When did the roof collapse? Late Miocene north-south extension in the high Himalaya revealed by Th-Pb monazite dating of the Khula Kangri granite

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ABSTRACT

Th-Pb ion microprobe measurements made on 12 monazite grains from the Khula Kangri granite, Tibet-Bhutan frontier, are interpreted to indicate that crystallization occurred at 12.5 ± 0.4 Ma. The leucogranite is cut by the Gonto La detachment, part of the Southern Tibet detachment system that has allowed upper-level, north-directed extension of the Himalayan orogen. Significant orogen-normal extension in southern Tibet appears to have continued 8–10 m.y. later than previously recognized. This is the first reported crystallization age for a leucogranite east of the Yadong cross structure, an apparent 70 km offset of the high Himalaya and Southern Tibet detachment. West of the Yadong cross structure, reliable ages for high Himalaya events (major Main Central thrust slip, granite generation and emplacement, attainment of critical topography, and major detachment extension) group between ca. 24 and 19 Ma. We interpret the west-to-east change across the Yadong cross structure to be due to either (1) an abrupt, ~10 m.y. younging of principal high Himalayan events or (2) a deeper (thus younger) exposed part of the footwall of the southern Tibet detachment. Near Khula Kangri, the Southern Tibet detachment is cut by the highly oblique Yadong-Gulu rift; a manifestation of Tibet plateau east-west extension. Integrated estimates of magnitude, and rate, of detachment displacement suggest that the observed postcrystallization north-directed extension lasted for 1–3 m.y., after which time the Yadong-Gulu rift formed. This interpretation is consistent with initiation of east-west extension of Tibet at ca. 8 Ma.

INTRODUCTION

The Himalayan mountains and Tibet are the prototypical products of continental collision and have been termed the "roof of the world" (Le Fort, 1975). Surprisingly, perhaps, two distinctive features of this textbook example of collisional tectonics are extensional and represent collapse of this "roof"; the Southern Tibet detachment system (Burg et al., 1984; Burchfiel et al., 1992) accommodated north-directed Himalayan extension whereas the north-trending rifts of southern Tibet accommodated east-west extension (Armijo et al., 1986; Harrison et al., 1995a). Knowing the timing of both these features improves our understanding of the India-Asia collision and the evolution of both the Himalaya and the Tibet plateau.

Arguably the two major Himalayan structures are the Main Central thrust and the Southern Tibet detachment, continuous for >2000 km along the orogen (Gansser, 1981; Burchfiel et al., 1992). The former probably accommodated between 150 and ~500 km of north-south convergence between India and Asia (e.g., Schelling and Arita, 1991), whereas the latter allowed north directed upper Himalayan extension (Burg et al., 1984; Herren, 1987; Searle et al., 1988; Burchfiel et al., 1992; Edwards et al., 1996). Burg et al. (1984) first suggested synchronous detachment extension and Main Central thrust contraction. This concept is consistent with more recent chronometric data for both structures: the Main Central thrust between Zanskar and eastern Nepal (Fig. 1A) probably moved significantly during the early Miocene, ca. 24–19 Ma (Schärer, 1984; Hubbard and Harrison, 1988; Coleman and Parrish, 1995; Noble and Searle, 1995; Harrison et al., 1995b). In this same area, dating of plutons and pods of leucogranite that are prekinematic, synkinematic, and postkinematic to the basal Southern Tibet detachment indicates it was active from ca. 25 to 18 Ma (Burg et al., 1984; Le Fort et al., 1987; Coleman and Parrish, 1995; Hodges et al., 1995; Harrison et al., 1995b; Noble and Searle, 1995; Searle et al., 1997). The crustal anatexis (partial melting) responsible for these leucogranites may well be due to Main Central thrust motion (Le Fort et al., 1987), north-directed extension is likely a result orogen collapse (Burg et al., 1984), and there is a marked association between plutonism, high topography, extremity of slope, and the detachment system (Burg, 1983; Molnar et al., 1993; Edwards et al., 1996; Fielding, 1996). It is now generally recognized, therefore, that the main high Himalayan events involved (1) a major period of Main Central thrust movement, (2) leucogranite generation and emplacement, (3) attainment of critical topography and/or stress in the orogenic wedge, and (4) unroofing via significant north-directed extension that, between Zanskar and eastern Nepal (Fig. 1), occurred prior to ca. 20 Ma.

