Building the Pamirs: The view from the underside

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[1]GSA Data Repository item 2003##, Zircon U-Pb geochronology data, is available online at www.geosociety.org/pubs/ft2003.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

ABSTRACT

The Pamir Mountains are an outstanding example of extreme crustal shortening during continental collision that may have been accommodated by formation of a thick crust—much thicker than is currently thought—and/or by continental subduction. We present new petrologic data and radiometric ages from xenoliths in Miocene volcanic rocks in the southeastern Pamir Mountains that suggest that Gondwanan igneous and sedimentary assemblages were underthrust northward, buried to >50–80 km during the early stage of the India-Asia collision, and then heated and partly melted during subsequent thermal relaxation before finally being blasted to the surface. These xenoliths, the deepest crustal samples recovered from under any active collisional belt, provide direct evidence for (1) early Cenozoic thickening of the Pamirs and (2) lower-crustal melting during collision; the xenoliths also suggest that (3) the present mountain range was a steady-state elevated plateau for most of the Cenozoic.

Keywords: Pamir region, continental collision, subduction, partial melting, orogenic plateaus

INTRODUCTION

Although many hypotheses have been advanced to explain (1) extreme shortening (e.g. Burtman and Molnar, 1993), (2) melting (e.g. Maheo et al., 2002), (3) continental subduction (e.g. Roecker, 1982; Searle et al., 2001) and (4) the development of high-elevation plateaus in collisional belts—specifically in the Cenozoic Himalayan-Tibetan orogen (e.g., Avouac and Tapponnier, 1993; Yin and Harrison, 2000; DeCelles et al., 2002)—we have few observations with which to test them. Our understanding of these processes is in part limited by the inability to directly observe the deeper crust and upper mantle beneath collisional orogens. Sedimentary and volcanic rocks can be subducted to ultrahigh-pressure depths and subsequently returned to the surface (Coleman and Wang, 1995), but their high-temperature history is obscured by retrograde metamorphism and deformation during exhumation (Kohn and Parkinson, 2002). Xenoliths from the lower crust and upper mantle beneath active collisional mountain ranges represent direct samples of these deeper levels and preserve compositional, thermal, and age information that cannot otherwise be obtained. Unfortunately, lower-crustal xenolith localities are rare in such environments (e.g., Hacker et al., 2000).

In this study, we present new petrographic, thermobarometric, and geochronologic data on deep-crustal xenoliths in Miocene volcanic rocks from the southern Pamir Mountains of central Asia. These samples unambiguously represent parts of the deepest crust beneath the western segment of the Himalayan-Tibetan collisional belt and provide a lower-crustal view for crustal thickening and melting beneath the Pamirs. Specifically, we show that (1) crustal thickening took place in the early stages of the India-Asia collision, (2) the region was a low-relief plateau for most of the Cenozoic, and (3) the crust partly melted after thermal relaxation.

SOUTH PAMIR XENOLITHS

Two extension-related Miocene eruptive centers, part of a spectacular belt of Cenozoic magmatism and metamorphism in the southeastern Pamir Mountains, Tajikistan (Fig. 1), contain deep-crustal and mantle xenoliths (Budanova, 1991). The xenolith-bearing volcanic suite is ultrapotassic, ranging from alkali basalt to trachyte and syenite. We analyzed samples of the Dunkeldik pipe belt (Fig. 1B), which is probably a result of local crustal extension (Dmitriev, 1976). Four xenolith types were recognized within a biotite-rich trachyte: felsic eclogites, felsic granulites, mafic eclogites, and phlogopite-garnet websterites (Lutkov, 2003). The websterites are basaltic, contain orthopyroxene, clinopyroxene, garnet, phlogopite, pyrrhotite, and apatite, and may be of mantle origin. The other rocks are unambiguously crustal; their mineral assemblages indicate ultrahigh temperatures and near-ultrahigh pressures. The eclogites consist of omphacite, garnet, and trace rutile, apatite, amphibole, plagioclase, and biotite, whereas the felsic eclogites include these phases plus sanidine, kyanite, quartz, and minor relict plagioclase. The granulites contain garnet, kyanite, quartz, and alkali feldspar and minor graphite and rutile. All but the websterites contain trace zircon and monazite. We determined xenolith eruption ages by $^{40}Ar/^{39}Ar$ dating, equilibration pressures and temperatures by using THERMOCALC (Powell and Holland, 1988), and provenance and orogenic history information from zircon and monazite U-Pb ages ($^{40}Ar/^{39}Ar$ chronology, thermobarometry, and U-Pb geochronology data tables are available[1]).

