Zircon fission-track ages from the Gasherbrum Diorite, Karakoram Range, northern Pakistan

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ABSTRACT

The Gasherbrum Peaks, in the Himalaya of Pakistan, reach elevations of >8000 m. The relief between the peaks and the adjacent valley (Baltoro Glacier) is in excess of 3000 m. Eight samples of the Early Cretaceous Gasherbrum Diorite at elevations between 4880 and 7165 m on Gasherbrum IV were collected for fission-track dating. Zircon fission-track ages from the Gasherbrum Diorite vary from Early Cretaceous to middle Tertiary in age. There is no consistent pattern between age and elevation. The Cretaceous ages indicate that these rocks were never deeply buried, i.e., heated to temperatures in excess of 175 °C, to reset the zircons during Cenozoic time. These results also indicate that the uplift of this part of the Himalaya has been either very rapid and recent, or very slow since Early Cretaceous time. This latter possibility is not consistent with the high relief at Gasherbrum and what is known about regional tectonics. Gasherbrum IV zircons, currently at ~4880 m, have never been at depths greater than 6 km, and less than 3 km of material has been removed from the top of the range by erosion since the Early Cretaceous. Rapid uplift has occurred very recently, and erosion rates have not been able to keep pace with this uplift.

INTRODUCTION

This paper addresses the uplift history of the Karakoram Range in northern Pakistan using zircon fission-track dating. Fission-track dating is especially useful in determining the low-temperature thermal histories of rocks. Fission tracks will fade in zircon at temperatures of approximately 200 °C over geologic time spans (Zeitler et al., 1982; Harrison et al., 1979). The thermally sensitive nature of fission tracks al-

