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The Punjab foreland basin of Pakistan: a reinterpretation of zircon fission-track data in the light of Miocene hinterland dynamics

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ABSTRACT

Sedimentary basins represent an archive of tectonic events of the hinterland source regions. By determining the variation in sediment lagtime over time, events can be distinguished which may no longer be available as the source has been eroded. In regions characterized by rapid exhumation this is most often the case but the erosion products form a record of these events. Detrital zircon fission-track ages from sediments of the Siwalik basin, Pakistan, originally presented by Cerveny *et al.* (*New Perspectives in Basin Analysis*, Springer-Verlag, New York, 1988, p. 43), have been reinvestigated and reinterpreted using a revised methodological approach. Detrital age populations were determined from different stratigraphic levels and were correlated through time in order to assess the change in lag time over the stratigraphic section. This information was combined with the many new ages from the hinterland to further interpret events in the source region. The new investigation suggests that steady-state evolution has not always existed. An overall trend of exhumation increasing by 0.1 mm Myr^{-1} (from 0.9 to 2.65 mm yr^{-1}) from 18 Ma to the present is evident with a major exception of a net pulse between 11.7 and 10.9 Ma associated with an increase in sedimentation increasingly rich in hornblende. Earlier studies suggested that at this time the source of the sediments was the presently outcropping Kohistan Arc. We are able to demonstrate that this cannot be so but was rather the rapidly exhuming Nanga-Parbat Haramosh syntaxis (> 2 mm yr^{-1}) coevally with transpressional displacement along the Main Karakorum Thrust, whereby the overlying Kohistan Arc sequences were removed. Furthermore, comparison of our detrital thermochronological data set with another one from the same basin and one from another foreland basin to the east, in NW India suggest that the Himalayan orogenesis was probably not synchronous for the late Early–Middle Miocene. Overall, regions that undergoes today's rapid uplift may be useless to reconstruct earlier phases of exhumation as the levels that may have yielded such info were eroded and deposited into the adjacent basin(s). Such scenario is reproducible in most orogens as in the Himalaya in NW Pakistan stressing the high potential of detrital thermochronological studies to trace hinterland dynamics.

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Introduction

Zeitler *et al.* (1982, 1986) and Zeitler (1985) were the first to report zircon fission-track (ZFT) ages on the basement rocks of northern Pakistan. Since then, many more ZFT ages have been determined – ranging from 120 to 0.5 Ma (e.g. Meigs *et al.*, 1995; Treloar *et al.*, 2000; Gubler, 2001; Zeilinger *et al.*, 2001; D. Seward, unpublished data, 2005) but in general Neogene or younger (Fig. 1).

Because the drainage basins of the palaeo- and modern-Indus were geographically extensive (Clift *et al.*, 2002; Clift and Blusztajn, 2005), covering many sub-tectonic blocks, each with its own thermal history, a large variation in ages must be expected in the eroded material. Zeitler *et al.* (1986) examined the age of the spectra obtained from five units ranging in stratigraphic age from 22 to 0 Ma. Cerveny *et al.* (1988) presented a slightly different approach as they restored the present-day ZFT ages of individual grains from eight Siwalik and Rawalpindi Group samples (ranging in age from 18 to 4 Ma) back to their ages at the time of deposition of the sediments.

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We have further re-utilized the data set of Cerveny *et al.* (1988), statistically resolved individual ZFT age populations, and plotted these age groups against their revised stratigraphic age as detailed in Ruiz *et al.* (2004). This allows an immediate inspection of the changes in lagtime and hence variations in cooling histories in the hinterland which can then be correlated to regional tectonic activity.

Geological framework

The Indus River and most likely the palaeo-Indus and tributaries drain(ed) the Northern Suture of Pakistan, across the Kohistan and Ladakh arcs that accreted to the southern margin of the Asian plate between 102 and 85 Ma (Treloar *et al.*, 2000), across the Indus Suture [the Main Mantle Thrust (MMT), Fig. 1]; later the Indian Plate accreted at *c.* 55 Ma (Treloar *et al.*, 2000). Peak metamorphism was reached in the Pakistan Himalaya during the Eocene (Treloar and Rex, 1990) and was followed by exhumation during the Early Miocene that was driven by north vergent extension (Burg *et al.*, 1996). The Main Boundary Thrust (MBT, Fig. 1) separates the Lesser Himalaya from the dominantly sedimentary sequences of the foreland basin. Initial displacement on this thrust occurred prior to 9 Ma (Meigs *et al.*, 1995) most likely at *c.* 11 Ma as evidenced by a net increase of tectonic subsidence in the foreland basin to the south of the MBT from 0.2–0.3 to 1 km Myr^{-1} (Burbank and Beck, 1989; Burbank *et al.*, 1996). In the foreland basin of Pakistan, the Siwalik and Rawalpindi Groups, well-dated, thick molasse-type sequences (Johnson *et al.*, 1985; Gee, 1989), are the Neogene record of exhumation in the western Himalayas.