The eruption age of the xenoliths is well constrained by biotite, K-feldspar, and groundmass $^{40}Ar/^{39}Ar$ ages (Table DR1) of 10.8–11.1 ± 0.15 Ma from the host trachyte and by biotite ages of 11.2 and 11.5 ± 0.2 Ma from two felsic eclogites (P337, P2104). Optical microscopy and electron-microprobe analysis reveal that the major phases in the xenoliths are well equilibrated—coarse and homogeneous or weakly zoned—and lack retrograde minerals signaling slow cooling or decompression. The garnet websterites were derived from the greatest depths, recording equilibration pressures of ~3–4 GPa (Budanova, 1991). Three felsic eclogites and one mafic eclogite equilibrated at temperatures of 1050–1200 °C and near ultrahigh pressures of 2.4–2.7 GPa (Table DR2). Rare relict hydrous phases and silicate glass as inclusions in the eclogite garnets suggest that dehydration melting accompanied prograde metamorphism. Bulk chemistry of these rocks and their unusual mineralogy (e.g. sanidine-bearing eclogites) also suggest that these rocks have experienced one or two stages of dehydration melting (muscovite and/or biotite) as they were being heated (Patino-Douce and McCarthy, 1998). To our knowledge, these xenoliths are the deepest crustal samples recovered from under any active collisional orogenic belt worldwide.

U-Pb GEOCHRONOLOGY

Zircons and monazites (Fig. 2) from felsic granulite P1503a and sanidine eclogite P1039 were analyzed in situ by using a 193 nm laser coupled to a Micromass Isoprobe multicollector ICP-MS (inductively coupled plasma–mass spectrometer) (Kidder et al., 2003) (Table DR3). The P1503a zircons are mostly inclusions in garnet and have anhedral, rounded shapes. Crystal shape and the presence of populations of different ages (see subsequent discussion) within a metasedimentary rock strongly suggest that these are detrital zircons. In contrast, the monazites are commonly subhedral matrix minerals grown during prograde metamorphism. During laser ablation, some spots yielded complex isotopic evolution, reflecting age zonation. We report only results that define a single age within 10% error.

The calculated bulk composition and mineral-inclusion suite for P1503a suggests that its protoliths was a sedimentary, probably two-mica pelite. Equilibration took place above 950 °C and 1.4 GPa, above biotite and phengite dehydration solidi (Castro et al., 2000). The zircon age distribution in P1503a includes distinct peaks at 84–57 Ma, 170–146 Ma, 465–412 Ma, 890 Ma, and 1400 Ma. The youngest zircon ages are 56.7 ± 5.4 Ma. Hence, the pelite was either deposited after ~57 Ma or underwent high-grade zircon growth at 57-84 Ma. The lack of 57-84 Ma rims on older zircon grains in the same sample suggest that the hypothesis of a young, post-57 Ma age is more likely. Monazites from P1503a yield U-Pb ages between 34.0 ± 0.5 and 50.3 ± 2.6 Ma.

Felsic eclogite P1309 was derived, on the basis of modal calculations, from a calc-alkaline quartz monzonite. It contains zircons whose ages average ca. 75 Ma. Two grains that do not show inheritance or late Cenozoic rim resetting or growth yielded $^{206}Pb/^{238}U$ ages of 87.6 ± 6.4 Ma and 63.8 ± 1.5 Ma. Older zircons have $^{206}Pb/^{238}U$ ages of ca. 250 Ma, ca. 195 Ma, and ca. 132 Ma. No pre-latest Permian zircons were found in this rock.