Between Nepal and Bhutan (Fig. 1, A and B), both the crest of the high Himalaya and the Southern Tibet detachment are left laterally offset >70 km (Burg, 1983; Burchfiel et al., 1992; Wu et al., 1995; Fielding, 1996) by a feature termed the Yadong cross structure (Burchfiel et al., 1992). The Main Central thrust is not offset, however, giving a greater surface exposure of high-grade detachment footwall rocks in Bhutan relative to Nepal (Gansser, 1981, 1983; Schelling and Arita, 1991). This change across the Yadong cross structure, and others (e.g., differing generations of kinematic structures), have been noted before (Burchfiel et al., 1992; Edwards et al., 1996); however, no clear constraints hitherto existed for any significant geochronologic difference. Existing data for Bhutan leucogranites include a broad suite of cooling ages from ca. 11 to 18 Ma (Dietrich and Gansser, 1981; Debon et al., 1985; Villa and Lombardo, 1986; Maluski et al., 1988; Ferrara et al., 1991), but no crystallization ages. We report here the first crystallization age for a leucogranite found in the Tibet-Bhutan high Himalaya, the Khula Kangri

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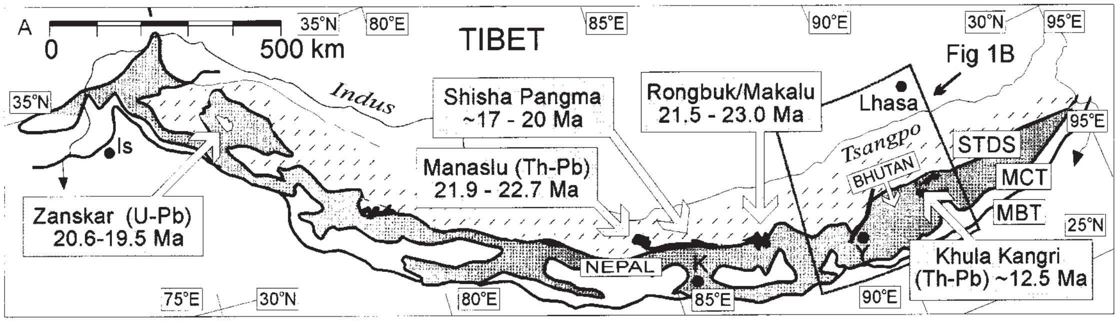

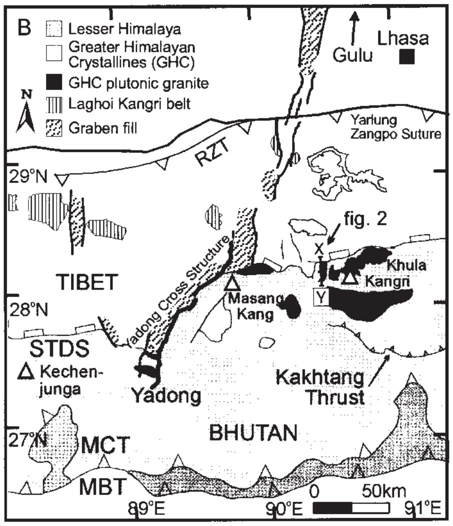

Figure 1. A: Tectonic map of Himalaya (after Gansser, 1983; Pêcher, 1991). White: Lesser Himalayan sequences. Gray: Greater Himalayan crystalline sequence. White with dashes: Tethyan sedimentary sequence. Black areas adjacent to arrows: high Himalayan granite plutons. Boxes with arrows locate specific crystallization ages of granites (from west to east, sources are Noble and Searle, 1995; Harrison et al., 1995b; Searle et al., 1997; Harrison et al., 1995b; this study). STDS is Southern Tibet detachment system; MCT is Main Central thrust; MBT is Main Boundary thrust. B: Tectonic map of area around southern Yadong-Gulu rift system (after Gansser, 1983; Burg, 1983; Burchfiel et al., 1992; Edwards et al., 1996). White (between STDS and suture): Tethyan sedimentary sequence. Heavy north-trending lines: normal faults due to east-west extension. White triangles: major peaks. Yadong cross structure is represented by ~70 km offset of high peaks and trace of STDS. Gulu (at north end of Yadong-Gulu rift) is ~100 km north-northeast of arrow. RZT = Renbu Zedong thrust.

granite, and show that there is an abrupt younging across the Yadong cross structure.