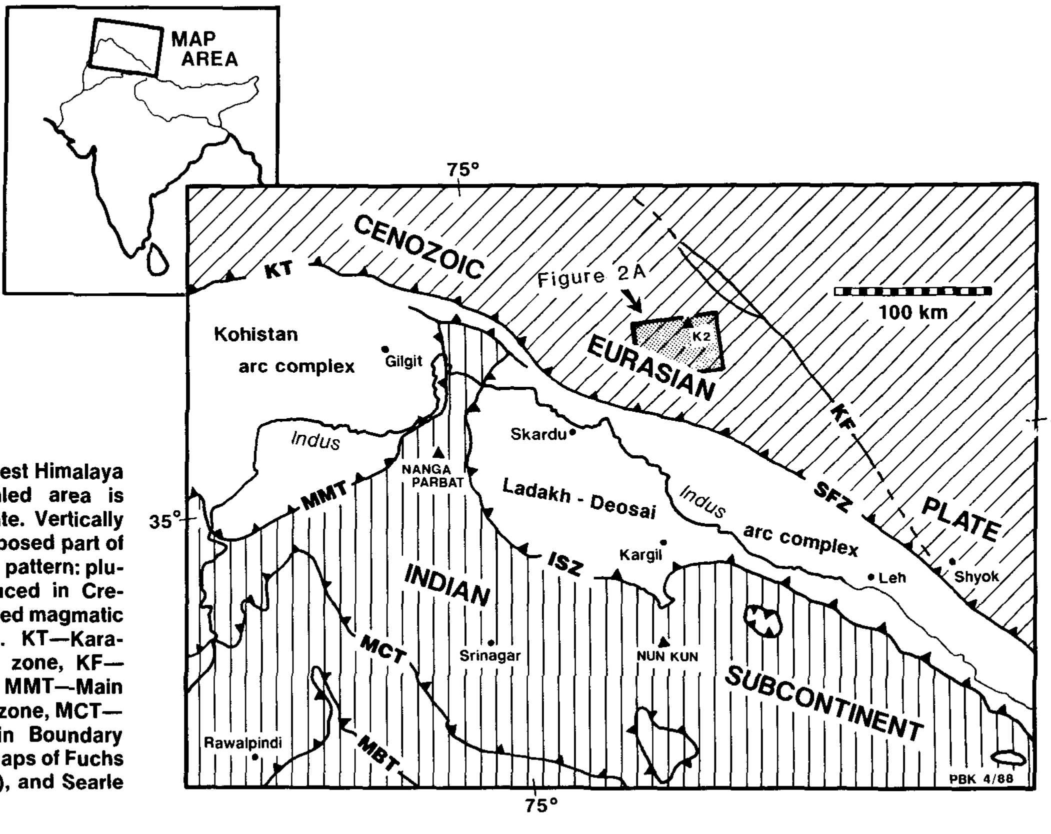

Figure 1. Tectonic map of northwest Himalaya and Karakoram. Diagonally ruled area is Cenozoic extent of Eurasian plate. Vertically ruled area is present extent of exposed part of northern Indian subcontinent. No pattern: plutonic and volcanic rocks produced in Cretaceous-Tertiary subduction related magmatic arcs, with associated molasse. KT—Karakoram thrust, SFZ—Shyok fault zone, KF—Karakoram fault (right lateral), MMT—Main Mantle thrust, ISZ—Indus suture zone, MCT—Main Central thrust, MBT—Main Boundary thrust. Compiled from geologic maps of Fuchs (1979), Tahirkheli and Jan (1979), and Searle et al. (1989).

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lows us to make inferences about the late-stage thermal history of the minerals that contain them.

Most of the rocks exposed in the northern Himalaya had cooled to well under 200 °C by the mid-Tertiary (Zeitler, 1985; Cerveny et al., 1988). The zircons in these rocks yield ages that record the time when they passed through the ~200 °C isotherm. Assuming a crustal geothermal gradient of ~30 °C/km (Zeitler, 1985), uplift from the 200 °C isotherm would represent ~6 km of erosion. In contrast to the mid-Tertiary ages in most of the region, zircons from the Nanga Parbat massif, 80 km southwest of the Gasherbrum Peaks (Fig. 1), yield Pliocene and Pleistocene ages. The Nanga Parbat region is characterized by recent high uplift and erosion rates. Uplift rates in the Nanga Parbat area of 0.87 ±0.15 mm/yr from 4.2 to 0 Ma and 0.20 mm/yr from 13.6 to 4.2 Ma have been reported (Zeitler, 1985). Net uplift rates are inversely proportional to fission-track ages; thus, younger ages imply more rapid uplift.

This paper examines a suite of eight samples taken from the Gasherbrum Diorite on Gasherbrum IV (elevation 8068 m) near the east end of the Baltoro glacier in the Karakoram Range of northern Pakistan (Figs. 1 and 2). The elevation of the sample sites ranges from 4880 to 7170 m above sea level. Fission-track dating allows us to compare the cooling history of the Gasherbrum Diorite to several other massifs in the Himalaya region.

The Gasherbrum Diorite intrudes pelitic and calcareous sedimentary rocks on the west face of Gasherbrum IV, at the head of the West Gasherbrum glacier (Fig. 2, A and B). To the west, and stratigraphically lower, the Baltoro Granite intrudes similar sedimentary rock. There is approximately 18–20 km of structural relief between the Gasherbrum Diorite and the Baltoro Granite (Desio and Zanettin, 1970) (Fig. 2A). This relief is believed to have resulted from an east-west axial large-scale folding event. The outcrop pattern and structural attitudes observed in these units are consistent with this interpretation. The Baltoro Granite forms the core of an anticlinorium, whereas the Gasherbrum peaks are sitting in a synclinorium plunging steeply to the south-southeast from K2 (Fig. 2A) (Desio and Zanettin, 1970).

Previous workers have obtained ages on the Baltoro Granite of 8.8 ±0.3 Ma (Rb/Sr biotite) and 8.5 ±0.8 Ma (average K/Ar on biotite, muscovite, and K-feldspar) (Debon et al., 1986, 1987). These data led them to conclude that the Baltoro Granite was emplaced at approximately 9.2 Ma. However, U/Pb crystallization ages of 21 Ma have been determined in the Baltoro Granite by R. Parrish and R. Tirrul (in prep.; Searle et al., 1989). The younger ages of ~9 Ma on the Baltoro Granite appear to be cooling ages rather than emplacement ages. In addition, a

