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History of Uplift and Relief of the Himalaya During the Past 18 Million Years: Evidence from Fission-Track Ages of Detrital Zircons from Sandstones of the Siwalik Group

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Abstract

Fission-track dating of individual detrital zircon grains can be used to characterize both ancient and modern sedimentary provenance. Ages of zircons in the modern Indus River drainage system of northern Pakistan are controlled dominantly by uplift rates of the source rocks in the Himalaya. Young detrital zircons come from rapidly rising terrain, whereas old zircon ages imply slow or negligible uplift. Modern Indus River sands contain a distinctive population of young, 1 to 5 Ma, zircons that are derived from the Nanga Parbat-Haramosh Massif, an area of rapid uplift (5 m/10^3 yr). Sandstones of the Siwalik Group deposited by the ancestral Indus River over the past 18 million years contain zircons that are only 1 to 5 million years older than the depositional age of the sandstones. Therefore, young zircons have been a consistent component of Himalayan surface rocks for the past 18 million years. These ages imply that a series of uplifted blocks or "massifs," analogous to the contemporary Nanga Parbat area, have been continually present in the Himalaya since 18 Ma, and that over that time the elevation and relief of the Himalaya, on a broad scale, have been essentially constant.

Introduction

This paper describes the relief and uplift in the upper Indus River watershed during the past 18 million years, based on fission-track ages of detrital zircons derived from the sediments of the present Indus River of northern Pakistan and from sandstones of the Siwalik Group, which originated from sediments deposited by the ancestral Indus River during Neogene time. The data analysis represents a new methodology in the study of source terrain. Previous studies have used fission-track dating of detrital zircons to identify source area based on the ages of the detrital grains (e.g., Hurford *et al.* 1984; Johnson 1984; Yim *et al.* 1985; Baldwin *et al.* 1986). However, none of these studies was directly concerned in detail with using the ages of the detrital grains in sedimentary rocks to interpret the *tectonic history* of the source terrain. Detailed interpretation of the tectonic history is the central purpose of this paper.

Zeitler (1985) and Zeitler *et al.* (1982b,c) have demonstrated that in the Himalaya, areas characterized by rapid uplift rates have zircons with young fission-track ages (Fig. 3.1). Zeitler *et al.* (1982a) showed further that young zircons are present in the detrital zircon suite currently being eroded from the Himalaya. These data suggest that by dating detrital zircons separated from Siwalik Group sandstones of known stratigraphic age, it would be possible to determine the ages of zircon that were being eroded from the basement source terrain in northern Pakistan at selected intervals during Neogene time, and that the detrital zircons might thus be a vehicle through which uplift rates from the geologic past could be assessed (Zeitler *et al.* 1982a). This possibility is explored in this paper. The primary objective of the present study is to determine if zircons with young ages, which are indicative of high uplift rates, have been present in the Himalaya over the past 18 million years.

Geography and Geologic Setting

The study area in the Punjab region of northern Pakistan (Fig. 3.2) contains the type sections for most of the formations of the Siwalik Group (Fatmai 1974), which consists of sandstones derived from

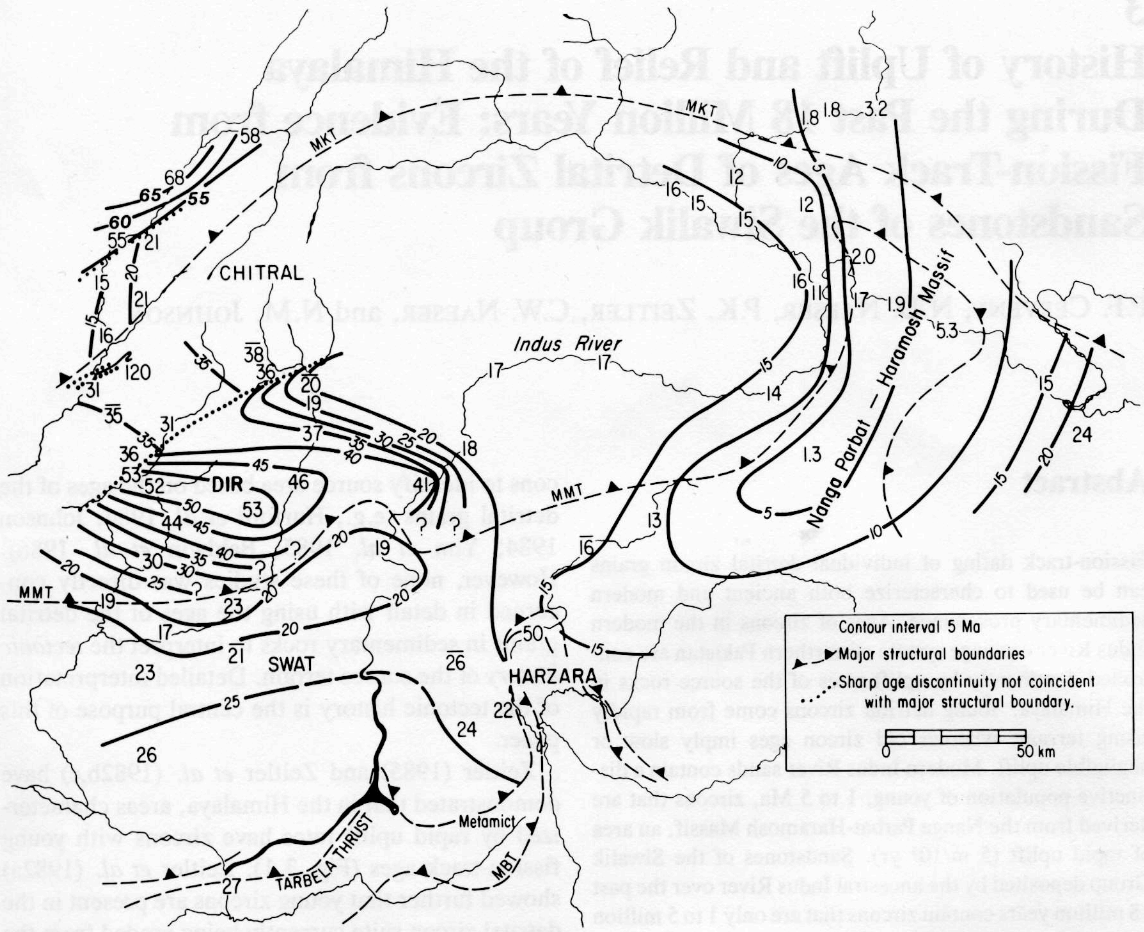


Fig. 3.1. Contour map of zircon fission-track ages from surface rocks in northern Pakistan (Zeitler 1985). Note the 50-fold variation in zircon age. MMT = Main Mantle Thrust; MKT = Main Karakoram Thrust; MBT = Main Boundary Thrust. The geographic location of this map may be identified in Figure 3.2 by the configuration of the Indus River, notably its right-angle, eastward bend in northern Pakistan.

Neogene fluvial sediments eroded from the Himalaya. The Siwalik Group is composed of fluvial cycles (Allen 1965), which represent the migrations of a major trunk river (the ancestral Indus) over the Punjab region. Over the past 18 million years, the return period of the major river in the Punjab region has been 10^4 to 10^5 yr (Johnson *et al.* 1985).

The ages of the Siwalik Group sandstones have been established by magnetic-polarity stratigraphy and fission-track dating techniques (Opdyke *et al.* 1979; Johnson *et al.* 1982, 1985). In the vicinity of Chinji Village and in the Trans Indus (Fig. 3.2), the Siwalik sequence begins at a basal contact with Eocene limestone and continues stratigraphically upward through the Lower, Middle, and, in the case of the Trans Indus section, Upper Siwalik sequences. The Chinji Village section is approximately 2 km thick and contains the Kamlial (oldest), Chinji, Nagri, and Dhok Pathan Formations (Fig. 3.3). The Trans Indus section is composed of approximately 4.2 km of sedimentary rocks and contains the Chinji, Nagri, Dhok Pathan, and Soan Formations.

