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SHORT PAPER

Post-metamorphic cooling history of the Indian Plate crystalline thrust stack, Pakistan Himalaya

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A post-metamorphic Himalayan cooling history for the crystalline internal zones of the northern Indian plate is defined by amphibole and mica K-Ar and Ar-Ar geochronology. Hornblende, muscovite and biotite cooling ages from cover sequences metamorphosed during the Himalayan orogeny are 35–40, 30 to 23, and 29 to 23 Ma respectively. The mica ages, together with those derived from zircon and apatite fission track data demonstrate a cooling rate of about 30 °C/Ma during the late Oligocene to early Miocene. This rapid cooling was initiated during the post-metamorphic development of the Indian Plate south-verging crustal-scale thrust stack. Most of the cooling occurred during the stripping of some 10 ± 2 km of overburden through a combination of erosion, recorded in the Miocene molasse sediments of the foreland basin, and major crustal extension within upper levels of the Indian Plate and the Main Mantle thrust zone. Both erosion and extension were the direct consequence of the evolution of the thrust stack.

In northwest Pakistan the Indian and Asian plates are separated by the Kohistan Island Arc which was sutured to Asia at about 100 Ma (Coward *et al.* 1986; Treloar *et al.* 1989*a*). Himalayan collision in the northwest Himalaya, at about 50 Ma, was therefore effectively between the island arc and India, with Kohistan thrust over India along the Main Mantle thrust. This thrust, a crustal scale north-dipping fault zone, is the westward continuation of the Indus–Tsangbo suture zone.

Detailed analyses of the metamorphic and tectonic development of the crystalline rocks of the north Indian Plate have been presented elsewhere (Coward *et al.* 1988; Greco *et al.* 1989; Treloar *et al.* 1989*b, c, d*) and only a brief summary is given here. Porphyroblast-fabric relationships show that peak metamorphism, at temperatures of up to 650 °C, was synchronous with early phases of ductile simple shearing associated with thrusting of Kohistan over India. During subsequent deformation the metamorphic pile was imbricated within an out-of-sequence south-verging crustal scale thrust stack formed of a number of lithologically distinct thrust nappes each of 5–10 km thickness. At least six thrust nappes can be recognized south of the Main Mantle thrust in the region between the Swat and Kaghan valleys (Fig. 1). Each nappe is internally imbricated by thrusts with higher grade rocks in hanging walls rather than in footwalls, a geometry that results in the development of an inverted metamorphic sequence. Muscovite and biotite were stable within these thrust zones, the shearing having taken place at temperatures no lower than mid-greenschist facies. A series of brittle north verging extensional faults post-date the development of the thrust stack, which was subsequently folded by broad, N–S trending, antiformal and synformal flexures.

In this paper we summarize K-Ar and Ar-Ar data from the Indian Plate thrust stack that record the post-metamorphic cooling history and describe their implications for the timing of uplift and unroofing. All samples are from areas sufficiently far to the west of the Nanga Parbat syntaxis to be unaffected by current uplift of the syntaxis. Samples were collected from five of the thrust nappes that form the post-metamorphic thrust stack, both from metamorphic rocks within the nappes and from shear zones which stack and imbricate them. Hornblende mineral separates were analysed by K-Ar and Ar-Ar techniques. K-Ar determinations were made on biotite and muscovite separates. Analytical details are given in Rex & Dodson (1970) and Parsons *et al.* (1988).

Argon system blocking temperatures used are: for hornblende, 500–550 °C (Harrison 1981); for muscovite, 350–400 °C (Purdy & Jager 1976); and for biotite, 275–325 °C (Harrison *et al.* 1985). Zircon and apatite fission track data define cooling through lower temperatures of 200 ± 25 and 100–140 °C (Zeitler 1985).

Himalayan cooling ages. *Hornblende.* Two U-shaped hornblende Ar-Ar spectra from this region were included in Treloar *et al.* (1989*a*). Sample BG35 from sillimanite rocks of the Hazara nappe has a minimum at 35 Ma, and sample MG 14 from the kyanite zone of the Swat nappe a minimum at 33 Ma. Lawrence *et al.* (1989) cited two hornblende Ar-Ar ages of 38 and 39 Ma from the Swat nappe. Here we include two more hornblende ages. Sample DR2 is from an amphibolite pod in sillimanite-bearing metasediments of the Hazara nappe. Although there is evidence of some excess argon in the low temperature steps, a plateau defined by 97% of the gas yields an age of 39 ± 1 Ma (Fig. 2a). Sample K38 is from an amphibolite body within kyanite schists in the Upper Kaghan nappe. This sample has a flat spectrum with a plateau age of 39 ± 2 Ma (Fig. 2b). These ages indicate cooling through the hornblende blocking temperature at between 40 and 35 Ma.