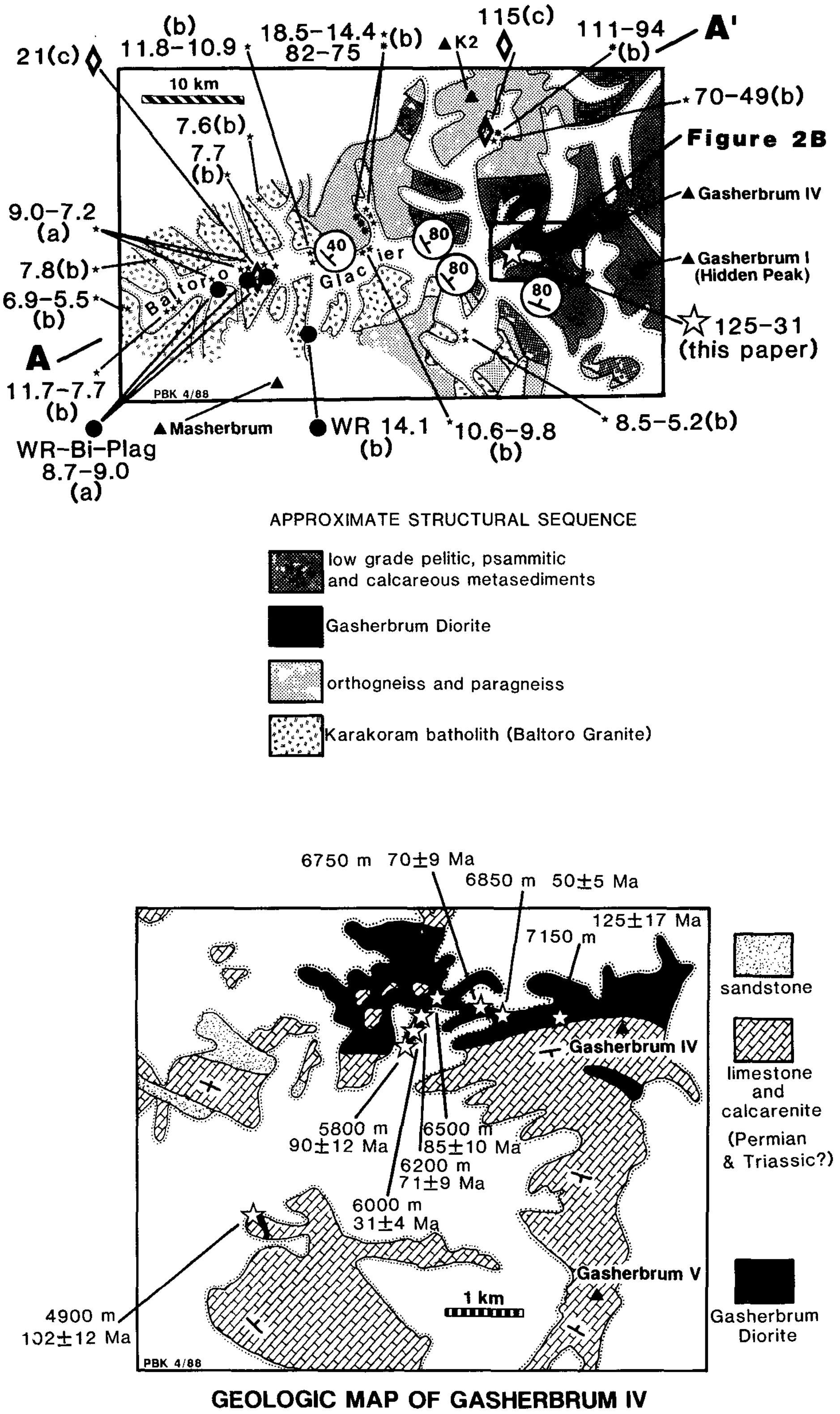


Figure 2. Geologic maps showing location of samples taken for geochronology in Baltoro glacier basin. A: Geologic map of Baltoro glacier basin, compiled from Desio and Zanettin (1970). Diamonds = U/Pb on zircon; solid circles = Rb/Sr on four whole rocks (Searle et al., 1989) and on whole-rock–biotite-plagioclase arrays (Debon et al., 1986); asterisks = K/Ar on hornblende; small solid stars = K/Ar on biotite, muscovite, and potassium feldspar; WR = whole rock; Plag = plagioclase; Bi = biotite; A-A' is line of section (Fig. 4). (a) Debon et al. (1986), (b) Searle et al. (1989), (c) R. Parrish (1988, personal commun.). B: Geologic map of Gasherbrum IV modified from Desio and Zanettin (1970). Locations, altitudes, and fission-track ages of zircon for samples collected in 1984 (open stars) are shown.