The rocks of the Himalaya, which were the source of the sediments forming the rocks of the Siwalik Group, are today being eroded and transported by the contemporary Indus River system. The distribution of zircon fission-track ages in the bedrock presently exposed in the Indus River watershed (Zeitler 1985) is illustrated in Figure 3.1. The Nanga Parbat-Haramosh Massif defines an area of 1.3 to 3.2 Ma zircons, which is surrounded by an area

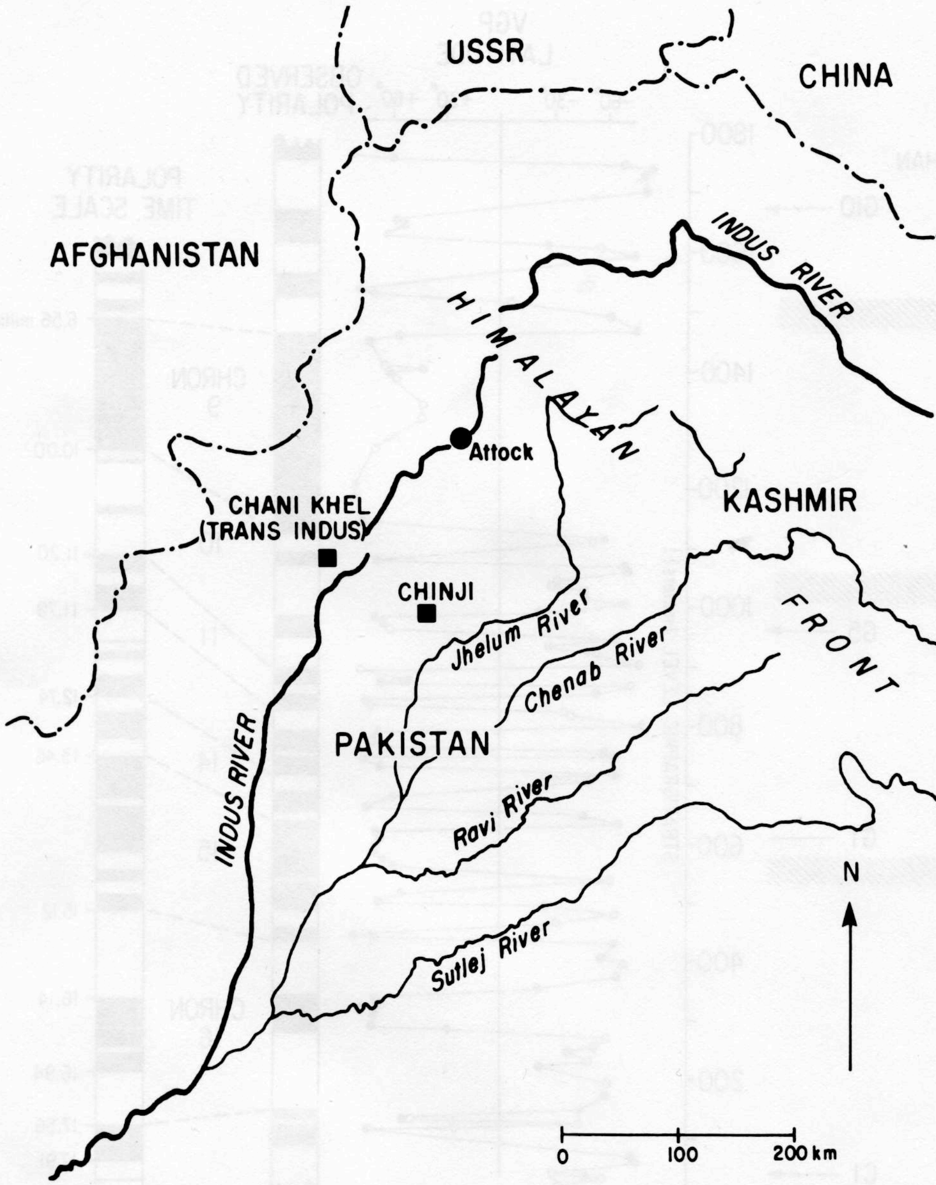


Fig. 3.2. Map of northern Pakistan showing: 1) location of Siwalik Group stratigraphic sections near Chinji Village and Chani Khel (Trans Indus), and 2) collection site for the present Indus River sand (Attock).

where ≈ 5 Ma zircons occur. Moving farther outward from the Nanga Parbat-Haramosh Massif, zircon ages range from 11 to 24 Ma. In the westernmost area, in the Dir-Chitral region, ages are concentrated in the 30 to 55 Ma range, with ages in outlying areas up to 120 Ma. However, essentially all the rocks in the Himalaya and the Lesser Himalaya of northern Pakistan are Mesozoic or older in age. Thus, as shown in Figure 3.1, the zircons from these rocks commonly yield fission-track ages much younger than their true ages. These age differences are explained by the fact that the rocks now at the surface were once at depth, at temperatures sufficiently high to reset their fission-track ages (see below). Thus, the ages of zircons at the surface today are recording the time when the rocks were uplifted through their closure temperature and started to retain fission tracks. In the Nanga Parbat-Haramosh Massif area, where the closure temperature for zircon is assumed to occur at a depth of ≈ 6 km (see

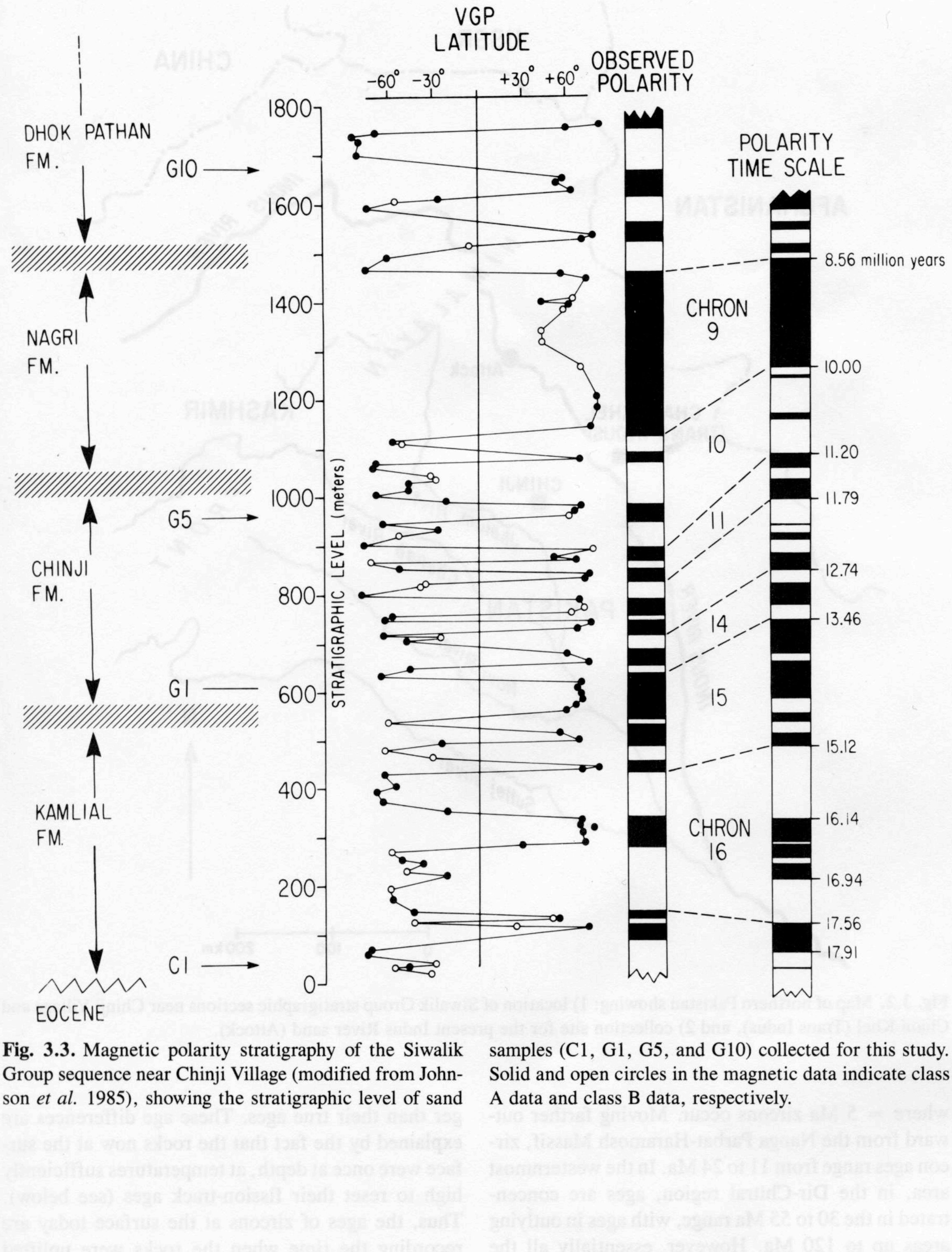


Fig. 3.3. Magnetic polarity stratigraphy of the Siwalik Group sequence near Chinji Village (modified from Johnson *et al.* 1985), showing the stratigraphic level of sand samples (C1, G1, G5, and G10) collected for this study. Solid and open circles in the magnetic data indicate class A data and class B data, respectively.

below), the 1.3 to 3.2 Ma zircon ages indicate that the mean uplift rate for this area at the present time is on the order of 5 m/10^3 yr; the area has been uplifted 10 km in the last 2 million years (Zeitler 1985).