LOCAL GEOLOGY

The Khula Kangri granite is a high Himalayan pluton >750 km^2, located near the Bhutan frontier. It is a typical high Himalayan two-mica (± tourmaline) leucogranite, truncated by the Gonto La detachment (Fig. 2) that, in classic fashion (Burchfiel et al., 1992), places Tethyan metasedimentary rocks over rocks of the Greater Himalayan crystalline sequence (Edwards et al., 1996). An ~300-m-thick horizon of granite mylonite lies directly below the detachment; strain magnitude decreases downward (Edwards et al., 1996). On the basis of hanging wall–footwall correlations, the Gonto La detachment accommodated a minimum of 15 km of displacement after emplacement of the Khula Kangri granite, and probably much more (Edwards et al., 1996). Taking the Himalayan convergence rate of 10–15 mm/yr (Lyon-Caen and Molnar, 1985) as a maximum displacement rate, the detachment would have remained active for 1–2 m.y. following granite emplacement, given the mapped minimum displacement of 15 km (Edwards et al., 1996). Detailed mapping shows that the Southern Tibet detachment continues west to where it is cut by, and hence is older than, one of the north-trending rifts that represent east-west extension of the plateau: the Yadong-Gulu rift (Edwards et al., 1996).

ANALYTICAL TECHNIQUES

We separated monazite from a sample (IE-26) obtained from the lowermost part of the granite mylonite underlying the detachment (Fig. 2) and measured $^{208}Pb/^{232}Th$ ages by using the CAMECA ims 1270 ion microprobe at the University of California, Los Angeles. Details of our analytical methods are summarized elsewhere (Harrison et al., 1995b). A mass resolving power of about 4500 is adequate to separate all molecular interferences (mostly light rare earth element PO^{2+}) in the 204 to 208 mass range, and instrumental mass discrimination of Pb isotopes is not detectable. Ages are determined relative to monazite standard 554, which yields a $^{208}Pb/^{232}Th$ age of 45 ± 1 Ma. The precision of the method is not limited by counting statistics but by the reproducibility of the standard calibration curve which is typically ±1% to 2%. Advantages of this approach over conventional U-Pb dating of Tertiary monazites include (1) the absence of unsupported ^{208}Pb, (2) typical radiogenic yields >85%, and (3) the ability to directly image, and thus avoid, restitic cores (Harrison et al., 1995b). The diffusion of Pb in monazite is sufficiently sluggish (Smith and Giletti, 1994) at the peak melting temperatures of Himalayan leucogranites (680–730 °C; Montel, 1993), to ensure that crystallization ages are recorded in the cores of ~100-µm sized grains.

RESULTS

We initially measured 35 $^{208}Pb/^{232}Th$ ages on 12 monazite grains from sample IE-26. For 11 of these grains, the 26 ages obtained yielded a weighted mean of 12.5 ± 0.15 Ma (2σ) with a mean squared weighted deviation [MSWD; $\chi^2/(n-1)$] of 6. For this number of ages, an MSWD of 6 indicates that analytical uncertainty alone cannot explain the distribution of ages, and accordingly we have increased the error by √MSWD to account for the excess scatter, yielding 12.5 ± 0.4 Ma. However, most of the excess χ^2 is derived from three measurements (esp1, fsp1, ksp1) and removing those data reduces the MSWD by half (full details of all measurements are available[1]). The twelfth crystal (grain c; Fig. 3) yielded two clusters, one at ca. 12 Ma and another between 35 and 21 Ma; this bimodal distribution we interpret to reflect a restitic core encompassed by a magmatic overgrowth. The three youngest ages, all from one edge of the crystal (csp2, csp2@1, csp7), yielded a weighted mean of 12.4 ± 0.4 Ma (MSWD = 0.5), which is indistinguishable from the average of that obtained from the other 11 grains. The other six ages, which vary from 21 to 35 Ma, are consistent with this being a restitic monazite grain that formed in the Indian

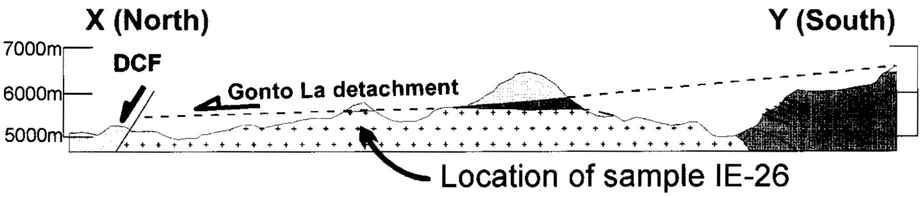

Figure 2. Generalized cross section (X-Y) through Gonto La valley. Plus pattern is Khula Kangri granite. Darker pattern is general Greater Himalayan crystalline sequence. Lighter pattern above detachment is Tethyan sedimentary sequence. DCF is Dzong Chu normal fault. Location of sample IE-26 is immediately below ~300-m-thick granite-mylonite horizon that is below Gonto La detachment. Half-arrows show relative movement direction of fault hanging walls. After Edwards et al. (1996).