Baltoro Granite whole-rock Rb/Sr age of 14.1 Ma was obtained by Searle et al. (1989) at a location 8 km to the south.

Northeast of the Baltoro Granite, and north-northwest of Gasherbrum IV, K2 is composed of the K2 Gneiss (Figs. 1 and 2A). R. Parrish and R. Tirrul (in prep.) have sampled the K2 Gneiss and determined a U-Pb zircon crystallization age of 115 ±3 Ma, and Searle et al. (1989) have obtained an age range of 68–49 Ma using K-Ar on biotite (Fig. 2A). The ages of Searle et al. (1989) are cooling ages for the K2 Gneiss, not emplacement ages.

TABLE 1. FISSION-TRACK DATA, GASHERBRUM DIORITE, NORTHERN PAKISTAN

SAMPLE	ELEVATION (m)	ρ_s (x 10^6 t/cm2)	ρ_s (no. tracks)	ρ_i (x 10^6 t/cm2)	ρ_i (no.tracks)	AGE (Ma: ± 2 sigma)
HM-1	4900	10.30	1416	5.31	364	101 ±12.7
HM-2	5800	9.67	1083	5.62	315	90 ±12.1
HM-3	6000	4.76	800	7.99	671	31.4 ±3.5
HM-4	6200	7.92	1061	5.79	388	71.7 ±9.0
HM-5	6500	9.64	1321	5.93	406	85.2 ±10.3
HM-6	6750	7.83	963	5.85	360	70.1 ±9.1
HM-7	6850	9.08	1226	9.56	344	49.9 ±5.3
HM-8	7150	11.00	1400	4.60	292	125 ±16.9

Note: ρ_s = spontaneous tracks, ρ_i = induced tracks, Ø (neutron dose) = 0.881 x 10^{15} n/cm^2 (2319 tracks counted, six grains counted for all samples, Zeta = 310.85 (Fish Canyon Tuff).

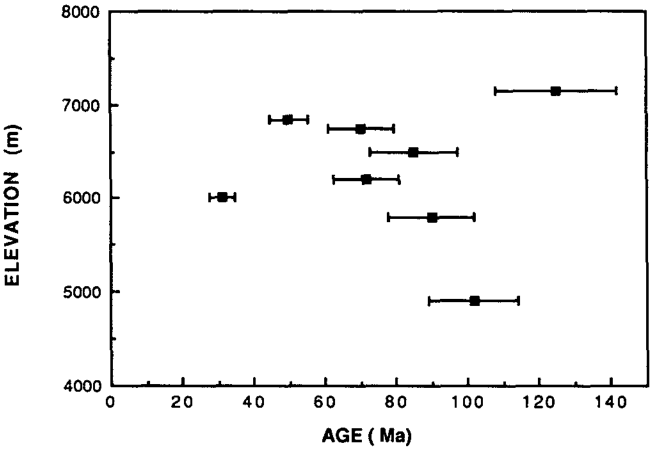


Figure 3. Graph of age vs. elevation for fission-track dates in Gasherbrum Diorite.

METHODS

Sample HM-1 was collected from a large dike of diorite at 4880 m elevation. HM-2 through HM-7 were collected along a climbing route that joins the northwest ridge at 6494 m and proceeds through the diorite to the summit (Fig. 2B). HM-8 was collected at 7165 m, approximately 300 m from the intrusive contact between diorite and the gray limestone that forms the summit of Gasherbrum IV. Elevations were determined by consensus altimeter readings, using three altimeters. The elevations are thought to be accurate to ±15 m.