Fission-Track Dating

Theory

Fission tracks can be thought of as analogous to a trace fossil found in uranium-bearing minerals such as apatite, zircon, and sphene. Each fission track records the decay by spontaneous fission of a single nucleus of ^{238}U into subequal halves, with the track being a tubular zone of damage within the host mineral's lattice. Chemical etching can make these damaged zones visible by means of an ordinary optical microscope (etched fission tracks are on the order of 10 to 20 µm in length and 1 to 3 µm in diameter). The fission-track method of dating is not one of high precision, because tracks tend to be relatively few in number (the probability of a given uranium atom decaying by fission in any given year is less than 1 in 10^{16}), but the method is extremely sensitive, with each track corresponding to a single fissioned uranium nucleus.

The most direct geological application of fission tracks is in geochronology. Irradiation with "slow" or "thermal" neutrons in a nuclear reactor induces fission of some of the ^{235}U found in the mineral (the isotopic composition of uranium in nature is constant, and the present-day value is $^{238}U/^{235}U = 137.88$). Together with the use of neutron-fluence monitors and standards of known ages, uranium-bearing minerals can be dated by counting, per unit area, the number of spontaneous or "fossil" fission tracks as well as the number of induced fission tracks created in the reactor. The density of spontaneous tracks is a function of age and uranium content, and the density of the induced tracks is in effect a measurement of uranium content by neutron activation. It is important to note that fission-track ages are very different than those derived using the conventional U-Pb method, which is based on the decay of uranium to lead through a series of intermediate daughters. Details about fission-track dating procedures can be found in Naeser (1976, 1979), Naeser *et al.* (in press a), and Hurford and Green (1982). The book by Fleischer *et al.* (1975) remains an invaluable introduction to the early history and fundamentals of fission-track dating and charged-particle tracks in general.

Annealing of Fission Tracks

Despite the great value of the fission-track method in dating young rocks, its most important contribution to geology lies in the determination of the thermal histories of rocks. At temperatures of several hundreds of degrees Celsius (about 100°C for apatite, 200°C for zircon, and 300°C for sphene), over geological time spans, fission tracks will fade or anneal. In response to increasing temperatures, observed track densities are reduced because tracks shorten; this shortening reflects repair of the host crystal's lattice as a consequence of the enhanced rate of solid-state diffusion that occurs at higher temperatures. Like vitrinite reflectance, track fading is a time-dependent and temperature-dependent process (Fleischer *et al.* 1965), and equivalent effects can be achieved by heating at low temperatures for prolonged periods or at high temperatures for shorter periods. Examples of studies demonstrating the way in which fission-track dating can be used to constrain thermal events include those by Briggs *et al.* (1981), Gleadow and Duddy (1984), and Naeser *et al.* (in press a). Gleadow *et al.* (1983) and Green *et al.* (in press) include a review of the use of track-length distribution as a further constraint on the thermal history of a sample. At high enough temperatures, fission tracks fade approximately as fast as they form. After sufficient cooling, a point will be reached where no annealing occurs and all tracks are fully retained. The temperature at which full retention begins is known as the closure temperature (Dodson 1979), and varies from mineral to mineral. Thus, when a mineral cools through its closure temperature, the fission-track clock begins to run. The closure temperature for cooling has a small but significant dependence on cooling rate (about a 10% increase per order-of-magnitude increase in cooling rate). Fixed values for the closure temperature of each mineral simply do not exist. Two examples of studies employing the closure behavior of fission tracks in minerals are those by Wagner *et al.* (77) in the Alps and Zimmermann *et al.* (1975) in the northern Appalachians.

In the present study, it is the thermally sensitive nature of fission tracks that is exploited. Most of the bedrock exposed in the northwestern Himalaya today has cooled by well over 200°C during Tertiary time in direct response to uplift and erosion. Thus, zircons entrained in these rocks yield young ages that record the time that they passed through 200°C (which is, roughly, the closure temperature for zircon). In an active mountain belt, an attempt to fix rigorously the location of a paleo-isotherm in the crust would require sophisticated modelling (Parrish 1982). However, as a rough approximation we can say that uplift from the 200°C isotherm represents approximately 6 km of uplift and erosion (less in areas of fast and sustained uplift). Clearly, uplift rate is inversely proportional to the fission-track age, and in a setting like the northwestern Himalaya, younger ages imply more rapid uplift.

Detrital Fission-Track Ages

Zircons deposited in a sandstone at a given time represent a composite of the zircons that were being eroded from the source area and deposited at that time. A detrital zircon acquires some fraction of its present age during its residence time in the uplift, transport, and post-depositional portions of its history.

Figure 3.4 is a schematic representation of the life history of a detrital zircon grain in the uplift-erosion-depositional cycle of the Himalayan-Siwalik system, where (in years before present)

T1 = time the zircon passes through its closure temperature and begins to accumulate fission tracks

T2 = time the zircon reaches the surface (through uplift and erosion) and enters the sedimentary cycle

T3 = time of deposition in the sedimentary basin

Thus,

T_u = T1 − T2 = elapsed time zircon required to reach surface and enter sedimentary cycle

T_t = T2 − T3 = elapsed time spent in transport

T_s = T3 − present = elapsed time since final deposition, i.e., the stratigraphic age of the sediment, and

$$\text{Observed Age} = T1 = T_u + T_t + T_s \quad (1)$$

For zircon ages measured in the bedrock of the Himalaya today (i.e., Fig. 3.1), $T_t = T_s = 0$ and, therefore, $T1 = T_u$. Zeitler (1985) was thus able to evaluate observed ages (T1) directly as uplift ages (T_u).

To obtain uplift ages from detrital zircons, however, it is necessary to know or constrain T_t and T_s. Stratigraphic ages (T_s) in the Himalayan-Siwalik system have already been established in detail by magnetic-polarity stratigraphy and fission-track dating of the Siwalik Group (Opdyke *et al.* 1979; Johnson *et al.* 1982, 1985). Data from modern Indus River sand allow us to evaluate detritus transport time, T_t (see below). By thus fixing T_s and T_t, we can effectively isolate T_u from the observed ages of detrital grains in the Siwalik sandstones and gain insight into the uplift history of the northwestern Himalaya over the last 18 million years, during the time of deposition of the Siwalik Group.

Methods

Sampling

Four Siwalik Group sandstone samples collected in the vicinity of Chinji Village (Figs. 3.2, 3.3) were dated. The stratigraphic ages of these sandstones range from 18 to 7 Ma (Johnson *et al.* 1985). Four additional Siwalik sandstone samples from the Trans Indus area 120 km to the west near Chani Khel (Fig. 3.2) were dated. The ages of these sandstones were estimated from their stratigraphic position and from the known ages of the formations elsewhere in Pakistan (Opdyke *et al.* 1979; Johnson *et al.* 1982, 1985). One sample collected from a sandbar of the modern Indus River was also dated.

In both stratigraphic sections, samples were collected from the base of the local Siwalik Group sequence above the contact with Eocene limestone. In the Chinji Village section, samples were collected from the basal Kamlial Formation (sample number C1), the Chinji Formation (G1 and G5), and the lower Dhok Pathan Formation (G10; Fig. 3.3). The Trans Indus section, where the Kamlial is not present, included samples from the Chinji (K-7 and CK-11), Nagri (CK-10), and Dhok Pathan Formations (CK-5).

Analysis of the heavy-mineral content from the nine dated samples and from 35 additional samples collected in the study area is given elsewhere (Cerveny 1986; Cerveny *et al.* in press).

