EXTENSIONAL EXHUMATION OF HIGH PRESSURE INDIAN PLATE ROCKS.

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Introduction

Although syn-convergent extension has been described from many compressional orogens, evidence that it may partition into multiple discrete phases is less clear, even though extension is predicted as continuing as long as shortening once a critical crustal thickness is attained. However, it is likely that Ultra-High Pressure (UHP) metamorphic rocks, metamorphosed early in an orogenic cycle, have come to the surface through more than one discrete phase of extensional exhumation with initial stages of exhumation of many HP to UHP terranes occurring before thermal relaxation of the thickened crust.. The major problem with analysing the exhumation path of UHP rocks is that, although the structures which brought them near to the surface through a combination of thrusting and normal faulting are well documented, few structures remain that relate to that part of the exhumation path that brought them from mantle to "mid"-crustal depths.

Coeval normal faults at high levels and thrust faults at lower level are now recognised in many orogens. Late-stage exhumation of many metamorphic terranes, including HP and UHP terranes, has been accommodated through movement along hinterland directed normal faults coeval with foreland-directed thrusting (c.f. Burchfield et al. (1994) and Vince & Treloar (1996) for the Himalaya, and Ratsbacher et al (1989) for the Alps). This implies bulk horizontal stretching of the upper crust, although not necessarily of the whole lithosphere.

By contrast with late orogenic extension, modelling by Chemenda et al. (1996) suggests that early orogenic extension implies bulk horizontal shortening of the lithosphere and the incorporation of the UHP rocks into a developing thrust stack. It is clear that the rapid unroofing of a UHP sequence cannot be due solely to orogenic collapse but, instead, requires the differential upward transport of a segment of crust with respect to the immediately overlying and underlying rocks. Rocks unroofed in this way should be bounded by normal faults above and reverse faults below. It is likely, therefore, that UHP rocks are bounded by stacks of fault- and shear-zone-bounded slices. Exhumation of UHP terranes early in the orogenic cycle should, therefore, be accompanied by the development of recumbent fold nappes as regional scale sheath folds, a widespread flat-lying transposition layering axial surface to these nappes, multiple transposition cycles with poly-metamorphic assemblages, high constrictional strains with L-S tectonites, and normal and reverse sense displacement along shear zones marked by metamorphic breaks. The distinction of extensional shears associated with deep level differential uplift of UHP rocks from shallow level faults associated with orogenic collapse is a major problem in collisional orogens

Greco & Spencer (1993) argued that exhumation of the eclogitic rocks in the Kaghan Valley of northern Pakistan was largely accommodated by large-scale nappe emplacement during continuing crustal shortening. Similarly, data from the subduction-obduction complex of the western Alps (Freeman 1999) show that exhumation of UHP rocks was coeval with crustal shortening. Exhumation there from depths of c. 100 km to within 15-20 ma of the surface occurred within a few million years. The loss of >80 km of vertical section along with emplacement of UHP rocks onto the upper lithosphere requires some form of extensional tectonics which was clearly not post-orogenic as it was post-dated by further crustal stacking.

A region where at least two distinct phases of exhumation of metamorphic rocks, that include UHP sequences, and where models for exhumation processes can be assessed is in the crystalline internal zones of the northern Indian Plate in North Pakistan. Here, geochronological and structural data from the Indian Plate of North Pakistan, to the west of the Nanga Parbat syntaxis, as well as from the structurally overlying Kohistan arc, permit construction of a model for Indian Plate exhumation that demands two discrete, short-lived phases of rapid exhumation separated by long periods of erosive exhumation with low unroofing rates. The evidence for this is summarised below and the mechanical implications assessed.

Deformation and metamorphism in the internal zones of the India Plate, North Pakistan.