Zircon was isolated and prepared for dating according to methods in Pettijohn and Krumbein (1938) and Naeser (1976). Apatite suitable for fission-track dating could not be recovered from these rocks. This is highly unusual because most rocks of this composition contain abundant apatite. Counting of fission tracks was done at 1250×, and irradiation standards were counted at 500×. Neutron dosimetry was performed using calibrated muscovite detectors placed over National Bureau of Standards Glass SRM 962 at the top and bottom of the irradiation tube. Fluences were calibrated against the Cu value determined at the National Bureau of Standards (Carpenter and Reimer, 1974). The decay constant of 7.03 × 10^{-17}/yr was used (Roberts et al., 1968), and the zircons were dated by the external detector method (Naeser, 1976, 1979a).

DATA AND ANALYSIS

The fission track data are shown in Table 1. Two of the samples give Early Cretaceous ages (HM-1,8), and four others are Late Cretaceous in age (HM-2,4,5,6). Two samples, however, yield Paleogene ages. No major trends in age vs. elevation (Fig. 3) are evident, even though these samples extend over a section of great relief (2300 m) in the Gasherbrum Diorite. In an uplifted terrane, one normally observes a general increase in fission-track age with increasing elevation (Wagner et al., 1977; Naeser, 1979b), but this is not the case here. A nonlinear data set may indicate that extensive faulting disrupted the relief section, or that the ages were partially reset by contact metamorphism in post-Paleogene time. Because this area does not appear to have been extensively faulted, regional intrusive events such as emplacement of the Baltoro Granite are a more likely explanation for the scattered ages. The variable nature of the resetting event may be explained by the migration of hydrothermal fluids through fracture systems in the rocks. The presence of chlorite and epidote in the Gasherbrum Diorite samples supports this conclusion (Desio and Zanettin, 1970). The data therefore indicate that several of these samples have undergone different thermal histories.

The ages of the Baltoro Granite and the Gasherbrum Diorite are peculiar in that these rock units are nearly adjacent, yet their ages differ by an order of magnitude (Figs. 2A and 4). Plutonism associated with the intrusion of the Baltoro Granite occurred about 25–15 Ma, whereas the Gasherbrum rocks yield fission-track ages as old as 125 Ma (Table 1). Our fission-track ages of the samples on Gasherbrum IV are very similar to those derived from the K2 Gneiss by U/Pb dating of zircon (Figs. 2A and 4) (R. Parrish and R. Tirrul, in prep.; Searle et al., 1989).

The presence of prograde andalusite- and chlorite-bearing assemblages in the contact aureole (Desio and Zanettin, 1970) suggests that the rocks of the Gasherbrum Diorite have not been deeply buried since Cretaceous time. These minerals are indicative of relatively low temperature and pressure conditions that are associated with shallow intrusions. Talus derived from the west-face contact zone includes mineralized skarn boulders, which also contain low-temperature assemblages. In contrast, the Nanga Parbat massif, 80 km to the southeast, is composed of amphibolite facies rocks, suggesting significant amounts of postmetamorphic uplift in this region. Rocks west of or within the Baltoro Granite also record high temperature and pressure conditions. Debon et al. (1987) reported that these rocks record garnet-andalusite-sillimanite-plagioclase pressures of about 4 kbar. Kyanite

