accretionary complex consists of slates, phyllites, schists, greywackes, cherts and local shallow-water sedimentary rocks. The grade of metamorphism is generally greenschist, but rises to amphibolite in the vicinity of intrusions. Red arkoses (? Devonian), the Tisnap Formation (Devonian) and the Permo-Carboniferous sedimentary rocks and intercalated volcanics represent the forearc facies. North of the Shahidullah/Yangi Davan axis the present vergence is dominantly north, but the cleavage is everywhere steep. South of this axis the cleavage remains generally steep, but the vergence flips to south.

North of the western Kuen-Lun wedge of accretionary material, no arc is today seen. We

think that the arc material exposed in the Maral Bashi outcrops in the western part of the Tarim Basin may be the remnants of the original backstop that was disrupted by the Permo-Carboniferous rifting of the Tarim back-arc basin.

The western Kuen-Lun wedge abuts against the western Qang-Tang block across the extremely sharp Ak Tagh suture. We suspect that this suture represents a later modification by considerable strike-slip faulting.

Large granodioritic plutons of late Palaeozoic through Cretaceous ages have invaded the western Kuen-Lun accretionary complex. Of these the earlier ones (Palaeozoic-Triassic) were probably related to subduction along the Ak Tagh suture, whereas the later ones to subduction along the Banggong-Nu Jiang suture.

The western Kuen-Lun accretionary complex can be traced eastward into the Qinghai Nan Shan, where even the associated arc is present (and where the Tarim basin is not !).

We present a new tectonic map of Asia to show the distribution of subduction accretion complexes in the Altaid collage which may consist up to 90% of these. A careful Nd/Sm model age dating along the Ob/Irtish system of the fine material may show how much of the accreted material may be juvenile.

Different shortening histories between the 'syntaxial' and 'non-syntaxial' areas of the Himalayan belt

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Recent plate tectonic models of Himalayan deformation (eg Dewey et al., 1989) are, as yet, the most advanced suggested for the understanding of the collision zone. North of the Indus suture, they show that shortening accommodation is not homogenous along the length of the mountain chain but varies: crustal thickening and uplift of the Tibetan plateau essentially occurring in north of the Central parts of the Himalaya and indentation with strike-slip faulting occurring in the Karakorum and Pamir region. Similarly, south of the suture, different amounts of shortening by thrusting are suggested to have occurred, although this does not explain how the structurally anomalous syntaxes are formed, their different structural, metamorphic and tectonic histories nor why they are confined to certain areas of the Himalaya.

It is suggested that the deformational history south of the suture is primarily influenced by the shape of the Indian plate promontory in the NW Himalaya and the lack of the promontory in the Central Himalaya. The effects of this promontory resulted in the initiation of subduction in the NW parts of the Himalayan belt and reach the greatest depths for the Indian plate, as evidenced by the high pressure eclogite and blueschist facies metamorphism, which are conspicuously lacking in the Central Himalaya. Also, the occurrence of extensional tectonics in the Central Himalaya and its absence in the NW Himalaya probably also attests to differential uplift histories.

The effect of the initial collision of the promontory caused the Indian plate to rotate anticlockwise in a force field adjustment. This

rotation produced a change of tectonic transport shortening direction within the promontory and subsequently led to large scale superimposed folding which explains syntaxial formation. By contrast, the central Himalayas were more of a 'head-on' collision with shortening easier north of the suture by plateau uplift and than by thrusting south of the suture.

Of fundamental importance in this interpretation is basically the argument about whether the Indian plate promontory actually exists and, if so, its shape. Indentation tectonics in the Pamirs with sinistral faulting on the western boundary and dextral faulting on the eastern boundary, deflection of Asian sutures older than Himalayan age, anticlockwise rotation of the Indian plate, the outline of the Higher Himalayan Crystalline, occurrence of syntaxes and differential rates of collision rates from NW to NE along the belt all attest to presence of a promontory and the subsequent progressive eastward closure of the suture. A 'triangular' shape for the promontory is thought to be the most appropriate.