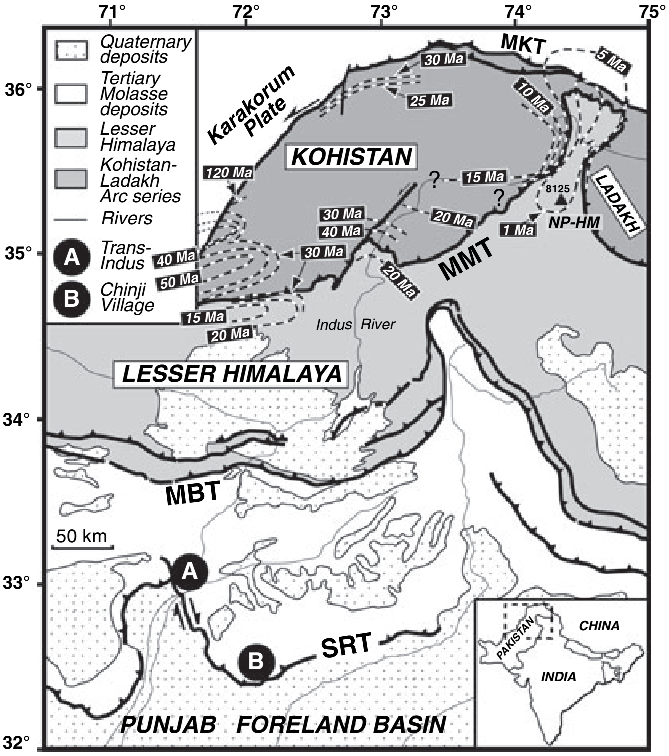

Fig. 1 Regional map of the Himalayan foreland of north-west Pakistan and surrounding regions showing the locations of major faults, tectonic units and drainage. Black circles represent the location of the Trans-Indus (A) and Chinji (B) sections (Cerveny *et al.*, 1988). MBT, Main Boundary Thrust; MMT, Main Mantle Thrust; NP-HM, Nanga-Parbat Haramosh Massif; MKT, Main Karakorum Thrust; SRT, Salt and Range Thrust. The black and white dashed lines represent zircon-fission track (ZFT) age contours from the Kohistan, NP-HM and Lesser Himalaya regions, where data are available. They are based on 46 ZFT ages (Zeitler, 1985; Treloar *et al.*, 2000; Gubler, 2001; Zeilinger *et al.*, 2001; D. Seward, unpublished data, 2001).

Methodology

The notion of lagtime as introduced by Zeitler *et al.* (1986) corresponds to the time taken for a mineral to be cooled through its closure temperature, brought to the surface, and transported to the depositional site. Assuming negligible transport time from source to basin, the lagtime can be interpreted as an exhumation rate in the source region after a series of assumptions concerning the necessary depth of closure are considered (Garver *et al.*, 1999). In essence this implies that as exhumation rate increases, the lagtime decreases; the converse situation is also true (Ruiz *et al.*, 2004). The lagtime of the various age populations, (P_n), from within a sedimentary horizon, is graphically represented by the horizontal distance between the P_n population and the 1/1 line (Fig. 2). A point lying on the 1/1 line, i.e. where the detrital age is the same as the stratigraphic age, represents either extremely fast denudation in the hinterland or the incoming of contemporary volcanic detritus. However, volcanism during the Miocene in this region of the Himalayas can be discounted (Cerveny *et al.*, 1988).

The detrital ZFT (DZFT) data from the Upper Rawalpindi (Kamlial Fm.) and Siwalik Groups (Fig. 2; Cerveny *et al.*, 1988) have been recompiled and the stratigraphic ages of levels from which they were extracted updated using a newer polarity time scale (Cande and Kent, 1995; Gautam and Rösler, 1999; Fig. 3).

Detrital zircon fission-track age populations were extracted from the raw data using two different approaches (Table 1): (1) the Binomfit software of Brandon (1996). This is based on a binomial peak fitting meaning that the best-fit solution is determined directly by comparing the distribution of the grain data to a predicted mixed binomial distribution (for details see Stewart and Brandon, 2004). We used the automated version of the program that fitted the *F*-test (Stewart and Brandon, 2004). (2) The Sambridge and Compston (1994) method using their Macmix software was also employed. Differences between these two approaches were negligible, i.e. age peaks overlapped (Table 1), validating the separation of age components. In consequence, data sets resulting from approach (1) were used in this study.

The resulting DZFT age groupings are termed P_1 to P_n where P_1 represents the youngest and P_n the oldest population, within a single horizon. The populations are plotted against their stratigraphic age (Fig. 2) and the different populations, P_n, are joined together per rank forming the D_n curves (Fig. 2) to investigate any possible genetic relationships (Ruiz *et al.*, 2004). The nature of the lines joining the P_n points through time represents meaningful trends. Such trends can be resolved into five types (for details see Ruiz *et al.*, 2004). Those that are pertinent in this report are (1) type 1, which is identified by an increase in both lagtime and detrital age upward within the stratigraphic column and is interpreted normally as an indication of change of source region but may also represent cannibalism of unreset sediments (e.g. Ruiz *et al.*, 2004) and (2) type 5, with both a decreasing lagtime and a decreasing age upwards representing an increasing exhumation rate in the source region. When the different D_n curves are parallel to sub-parallel with each other, this probably implies that the regional source areas for the various (P_1–P_n) age populations experienced similar cooling/exhumation rates, assuming that a constant regional geothermal gradient prevailed regionally and through time (Ruiz *et al.*, 2004). The D_1 patterns are the easiest to interpret as there is less chance of multiple events recorded in the ages. The methodology is fully detailed in Ruiz *et al.* (2004).