Muscovite. Table 1 summarizes muscovite K-Ar ages from the northern Indian Plate in NW Pakistan. The table includes some data listed in Treloar *et al.* (1989*a*). Other data include muscovite Ar-Ar ages of 29 Ma from the Upper Kaghan (Zeitler 1985) and Swat nappes (Maluski & Matte 1984). The muscovite ages cluster between 23 and 30 Ma and we interpret the data as implying that the rocks cooled through the muscovite blocking temperature at between 30 and 24 Ma.

Biotite. Biotite K-Ar ages span a range from 23 Ma to >500 Ma. Much of this scatter is undoubtedly due to excess argon. Ages which fall within the time span of the 'Himalayan' event are listed in Table 1 and cluster at around 23 Ma.

Thermal and tectonic evolution of the internal zones. The data described above allow us to construct a temperature–time plot for the post-metamorphic thermal history of the internal zones of the Pakistan Himalaya (Fig. 3). Peak metamorphism occurred prior to 35–40 Ma, the age of cooling through the hornblende blocking temperature.

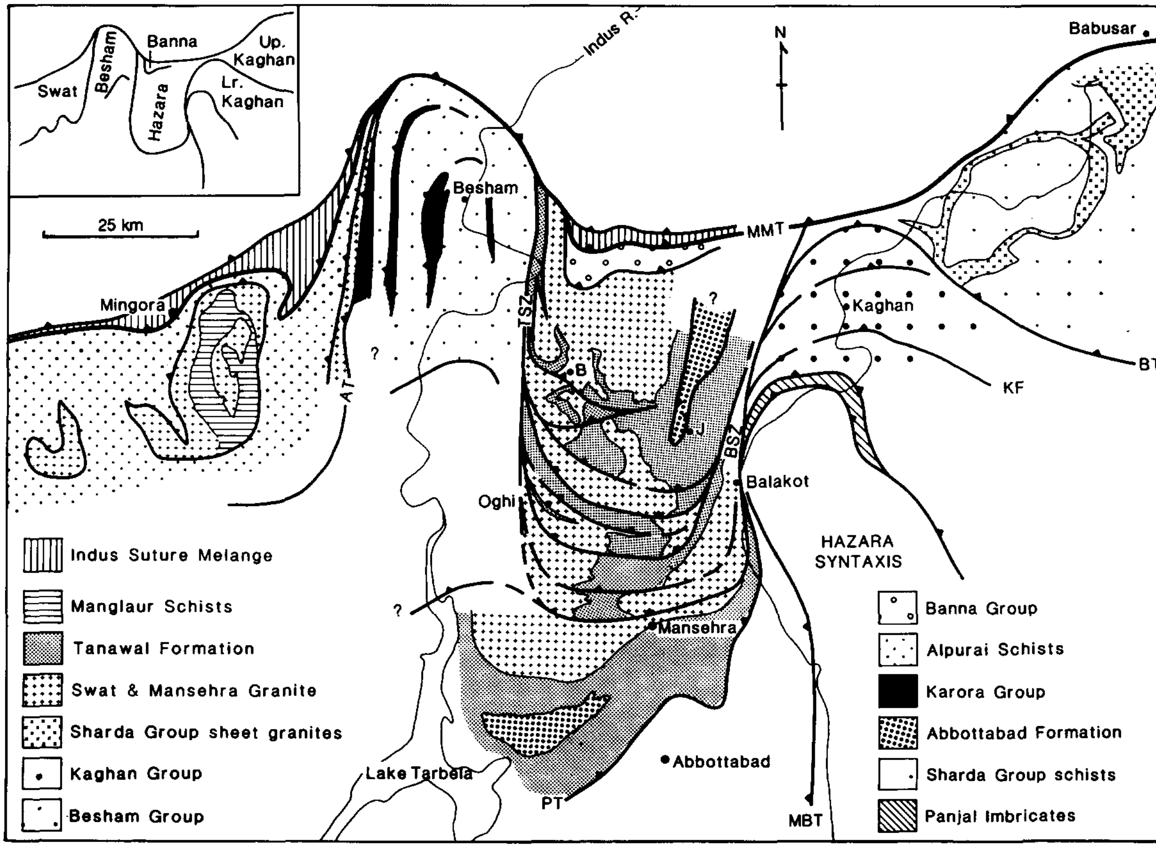

Fig. 1. Geological map of the northern part of the Indian Plate, south of the Main Mantle Thrust, between the Swat and Kaghan valleys. The inset shows how the region is divided into a series of large scale thrust nappes. Place names: B, Batagram; J, Jabori. Thrusts and shear zones: AT, Alpurai thrust; BT, Batal thrust; KF, Khannian fault; MBT, Main Boundary thrust; MMT, Main Mantle thrust; MT, Mansehra thrust; OS, Oghi shear; PT, Panjal thrust; BSZ and TSZ, Balakot and Thakot shear zones.