It is obvious that the promontory did not act as a rigid indenter as thrusting occurred south of the suture. Similarly, during the uplift of the nappes, folding played a major part in the shortening history, in some cases producing a 'Penninic' sheet-like deformation in the more internal units. Examples of fold interference are presented from the Hazara - Kashmir, Kaghan and Nanga Parbat - Haramosh Syntaxes, as well as basin and dome patterns in the Upper Kaghan area and are mainly due to a horizontal, anticlockwise

translation of deformation, comparable and probably coeval with the movements of the Indian plate. Small-scale structures, as well as the metamorphic and geochronological considerations (Pognante, this volume) correlate well with these modifications.

It is therefore suggested that folding is a crucial accomodation feature south of the suture in the syntaxial areas of the Himalaya and has been mainly neglected

in shortening history models of the mountain belt. Slight modifications are therefore applicable to explain the deformational features south of the suture, where folding, as well as thrusting, are thought to be of great importance in the understanding of the different shortening histories between the 'syntaxial' and 'non-syntaxial' areas of the Himalayan belt.

Reference

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A revised stratigraphy for the Higher and Tethyan Himalaya in North Pakistan

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Recent investigations into the stratigraphy of the Higher Himalaya in Upper Kaghan valley, north Pakistan has led to a complete revision for the tectono-stratigraphy for this region of the Himalayas. The whole of the region south of the suture was always correlated with the Salkhala unit until workers located the Main Central Thrust and divided the area into the Lesser and Higher Himalaya. The latter unit was again all classified under one group, the Sharda Group (Ghazanfar et al., 1989), until recently when another reclassification (Greco et al., 1989) was made. Modifications to this are now proposed:

Basement: The oldest pre-Cambrian unit consists of granitoids that have intruded into an even older meta-pelite.

First cover: Unconformably overlying the basement is a lower Paleozoic metagraywacke unit. The unconformity is only recognised on a regional scale with a transgression gently cutting out the underlying granite. Excellent metamorphically-reversed graded bedding is found in the unit showing the original way-up structure. Its composition suggests a turbidite environment.

Second cover : Unconformably above

these two units is a Tethyan sedimentary sequence. Recognition of this unit is difficult and controversial, as it was metamorphosed and deformed during the nappe formation to eclogite and amphibole grades, which is not seen in the rest of the Himalaya where they are unmetamorphosed. It unconformably lies over the first cover and then eventually the basement, again showing the transgressive nature of the unit. They begin with the Permian Panjal Traps, which are subaerial basaltic lavas with intercalated limestone, now marble, horizons, before a Triassic sequence of marbles, dolomites and garnet-mica schists.

Himalayan leucogranites: All the units are cut by Himalayan age tourmaline-bearing leucogranites with some minor *in situ* anatexis found.

The Higher- and Tethyan Himalayan units are bound to the south by the Main Central Thrust mylonites which separate it from the Lesser Himalayan Salkalah Unit and to the north by the Indus Suture Melange Group which separates it from the Kohistan Island Arc Group. This revised stratigraphy has already been used in the recognition of the controversial Main Central Thrust in the Swat area of the western Himalaya.

Penninic style of nappe deformation in the NW Himalaya

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The Upper Kaghan nappe of the NW Himalaya is of crucial importance in the understanding of the deep seated orogenic processes associated with the Himalayan collision. Bounded by the Main Central Thrust to the south and the Indus Suture to the north, this Higher Himalayan and Tethyan tectonic unit thus represents the deepest exposed part of the Indian plate. Evidence of the deep subduction and subsequent erosion of the tectonic unit is shown by the presence of eclogites - the only eclogites so far recorded in the whole of the Himalayan belt - from which recent analysis suggest formation at temperatures of 650° C +/- 50° C and pressures of 14 kbar (Pognante and Spencer, in prep.). The exhumation rate for this unit is very rapid.

Stratigraphically, the basement consists of granites that have intruded into a garnet-mica schist: its first cover (a metagraywacke unit showing excellent metamorphically reversed graded bedding) and a second cover of Permian Panjal Trap volcanics with associated syn-sedimentary marine deposits, which give carbon and oxygen stable isotope ratios of a high temperature, deep marine water environment (Spencer and Spencer-Cervato, in prep.). All units have a very unusual metamorphic history of progressive eclogite facies metamorphism and retrogressive amphibolite facies metamorphism.

The structural evolution of the High Himalayan and Tethyan units in Pakistan

show a remarkable similarity to the Pennine style of nappe formation and deformation in the Alps: ie. complex large scale folding subsequent to nappe emplacement. Previous research suggests that, in general, the large scale crustal nappes in the NW Himalaya are each internally imbricated and separated from each other by late thrusts.