INTERPRETATIONS

The broad range of detrital-zircon and monazite ages provides a rich data set with which to interpret the tectonic history of the southern Pamir lower crust by reference to the evolution of the Himalayan-Tibetan collision zone. Proterozoic and early Paleozoic ages are similar in the Qiangtang block, the Lhasa block, the Tethyan Himalaya, and the Greater Himalaya, all rifted fragments of Gondwana (Fig. 3; DeCelles et al., 2000; Kapp et al., 2003), suggesting that P1503a was derived from Gondwana crust (Dewey et al., 1988; Yin and Harrison, 2000). The Mesozoic ages preclude derivation of the xenoliths from Indian crust (Hodges, 2000). The 196–132 Ma ages are equivalent to those of the Hindu Kush–Karakoram–southern Pamir active margin arc, which developed through Early Jurassic–Late Cretaceous oceanic subduction and the accretion of the Karakoram, Kohistan, Hindu-Kush, and southern Pamir blocks (Fraser et al., 2001). The predominant ca. 75 Ma zircons, together with the mineral assemblage and calc-alkaline composition, suggest that P1309 was a hydrous (biotite- and/or amphibole-bearing) quartz monzonite emplaced in the upper crust during the Late Cretaceous. We interpret this sample as a fragment of the Kohistan-Ladakh arc thrust sheet emplaced beneath the southern Pamir during the early stage of the Indo-Asian collision (Hodges, 2000). Kohistan-Ladakh arc accretion caused high-grade metamorphism in the Hindu Kush–Karakoram blocks at 80–50 Ma (Fraser et al., 2001) and is likely reflected in the zircon ages from P1503a. High-grade metamorphism and magmatism in the Karakoram began as early as ca. 63 Ma and continues today (Fraser et al., 2001). Most of the P1503a monazite ages as well as zircon rim ages of 20–15 Ma likely reflect this prolonged regional heating.

Our results suggest that sedimentary rocks and Jurassic–Late Cretaceous Tethyan-margin igneous rocks of Gondwana affinity were subducted beneath the Pamirs during the early stages of the India-Asia collision. After burial in the early Cenozoic, these supra-crustal rocks were heated, dehydrated, and partly melted from ~35 to ca. 11 Ma. The absence of retrograde metamorphic effects indicates that initial Cenozoic crustal thickening was not succeeded by significant cooling and/or exhumation. A one-dimensional conductive thermal model simulating crustal doubling with initial and boundary conditions appropriate for the Pamir shows that a hypothetical intermediate-composition calc-alkaline rock at 70 km depth should reach >1100 °C after ~30 m.y., assuming negligible denudation (<0.01 mm/yr). This simple model includes crustal thickening at ca. 50 Ma, followed by thermal relaxation with virtually no denudation, and provides an excellent match to the xenolith geochronology and thermobarometry. Any model that explains the long-term heating and lack of retrogression, must involve minimal exhumation and thus very low erosion rates. The mantle heat flow is assumed to have remained constant throughout thickening.

IMPLICATIONS FOR THE INDO-ASIAN COLLISION

The potassic, hot, dry, and deep granulitic and eclogitic xenoliths are very unusual, but are similar to xenoliths 1200 km to the east in central Tibet (Hacker et al., 2000). The presence of felsic calc-alkaline, sanidine-bearing eclogites is particularly intriguing (Lutkov, 2003). We propose that a significant component of the thickened crust of the southern Pamir Mountains is an underthrust Late Cretaceous arc—perhaps part of the Ladakh arc as Kapp et al. (2003) and McMurphy et al. (1997) have suggested—on the basis of surface geology and analogies with Tibet. Similarly, subduction of a Cretaceous arc occurred beneath southern Tibet during the development of the Gangdese thrust system (Yin et al., 1994; Yin et al., 1999) The southern Tibetan plateau also contains a large amount of lower crust with P-wave velocities and Poisson's ratios typical of intermediate-composition calc-alkaline rocks (Owens and Zandt, 1997), similar to what we infer here from the xenoliths. A partly subducted arc may also make up much of the southern Tibetan lower crust.

The enigmatic potassic magmatism that characterizes Cenozoic Tibet and the southern Pamirs may have resulted from successive dehydration and melting events that consumed mica and amphibole during thermal reequilibration. Although Turner et al. (1996) argued for a subcontinental lithospheric-mantle origin for the late Cenozoic shoshonitic magmatism in southern Tibet, many of the syenites and trachytes in Tibet and the southern Pamirs could represent partial melts of lower-crustal materials (Meyer et al., 1998; Roger et al., 2000). The xenolith data show that dehydration melting of metasedimentary rocks and calc-alkaline arc-like assemblages took place beneath the southern Pamirs, providing support for a lower-crustal origin of at least some of the high-K magmas in the region. The simplest interpretation is that crustal melting is a result of thermal relaxation. Alternatively, lower crustal melting could have been caused by slab break off and associated mantle upwelling (Maheo et al., 2002).