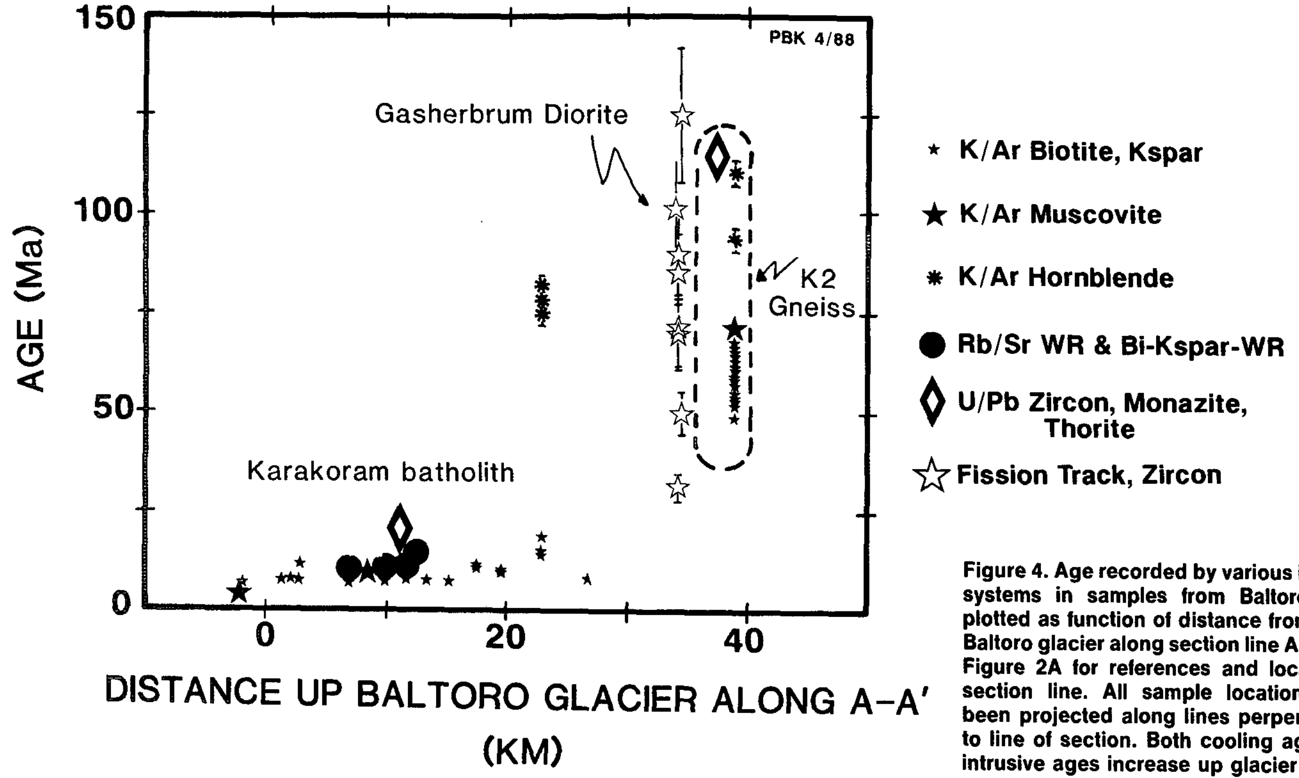
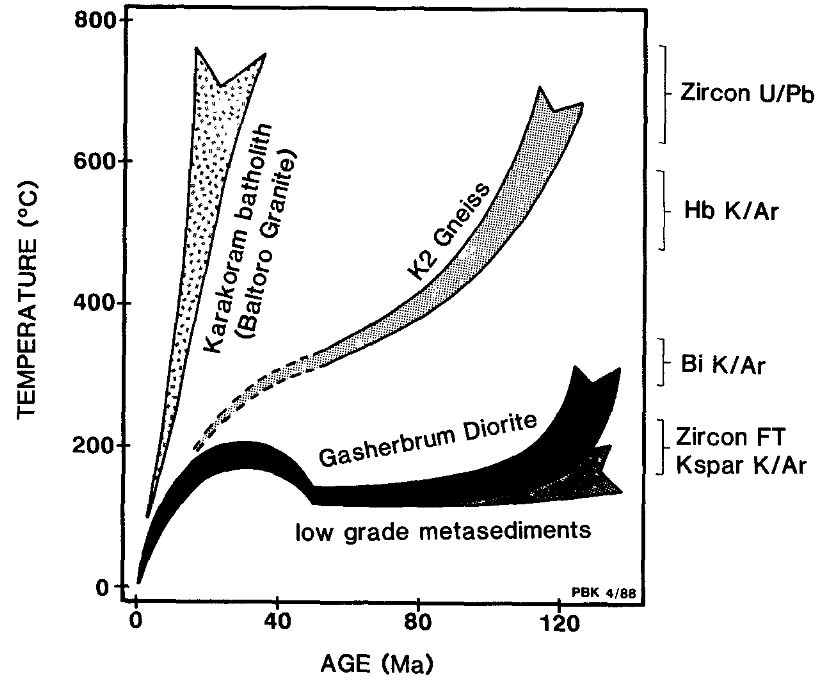


Figure 4. Age recorded by various isotopic systems in samples from Baltoro basin plotted as function of distance from toe of Baltoro glacier along section line A-A'. See Figure 2A for references and location of section line. All sample locations have been projected along lines perpendicular to line of section. Both cooling ages and intrusive ages increase up glacier and up section.