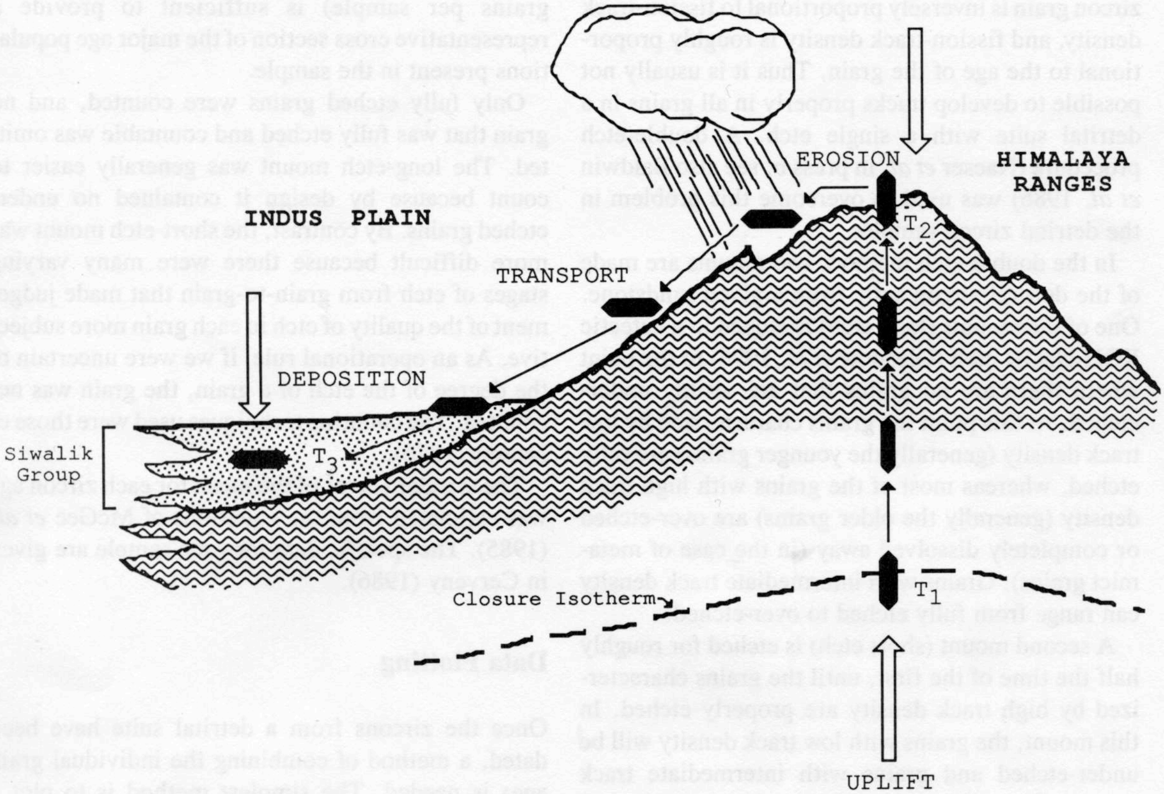


Fig. 3.4. Schematic representation of the life history of a zircon grain (solid symbol) in the Himalaya-Indus-Siwalik system. Dashed line = approximate position of closure isotherm for retention of fission tracks in zircon (see text). For explanation of T1, T2, T3, see text.

Laboratory Procedures

The external-detector method (Naeser 1976, 1979) was used to determine the age of each of the detrital zircons. In the external detector method, the fossil tracks are counted in a single grain and the induced tracks are counted in a muscovite detector that covered that grain during the neutron irradiation. This procedure permits the determination of an age for each individual grain in the mount. Zircon crystals must be dated individually because: 1) uranium is distributed inhomogeneously within and between zircon crystals; and 2) in the case of detrital grains in sediments, each zircon crystal may have a different age.

Thermal neutron fluence was determined from a calibrated muscovite detector covering National Bureau of Standards glass standard SRM 962 (37.38 ± 0.08 ppm U) placed at the top and bottom of each irradiation tube. The fluences were calibrated against the Cu value determined at the National Bureau of Standards (Carpenter and Reimer 1974). The fluence for each sample was calculated by interpolation between the values determined for the standards. This method of fluence determination, when used in conjunction with a value of 7.03 × 10^{-17} yr^{-1} (Roberts *et al.* 1968) for the spontaneous fission decay constant and with the laboratory procedures followed in the United States Geological Survey fission-track laboratory, consistently yields fission-track ages that are concordant with K-Ar ages of co-existing phases in rapidly cooled (volcanic and hypabyssal) rocks (e.g., Naeser *et al.* 1977).

The methods used to prepare zircons from a sample of unimodal age for fission-track dating are well known (Naeser 1976; Naeser and Naeser 1984). However, in a detrital zircon suite the conventional procedure must be modified to allow grains from a wide range of ages to be properly etched. Generally, the time required to etch fission tracks properly in a zircon grain is inversely proportional to fission-track density, and fission-track density is roughly proportional to the age of the grain. Thus it is usually not possible to develop tracks properly in all grains in a detrital suite with a single etch. A double-etch procedure (Naeser *et al.* in press b; see also Baldwin *et al.* 1986) was used to overcome this problem in the detrital zircon samples.

In the double-etch method, two mounts are made of the detrital zircon suite from a given sandstone. One of the mounts (long etch) is etched in a eutectic KOH-NaOH melt (Gleadow *et al.* 1976) to the point where there are no grains that are visibly under-etched. At this point the grains characterized by low track density (generally the younger grains) are fully etched, whereas most of the grains with high track density (generally the older grains) are over-etched or completely dissolved away (in the case of metamict grains). Grains with intermediate track density can range from fully etched to over-etched.

A second mount (short etch) is etched for roughly half the time of the first, until the grains characterized by high track density are properly etched. In this mount, the grains with low track density will be under-etched and grains with intermediate track density (generally the intermediate ages) will usually range from under-etched to fully etched.

The end result is that young grains will usually be properly etched in the long-etch mount and old grains will be properly etched in the short-etch mount, whereas grains with intermediate ages will be properly etched in one or the other or both of the two mounts. Therefore, by using the double-etch method, we hope to have properly etched grains available for counting from the full range of ages in the detrital zircon suite. Data from the short-etch and long-etch mounts were not combined when plotting the ages of individual grains in a sample (see below) because such a combined plot would overemphasize the grains from age populations that are properly etched and countable in both mounts (usually the intermediate-age grains). The following discussion of the detrital zircon ages will concentrate on data from the long-etch mounts because the primary interest in this study is determining the ages of the *youngest* zircons present in the detrital suites.

In a sample with a single age, it is usually sufficient to count fission tracks in only 6 to 12 grains (Naeser 1976). However, in most detrital suites there is a wide range of ages and 6 to 12 grains are unlikely to be representative of the sample. Experience suggests that dating 40 grains per mount (80 grains per sample) is sufficient to provide a representative cross section of the major age populations present in the sample.

Only fully etched grains were counted, and no grain that was fully etched and countable was omitted. The long-etch mount was generally easier to count because by design it contained no under-etched grains. By contrast, the short-etch mount was more difficult because there were many varying stages of etch from grain-to-grain that made judgement of the quality of etch in each grain more subjective. As an operational rule, if we were uncertain of the degree of the etch of a grain, the grain was not counted. The counting techniques used were those of Naeser (1976).

The standard error of the mean for each zircon age was estimated from the equations of McGee *et al.* (1985). The specific data for each sample are given in Cerveny (1986).

Data Plotting

Once the zircons from a detrital suite have been dated, a method of combining the individual grain ages is needed. The simplest method is to plot a histogram of the individual calculated ages. However, a more realistic representation of the age populations in a detrital suite must take into account the analytical uncertainty in each individual grain age. A probability density distribution of age for each grain may be determined from its calculated age (A_i) and standard error of the age (s_i):

$$f(a) = s_i^{-1}(2\pi)^{-1/2} \exp\text{-}(a-A_i)^2/2s_i^2 \qquad (2)$$

where a is any given age.

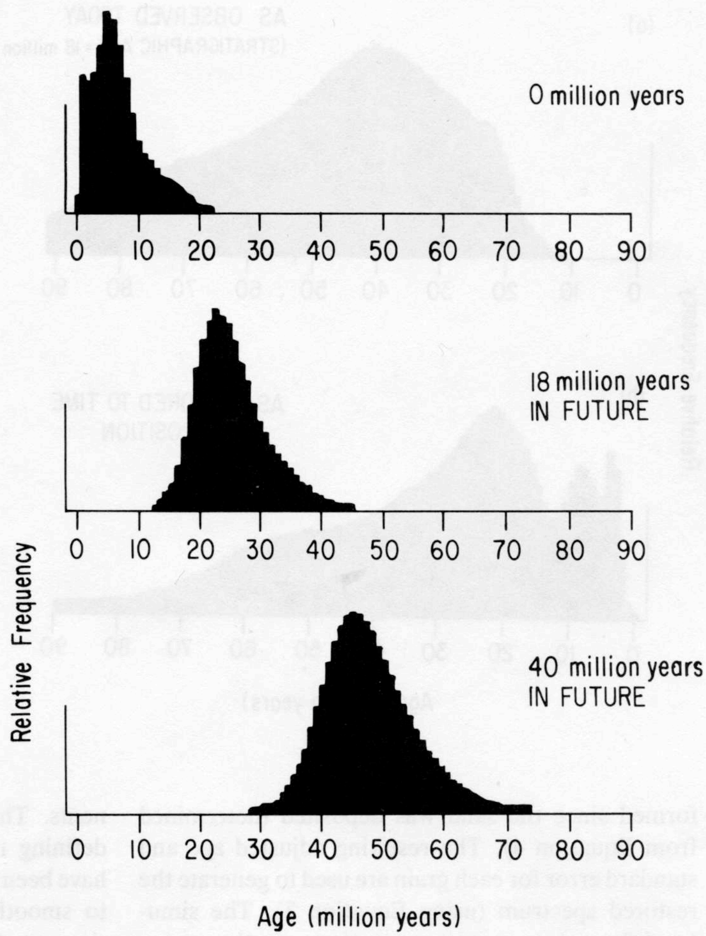
The probability density distribution for all the zircons dated in a detrital suite is formed by combining the probability distributions of the individual grains:

$$f'(a) = \sum_{i=1}^{n} s_i^{-1}(2\pi)^{-1/2} \exp\text{-}(a-A_i)^2/2s_i^2 \qquad (3)$$

This summation produces a plot, or age spectrum, of relative probable frequency versus age for the detrital suite (e.g., Fig. 3.5).