Collision between the leading edge of continental India and the Kohistan arc is dated at between 50 and 55 Ma. This is constrained by changes in the rate of the northward movement of India (Patriat & Achache, 1984), and the timing of the change of environment of sedimentary deposition form marine to terrestrial (Bossart & Ottiger, 1989; Garzanti & Critelli 1996; Pivnik & Wells, 1996; Rowley, 1996) Peak metamorphism in the highest grade parts of the Indian Plate internal zones in northern Pakistan, that post-dated thrusting of Kohistan onto the Indian Plate along the Main Mantle Thrust (MMT), was at c. 47 $\pm$ 3 Ma (Smith et al. 1994; Tonarini et al. 1993) Within much of the internal zones metamorphism was along a Barrovian-type geothermal gradient from chlorite to sillimanite grade. In the highest grade zones anatectic conditions were attained with temperatures as high 750^{o}C (Treloar 1997). Throughout most of these zones metamorphic pressures were in the region of 9 $\pm$ 2 kbar (Treloar et al. 1989a, b; DiPietro 1991; Treloar 1997). Locally, as in the Kaghan and Neelum Valleys, eclogites are present in late-Precambrian to Permo-Triassic sequences. (Pognante & Spencer, 1991, Tonarini et al. 1993; Fontan et al. 2000; Lombardo et al. 2000). The eclogitic assemblages are best preserved in mafic volcanic rocks of the Permo-Triassic Panjal Traps sequence and feeder dykes in them that cross-cut late Precambrian sediments and Cambrian-aged granites intrusive into them. The recent discovery of coesite in the Kaghan eclogites (O'Brien et al., 1999) suggests pressures in the eclogites of at least 22 kbar. Metamorphism was followed by *c*. 40 Ma, by rapid decompression-related cooling to ca 500^{o}C (Treloar & Rex 1990; Tonarini et al. 1993), much of it probably between 43 - 40 Ma at a cooling rate of 50^{o}C Ma^{-1}. This cooling resulted from rapid exhumation of all the metamorphic rocks, not just the highest pressure ones.

Only some of the structures which accommodated this exhumation are clear. The metamorphic rocks, including the eclogites, contain strongly transposed, planar shear fabrics which locally show evidence, marked by L-S tectonites for high constrictional strains. Greco & Spencer (1993) describe nappe-structures from the Kaghan valley, although these have not been identified elsewhere in northern Pakistan. The transposed fabrics are likely axial planar to these recumbent folds. The dominant transport direction is southward. The metamorphic rocks are stacked on the footwall of the MMT such that metamorphic grade decreases structurally downward and that the highest pressure rocks are at the structural top of the Indian Plate sequence. Rocks of the different metamorphic zones are separated from each other by major N-dipping S-vergent shear zones across which there are distinct metamorphic breaks. Treloar (1997) explained this geometry through sequential accretion of metamorphosed Indian Plate rocks onto the base of the arc and uplift of the whole sequence on the hanging wall of structurally underlying south-vergent thrusts. In this way the eclogites structurally overlie a zone of imbricately sheared lower pressure metamorphic rocks with the same metamorphic age. The age of stacking, at pre-40 Ma, was clearly coeval with continued lithospheric shortening in the early stages of Himalayan orogenesis. The structures which structurally overlie the eclogites are not clear as they have been transposed during late-Tertiary extension although it is likely that a major, ductile extensional shear separated the eclogites from the overlying base of the Kohistan arc at about 40 Ma. K-feldspar Ar-Ar data from southern Kohistan date rapid cooling there at ca 40-42 Ma (Krol et al. 1996) implying that Eocene-aged extension was not limited to shearing along the Kohistan/India boundary but was also located in the upper, brittle, parts of the over-riding Kohistan arc slab.