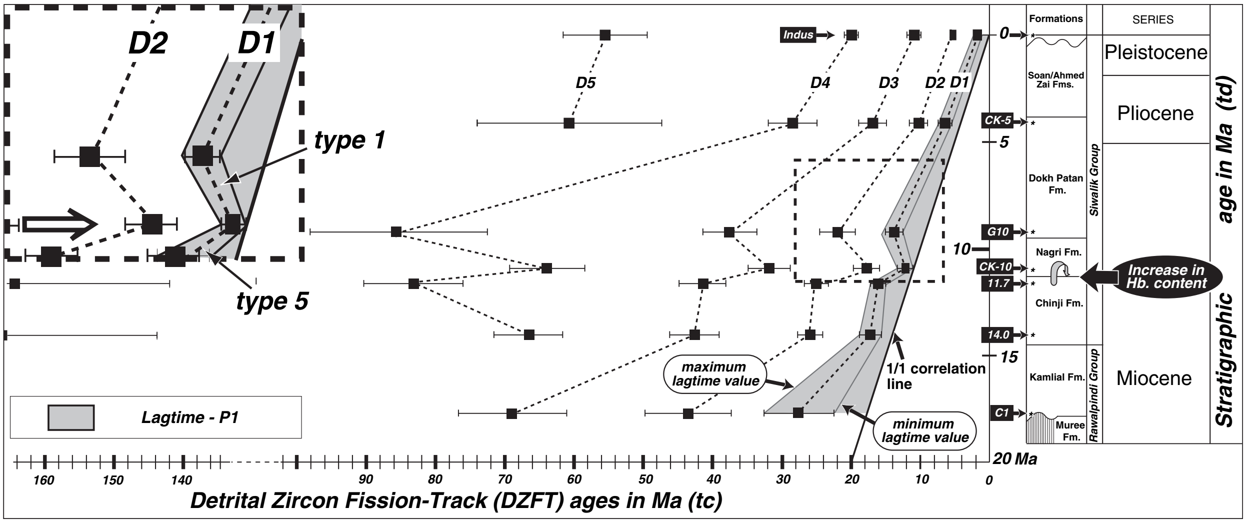

Fig. 2 A comparison of the stratigraphic age (td, time of deposition indicated by arrows), and the detrital zircon fission-track (DZFT) age of distinct FT age populations (tc, time of closure) from sedimentary formations of the foreland basin of northern Pakistan (re-compiled from data presented in Cerveny *et al.*, 1988). The data set is summarized in Table 1. Where possible, the plotted points of each DZFT age population P_n are joined together in a linear fashion in order to construct the detrital curves D_n (Ruiz *et al.*, 2004). The 1/1 correlation line represents the limit below which detrital grain age populations must have been reset by post-depositional heating in the basin. Error bars are ±2 standard deviation for population ages. The variation of the lagtime up-sequence along the D1 curve is shaded in dark grey within 95% confidence (min. and max. lagtime value). Upper left corner: zoom of the 11.7–4 Ma episodes for the D_2 and D_1 curves with the associated type 5 and 1 paths.

Results and interpretation

The number of grains counted for each sample was about 80 (Cerveny *et al.*, 1988). At all horizons the samples failed the chi-square test indicating a multicomponent data set (Gailbraith, 1981) while post-depositional resetting can be excluded (Najman *et al.*, 2005). Thus, the ZFT data represent the timing of cooling through 260–215 °C in the source region (Brandon *et al.*, 1998) First-order results from the 730 individual ZFT grain ages (Table 1) reveal populations ranging from 167 to 1.8 Ma (Table 1A). Very few populations are older than 80 Ma. These old grains may be variably sourced, e.g. the northern margin of the Indian Plate, the Kohistan Arc, or the southern margin of the Eurasia Plate where bedrocks still yield such relatively old ZFT ages (Fig. 1). A second cluster ranging from 52 to 30 Ma is in complete agreement with identical $^{40}Ar/^{39}Ar$ cooling ages determined on muscovite extracted from Late Eocene–Early Oligocene sedimentary rocks in the nearby Hazara-Kashmir region to the east (Najman *et al.*, 2001). Overlapping ages from these radiometric systems probably implies rapid exhumation in the hinterland because of progressive collision of the Kohistan arc with the Indian-Pakistan plate since 55 Ma.

The high representation of ages younger than 30 Ma suggests extensive exhumation since 30 Ma in the hinterland, which is once again in agreement with $^{40}Ar/^{39}Ar$ muscovite Early Miocene cooling ages extracted from molasse-type deposits in north-western India (Najman *et al.*, 1997) and with the documented post-metamorphic cooling history of the internal Himalayan zone in northern Pakistan (Treloar *et al.*, 2000).

The oldest sample (C1, Table 1) reveal a lagtime value of *c.* 5 to 15 Ma that is in agreement with the lagtime value produced on detrital $^{40}Ar/^{39}Ar$ mica ages on a sandstone with identical stratigraphic age (18 Ma; Najman *et al.*, 2003) that was sampled in the same region.