This plotting method has been used in several previous studies to identify the age populations present in a detrital suite (Hurford *et al.* 1984; Kowallis *et al.* 1986). Naeser *et al.* (in press b) have demonstrated, by working with a "detrital suite" manufactured from zircon populations of known age, that the age modes, or peaks, in a spectrum do

Fig. 3.5. Expected distribution of detrital zircon ages when the age spectrum from the contemporary Indus River sands (long-etch mounts) is projected into the future (see text).



accurately portray the age populations present in the suite. The peaks are particularly well defined for the younger age populations.

To compare the age spectra of detrital grains from different samples, it is useful to standardize them to equivalent geologic conditions, for example, as they existed at the time of deposition of the sediment. This requires a transformation of each age spectrum as it is observed today into what it was at the time of deposition. This transformation requires that the number of spontaneous fission tracks (N_s) used to calculate the age and standard error of the age for each grain be changed as a function of time. The number of neutron-induced fission tracks is set by the particular neutron dose used in the experiment; it is independent of the age of the zircon and is used only to estimate the uranium concentration in the grain being dated. Because of the stochastic nature of the fission process, it is not possible to predict exactly what number of spontaneous fission events has occurred in the time interval concerned. It is possible, however, to predice the *most likely* number of spontaneous fission events (ΔN_s) that would have occurred in a given time interval (Δt) for each grain (McGee *et al.* 1985):

$$\Delta N_s = (2/3)\ \lambda_F\ {}^{238}U\ (\Delta t) \qquad (4)$$

where:

λ_F = fission constant of U^{238} (7.03×10^{-17} yr^{-1})

${}^{238}U$ = ppm of common uranium $\times$ (${}^{238}U/U$)

The 2/3 factor accounts for the probability of a fission track from the cubical volume [(range of fission fragment)^3] around the fissioning nucleus reaching the polished surface on which tracks are counted. Equation 4 may be recognized as the basic radioactive decay law for conditions where Δt is short compared to the half-life.

To restore an age spectrum to its original state at the time of deposition, we must subtract, grain by grain, the number of spontaneous tracks that have

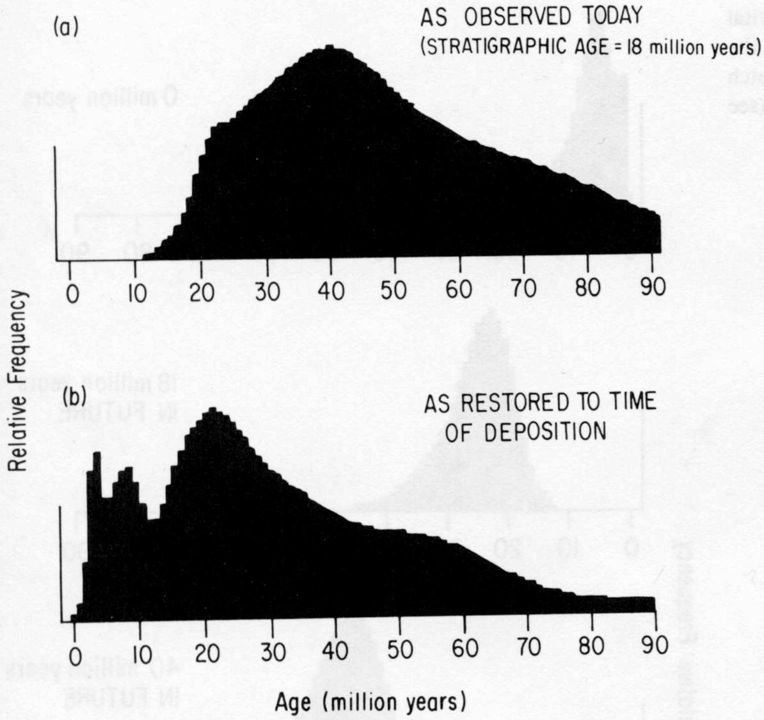


Fig. 3.6. Comparison of detrital zircon-age spectrum as (a) observed today and (b) after restoration to the time of deposition (18 million years ago). Sample is C1 from the basal Kamlial Formation, Chinji Village section (Fig. 3.3).

formed since the sand was deposited (determined from Equation 4). The resulting adjusted age and standard error for each grain are used to generate the restored spectrum (using Equation 3). The simulated de-ageing process, or its converse the ageing process, as derived from Equation 4 is completely reversible and a synthetically derived spectrum could be restored intact to its original state. Equation 4 is not capable of predicting exactly what happened, but it is capable of predicting what would most likely have happened.

By way of illustration, Figure 3.5 shows how the zircon-age spectrum determined from the long-etch mount of the modern Indus River sand sample will most likely appear at various times in the future. As this particular age spectrum becomes older in the future, the peaks broaden and become less distinct. In the opposite sense, Figure 3.6 shows the result of moving an age spectrum backward in time. Figure 3.6a is the age spectrum as it appears today for a sample whose stratigraphic age is 18 Ma. Figure 3.6b shows the result when the age spectrum of this sample is restored to its likely appearance at the time of deposition (i.e., 18 million years ago) using Equation 4. Note that this transformation has sharpened the peaks, transforming an otherwise smooth age distribution into at least three distinct age components. This transformation thus has the effect of defining more clearly zircon age populations that have been obscured by time. Thus, adding time tends to smooth an age spectrum, whereas subtracting time tends to sharpen it. The transformation in shape of an age spectrum is differential over time because as the age of a given grain increases, so does the standard error of the age (s_i in Equations 2 and 3) in years, and vice versa.

Detrital Zircon Fission-Track Data

The age spectra for the long-etch and short-etch mounts of the detrital zircons collected from a sandbar in the modern Indus River are shown in Figure 3.7. The range of ages in this sample corresponds well with the range of ages present in the surface rocks of the Indus watershed (Fig. 3.1). In fact, essentially all of the surface zircon ages as mapped by Zeitler (1985) in the Indus watershed (Fig. 3.1) are represented in either the long-etch or the short-etch spectrum of the Indus River sand (Fig. 3.7). The only ages not represented in modern Indus River detrital zircons are those greater than 100 Ma. We conclude, therefore, that the sands of the modern

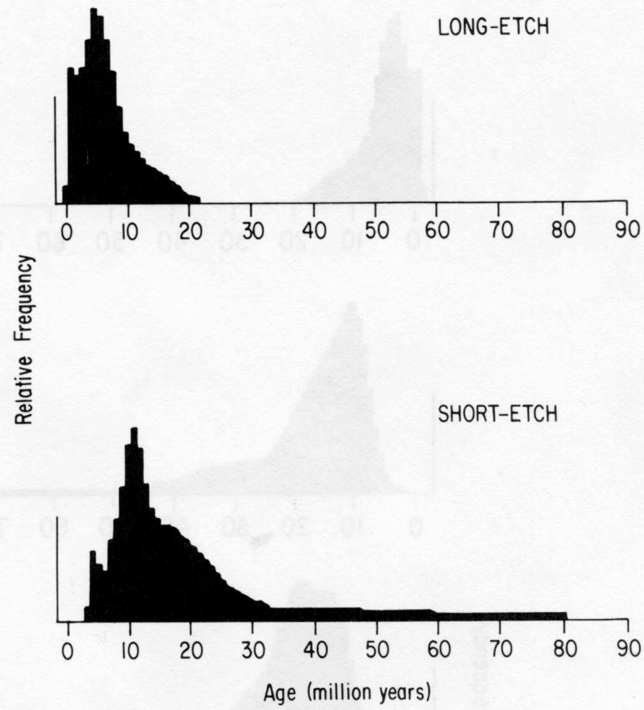


Fig. 3.7. Zircon-age spectra, contemporary Indus River sand. Note that most of the surface-rock ages from northern Pakistan (Fig. 3.1) are represented. Sample location is shown in Figure 3.2.

Indus River are representative of the rocks exposed in its contemporary watershed.

A significant population of 1 to 5 Ma zircons occurs in modern Indus River sand, suggesting that only 1 to 5 million years were required for these zircons to pass through their closure temperature and subsequently be uplifted, eroded, and become Indus River detritus. The important implication of this observation and of the observed general close correspondence between the ages of zircons present in the surface rocks of the Indus River watershed and those present in the modern Indus River is that the transport time (T_t) for detritus in the modern Indus River is quite short on a geologic scale, probably less than 10^6 yr, and for purposes of our analysis can be ignored. We assume that this relatively brief transport time has also been true of the Indus River system over the past 18 million years.