A period of slow cooling in the upper Indian Plate followed until *c*. 22 Ma when ductile through to brittle extensional displacement was initiated along N-vergent structures developed along the MMT, and in rocks immediately above and below it (Burg et al. 1996; Vince & Treloar 1996). The end result of this extension is that major metamorphic breaks are recognised within the upper Indian Plate and along the Main Mantle Thrust. Within the Indian Plate, greenschist facies rocks locally outcrop on the footwall of the MMT, structurally above sillimanite or kyanite grade sequences. The MMT zone itself is marked by the presence of blueschist and low-grade greenschist facies rocks that lie structurally immediately above mid- to upper-amphibolite Indian Plate rocks. How much of the metamorphic sequence has been cut out is uncertain due to the inversion related to Late-Eocene eclogite uplift and imbrication of the Eocene metamorphic sequence below the eclogites. In addition, as the Early Miocene extension spans the ductile through to the brittle field makes it difficult to identify the N-side down extensional structures that should have developed during Late-Eocene eclogite uplift as they have been thoroughly transposed during the earliest, ductile, stage of the Miocene extension. Miocene extension, coeval with renewed deposition in the foredeep, resulted in *c* 300^{o}C cooling at a rapid rate of *c* 60^{o}C Ma^{-1} in rocks on the MMT footwall (Vince & Treloar, 1996).

Exhumation Mechanisms

Two phases of exhumation accommodated by extension, and separated by a long stand-still with minimal apparent uplift, are clearly indicated for the metamorphic rocks, including UHP rocks, of the northern part of the Indian Plate in Pakistan. Although both the late-Eocene and early-Miocene phases are synchronous with continued lithospheric shortening, the driving force for each is different although there are similarities in the structures which accommodate extension.

That all of the earliest formed metamorphic rocks were partially exhumed during the late-Eocene, and that the highest pressure rocks are located in cover sediments rather than Palaeo- to Meso-Proterozoic basement gneisses, excludes the simple application of a Chemenda et al. (1996) type model for this phase of exhumation and cooling (c.f. Anczkiewicz et al. 1998). Instead of eclogite uplift being the result of the rapid rise of a positively buoyant, deeply subducted basement slice, it is more likely to follow from delamination of Neo-Proterozoic to Phanerozoic sediments, and granites intrusive into them, that were metamorphosed to eclogite facies at depths of >70 km within *c*. 5 Ma of initiation of Kohistan/India collision. It is a peculiarity of the Tertiary metamorphism of the Indian Plate in northern Pakistan that, outside of the core of the Nanga Parbat syntaxis, the Palaeo- to Meso-Proterozoic basement gneisses do not record the Tertiary-age metamorphism. It is likely that once the eclogite facies cover sequences had been delaminated, the the basement gneisses of the mid- and lower-crust subducted to mantle depths remained there.

Erosion of the Kohistan slab is recorded in the base of the Upper Eocene Murree formation in the Hazara syntaxis (Bossart & Ottiger, 1989). This is synchronous with the Late Eocene exhumation and implies the erection of a proto-topographic high synchronous with that exhumation, although the rate of erosion would not have been fast enough to accommodate the extremely rapid cooling indicated by the geochronological data.

Both the discrete exhumation events can be linked to short-lived phases of ductile thrusting at the, then active, base of the thrust wedge. For the Late Eocene event, this was the result of the uplift of a positively buoyant slice of eclogitic facies cover rocks, delaminated from their basement, which caused imbrication of the metamorphic complex on the MMT footwall. Extrusion of the eclogites from depth and their emplacement into a crustal section bounded by compressional shears below and extensional shears above, with extrusion acommodated by pervasive shear zones above and below but with deformation not restricted to the bordering shear zones (c.f. Burchfield et al 1994) is a form of channel flow (Mancklelow 1995). The upper, extensional, part of this channel flow system has since been removed during Early Miocene extension. For the Early Miocene event, the metamorphic complex was transported passively south along the Panjal Thrust. At the same time, extension was initiated along the Kohistan/India boundary (the MMT zone) near to the ductile-brittle interface with earlier extensional phases ductile and later phases brittle. There is no evidence for pervasive channel flow deformation during this latter event. Rather extrusion of, a largely brittle wedge, appears to have been accommodated by discrete, narrow fault systems at its top and base.