However, in the Higher Himalaya of Khagan, where ductile deformation was the main process of deformation, this is certainly not the case, as no internal thrusts or shear zones were recognised. Evidence suggests that a polyphase ductile - penetrative overprinting occurred after the original nappe forming movement. This led to the development of a system of major post nappe folds which deformed a pre-Himalayan history of deformation.

As with the Pennine nappes of the European Alps, the post-nappe folds can be subdivided into two groups: main Himalayan folds and late Himalayan folds. The main Himalayan folds are large, isoclinal and recumbent fold structures, which produce a series of sheets that are associated with a penetrative foliation, which is either a newly formed axial planar schistosity or a rotated and modified earlier foliation on the limbs of folds. The late Himalayan folds which affect an already developed penetrative foliation and, when present, lineation show a minor crenulation cleavage. They are superimposed on the main Himalayan folds with type 1 or 3

interference patterns giving very large scale domes, which are found in the Hazara-Kashmir, Kaghan and Nanga Parbat syntaxis, as well as basins and domes in the areas

between the syntaxes, such as that in Upper Kaghan.

Upper Kaghan III

Panjal \rightarrow ... log. + ... base. ... marks ...
 ...
 HP
 Med P. ...
 Basal.
 ...
 ...
 HP MM only in the NW
 all ... as top \rightarrow 5 11/0 5, - 0-5

MI
 ...
 ... \Rightarrow ...
 absence of ... etc.
 650 \pm 50 p 13-14 15b play < jde
 - 55 50 ... < 18 kb

The significance of eclogites in the Indian plate, NW Himalaya

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TURIN

High pressure assemblages are widespread in the Alpine belt with blueschist and eclogite facies rocks occurring both in ophiolitic and in continental rocks. However, in the Himalayan belt, only blueschist rocks have been recognised in the ophiolites associated with the suture and, to date, true high pressure assemblages were never recognised in the continental rocks. A new discovery of eclogite facies metamorphism in the Higher- and Tethyan Himalaya of the Indian plate in north Pakistan leads to the suggestion that the Upper Kaghan nappe represents the deepest derived rocks of the Indian shield known.

The medium grained, granoblastic and metamorphically foliated eclogites consist of: sodian augite and omphacites with $X_{jd} < 0,42$, almandine garnets ($X_{Alm} = 0,46 - 0,60$) with low grossular and pyrope contents. Only slight zoning with almandine and spessartine rims occur and minor simplectic reaction rims are seen, consisting of diopside and albite. Preliminary temperature estimates, based on the CPX-GRT geothermometer, give $T = 650 \pm 50^\circ \text{C}$, while pressure estimates, based on the stability of the

omphacite ($X_{jd} < 0,42$) and quartz, give $P > 13-14 \text{ Kbar}$. These pressure estimates are significantly greater than any other estimates concerning the Higher Himalaya of Indian plate. The eclogite facies assemblage shows an incipient recrystallisation producing amphibole, epidote, diopside and albite. This recrystallisation registers a decompressional path at decreasing temperatures which probably reflects high uplift rates. This was achieved initially by thrusting along the Main Central Thrust and then by post-nappe folding, resulting in the doming of the structure to its present elevation.

The significance of this only true high pressure assemblage to be discovered so far in the Indian plate Himalaya raises many questions as to why it only occurs in one particular area (total area approx. 700 km²) of the orogenic belt. A relationship to the Indian plate promontory and the syntaxes of the western Himalaya is suggested which account for some of the most unusual tectonic features of the Himalaya. A comparison is also made to the Central parts of the Himalaya where none of these features are seen.



Stable isotope analysis of the carbonates in the Higher and Lesser Tethyan Himalaya, North Pakistan

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The Upper Kaghan nappe in the NW Himalaya of Pakistan consists of a lower granitoid basement with two cover units: first, a metagraywacke unit of Lower Paleozoic age and second, a Tethyan sedimentary sequence which has at its base the Permian Panjal Traps, which are continental tholeiitic to mildly alkaline basaltic lavas that evolved in the passive continental margin of neo-Tethys. Syn-depositional limestone (new-marble) intercalations occur between the lava flows. These marbles show extensive extensional structures, associated with the rifting and subsequent extrusion of the lavas themselves. Due to the high grade of metamorphism under which the whole nappe has undergone (eclogite-amphibolite facies metamorphism) only a few fossils were found to indicate the age of the unit.