In the Siwalik Group sandstones in the Chinji Village section (Figs. 3.3, 3.8), the oldest sample (C1) is from the basal Kamlial Formation and has a stratigraphic age of 18 Ma (Johnson *et al.* 1985). The youngest peak in the zircon-age spectrum (long-etch mount) for this sample occurs at ≈ 22 Ma. Moving up section, the youngest peak in the spectrum of sample G1 from the lower Chinji Formation (14 Ma) occurs at ≈ 18 Ma. Sample G5 from the uppermost Chinji (10.8 Ma) has a peak at 14 Ma and sample G10 from the middle Dhok Pathan Formation (7.9 Ma) has a distinct 11 Ma peak. The Siwalik sandstones at Chinji Village, therefore, consistently contain zircons that are only ≈ 3 to 4 million years older than their depositional age, a situation comparable to that found in the modern Indus River (Fig. 3.7).

In the Trans Indus section (Fig. 3.9), sample K-7 is from the basal Siwalik sandstone unit overlying the Eocene strata. Based on lithologic similarity with the Chinji-Kamlial boundary, the stratigraphic age of K-7 is estimated to be approximately 14 Ma. The youngest peak in the age spectrum for this sample occurs at 17 Ma (Fig. 3.9). Moving up section to sample CK-11 (upper Chinji, stratigraphic age ≈ 11 Ma), a subtle peak or shoulder occurs at 14 Ma. CK-10 (lower Nagri, ≈ 10 Ma) shows a definite peak at 11 Ma, and CK-5 (upper Dhok Pathan, ≈ 4 Ma) has a peak at 6 Ma. The stratigraphic ages of these samples have been estimated by assuming that formation ages in the Trans Indus area are identical to those in the Potwar Plateau (Johnson *et al.* 1982, 1985). These age estimates are therefore not as precise as those specified for the Chinji Village area, having perhaps an error of a million years or so. Nevertheless, there seems to be a 1 to 3 million-year age difference between the youngest zircons present

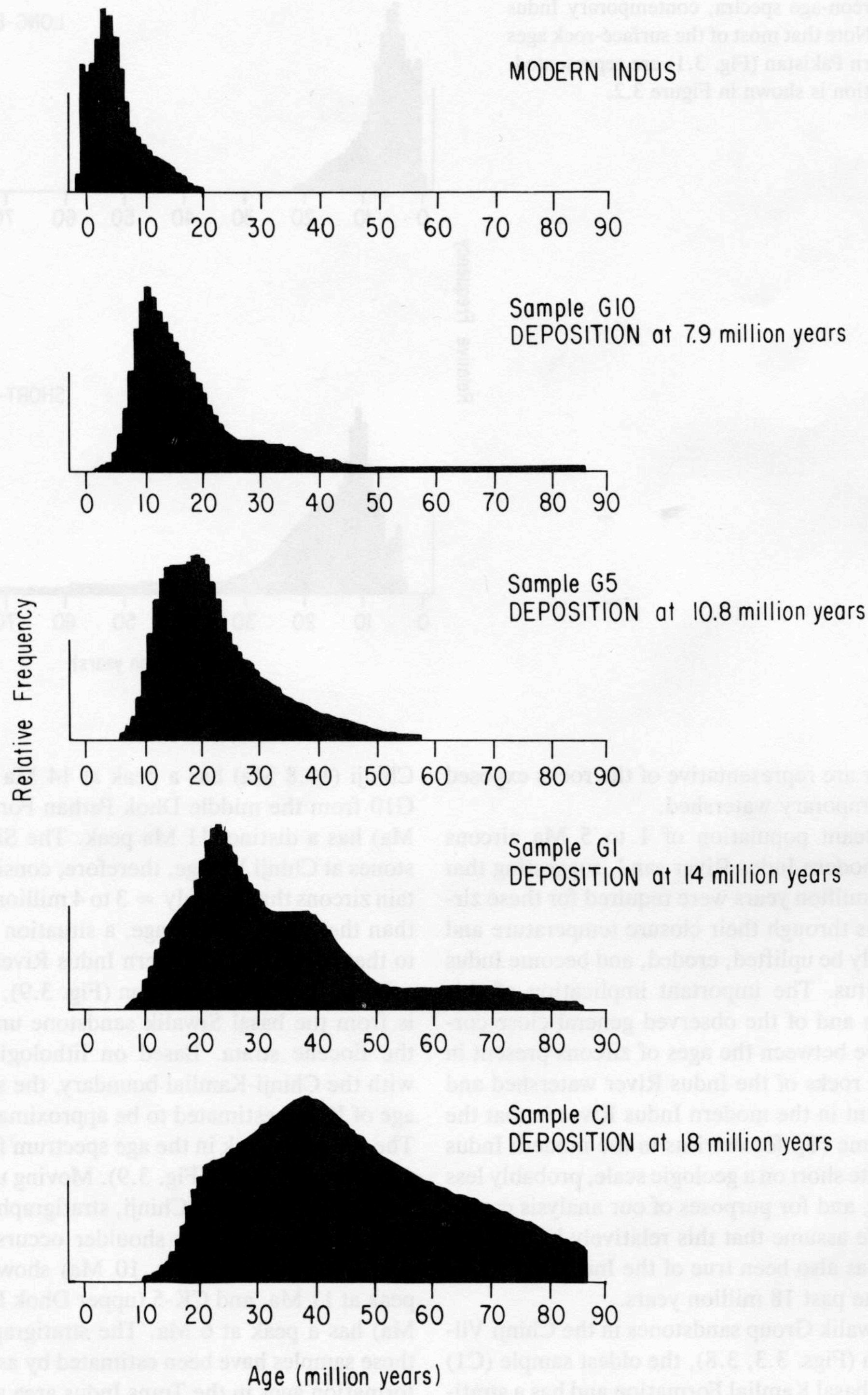


Fig. 3.8. Zircon-age spectra (long-etch mounts) for the Chinji Village section. Spectrum from the modern Indus River sand sample is included for reference. The presence of a youthful tail in the spectra, which may be younger than the stratigraphic age, is an artifact of the statistical assumptions used in generating the age spectrum (Equation 3).