Monazite ages as old as ca. 50 Ma and the absence of retrograde reactions in these lower-crustal xenoliths indicate protracted Cenozoic high-grade metamorphism and minimal exhumation at least through 11 Ma. Despite the large shortening constrained by surface geology (Burtman and Molnar, 1993; Coutand et al., 2002), the lack of decompression and, by inference, the insignificant surface denudation suggest that the area that is now the Pamirs formed a low-relief plateau throughout much of the Cenozoic.

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FIGURE CAPTIONS

Figure 1. A: Central, and southern Pamir Region of Tajikistan and western China with major sutures and magmatic belts on the basis of U-Pb zircon geochronology. Pre-Cenozoic terrane division is primarily from Yin and Harrison (2000). B: Location of Dunkeldik xenolith-bearing volcanic field in southeast Pamirs.

Figure 2. Microphotographs of samples analyzed for U-Pb geochronology. A: Zircon inclusion in garnet from P1309 (plane-polarized light). B: Metamorphic monazite in metapelite P1503a (plane-polarized light). C: Detrital-zircon inclusions in garnet in P1503a (cross-polarized light).

Figure 3. A: Cumulative-probability plots illustrating age groups of zircons from southeastern Pamir xenoliths (red; this paper) compared with two southeastern Pamir monzogranite samples (Schwab, unpublished work) and basement outcrops of Qiangtang block of central Pamirs (Schwab, unpublished work) and Tibet (Kapp et al., 2003). Lower part of diagram shows distribution of detrital-zircon ages of Tethyan and Greater Himalaya successions of southern Tibet and Himalayas (DeCelles et al., 2000). Proterozoic and Paleozoic xenolith zircon ages are most likely of Qiangtang–Lhasa–Greater Himalaya, and thus Gondwana, origin. B: Zircon, monazite, and uraninite ages of magmatic and high-grade sedimentary successions of Hindu Kush–Karakoram (Hildebrand et al., 2001; Fraser et al., 2001) and Kohistan-Ladakh-Lhasa block (Schwab, unpublished work) of Pamirs and Tibet.