Previous geochemical correlations between the Higher Himalayan-Tethyan Panjal volcanics with known Lesser Himalayan-Tethyan Panjal volcanics in Kaghan valley revealed that a correlation between the two

units could be made. Carbon and oxygen isotope analyses on the marbles between the lavas, as well as those above the analytical groups consist of the Higher Himalayan Panjal Traps (HHPT), Lesser Himalayan Panjal Traps (LHPT), Higher Himalayan Tethyan Triassic series (HHTSS) and the Lesser Himalayan Triassic Rara Formation (LHTRF).

Preliminary analyses show that the marbles from the Panjal Trap units give a marine carbon isotope signature whilst the younger sedimentary series gave a different result. Such stable isotopic correlation is only possible because of the well defined nature of the units being studied, and that the actual stratigraphic correlations with other documented sections are available. It is therefore considered as a powerful tool in the analysis and reconstruction of similar sedimentary environments that have subsequently undergone different tectonic histories.

Tectonique et métamorphisme des séries sédimentaires dans la région de Sarchu (SE Zanskar - haut Lahul)

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Dans cette région, plusieurs unités tectoniques ont été reconnues par diverses expéditions géologiques (Baud et al. 1984, Masson et Steck, 1985 et 1989). Les contacts entre ces unités ont été interprétés comme des chevauchements de nappes. Par l'analyse structurale, la stratigraphie et l'étude du métamorphisme, nous pouvons préciser la nature de ces contacts et individualiser plus finement les grandes unités tectoniques.

Après avoir subi deux déformations en procharriage, où le métamorphisme atteint le faciès amphibolite durant la phase principale, et une phase de rétrocharriage, l'ensemble des terrains subit une tectonique d'extension. Celle-ci est tout d'abord marquée par un doming, puis par l'apparition de plusieurs générations de failles normales ayant par endroits rejoué plus ou moins le long de plans de failles inverses. Ce sont ces failles normales tardives qui sont responsables de l'état final des contacts entre certaines unités. Elles peuvent soustraire à l'observation les chevauchements frontaux des nappes. Le rejet

vertical apparent de ces failles atteint 10 km, et l'influence latérale dépasse la zone d'étude, soit 30 km; il est probable qu'elle s'étende bien au-delà.

Ces failles normales sont mises en évidence sur le terrain lorsqu'elles :

- recourent obliquement les structures de rétrocharriage,
- mettent en contact des terrains plus jeunes sur des terrains plus vieux,
- mettent en contact des terrains moins métamorphiques sur des terrains qui le sont davantage,
- mettent en contact des terrains mésozoïques métamorphiques sur des terrains paléozoïques non-métamorphiques (réactivation d'une surface de chevauchement de procharriage).

La présence de ces failles normales pose le problème de l'existence d'une phase d'extension ou de décrochement assez importante survenant après les grands mouvements de rétrocharriage.

Continental margin volcanism along the leading edge of Eurasia : the Dir volcanics

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In northwestern Pakistan (Kohistan) volcanic rocks associated with the northward subduction of Indian oceanic crust beneath Eurasia record two discrete episodes of activity:

1/ Early tholeiitic and calc-alkaline basalts, andesites and rhyodacites which make up part of the Kohistan island-arc (early Cretaceous Chalt Volcanics).

2/ Later silicic lavas and tuffs (Dir Volcanics dated at 55 Ma ^{40Ar-39Ar}) which erupted subsequent to the accretion of the Kohistan arc onto Eurasia, but prior to the collision of India.

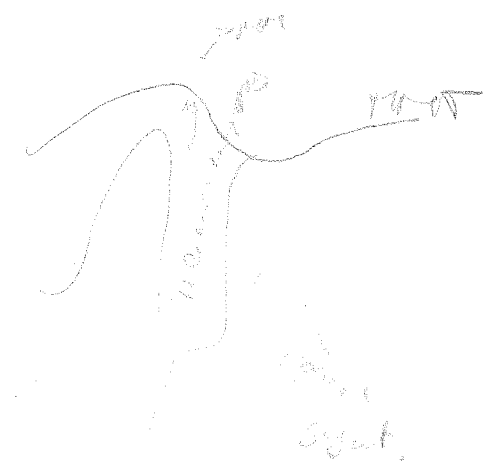
Mineralogical and geochemical characteristics indicate that as a whole the Dir volcanics belong to a calc-alkaline continental-margin series. They are L.I.L.E. enriched, depleted in H.F.S.E. (i.e. Nb) and show L.R.E.E. enrichment. The majority of material is rhyolitic in composition with few basalts.