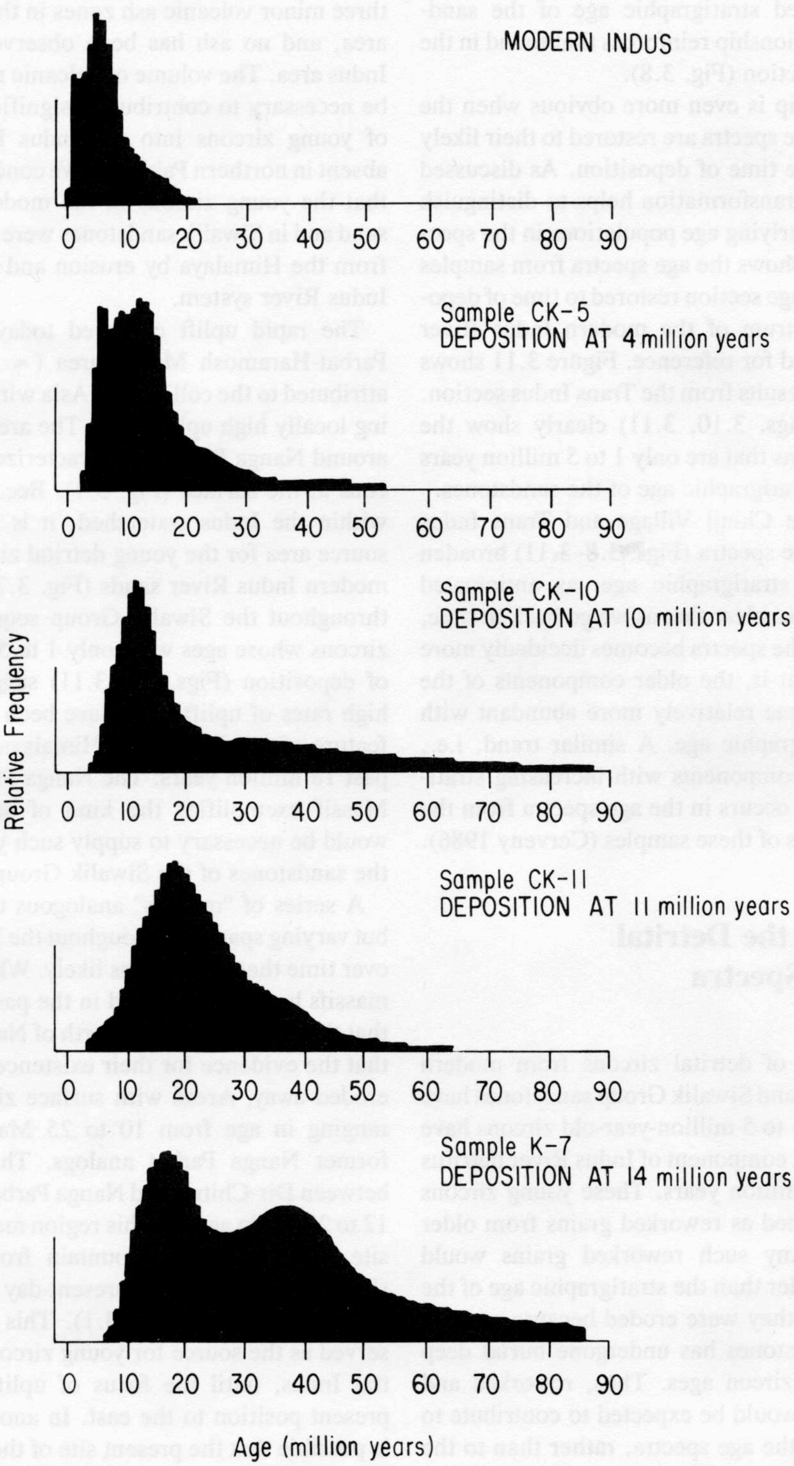


Fig. 3.9. Zircon-age spectra (long-etch mounts) for the Trans Indus section. Note spectrum from modern Indus River sand for reference.

and the estimated stratigraphic age of the sandstones. This relationship reinforces that found in the Chinji Village section (Fig. 3.8).

The relationship is even more obvious when the detrital zircon-age spectra are restored to their likely appearance at the time of deposition. As discussed previously, this transformation helps to distinguish and identify underlying age populations in the spectra. Figure 3.10 shows the age spectra from samples in the Chinji Village section restored to time of deposition. The spectrum of the modern Indus River sample is included for reference. Figure 3.11 shows the comparable results from the Trans Indus section. These results (Figs. 3.10, 3.11) clearly show the presence of zircons that are only 1 to 5 million years older than the stratigraphic age of the sandstones.

In general, the Chinji Village and Trans Indus detrital zircon-age spectra (Figs. 3.8–3.11) broaden with increasing stratigraphic age, as anticipated (Fig. 3.5). It is also clear that as we go back in time, the older part of the spectra becomes decidedly more conspicuous. That is, the older components of the age spectra become relatively more abundant with increasing stratigraphic age. A similar trend, i.e., enhanced older components with increasing stratigraphic age, also occurs in the age spectra from the short-etch mounts of these samples (Cerveny 1986).

Interpreting the Detrital Zircon-Age Spectra

The age spectra of detrital zircons from modern Indus River sand and Siwalik Group sandstones have established that 1 to 5 million-year-old zircons have been a significant component of Indus River detritus for the past 18 million years. These young zircons cannot be explained as reworked grains from older Siwalik units. Any such reworked grains would necessarily be older than the stratigraphic age of the unit from which they were eroded because none of the Siwalik sandstones has undergone burial deep enough to reset zircon ages. Thus, reworked and recycled zircons would be expected to contribute to the older end of the age spectra, rather than to the younger end. It is also unlikely that the presence of young detrital zircons in Siwalik sandstones can be explained by continuous volcanism during the past 18 million years. Very little evidence exists for volcanism of any sort affecting northern Pakistan during Neogene time. The Siwalik Group contains only three minor volcanic ash zones in the Chinji Village area, and no ash has been observed in the Trans Indus area. The volume of volcanic rocks that would be necessary to contribute a significant component of young zircons into the Indus River system is absent in northern Pakistan. We conclude, therefore, that the young zircons in the modern Indus River sand and in Siwalik sandstones were derived directly from the Himalaya by erosion and transport in the Indus River system.

The rapid uplift observed today in the Nanga Parbat-Haramosh Massif area ($\approx$ 5 m/10^3 yr) is attributed to the collision of Asia with India, producing locally high uplift rates. The area of rapid uplift around Nanga Parbat is characterized by young zircons at the surface (Fig. 3.1). Because this area is within the Indus watershed, it is the most likely source area for the young detrital zircon seen in the modern Indus River sands (Fig. 3.7). The fact that throughout the Siwalik Group sequence there are zircons whose ages were only 1 to 5 Ma at the time of deposition (Figs. 3.8–3.11) suggests that these high rates of uplift must have been a characteristic feature of portions of the Himalaya for at least the past 18 million years. The Nanga Parbat-Haramosh Massif exemplifies the kind of source area that would be necessary to supply such young zircons to the sandstones of the Siwalik Group.

A series of "massifs" analogous to Nanga Parbat but varying spatially throughout the Indus watershed over time therefore seems likely. Where might these massifs have been located in the past? It is possible that they were in an area north of Nanga Parbat, and that the evidence for their existence has since been eroded away. Areas with surface zircons presently ranging in age from 10 to 25 Ma also might be former Nanga Parbat analogs. The broad region between Dir-Chitral and Nanga Parbat shows zircons 12 to 20 Ma in age and this region may have been the site of an ancestral mountain front, tectonically similar to that of the present-day Nanga Parbat-Haramosh Massif (Fig. 3.1). This area may have served as the source for young zircons to the ancestral Indus, until the focus of uplift shifted to its present position to the east. In another scenario it is possible that the present site of the Nanga Parbat-Haramosh Massif has been the locus of long-sustained, rapid uplift. This would, of course, require a constant replenishment of crustal rock to the area to compensate for the large amount of erosion that would have taken place. From the opposite point of view, we can say with some confidence that the

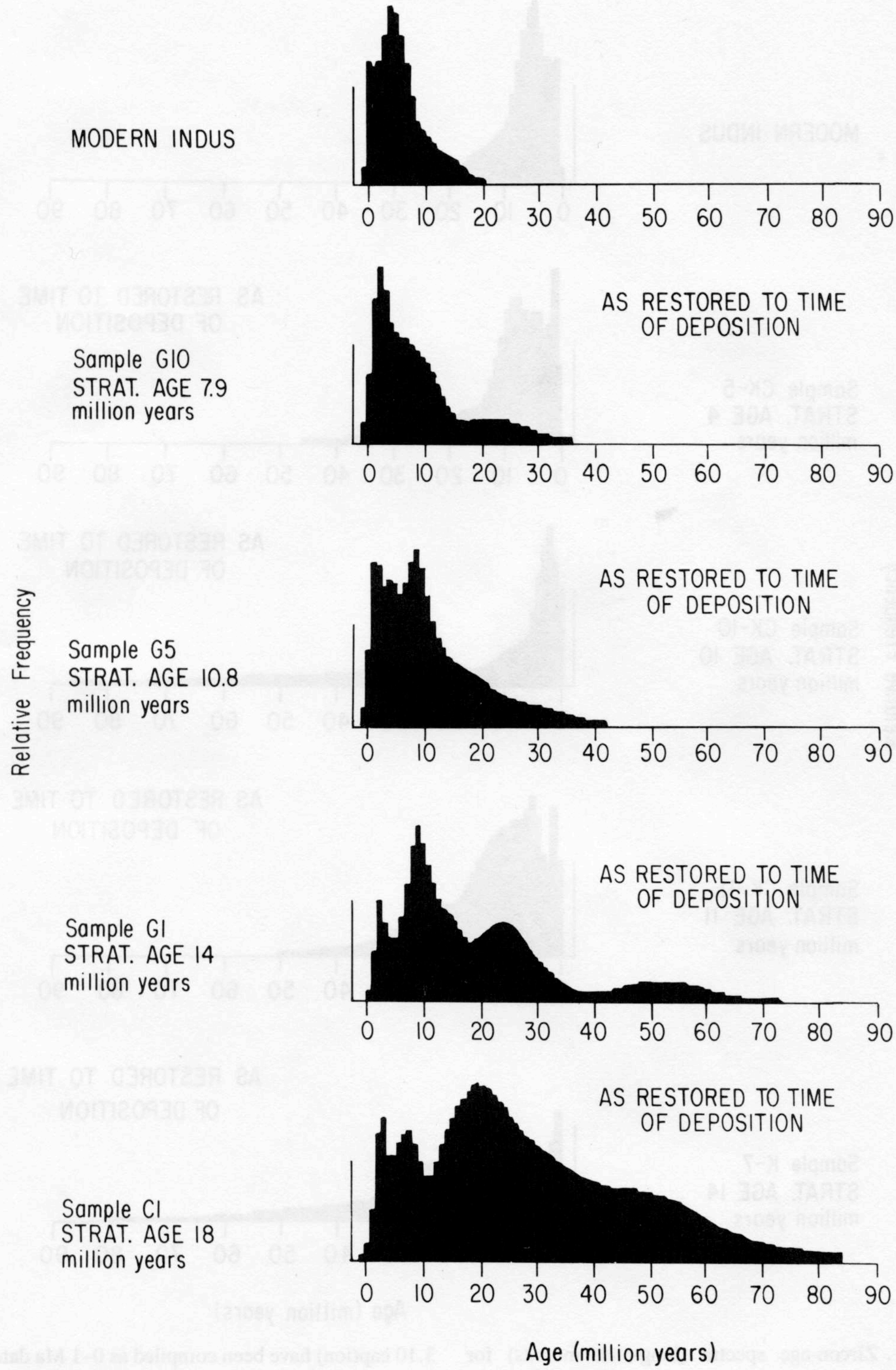


Fig. 3.10. Zircon-age spectra (long-etch mounts) for Chinji Village section, *restored to time of deposition*. Note zircon ages <5 Ma in all samples. Negative ages are the result of statistical dispersion inherent in the de-aging transformation (Equation 4).