[1] GSA Data Repository item 9730, Th-Pb monazite results for sample IE-26, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

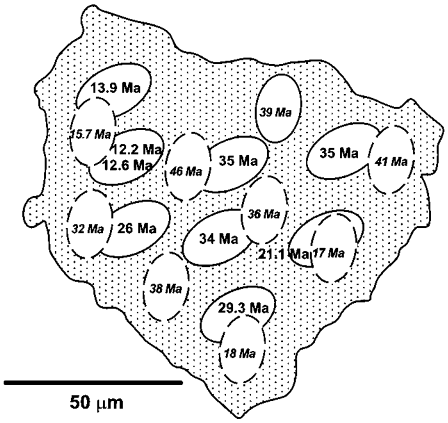

Figure 3. Map of monazite grain c, sample IE-26, showing locations and ages of individual spots analyzed by ion microprobe. Results from first and second analysis set are shown as solid and dashed ellipses, respectively. Note proximity of oldest (46 Ma) and youngest (12 Ma) results (see text). Because old core likely represents Eo-Himalayan metamorphism and youngest age represents time of anatexis, lack of equilibration over ~10 μm distance restricts time at peak temperature to no more than ~1 m.y.

basement during Eo-Himalayan metamorphism (i.e., Le Fort, 1996) of the granite protolith. To gain further insight into this age distribution, we repolished the sample and measured eight additional spots, which yielded ages between 15 and 46 Ma (Fig. 3). The pattern of ages is consistent with the first run (Fig. 3), and we interpret the oldest age of 46 Ma as a minimum age of the protolith. The preservation of inherited Pb* in this grain indicates that the thermal history during anatexis was insufficient to cause diffusive equilibration of Pb over length scales of 10–50 μm. We can thus infer that the age of 12.5 ± 0.4 Ma dates the episode of magmatism that resulted in the emplacement of the Khula Kangri granite and that individual monazite grains did not allow significant Pb* loss while at high temperature.

IMPLICATIONS

Khula Kangri's 12.5 ± 0.4 Ma crystallization age is the youngest reported from the high Himalaya. It is ~10 m.y. younger than that of high Himalayan leucogranites west of the Yadong cross structure, but it is similar in age to the Laghoi Kangri belt (also north Himalayan Granite belt–Le Fort et al., 1987). Assuming a detachment displacement rate of 10 mm/yr, our result suggests that north-directed extension accommodated by the Southern Tibet detachment system in the eastern Himalaya continued until ca. 10 Ma. This date is 8–10 m.y. younger than has been previously suggested for main detachment activity (Hodges et al., 1992; Coleman and Hodges, 1995; Searle, 1995; Noble and Searle, 1995).

Two alternative interpretations are possible. In the first, there is an abrupt, ~10 m.y. younging of main Himalayan events across the Yadong cross structure. The Main Central thrust did not accommodate significant displacement during the ca. 12 Ma Bhutan Himalaya events as it is not offset across the Yadong cross structure. The additional south-directed shortening required in Bhutan, and the anatexis, migration, and emplacement of the Khula Kangri granite, may therefore be related to motion on a later thrust fault structurally above, and thus out of sequence with, the Main Central thrust. The Kakhtang thrust (Fig. 1B), located midway between the Main Central thrust and the crest of the Himalaya, and documented only in Bhutan (Gansser, 1983), is a possible proxy for the Main Central thrust. This hypothesis requires that the detachment along the Bhutan Himalaya is wholly separate from, although mechanically equivalent to, the detachment west of the Yadong cross structure. This interpretation is consistent with interpreted deep seismic reflection profiles on either side of the Yadong cross structure that show that the detachment on the Nepal side continues to ~27 km depth (Hauck and Edwards, 1997), whereas on the Bhutan side, the detachment continues for >100 km at <10 km depth (Nelson et al., 1996). A west-to-east detachment-system discontinuity is consistent with changes across the projection north from the Yadong cross structure that include (1) a predominance of deeper-water facies, (2) possible left-lateral offset of the Laghoi Kangri belt (Fig. 1B), and (3) excision of the Gangdese thrust, Xigaze Group, and ophiolitic remnants (Burg, 1983; Yin et al., 1994). If there is a separate mechanism for accommodating the detachment hanging wall on the east side of the Yadong cross structure, the north-vergent Renbu Zedong thrust (Fig. 1B) may be involved. This thrust defines the Yarlung Zangpo suture along much of its eastern portion (Yin et al., 1994) and locally accommodated >20 km of slip at ca. 18–11 Ma (Ratschbacher et al., 1994; Quidelleur et al., 1997). This may indicate that there was some synchronous movement on the two structures and/or movement on the Renbu Zedong thrust that allowed sufficient change in the local stress tensor east of the Yadong cross structure to trigger north-directed extension at Khula Kangri. Interpreted deep seismic reflection profiles are consistent with the two faults connecting at depth (Nelson et al., 1996).