Such substantial amounts of silicic volcanism imply the existence of extensional tectonics. Limestone clasts in conglomerate at the base of the Dir Volcanics are dated at 58 Ma, and record a period of marine incursion onto the margin of Eurasia. Attenuation of the continental lithosphere may have resulted in the development of small marginal seas, in contact with the ocean, which later were subject to uplift and erosion at the onset of volcanism at 55Ma.

Along the northern margin of Kohistan the Shamran Volcanics have yielded a radiometric age of 54 Ma (^{40Ar-39Ar}). This implies that rather than being associated with the Chalt Volcanics they are more likely contemporaneous with the later Dir Volcanics. They have similar geochemical characteristics and indicate that the extent of continental margin volcanics in Kohistan is greater than was first thought, recording perhaps the migration of the magmatic-arc with time.

Dir Volc
 60
 65
 → 56
 20% vs →
 L.I.L.E. ↑
 H.F.S.E. ↓

Uhorrobas
 Barone Basalt Tuff
 Dir Volc
 of local origin
 unsoftening of arc zone
 Tuff coarsened to rhyolite
 may have sealed W-entire
 tectonic controls



S → N = ↗ stack of nappes

≅ P ↗
(VIM ↗)

MM shear related
as India → Kol.

prostr. MM
K. MM.

MM → KP

MM → LP

case - MM P → 5-10
T → 600-700

follow P ↓

MM ~ burial of Indian plate
below MM

Ar/Ar - 39 ± 2 Ma. kont.

P—T—t paths of metamorphism, Pakistan Himalaya: implications for crustal subduction and stacking.

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One of the main contributions that metamorphic petrology can make to our understanding of the tectonic evolution of orogenic belts is by contributing hard data pertaining to the P-T-t paths of crustal thickening, metamorphism and exhumation. This involves a consideration not just of thermodynamically calculated metamorphic Ps and Ts, but the use of inclusion suite thermobarometry and the forward modelling of P-T trajectories based on chemical zonations. Such trajectories, when coupled with microstructural analysis of fabric-porphyroblast relationships and Ar-Ar and fission track mineral cooling chronologies, enable the construction of well defined P-T-t-deformation histories.

Within the crystalline internal zones of the Indian Plate, west of the Nanga Parbat syntaxis, fabric-porphyroblast relationships demonstrate that metamorphism was synchronous with early stages of ductile deformation. This deformation was related to the development of the first Himalayan mountain front. It is now well established that this metamorphic pile was subsequently deformed within a post-metamorphic thrust stack which contains a number of individual thrust nappes, each with tectonically controlled metamorphic inversions. This period of post-metamorphic thrust stacking documents the development of a second Himalayan mountain front.

In the Upper Kaghan, Hazara and Swat nappes forward modelling of garnet zonation profiles in low variance assemblages, as well as changes in inclusion suite parageneses from

core to rim (especially ilmenite in garnet cores and rutile in garnet rims in rocks saturated with plagioclase and kyanite), both indicate that the main period of metamorphic mineral growth was along a path of increasing T and P. Maximum Ps of 9 to 12 kbar are routinely recorded, with ΔP s during metamorphism of ≥ 6 kbar. These substantial syn-metamorphic pressure increases reflect thickening of the Indian Plate crust during active subduction beneath Kohistan.