The most likely source of the youngest P_1, i.e. 1.8 ± 0.4 Ma (Table 1) present in the Indus River (Fig. 1) at the Chinji section is the Nanga Parbat-Haramosh Massif (NP-HM; Fig. 1), which yields 'today' the youngest ZFT ages of 0.5–2 Ma (Zeitler, 1985; Treloar *et al.*, 2000; Fig. 1). Other age groups also exist within this fluvial deposit; the oldest DZFT population (P_7; Table 1) has an age of 55.4 ± 7.3 Ma. These old ages are most likely sourced from regions located to the north-west, where ZFT ages between 50 and 60 Ma (Fig. 1) have been determined (Zeitler, 1985; Gubler, 2001), but may also be due to cannibalism of preexisting sedimentary rocks (Zeitler *et al.*, 1986) because similar ages are recorded within the Miocene–Pliocene series (Fig. 2, Table 1).

Samples K7 and G1 from sites A and B (Fig. 1) have almost identical stratigraphic ages, i.e. 13.8–14.1 Ma as samples CK-11 and G5 (Table 1; Fig. 4). The youngest population of each is the same within 2 σ (Table 1). Assuming that the sources for both sites were similar, we feel it is reasonable to combine data from these two pairs of samples to increase the reliability of peak-fitting procedure. Hence, this generates two samples labelled 14.0 and 11.7 (Table 1; Fig. 2). The Chinji and Trans-Indus sections are thus joined together in Fig. 2 to increase the precision in the changing D_n patterns in the light of

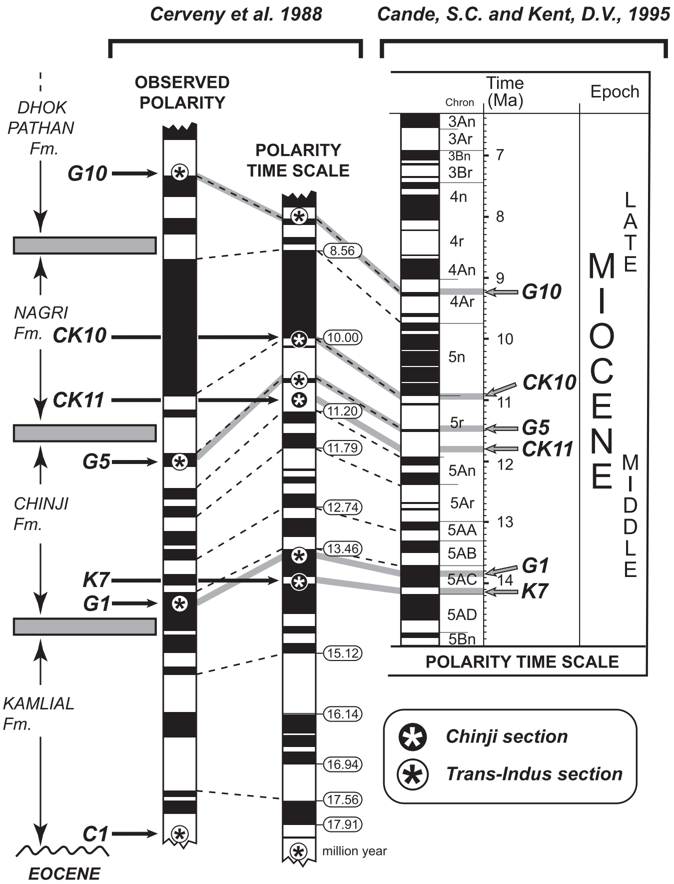

Fig. 3 Updated polarity time scale of the Siwalik group in northern Pakistan. Stratigraphic ages of sand samples from the Chinji section (C1, G1, G5 and G10) were corrected using their observed polarity (Cerveny *et al.*, 1988) and recent polarity time scale (Cande and Kent, 1995; Gautam and Rösler, 1999). The stratigraphic ages of sand samples from the Trans-Indus section (CK10, CK11 and K7) were corrected the same way using their assumed stratigraphic age in 1988 because observed polarity was not reported (Cerveny *et al.*, 1988).

cooling/tectonic activity in the source region. The commonality of the trends of the D_n curves is thus quite remarkable. We believe that this is not an artefact of the method of dividing the populations (Ruiz *et al.*, 2004). From 12 Ma onwards all D_n curves are subparallel or parallel to the D_1 line with a marked decrease in lagtime between 12 and 10.9 Ma (a strong type 5 path; Ruiz *et al.*, 2004); the ZFT and depositional ages of the youngest population (P_1) of sample CK-10 are identical within error bars at approximately 10.9 Ma, implying that source rocks were cooling at extremely high rates yielding exhumation rates > 2 mm yr^{-1} (Table 1). For comparison, such rates are currently found in the NP-HM region. It is followed by an increase in lagtime from 10.9 to 9.2 Ma (type 1 path). Subsequently and until today, lagtime decreases along a type 5 path (Fig. 2) that is characteristic of accelerating exhumation of the source region (Ruiz *et al.*, 2004).