Subsequent cooling through the mica blocking temperatures was achieved by about 23 Ma, although there appears to be little difference between ages of cooling through the muscovite and biotite blocking temperatures. Zircon and apatite fission track ages of 19–26 Ma and 16–23 Ma respectively are from Zeitler (1985). We have used only those of Zeitler's data from what we now define as the Swat and Hazara nappes. Eastward the lower temperature cooling ages are increasingly affected by recent Nanga Parbat uplift.

We believe that thrust stacking followed cooling through the hornblende blocking temperature, and continued as the rocks cooled towards the muscovite blocking temperature. As muscovite ages from shear zones within the thrust stack are similar to those from unsheared rocks, it appears that stacking occurred no later than cooling through the muscovite blocking point; had it post-dated that cooling, isotope systems within the shear zones would have been reset. Hence we conclude that post-metamorphic thrust stacking probably predated 30 Ma ago.

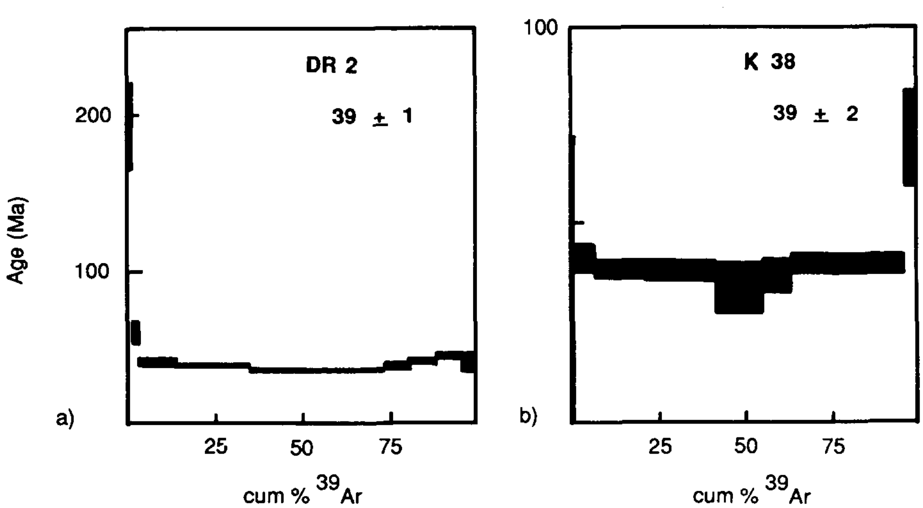

Fig. 2. Ar-Ar spectra of Himalayan hornblendes with cooling ages which post-date the main phase Himalayan metamorphic peak.

Table 1. *K-Ar data and derived ages for muscovites and biotites from the Indian Plate crystalline thrust stack of North Pakistan*