Each thrust event had the effect of thickening the thrust wedge either by intruding material into it (Late Eocene) or cutting down into its footwall (Early Miocene) and can be coupled with the development of N-vergent extensional faulting in the upper part of the thickened crust. In the former case, the locus of brittle extensional faulting was at a high level within the Kohistan arc. In the latter, extensional faulting, which spanned the ductile to brittle transition, developed within the MMT zone. Both extensional events are coeval with sedimentary pulses within the foredeep. This suggests that they are the direct result of the erection of a topographic high as a result of ductile thrusting and imbrication at the base of, or within, the evolving thrust wedge.

Extensional faulting during the Early Miocene developed near the brittle-ductile transition and can be modelled as the mechanical consequence of the requirement to maintain the critical taper of a wedge being thickened by ductile processes at its base. Not only did thrusting propagate downward within the wedge, but extension also stepped downward following the brittle-ductile boundary, with brittle fractures transposing ductile extensional shears. Periods when extension is dominant over erosion are the result of over-thickening of the orogenic wedge, possibly due to short-lived high rates of thrusting at the base of the wedge. It should be noted that the extensional fault at the top of the Early Miocene wedge did not accommodate a down-dip slip of the hanging wall block which was block buttressed to the north. Instead, the footwall block was pulled out to the south on the hanging wall of the thrusts developing at the base of the thrust wedge, the thinning in the upper part of the wedge maintaining critical wedge taper by matching the thickening at its base.

Since the Miocene the Pakistani topographic high has been reduced by erosion rather than extension. Although thrusting has continued at the base of the wedge, growth of high mountains has been retarded by the presence of an Eocambrian salt layer within which the basal thrusts are now located. As a result, critical taper of the wedge is now maintained by out-of-sequence thrusting at the rear of the wedge, rather than thickening at its frontal base.

References

Anczkiewicz, R., Burg, J-P., Hussain, S.S., Dawood, H., Ghazanfar, M. & Chaudhry, M.N. 1998, Stratigraphy and structure of the Indus suture in the Lower Swat, Pakistan, NW Himalaya, Journal of Asian Earth Sciences, 16, 225-238

Bossart, P. & Otttiger, R. 1989, Rocks of the Murree Formation in northern Pakistan: indicators of a descending foreland basin of late Paleocene to middle Eocene age. Eclogae Geologicae Helvetiae, 82, 133-165

Burchfield, B.C., Zhiliang, C., Hodges, K.V., Yuping, L., Royde, L.H., Chengrong, D. & Jiene, X. 1994. The South Tibetan detachment system, Himalayan orogen: extension contemporaneous with and parallel to shortening in a collisional mountain belt. Gelogical Society of America, Special paper. No. 269.

Burg, J-P., Chaudhry, M.N., Ghazanfar, M., Anczkiewicz, R. & Spencer, D.A. 1996, Structural evidence for backsliding of the Kohistan arc in the collisional system of NW Pakistan, Geology, 24, 739-742

Chemenda, A.I., Mattauer, M., & Bokum, A.N. 1996. Continental subduction and a mechanism for exhumation of high-pressure metamorphic rocks: new modelling and field data from Oman. Earth and Planetary Science Letters, 143, 173-182.

DiPietro, J.A. 1991. Metamorphic pressure-temperature conditions of Indian Plate rocks sout of the Main Mantle Thrust, Lower Swat, Pakistan. Tectonics. 10, 742-757.

Fontan In: Khan, M.A., Treloar, P.J., Searle, M.P. & Jan, M.Q. (eds) “Tectonics of the Nanga Parbat syntaxis and the western Himalaya”, Geological Society of London Special Publication, 170, 431-454

Freeman,

Garzanti, E, Critelli, S. & Ingersoll, R.V. 1996. Paleogeographic and paleotectonic evolution of the Himalayan range as reflected by detrital modes of tertiary sandstones and modern sands (Indus transect, India and Pakistan). Geological Society of America Bulletin, 108, 631-642.