Discussion

The data set based on the P_1 populations for the 18–0 Ma period fits a linear relationship (R^2 = 0.94) suggesting that the exhumation rate has been increasing by 0.1 mm Myr^{-1} since 18 Ma (from 0.9 to 2.65 mm yr^{-1}, Fig. 2) with the exception of a net pulse between 11.7 and 10.9 Ma. Najman *et al.* (2003) reported short lagtime values (0–6 Myr) from detrital mica ages in the Kamlial Fm. in the same locations since *c*. 18 Ma until 13.9 Ma and concluded, on the basis of sediment petrography and detrital thermochronology that the uplift of the NPHM initiated by this time. White *et al.* (2002) using the same methodology evidenced a rapid phase of exhumation in the Himalayan range of NW India for the time of deposition of the lower Dharamsala Fm. (21–17 Ma) while lagtime values for the upper Dharamsala Fm. and Lower Siwalik (17–12.5 Ma) are larger, i.e. 7–8 to 10 Myr. The combination of these data sets from the foreland basins of NW Pakistan to the west and NW India to the east, with our results clearly suggests a diachroneity of exhumation in the hinterland for the late Early–Middle Miocene, while Najman *et al.* (2005) concluded that this may not have been the case for the early development of the Himalayan chain in the Eocene.

The identification of accelerated exhumation (Table 1, > 2 mm yr^{-1}) within the source regions between 11.7 and 10.9 Ma is the major feature of this re-evaluation of Cerveny *et al.*'s (1988) data set. This period is contemporaneous with (1) a significant increase in blue–green hornblende content in the heavy mineral fraction in the upper Chinji Formation and the Nagri Formation, i.e. from *c*. 5% to 40% (Cerveny *et al.*, 1989), (2) a twofold increase in sedimentation rates from the Chinji to the Nagri Formations (Zeitler *et al.*, 1986), and (3) an important interval of thrust loading by the MBT in the basin beginning at *c*. 11 Ma (Burbank and Beck, 1989) but which may have occurred slightly earlier as suggested by the refinement of stratigraphic ages (Fig. 3).

The observed change in the heavy mineral assemblage was, according to Cerveny *et al.* (1989) and Willis (1993), unequivocal evidence that the blue-schist to amphibolite grade rocks identified in the Kohistan arc terrane were the only possible source. However, any potential source region for the P_1 population must have, today, ZFT ages younger than 12 Ma. No ZFT ages < 12 Ma have yet been obtained from the bedrocks of Kohistan arc (Fig. 1). This implies then, that the present outcropping arc, even though it contains abundant blue–green hornblende, cannot have been

Table 1 Zircon fission-track age populations (in Ma) from the Miocene to Recent Siwalik and Rawalpindi Group sediments of northern Pakistan – using the data of Cerveny (1988). For sample localities see Fig. 1. Abbreviations for the sections are: T (Trans-Indus) and Ch (Chinji). The initial stratigraphic age (in Ma) of each dated level (*Strat. 1*, Cerveny *et al.*, 1988) was corrected using recent revisions of the geological time scale (*Strat. 2*, Cande and Kent 1995, Gautam and Rösler, 1999 – see Fig. 4). N represents the number of grains analysed. *Combined*: data from samples with similar stratigraphic ages from the Chinji and trans-Indus sections, i.e. G5 (Ch – 11.5 Ma) – CK11 (T – 11.8 Ma), and G1 (Ch – 13.8 Ma) – K7 (T – 14.1 Ma) were mixed and compiled to increase the reliability of peak-fitting procedure. The P(χ^2) value is used to distinguish the possible presence of multi-components. When the distribution of detrital cooling ages from a particular sedimentary rock yields a P(χ^2) value of less than 5% (Gailbraith, 1981, and reply, pp. 485–488), it is assumed that more than one age population is present. (A) Peak ages or populations (P_n) and 95% confidence interval were estimated using binomial-fit method (Gailbraith and Green, 1990) – note that there is no overlapping. Exhumation rate calculations (in mm yr^{-1}) are based on the lagtime (in Myr) of the P_1 populations (see Garver *et al.*, 1999 for details). % = per cent of total number of dated grains in individual peak. (B) Below: age peak fitting (95% confidence) obtained with macmix software. %: number of grains attributed to each population.