Within the Upper Kaghan and Swat nappes, near rim Ca zonation in garnets and the mantling of matrix rutile by ilmenite testify to a phase of pressure decrease, although still at elevated pressures, which must represent early stages of exhumation of the deeply buried rocks. This exhumation is recorded in the late Eocene molasse sediments of the Murree Formation. That no extensive down temperature and pressure cooling path recorded in the zonation profiles suggests extremely rapid cooling that can only have been accommodated by rapid unroofing such as uplift-driven erosion and upper crustal extension on the hanging wall of a major S-verging thrust located beneath the currently exposed crystalline rocks. That this cooling, from $>600^{\circ}\text{C}$, was rapid is indicated by mineral cooling ages that date cooling through 500°C at ca. 40 Ma. In passing we may note that this early timing of metamorphism and post-metamorphic cooling is inconsistent with a combination of the normally accepted timing of Himalayan collision and one-dimensional conductive models of the thermal evolution of thickened crust. They imply that either Himalayan collision was earlier than

normally predicted, or that frictional processes of heating are more important in deformation zones than hitherto suggested.

Apart from the growth of calcic rims on garnets in the garnet and staurolite zones of the Hazara nappe there is little evidence for metamorphic overprinting during post-metamorphic stacking. These calcic rims are, though, important. Modelling across the zonations demonstrate that they record abrupt pressure increases, equivalent to about 10 kms of new tectonic burial. Inside the rim regions, the garnets record normal growth patterns relating to metamorphism during development of the first mountain front. The calcic rims relate to tectonic thickening during the second mountain building phase. Within the post-metamorphic stack, the ductile nature of the shear fabrics and K-Ar geochronology suggest that temperatures were $> 350^{\circ}\text{C}$ throughout the period of stacking.

Within the post-metamorphic stack there is a systematic increase in metamorphic pressure from the structurally lowest to the structurally highest nappes. This is most clearly shown in the Kaghan Valley where pressures range from ca. 5 kbar in the lowermost nappes to eclogite conditions in the highest ones, as David Spencer has recently, and most excitingly, shown. This is convincingly firm evidence that, following subduction-related metamor-

phism, the subducted slab was acutely telescoped, largely by crustal scale thrusting that was entirely confined to sequences on the MMT footwall. That the uppermost nappes are essentially composed of cover sequences has important implications for processes of cover-basement decoupling during continental subduction. Displacement amounts for those rocks originally most deeply subducted, and now structurally uppermost in the internal zones, must have been substantial and imply that total shortening amounts for the Indian Plate are well in excess of the 500 km or so generally assumed.

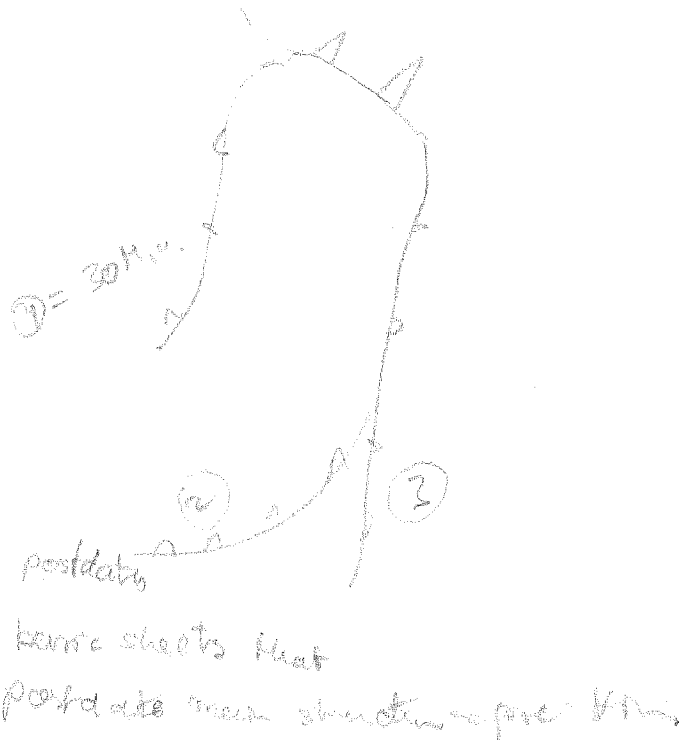
Consequently the full metamorphic story for the Indian Plate internal zones involves :

1) pre 50 Ma, and associated with the growth of the first mountain front, syn-subduction metamorphism (were the heat for this metamorphism not largely driven by frictional heating the collision and crustal thickening must have pre-dated 60 Ma);

2) rapid, pre-40 Ma, exhumation-driven, cooling;

3) pre-25 Ma, and during the growth of the second mountain front, the telescoping and stacking of the cooled and partly exhumed subducted slab with tectonic metamorphic inversions;

4) a second phase (pre-15 Ma) of extension and erosion-driven cooling.