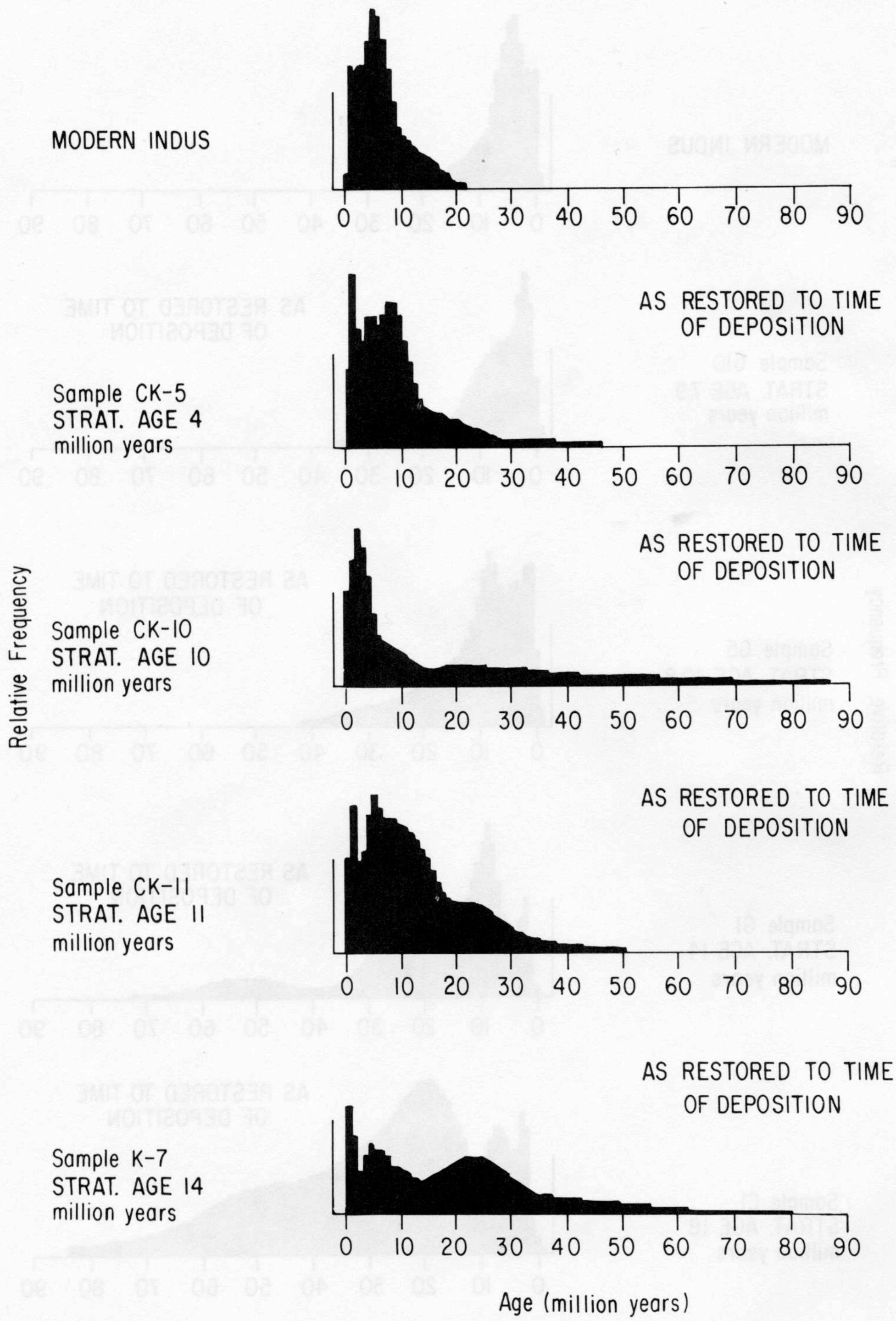


Fig. 3.11. Zircon-age spectra (long-etch mounts) for Trans Indus section, *restored to time of deposition*. Note zircon ages <5 Ma in all samples. Negative ages (see Fig. 3.10 caption) have been compiled as 0–1 Ma dates, which tends to enhance or produce a peak in this interval.

Dir-Chitral region to the west of Nanga Parbat could *not* have been the source of the young zircons found in Siwalik sandstones because most of the surface rocks in that region have zircons with old ($\geq$30 Ma) ages (Fig. 3.1).

Older zircons are decidedly less abundant today in Indus River sand than they were in the past (Figs. 3.7–3.11). As seen in Figure 3.7, the detrital-age spectra of the modern Indus River are dominated by zircons between 1 and 30 Ma in age. Zircons older than this are present, but not in significant amounts. In contrast, detrital zircons with ages greater than 30 Ma were prevalent in the Indus River in the past (Figs. 3.10, 3.11). This suggests that in the past larger areas of "old" terrain were present in the Himalaya. In this scenario we envision that for some time after continental docking, rocks with "old" zircons provided the main source of detritus to the Indus River. These rocks were not buried to great depths so their zircons were not annealed. As these "old" rocks were systematically consumed by uplift and erosion, successively deeper and partially annealed zircons, and then fully annealed zircons, made their way to the surface.

The detrital zircon-age spectra suggest that lofty Himalayan peaks and ranges, much like those present today, must have been present in northern Pakistan for the past 18 million years. To the extent that the high Himalaya of today have a profound effect on the climate of central Asia, we suggest that this orographic effect has been a long-term (18 million year) feature of central Asia.

Summary and Conclusions

This study has established that the contemporary Indus River contains young, 1 to 5 Ma, zircons as a major component of its detrital zircon suite. These zircons have not aged significantly since they were released from bedrock by erosion. The ancestral Indus River sands (Siwalik Group sandstones) also contain zircons whose ages were only 1 to 5 Ma at the time they were deposited. "Old" zircons become systematically more abundant going stratigraphically downward.

These observations lead to several important conclusions, the most general being that for at least the last 18 million years there have been areas in the Indus River watershed with uplift rates, relief, and erosion rates comparable to those observed in the Nanga Parbat region today. In effect, the contemporary Himalayan landscape, on a broad scale, has been a relatively steady-state feature for at least the past 18 million years. Over this time period there has always been an area of rapid uplift, similar to the region around Nanga Parbat, supplying 1 to 5 Ma zircons to the fluvial system and delivering them to the Indo-Gangetic plain.

At present the Indian plate is being thrust under the Asian plate. At first, this would necessitate that the upper crustal plate, the Asian plate, would be the first eroded. Rocks from this upper plate would have older zircon ages because they were never buried deeply enough and long enough to reset their zircon ages. Today, however, rocks of the lower plate are being eroded and evidently these rocks have been buried deeply enough for a long enough time to anneal the fission tracks in their contained zircons. This sequence of events would require older zircons to be eroded first and then, with the passage of time, to be replaced by progressively younger zircons. This scenario is supported by the observed data from the Siwalik record.

In studying paleo-climates it is essential to know what topographical constraints were placed on weather systems in the past. We infer from our detrital zircon data that the Himalaya have continuously maintained their presence and relief during the past 18 million years. To the extent that the monsoon system of Asia may be affected by the modern high Himalaya, we may infer that this condition has existed for the past 18 million years. Furthermore, it is quite likely that the high Himalaya have been present for even longer than this, but we lack data below the 18-Ma stratigraphic level. The critical evidence prior to 18 Ma is lacking as there is a conspicuous absence of Oligocene and older fluvial deposits suitable for study in the Punjab area.

In summary, the case study presented here suggests that detrital zircon fission-track ages are a powerful tool for the analysis of sedimentary provenance. The concepts and technology behind this tool are rather simple, straightforward, and readily available.

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