					P_1				Exhumation	P_2			P_3			P_4			P_5		
Site	Strat. 1 (Ma)	Strat. 2 (Ma)	*N*	P(χ^2)	Age	95% CI	%	Lagtime (Myr) ± 2σ	rate (mm yr^{-1})	Age	95% CI	%	Age	95% CI	%	Age	95% CI	%	Age	95% CI	%
(A) Binomfit separation																					
Indus	0	0.0	83	0	1.8	−0.4 to +0.5	6.9	1.8 ± 0.4	2.3–3.0	5.3	−0.5 to +0.5	27.4	10.8	−0.8 to +0.9	34.3	19.8	−1.6 to +1.7	24.1	55.4	−6.8 to +7.8	7.3
CK-5 (T)	4	4.0	80	0	6.4	−1.0 to +1.2	8.7	2.4 ± 1.0	1.8–3.0	10.1	−1.4 to +1.5	15.0	16.9	−1.8 to +2.1	42.1	28.4	−3.5 to +4.0	29.0	61.1	−11.8 to +14.7	5.2
G10 (Ch)	7.9	9.2	80	0	13.7	−1.3 to +1.4	33.8	4.5 ± 1.3	1.2–1.7	21.7	−2.5 to +2.8	31.7	37.5	−3.7 to +4.1	26.1	85.7	−12.2 to +14.2	8.4	–	–	–
CK-10 (T)	10	10.9	84	0	12.2	−1.1 to +1.2	28.4	1.3 ± 1.1	2.0–9.0	17.8	−1.8 to +2.0	24.6	31.8	−3.0 to +3.0	22.0	63.9	−5.3 to +5.8	25.0	–	–	–
G5 (Ch)	10.8	11.5	79	0	15.9	−1.8 to +2.1	16.0	4.4 ± 1.9	1.1–2.2	23.4	−2.1 to +2.3	36.6	43.4	−3.8 to +4.2	33.5	93.6	−11.0 to +12.5	13.9	–	–	–
CK-11 (T)	11	11.8	80	0	16.8	−1.4 to +1.5	29.2	5.0 ± 1.5	1.0–1.7	29.6	−2.2 to +2.3	51.9	66.7	−2.2 to +2.3	19.0	–	–	–	–	–	–
G1 (Ch)	14	13.8	80	0	16.6	−2.2 to +2.5	5.3	2.8 ± 2.3	1.3–5.3	26.6	−1.8 to +1.9	37.1	43.8	−3.0 to +3.2	40.3	75.7	−7.6 to +8.4	17.2	–	–	–
K7 (T)	14	14.1	82	0	19.7	−1.6 to +1.8	26.6	5.6 ± 1.7	0.9–1.5	37.9	−4.2 to +4.7	26.3	62.7	−5.4 to +5.9	39.0	163.5	−22.6 to +26.2	10.0	–	–	–
C1 (Ch)	18	18.0	80	0	27.7	−4.4 to +5.3	17.8	9.7 ± 4.9	0.4–1.4	43.5	−5.8 to +6.7	45.8	68.8	−7.6 to +8.5	36.5	–	–	–	–	–	–
Combined																					
CK11-G5	–	11.7	159	0	15.8	−1.4 to +1.5	14.7	4.1 ± 1.4	1.2–2.0	23.3	−2.4 to +2.7	24.3	36.3	−3.9 to +4.4	28.6	64.9	−5.1 to +5.5	26.8	164.1	−22.2 to +25.6	5.6
K7-G1	–	14.0	162	0	17.2	−1.2 to +1.6	9.5	3.2 ± 1.4	1.4–3.0	25.9	−1.8 to +1.9	25.9	42.5	−2.9 to +3.1	32.9	66.6	−4.8 to +5.1	26.0	167.0	−19.6 to +22.2	5.7

					P_1			P_2			P_3			P_4			P_5		
Site	Strat. 1 (Ma)	Strat. 2 (Ma)	*N*	P(χ^2)	Age	95% CI	%	Age	95% CI	%	Age	95% CI	%	Age	95% CI	%	Age	95% CI	%
(B) Macmix separation																			
Indus	0	0.0	83	0	1.9	−0.6 to +0.6	5	5.1	−0.6 to +0.6	23	10.3	−1.0 to +1.0	28	18.7	−1.8 to +1.8	20	49.1	−7.2 to +7.2	5.0
CK-5 (T)	4	4.0	80	0	6.3	−1.2 to +1.2	7	9.5	−1.4 to +1.4	10	15.0	−1.4 to +1.4	30	22.6	−2.4 to +2.4	25	36.1	−6.2 to +6.2	8.0
G10 (Ch)	7.9	9.2	80	0	13.4	−1.2 to +1.2	31	21.7	−2.8 to +2.8	24	37.8	−3.6 to +3.6	20	89.3	−22.2 to +22.2	5	–	–	–
CK-10 (T)	10	10.9	84	0	11.3	−1.0 to +1.0	22	16.8	−1.8 to +1.8	24	30.6	−3.2 to +3.2	18	59.4	−4.6 to +4.6	20	–	–	–
G5 (Ch)	10.8	11.5	79	0	15.8	−1.8 to +1.8	15	23.1	−2.0 to +2.0	30	42.5	−4.6 to +4.6	25	91.6	−12.6 to +12.6	9	–	–	–
CK-11 (T)	11	11.8	80	0	15.4	−1.2 to +1.2	27	22.4	−2.0 to +2.0	26	31.7	−5.2 to +5.2	20	72.9	−8.8 to +8.8	7	–	–	–
G1 (Ch)	14	13.8	80	0	16.5	−2.2 to +2.2	6	26.3	−1.6 to +1.6	32	43.2	−2.8 to +2.8	33	69.7	−8.8 to +8.8	11	–	–	–
K7 (Ch)	14	14.1	82	0	18.7	−1.4 to +1.4	23	37.7	−5.0 to +5.0	24	60.8	−6.4 to +6.4	29	138.2	−26.8 to +26.8	6	–	–	–
C1 (Ch)	18	18.0	80	0	25.4	−3.4 to +3.4	11	37.7	−4.2 to +4.2	34	59.2	−6.8 to +6.8	35	–	–	–	–	–	–
Combined																			
CK11-G5	–	11.7	159	0	15.3	−1.0 to +1.0	32	22.4	−2.0 to +2.0	48	31.7	−5.2 to +5.2	37	45.8	−9.0 to +9.0	27	81.2	−13.0 to +13.0	15
K7-G1	–	14.0	162	0	16.7	−1.6 to +1.6	18	25.6	−1.6 to +1.6	46	42.9	−2.6 to +2.6	59	67.9	−6.4 to +6.4	35	215.4	−57.0 to +57.0	4