Figure 5. Schematic illustration of cooling history of Baltoro Granite, K2 Gneiss, Gasherbrum Diorite, and low-grade metasedimentary host rocks to Gasherbrum Diorite, based on interpretation of geochronologic results in Figures 2 and 4. Schematic closure temperatures for K/Ar and fission-track systems and temperature estimate for growth of zircon in felsic igneous rocks and orthogneiss are shown at right.



and sillimanite coexist a few kilometres west of the Baltoro Granite.

East of the Baltoro Granite, andalusite and sillimanite are found together on Mitre Peak, a few kilometres west of Gasherbrum IV. The presence of coexisting muscovite and quartz in the Baltoro Granite (Desio and Zanettin, 1970; Debon et al., 1987) suggests that the granite crystallized from a melt at a pressure greater than about 3.5 kbar (Evans, 1965). The presence of andalusite may be a good indicator of how much postmetamorphic uplift the upper Baltoro Granite region has undergone. Andalusite is a useful geobarometer because its presence indicates that the Baltoro Granite was emplaced at depths of less than 13 km.

The lowest sample at Gasherbrum IV (4880 m) has a fission-track age of 101.7 ±12.4 Ma, which indicates that there has been little erosion (or net uplift) in the Gasherbrum region since Cretaceous time. In the Nanga Parbat region, ages as young as 1.3 Ma (zircon fission-track) have been reported at equivalent elevations (Zietler, 1985). This indicates that there has been approximately 6 km (closure isotherm for zircon) of uplift in the Nanga Parbat region during the past 1.3 m.y. Because old ages are present in the lower elevations of the Gasherbrum Peaks region, we know that the total amount of erosion has been substantially smaller here as compared to Nanga Parbat. However, the Gasherbrum Peaks are at an extremely high elevation (8000+m). This suggests that recent uplift rates have been very high and erosion has not yet been able to keep pace. Presumably, as uplift and erosion progress, younger zircon ages will begin to appear at lower elevations.

The metamorphic assemblages and the fission-track data indicate that the Gasherbrum Diorite was emplaced at shallow levels, or at least reached shallow levels by about 110 Ma (possibly during closure of the Tethys Sea). The K2 Gneiss was emplaced at deeper levels at around 110 Ma, and subsequently uplifted at 95–50 Ma (Searle et al., 1989); the Gasherbrum Diorite was not (Figs. 4 and 5). The Baltoro Granite was emplaced at pressures greater than 4 kbar at around 20 Ma; it cooled very rapidly and was uplifted at approximately 10 Ma. Both Gasherbrum and K2 appear to have remained at a relatively constant depth beneath the erosion surface during this period (Fig. 5). The differences in cooling history between the Baltoro Granite and the Gasherbrum Diorite may have resulted from large-scale east-west axial folding rather than by faulting. The anticlinorium cored by the Baltoro Granite may have been formed by differential uplift at approximately 10 Ma when the granite was uplifted relative to the Gasherbrum Diorite.

CONCLUSIONS

Zircons on Gasherbrum IV have been relatively near the surface (within 6 km) for at least the past 100 m.y. The peaks at Gasherbrum are currently standing at high relief, therefore erosion has not kept pace with uplift. This latest episode of uplift was very recent and rapid. Analysis of zircon fission-track ages from throughout the region (Zeitler, 1985; Cerveny et al., 1988) has shown that uplift rates have been variable throughout the Himalaya, and that rapid uplift has been characteristic in various isolated areas over the past 20 m.y.

The ages obtained by fission-track dating of the Gasherbrum Diorite are significantly older than cooling ages obtained by other workers for the nearby Baltoro Granite. The two are separated by approximately 18–20 km of structural relief, though both intrusive units are exposed at the same elevation. This suggests that intrusion of the Baltoro Granite and subsequent folding (post–10 Ma) is responsible for the differential uplift observed in the Gasherbrum IV region.