The second interpretation precludes the first and assumes that the Southern Tibet detachment is a single northward-propagating fault whose surface is continuous across the Yadong cross structure. In this case, 70 km of offset accompanies the Yadong cross structure because the exposed portion of the Southern Tibet detachment on the Tibet-Bhutan frontier is 70 km closer to the propagating tip of the detachment surface (relative to Nepal). Detachment footwall anatexis is therefore younger in the north, as evidenced by the 12.5 ± 0.4 Ma Khula Kangri granite. This interpretation would imply a continuous portion, or strip, of the Southern Tibet detachment footwall along which plutonism is ~10 m.y. younger than, and ~70 km north of, the portion of the detachment exposed along the Nepal high Himalaya. We note that the Khula Kangri granite is similar in age, and crops out near, the Laghoi Kangri belt that extends along the arc west of the Yadong cross structure, 50–100 km north of the Nepal high Himalaya (Schärer et al., 1986). We can therefore propose that the two are tectonically equivalent, although the Khula Kangri granite has the morphology of a high Himalayan pluton whereas the Laghoi Kangri belt comprises diapirically emplaced domes. The morphological contrasts can be explained by the relative depths of crustal exposure across the Yadong cross structure; the basal portions of the Khula Kangri granite are exposed whereas only the diapirically intruding tips of the north Himalayan Granite belt are currently visible.

Because the Southern Tibet detachment is cut by the north-trending Yadong-Gulu rift, north-directed extension must have ceased before the initiation of east-west extension. Our data constrain detachment system extension to 12.5 ± 0.4 Ma and indicate that it continued until ca. 10 Ma, requiring the Yadong-Gulu rift to be younger than ca. 10 Ma. This requirement is consistent with initial opening of the Yadong-Gulu rift at 8 ± 1 Ma (Harrison et al., 1995a). Several models suggest that the current east-west extension in southern Tibet reflects a change in the stress regime within the plateau caused by attainment of a critical elevation (Tapponnier et al., 1986; Dewey, 1988; England and Houseman, 1989; Molnar et al., 1993). Harrison et al. (1995a) proposed that this change in the stress regime occurred at ca. 8 Ma, as opposed to between 17 and 14 Ma (Coleman and Hodges, 1995). On the basis of our results, we concur. Other effects possibly related to plateau uplift include intensification of the Asian monsoon (Kroon et al., 1991) and a major climatological shift in the Himalayan foreland (Quade et al., 1989), documented to have begun at ca. 8 Ma.

CONCLUSION

A 12.5 ± 0.4 Ma Th-Pb monazite date is interpreted as the crystallization age for the Khula Kangri pluton. North-directed extension of the high Himalaya is clearly later than plutonism and probably continued until ca. 10 Ma, significantly more recently than previously recognized. The Yadong cross structure appears to mark an abrupt younging in the age of granites in the Southern Tibet detachment footwall, allowing two alternative hypotheses: (1) Main Himalayan orogenic events in Bhutan are ~10 m.y. younger than to the west in Nepal and Zanskar. (2) Khula Kangri is part of a belt of plutonism in the detachment footwall that is ~10 m.y. younger than, and ~70 km north of, the detachment exposed along the Nepal to Zanskar Himalaya. Because the Southern Tibet detachment is cut by the Yadong-Gulu rift, the onset of east-west extension of the plateau must be much younger than ca. 12 Ma, and probably younger than ca. 10 Ma. This interpretation is consistent with previous geologic and tectonic data that indicate that the Yadong-Gulu rift began to open at ca. 8 Ma.

ACKNOWLEDGMENTS

Sample IE-26 was collected during 1994 surface geology field investigations of project INDEPTH, supported by the National Science Foundation (NSF). We thank Brad Hacker and an anonymous individual for reviews of the manuscript. Harrison thanks M. Grove and K. McKeegan for technical assistance and acknowledges support from the NSF for this research. Edwards thanks W. S. F. Kidd for guidance and his Gonto La companions Jixiang Li and Marin Clark.

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Manuscript received December 23, 1996
Revised manuscript received March 3, 1997
Manuscript accepted March 17, 1997