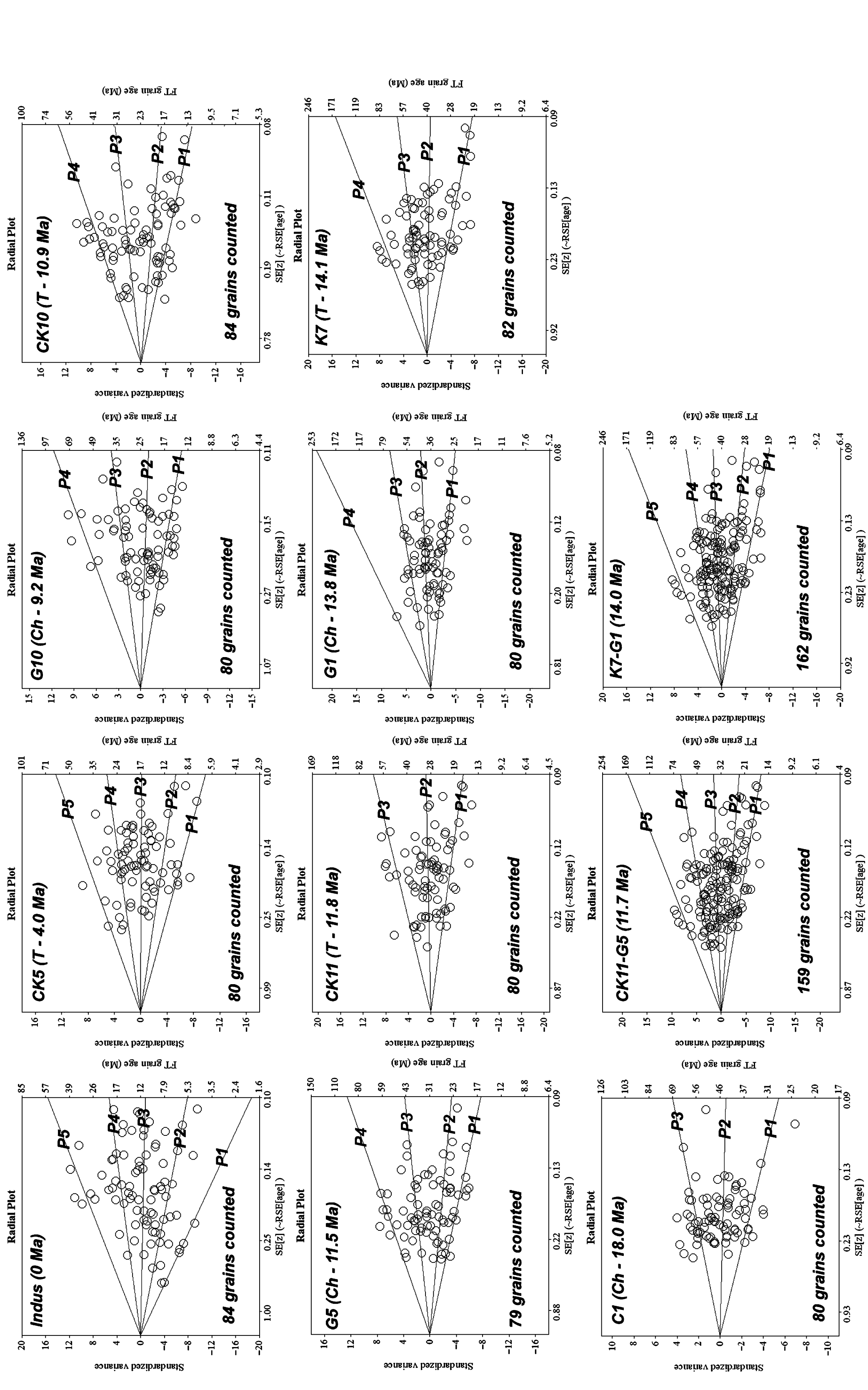

Fig. 4 Radial plots (Gailbraith, 1990) for zircon fission-track age determinations of nine samples from the Miocene basin fill series in northern Pakistan. The different peaks or age populations (P_n) were separated using Binomfit software, version 1.0.51 (Brandon, 1996; Table 1). The *x*-axis corresponds to the precision for each grain or relative error, precision increases to the right along the horizontal scale (see Brandon, 1996 for details). Two pairs of samples, one from each sample site were mixed because they have almost identical stratigraphic ages, and are labelled 14.0 and 11.7.

the major source for the P_1 population during the Late Miocene. ZFT ages that are < 12 Ma are only encountered within bedrocks of northern Pakistan in the region of the NP-HM (Fig. 1).