Sample	Location (Thrust nappe)	% K	Vol ^{40}Ar Rad cc STP/g $\times 10^{-5}$	% ^{40}Ar Rad	K-Ar Age (Ma)
Muscovites					
PJT 774	Swat	6.95	0.7660	74.2	28 ± 2
MPW 422	Besham	7.98	1.2183	78.8	24 ± 1
PJT 665c	Hazara	7.93	0.7580	61.1	24 ± 1
PJT 666	Hazara	8.09	1.0004	75.2	32 ± 1
PJT 682	Hazara	8.11	0.7304	68.3	23 ± 1
PJT 684	Hazara	8.07	0.7870	67.4	25 ± 1
PJT 694	Hazara	7.61	0.7597	71.1	26 ± 1
PJT 703	Hazara	8.83	0.8033	57.4	23 ± 1
PJT 776	Hazara	9.19	0.8597	76.5	24 ± 1
S 499	Hazara	10.15	1.2778	87.7	32 ± 1
N 32*	Hazara	6.58	0.7792	47.8	30 ± 1
K 39	U. Kaghan	8.62	0.7888	55.7	23 ± 1
Biotites					
N 756*	Swat	6.71	0.6368	28.5	24 ± 1
N 722*	Swat	7.83	1.0106	71.2	33 ± 1
MPW 422	Besham	7.08	0.6643	60.1	24 ± 1
MPW 442	Besham	6.57	0.6067	76.6	24 ± 1
PJT 714	Hazara	7.19	0.7471	83.8	27 ± 1
N 30*	Hazara	6.37	0.8274	42.5	33 ± 1
PJT 547	U. Kaghan	7.89	0.8767	89.0	28 ± 1
PJT 548	U. Kaghan	7.35	0.6817	84.1	24 ± 1
K 40	U. Kaghan	7.20	0.8638	80.5	31 ± 1
PJT 584	L. Kaghan	6.14	0.5524	64.9	23 ± 1
PJT 599	L. Kaghan	5.89	0.5989	76.7	26 ± 1

Sample collection: PJT, P. J. Treloar; MPW and S, M. P. Williams; K, M. N. Chaudhry; N, B. F. Windley.

* Data from Treloar *et al.* 1989*a*, table 5.

It is evident that cooling rates since 40 Ma have varied (Fig. 3). As an approximation, the mid-points of the hornblende and muscovite cooling data (525 ± 25 °C at 37.5 ± 2.5 Ma, and 375 ± 25 °C at 27.0 ± 3.0 Ma respectively) constrain a time-averaged cooling rate of about 15° C Ma^{-1}. A cooling rate calculated between the mid-points of the muscovite and apatite data (120 ± 10 °C at 19.5 ± 2 Ma) has a higher time-averaged rate of >30 °C/Ma. Subsequent to passing through the apatite blocking temperature average cooling over the last 20 Ma has been at a rate of <6 °C/Ma. Although these time-averaged cooling rates are approximations, the steepening of the temperature–time curve (Fig. 3) between *c.* 30 and *c.* 18 Ma is significant.

Once thrust stacking was completed it was followed by a period of rapid cooling of between 250 °C and 300 °C in about 10 Ma. As the enhanced cooling rate must equate with enhanced exhumation rates this converts, for an evolved geothermal gradient of 25 to 35 ° km^{-1}, to 10 ± 2 km of unroofing. At the end of this unroofing the rocks exposed today cannot have been more than 3 or 4 km below the erosion surface. This cooling was the result of two distinct processes of exhumation, erosion and extension, both of which can be viewed as the direct result of the development of the crustal scale thrust stack.

Erosion of the topographic high generated by the thrust stacking is recorded in the deposition of thick sequences of Miocene Siwalik molasse sediments in the foreland basins. Although some Eocene molasse is exposed in the core of the Hazara syntaxis (Bossart & Ottiger 1989), the main period of molasse deposition in north Pakistan began in the early Miocene at about 22.5 Ma (Johnson *et al.* 1979), i.e. within the period of more rapid cooling.

At this time the Main Mantle thrust ceased to behave as a south-verging thrust but, instead, began to act as part of a zone of extensional faulting, with an overall north-side down sense of displacement that was developed in the upper levels of the Indian Plate and in the suture zone itself (Treloar *et al.* 1989*c*). A large number of brittle extensional structures document this extension. Among these are many small-scale, extensional shear bands within both the upper parts of the Indian Plate and the Main Mantle thrust zone; large-scale, moderate angled north-verging extensional faults within the Indian Plate, such as the Banna Thrust (Treloar *et al.* 1989*c*), which has sillimanite-bearing rocks in its footwall and greenschist-facies rocks in its hanging wall; similar large-scale north-side down structures within the thrust zone itself, where at one point blueschist-bearing melange lithologies ($T < 400$ °C) are juxtaposed against