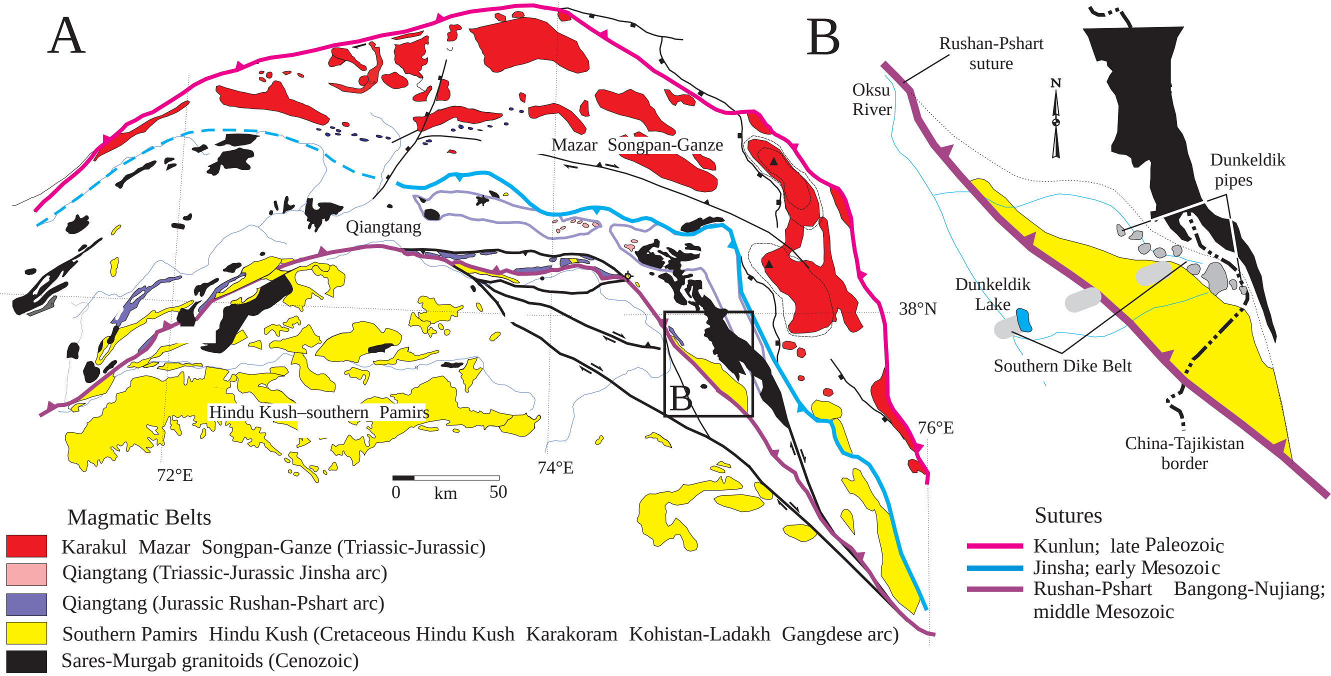

Figure 1, Ducea et al., G19707

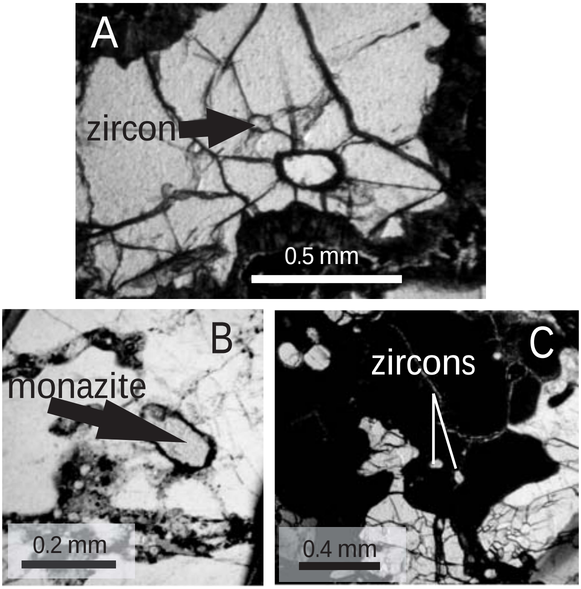

Figure 2, Ducea et al., G19707

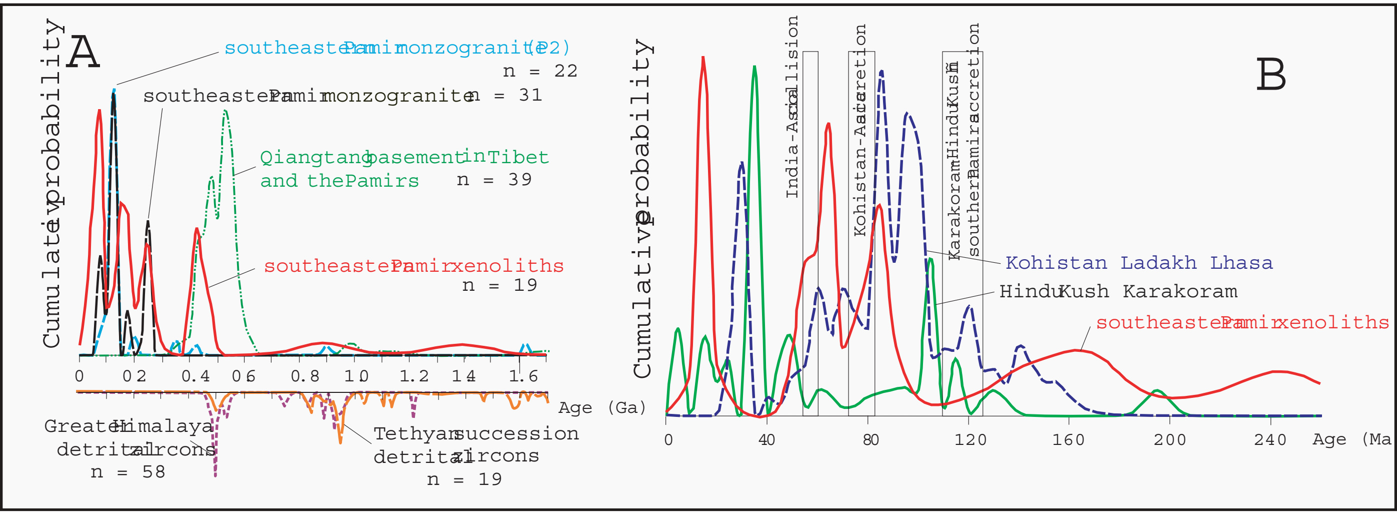

Figure 3, Ducea et al., G19707