The NP-HM is bounded to (1) the east and west by the Ladakh and Kohistan arcs, respectively and (2) to the north by the rapidly exhuming Karakorum range (Lemennicier *et al.*, 1996; Villa *et al.*, 1996; Rolland *et al.*, 2001), and separated from them, respectively, by the MMT and the Main Karakorum Thrust (MKT, Fig. 1). Prior to the exhumation of the NP-HM, this region was also overlain by suites similar to the arcs that now border it – hence a possible source of the blue–green hornblendes. Thus, we conclude that the eroded cover of the NP-HM is the strong contender for the source of this population at this time. The palaeo-Indus, an antecedent system, was eroding rapidly cutting through the growing anticline, thus removing the upper arc suites and transporting the detritus to the foreland basins. Based on geochronological constraints Treloar *et al.* (2000) concluded that early doming of the NP-HM massif predated 9 Ma which is corroborated by bodily uplift along vertical shears at 9 Ma along the western margin of the NP-HM (Reddy *et al.*, 1997), while Najman *et al.* (2003) suggest that initiation of uplift/exhumation in the NPHM region began at *c.* 18 Ma based on a detrital $^{40}Ar/^{39}Ar$ study. Schneider *et al.* (2001) revisited the geological constraints on the tectonic evolution of the NPHM. The authors concluded that a crustal scale doming occurred by the Late Miocene in the NPHM region that can be traced further north and east in the Karakorum range. Such phase would be related to transpression along the South Karakorum Fault (Pecher and Le Fort, 1999; Fig. 1). Such doming is in accord with the rapid phase of exhumation we evidenced for the Late Miocene at *c.* 11.7 Ma through the dating of syn-orogenic sediments.

A change of source region is induced for the 10.9–9.2 Ma period from the D_{1-3} curves (Fig. 2). This corresponds to a period of increasing thrust loading by the MBT in the basin (Burbank and Beck, 1989). Such movement along the MBT may have uplifted the proximal series of the foreland basin of Pakistan. Cannibalized material from these units most likely hosted slightly older DZFT ages than those derived from the NP-HM, but similar to the ones present in the older formations (sample G10; Table 1; Fig. 2).

At the end of this phase, from 9.2 Ma to present-day (Fig. 2), no major events can be detected because the resolution of this data set is low and based only on three samples (G10, CK-5 and Indus; Fig. 2). It is thus impossible to trace from our data sets the reorganization of the western Himalayan river system 5 Ma as evidenced by Clift and Blusztajn (2005) by Nd isotopic measurements and seismic reflection data in the Indus fan.

The young ages of 1.8 Ma today in the bedload of the Indus River suggest an exhumation rate in the order of 2–3 mm yr^{-1} that is in agreement with rapid denudation (*c.* 3–5 mm yr^{-1}) in the NP-HM evidenced for the Pliocene–Pleistocene based on petrologic and U/Pb data on zircon and monazites (Zeilter *et al.*, 1993) as well as sediment budget (Garzanti *et al.*, 2005). This phase is associated with rapid cooling, deformation as a pop-up structure, anatectic melting and granulite-grade metamorphism (Schneider *et al.*, 2001). The younger ages are also synchronous with major subsidence in the Peshawar and Kashmir basins on either side of the syntaxis (Burg and Podladchikov, 2000). Present-day thermochronological ages from the NPHM region are too young (< 2 Ma) to reconstruct earlier phases of exhumation as the levels that may have yielded such info were eroded and deposited into the basin. This explains why some earlier studies (e.g. Zeilter *et al.*, 1993) erroneously concluded that doming in the NP-HM region was restricted to very recent times.

Conclusions

Detrital grain ages of the Siwalik or Punjab basin in northern Pakistan reveal an increase in exhumation rate since 18 Ma taking place in the source region. This implies that there has not been a steady state of erosion from early Mid-Miocene to Recent. This region of the Himalayan orogeny is in a constructional phase and was diachronous for the late Early–Middle Miocene from NW Pakistan to NW India.

The event identified between 11.7 and 10.9 Ma as a phase of rapid exhumation is coincident with the increase of blue–green hornblendes in the sedimentary sequences. The Kohistan Arc has previously been cited as the sole source of these minerals. But the many new fission-track ages of rocks presently exposed in the Kohistan arc are all older than 12 Ma, negating this possibility. A potential region with the prerequisite younger zircon ages was the region of the growing NP-HM syntaxis. The down cutting palaeo-Indus, and its tributaries, removed the upper sections of the syntaxis-arc material – the Kohistan lateral equivalent – before exposing the underlying sequence of the Indian subcontinent. The conclusions imply that the doming of the NP-HM region have accelerated at *c.* 11.7 Ma and was related to transpressional displacement along the MKT.

The combination of all data sets from both the hintherland and adjacent Punjab foreland basin in NW Pakistan suggests that the NPHM region underwent more than one rapid phases of uplift: an early uplift at *c.* 18 Ma, a rejuvenation of doming at *c.* 11.7 Ma, and a more recent uplift since the Plio-Quaternary as a pop-up structure that generates very young ZFT ages (i.e. 1.8 Ma) in the present-bedload of the Indus river.

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