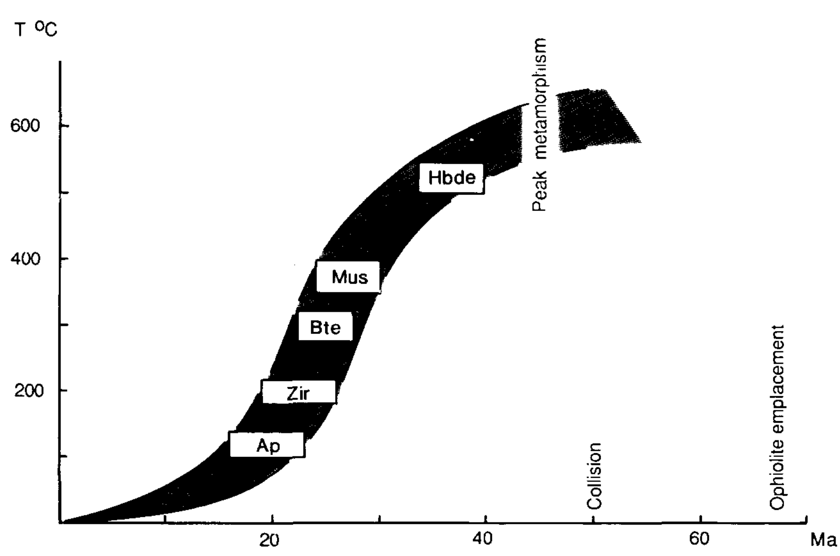

Fig. 3. Temperature-time plot showing the cooling history of the crystalline internal zones of the Indian Plate. As the steepness of the slope of the cooling curve reflects the rate of cooling, it is clear that the greatest cooling rate is between the muscovite and apatite blocking temperatures.

kyanite schists metamorphosed at temperatures of 625 ± 50 °C (Treloar *et al.* 1989*d*); and normal faults within Kohistan which accommodated thinning in the hanging wall of the main mantle thrust. Temperature differentials across the larger extensional structures are consistent with their having accommodated tectonic denudation of some 8 km.

This combination of post-metamorphic shortening and thrusting, followed by crustal scale extension, foreland basin development and molasse sedimentation is a tectonic scenario recognized along the length of the Himalayan chain.

Further implications. Three further points emerge from the cooling history data. As peak metamorphism must predate cooling through the hornblende blocking temperature at 35–40 Ma, metamorphism must have followed very shortly after Himalayan collision. The actual timing of the Kohistan–India collision is uncertain but is assumed to have been at about 50–55 Ma (Coward *et al.* 1986), although preceded by ophiolite obduction. If collision in North Pakistan was at 50–55 Ma, this leaves only 10–15 Ma for post-collision heating, deformation and metamorphism, and subsequent initiation of cooling. The metamorphic time-scale in this part of the collision zone is thus short, and long time-scale conductive models for the metamorphic thermal evolution may be inappropriate.

Basement rocks within the Besham nappe were imbricated with Phanerozoic cover sediments during the thrust stacking event. These sediments were metamorphosed early during Himalayan tectonism and their isotope systems record the cooling history outlined above. By contrast, the basement gneisses record a Proterozoic thermal history (Treloar *et al.* 1989*a*) with no evidence of a Himalayan thermal overprint. That substantial parts of the Indian Plate basement were thermally unaffected by Himalayan metamorphism implies that basement and cover sequences must have followed different *P-T-t* paths during Himalayan deformation. Early deformation probably involved the decoupling of cover and basement sequences (Coward & Butler 1985), the two being deformed and metamorphosed separately, prior to re-imbrication later in the Himalayan event.

Finally, there is no evidence in north Pakistan of the *c.* 20 Ma ages recorded further east in the Himalayan chain (Deniel *et al.* 1987; Hubbard & Harrison 1989). There leucogranite emplacement at *c.* 20 Ma is related to high grade metamorphism and movement along the Main Central Thrust.

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References

Bossart, P. & Ottiger, R. 1989. Rocks of the Murree Formation in northern Pakistan: indicators of a descending foreland basin of late Paleocene to middle Eocene age. *Eclogae Geologae Helvetica*, **82**, 133–165.

Coward, M. P. & Butler, R. W. H. 1985. Thrust tectonics and the deep structure of the Pakistan Himalaya. *Geology*, **13**, 417–420.

——, ——, Chambers, A. F., Graham, R. H., Izatt, C. N., Khan, M. A., Knipe, R. J., Prior, D. J., Treloar, P. J. & Williams, M. P. 1988. Folding and imbrication of the Indian crust during Himalayan collision. *Philosophical Transactions of the Royal Society of London*, **A326**, 377–391.