Structure of the northern Nanga Parbat syntaxis and its relation to the Kohistan arc

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The Nanga Parbat syntaxis of Pakistan is a region of basement gneiss belonging to the Indian continental plate, structurally overlain by amphibolites of the Kohistan Island Arc which were emplaced along a complex set of faults, the Main Mantle Thrust (MMT). In turn, these arc rocks are bounded to the north in the Hunza region by Asian plate metasediments, the contact being the Northern Suture. The relation between the MMT and the Northern Suture, where they approach each other in an area north of the Indus gorge, is critical to understanding the relation between the formation of the Nanga Parbat syntaxis and possible late movements on the two major sutures

They are three lithotectonic units identified within the northern part of the syntaxis. The Iskere Unit, found on the west side, consists of migmatic orthogneiss yielding Proterozoic ages. The Shengus Unit occurs on the east side of the syntaxis in the Indus gorge and further south, and contains metapelites and calc-silicate rocks, again sometimes migmatic. In the north and northeast, immediately underlying the MMT, is the Layered Unit. This is strikingly banded on the scale of 100s of metres, consisting of biotite gneiss alternating with thick sheets of orthogneiss, sometimes garnetiferous. Sheets of marble, and boudinaged sheets of amphibolite, are common.

The Shengus and Iskere units contain

sheets of amphibolite, sometimes discordant to the banding in the surrounding gneisses, and inferred to be original basic dykes. The age of these is not certain; though both dykes and gneisses share a dominant N-S trending stretching lineation, and the dykes are frequently foliated parallel to their margins. Dykes were encountered in two areas.

1) In the Indus gorge, field relations suggest the dykes were less ductile than gneisses during the post-dyke deformation. The main shape fabric in dykes and gneisses, and the N-S lineation, are Himalayan in age and relate to the initial emplacement of the Kohistan arc over the Indian plate. This main fabric is folded into a broad antiform trending NNE, slightly oblique to the lineation.

2) Further N near the village of Iskere, dykes are arched into an antiform with a roughly N-S axis and intrude migmatites of the Iskere unit. The dykes are foliated, but foliation in the gneisses is poorly developed and usually N-S subvertical. The migmatites were thus relatively rigid during folding, with dykes as "easy-slip" horizons accommodating flexure whilst the gneisses formed a crude axial-planar fabric.

A contact interpreted as the MMT is well displayed in mountain sides to the N and E of Iskere, where it separates epidotic banded greenschists and amphibolites from gneisses of the Layered Unit. Banding in both units appears to parallel the contact. Where it is seen

further S, bounding the E side of the syntaxis in the Indus gorge, the contact is vertical and foliations on both sides are concordant. In contrast, on the W side of the syntaxis, at Sassi and further N, it is heavily modified by ductile and brittle dip-slip and oblique-slip movements.

At least 1-2 km of Kohistan amphibolites are seen above the MMT north of Iskere: these are upper-arc rocks. However, glacial rubble includes abundant pale green phyllites with garbenschiefer amphiboles. This distinctive lithology is characteristic of metasediments of the Asian plate, and possibly the Kohistan amphibolites are roofed by these rocks. This would imply that the "Northern Suture" is not a strait subvertical join here, as it is further west in the Hunza area, but a N-dipping contact.

Tourmaline pegmatites showing little deformation are present throughout the syntaxis. In addition larger granitic sheets are common and, NW of Iskere, an undeformed

2-mica leucogranite intrudes syntaxis rocks.

Summary of history of syntaxis:

1) Formation of Proterozoic banded ortho- and para-gneisses and their intrusion by basic dykes, and formation of Layered Unit.

2?) Emplacement of Asian plate rocks over upper Kohistan arc.

2) Pervasive deformation in Indian plate during emplacement of arc southwards over continental margin. Dykes were less ductile than paragneiss and more ductile than orthogneiss.

3) Arching of this fabric and overlying Kohistan nappe to form broad outline of syntaxis. Any pre-existing Northern Suture must have been involved in this deformation (though the present contact between Asian plate material and Kohistan may be late).

4) Modification of west margin of syntaxis by later ductile and brittle deformation, causing further uplift of syntaxis relative to Kohistan rocks.



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