The highly variable ages throughout the diorite may have resulted from post-Paleogene, low-temperature contact metamorphism and associated hydrothermal activity, most likely during emplacement of the Baltoro Granite. The presence of epidote and chlorite alteration products in the Gasherbrum Diorite supports this hypothesis.

REFERENCES CITED

Carpenter, B.S., and Reimer, G.M., 1974, Standard reference materials: Calibrated glass standards for fission track use: National Bureau of Standards Special Publication 260-49, 16 p.

Cerveny, P.F., Naeser, N.D., Zeitler, P.K., Naeser, C.W., and Johnson, N.M., 1988, 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, *in* Kleinspehn, K.D., and Paola, C., eds., New perspectives in basin analysis: New York, Springer-Verlag, p. 43–61.

Debon, F., Zimmermann, J.L., and Bertrand, J.M., 1986, Le granite du Baltoro (batholite axial du Karakorum, nord Pakistan); une intrusion subalcaline d'âge Miocène Supérieur: Paris, Académie des Sciences Comptes Rendus, v. 303, p. 463–468.

Debon, F., Lefort, P., Dautel, D., Sonet, J., and Zimmermann, J.L., 1987, Granites of western Karakoram and northern Kohistan (Pakistan): A composite mid-Cretaceous to upper Cenozoic magmatism: Lithos, v. 20, p. 19–40.

Desio, A., and Zanettin, B., 1970, Geology of the Baltoro Basin: Leiden, Netherlands, E.J. Brill, 308 p.

Evans, B.W., 1965, Application of a reaction-rate method to the breakdown of muscovite and muscovite plus quartz: American Journal of Science, v. 263, p. 647–667.

Fuchs, G., 1979, On the geology of Western Ladakh: Geologische Bundesanstalt Jahrbuch, v. 122, p. 513–540.

Harrison, T.M., Armstrong, R.L., Naeser, C.W., and Harakal, J.E., 1979, Geochronology and thermal history of the Coast Plutonic Complex, near Prince Rupert, British Columbia: Canadian Journal of Earth Sciences, v. 16, p. 400–410.

Naeser, C.W., 1976, Fission track dating: U.S. Geological Survey Open-File Report 76-190, 65 p.

——1979a, Fission track dating and geologic annealing of fission tracks, *in* Jager, E., and Hunziker, J.C., eds., Lectures in isotope geology: New York, Springer-Verlag, p. 154–169.

——1979b, Thermal history of sedimentary basins: Fission-track dating of subsurface rocks: Society of Economic Paleontologists and Mineralogists Special Publication 26, p. 109–112.

Pettijohn, F.J., and Krumbein, W.C., 1938, Manual of sedimentary petrography: New York, Appleton-Century-Crofts Inc., 549 p.

Roberts, J.A., Gold, R., and Armani, R.J., 1968, Spontaneous fission decay constant of ^{238}U: Physical Review, v. 174, p. 1482–1484.

Searle, M.P., Rex, A.J., Tirrul, R., Rex, D.C., and Barnicoat, A., 1989, Metamorphic, magmatic and tectonic evolution of the Central Karakoram in the Biafo-Baltoro-Hushe regions of northern Pakistan: Geological Society of London (in press).

Tahirkheli, R.A.K., and Jan, M.Q., 1979, Geology of Kohistan, Karakoram Himalaya, northern Pakistan: University of Peshawar Geological Bulletin, Special Issue, v. 13, p. 1–187.

Wagner, G.A., Reimer, G.M., and Jager, E., 1977, Cooling ages derived by apatite fission track, mica Rb-Sr and K-Ar dating: The uplift and cooling history of the central Alps: Memorie Istituti Geologia e Mineralogia dell Universita di Padova, v. 30, p. 1–28.

Zeitler, P.K., 1985, Cooling history of the NW Himalaya, Pakistan: Tectonics, v. 4, p. 127–151.

Zeitler, P.K., Tahirkheli, R.A.K., Naeser, C.W., and Johnson, N.M., 1982, Unroofing history of a suture zone in the Himalaya of Pakistan by means of fission-track annealing ages: Earth and Planetary Science Letters, v. 57, p. 227–240.

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