——, Windley, B. F., Broughton, R. D., Luff, I. W., Petterson, M. G., Pudsey, C. J., Rex, D. C. & Khan, M. A. 1986. Collision tectonics in the NW Himalayas. *In:* Coward, M. P. & Ries, A. C. (eds) *Collision Tectonics*. Geological Society, Londin Special Publication, **19**, 203–219.

Deniel, C., Vidal, P., Fernandes, A. & Le Fort, P. 1987. Age, origin and emplacement of an Himalayan leucogranite: the Manaslu example (Nepal). *Contributions to Mineralogy and Petrology*, **96**, 78–92.

Greco, A., Martinotti, G., Papritz, K., Ramsay, J. G. & Rey, R. 1989. The crystalline rocks of the Kaghan Valley (NE-Pakistan), *Eclogae Geologae Helvetica*, **82**, 629–653.

Harrison, T. M. 1981. Diffusion of ^{40}Ar in hornblende. *Contributions to Mineralogy and Petrology*, **78**, 324–331.

——, Duncan, I. & McDougall, I. 1985. Diffusion of ^{40}Ar in biotite: temperature, pressure and compositional effects. *Geochimica et Cosmochimica Acta*, **49**, 2461–2468.

Hubbard, M. S. & Harrison, T. M. 1989. ^{40}Ar-^{39}Ar age constraints on deformation and metamorphism in the MCT zone and Tibetan slab, Nepal Himalaya. *Tectonics*, **8**, 865–880.

Johnson, G. D., Johnson, N. M., Opdyke, N. D. & Tahirkelli, R. A. K. 1979. Magnetic reversal stratigraphy and sedimentary tectonics of the Upper Siwalik Group, eastern Salt Ranges and southwestern Kashmir. *In:* Farah, A. & de Jong, K. (eds) *Geodynamics of Pakistan*. Geological Survey of Pakistan, Quetta, 149–165.

Lawrence, R. D., Kazmi, A. H. & Snee, L. W. 1989. Geological setting of the emerald deposits. *In:* Kazmi, A. H. & Snee, L. W. (eds) *Emeralds of Pakistan: gemmology and genesis*. Van Nostrand Reinhold, New York, 1–25.

Maluski, H. & Matte, P. 1984. Ages of Alpine tectono-metamorphic events in the northwestern Himalaya (northern Pakistan). *Tectonics*, **3**, 1–18.

Parsons, I., Rex, D. C., Guise, P. G. & Halliday, A. N. 1988. Argon loss by alkali feldspars. *Geochimica et Cosmochimica Acta*, **52**, 1097–1112.

Purdy, J. W. & Jager, E. 1976. K-Ar ages on rock forming minerals from the central Alps. *Memoir of the Institute of Geology and Mineralogy, University of Padova*, **30**, 1–31.

Rex, D. C. & Dodson, M. H. 1970. Improved resolution and precision of argon analysis using an MS10 mass spectrometer. *Eclogae Geologae Helvetica*, **63**, 275–280.

Treloar, P. J., Rex, D. C., Guise, P. G., Coward, M. P., Searle, M. P., Petterson, M. G., Windley, B. F., Jan, M. Q. & Luff, I. W. 1989*a*. K-Ar and Ar-Ar geochronology of the Himalayan collision in NW Pakistan: constraints on the timing of collision, deformation, metamorphism and uplift. *Tectonics*, **8**, 881–908.

——, Broughton, R. D., Williams, M. P., Coward, M. P. & Windley, B. F. 1989*b*. Deformation, metamorphism and imbrication of the Indian Plate, south of the Main Mantle Thrust, North Pakistan. *Journal of Metamorphic Geology*, **7**, 111–125.

——, Williams, M. P. & Coward, M. P. 1989*c*. Metamorphism and crustal stacking in the north Indian plate, North Pakistan. *Tectonophysics*, **165**, 167–184.

——, Coward, M. P., Williams, M. P. & Khan, M. A. 1989*d*. Basement-cover imbrication south of the Main Mantle Thrust, North Pakistan. *Geological Society of America Special Paper*, **232**, 137–152.

Zeitler, P. K. 1985. Cooling history of the NW Himalaya. *Tectonics*, **4**, 127–151.

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