Greco. A. & Spencer, D.A. 1993. A section through the Indian Plate, Kaghan Valley, NW Himalaya, Pakistan. In: Treloar, P.J. & Searle, M.P. (eds) “Himalayan Tectonics”, Geological Society of London Special Publication, 74, 221-236.

Krol, M.A., Zeitler, P.K. & Copeland, P. 1996, Episodic unroofing of the Kohistan batholith, Pakistan: implications from K-feldspar thermochronology, Journal of Geophysical Research, 101, 28149-28164

Lombardo, B., Rolfo, F. & Compagnoni, R. 2000. Glaucophane and barroisite eclogites from the Upper Kaghan nappe: implications for the metamorphic history of the NW Himalaya. In: Khan, M.A., Treloar, P.J., Searle, M.P. & Jan, M.Q. (eds) “Tectonics of the Nanga Parbat syntaxis and the western Himalaya”, Geological Society of London Special Publication, 170, 411-430.

Manckletow, N.S. 1995. Nonlithostatic pressure during sediment subduction and the development and exhumation of high pressure metamorphic rocks. Journal of Geophysical Research, 100, 571-583.

O’Brien, P.J., Zotov, N., Law, R.D., Khan, M.A. & Jan, M.Q. 1999. Coesite in eclogite from the Upper Kaghan Valley, Pakistan: a first record and implications. Terra Nostra, 99, 109-111.

Patriat, P. & Achache, J. 1984. India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. Nature, 311, 615-621.

Pivnik, D.A. & Wells, N.A> 1996. The transition form Tethys to the Himalaya as recorded in NW Pakistan. Geological Society of America Bulletin, 108, 1295-1313.

Pognante, U. & Spencer, D.A. 1991. First report of eclogites from the Himalayan belt, Kaghan Valley (northern Pakistan). European Journal of Mineralogy, 3, 613-618.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S.M. & Neugebauer, J. 1989. Extension in compressional orogenic belts: the Eastern Alps. Geology, 17, 404-407.

Rowley, D.B. 1996. Age of initiation of collision between India and Asia: a review of the stratigraphic data. Earth and Planetary Science Letters, 145, 1-13.

Smith, H.A., Chamberlain, C.P. & Zeitler, P.K. 1994. Timing and duration of Himalayan metamorphism within the Indian Plate, northwestern Himalaya, Pakistan. Journal of Geology, 102, 493-508.

Tonaraini, S., Villa, I., Oberli, F., Meier, M., Spencer, D.A., Pognante, U. & Ramsay, J.G. 1993, Eocene age of eclogite metamorphism in the Pakistan Himalaya: implications for India-Eurasian collision, Terra Nova, 5, 13-20

Treloar, P.J., 1997, Thermal controls on early-Tertiary, short-lived, rapid regional metamorphism in the NW Himalaya,

Pakistan, Tectonophysics, v. 273, p. 77-104
Treloar, P.J., Coward, M.P., Williams, M.P. & Khan, M.A. 1989a. Basement-cover imbrication south of the Main Mantle Thrust, North Pakistan. In: Malinconico, L.L. & Lillie, R.J. “Tectonics of the Western Himalaya”. Geological Society of America Special Paper, 232, 137-152
Treloar, P.J., Boughton, R.D., Coward, M.P. Williams, M.P. & Windley, B.F. 1989b. Deformation, metamorphism and imbrication of the Indian Plate south of the Main Mantle Thrust, north Pakistan. Journal of Metamorphic Geology, 7, 111-125.
Treloar, P.J. & Rex, D.C. 1990, Cooling history of the crystalline thrust stack of the internal zones of the Pakistan Himalaya, Journal of the Geological Society of London, 147, 735-738.
Vince, K.J. & Treloar, P.J. 1996. Miocene north-vergent extensional displacements along the Main Mantle Thrust, NW Himalaya, Pakistan, Journal of the Geological Society of London, 153, 677-680