Cenozoic and Mesozoic metamorphism in the Longmenshan orogen: Implications for geodynamic models of eastern Tibet

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ABSTRACT

New zircon U-Pb and mica $^{40}$Ar/$^{39}$Ar dating combined with structural studies in the Longmenshan orogen confirm that most of the upper crustal deformation in the eastern margin of Tibet is Mesozoic. However, at lower structural levels, apatite U-Pb and monazite electron microprobe dating reveals a previously unknown domain of Cenozoic (ca. 65 Ma) Barrovian-type metamorphism and deformation. This discovery shows that the crust in the eastern margin of Tibet was already a substantial thickness around the time of the India-Asia collision. Associated deformation has a N-S-oriented stretching lineation, implying that deformation was not driven by topographic gradients in the Tibetan Plateau. The observed moderate amounts of distributed postmetamorphic E-W shortening can probably explain the present thickness of the continental crust in the area. These results do not support models of crustal thickening caused by solid-state lateral flow of midcrustal metamorphic rocks.

Keywords: Tibetan Plateau, radiometric dating, metamorphism, Cenozoic tectonics.

INTRODUCTION

Despite its great elevation, the Tibetan Plateau is remarkably flat (e.g., Fielding et al., 1994). It is generally thought that the lack of great relief is due to the compensating flow of highly mobile midcrustal metamorphic rocks (e.g., Royden et al., 1997). This proposal has lead to a radical new idea in continental tectonics that horizontal outflow of mobile midcrustal rock from topographic highs is one of the principal mechanisms by which plateaus grow laterally (Royden et al., 1997). The best case for such a mechanism is made in the eastern border of Tibet in the Longmenshan. The Longmenshan is a region of relatively thick continental crust (Holt and Wallace, 1990), high elevation, and intense upper crustal deformation (Dirks et al., 1994; Burchfiel et al., 1995; Hou et al., 1995) with clear geomorphological continuity with the rest of the Tibetan Plateau (Clark and Royden, 2000). However, a number of studies have emphasized that the upper crustal deformation in the Longmenshan is almost entirely Mesozoic (Dirks et al., 1994; Burchfiel et al., 1995) and, therefore, unrelated to the India-Asia collision, which began ca. 54 Ma (Rowley, 1996). To explain this discrepancy, Royden et al. (1997) proposed that crustal thickening in the Longmenshan was caused by solid-state influx of mobile midcrustal metamorphic rocks from a topographic high. This proposal is compatible with recent radiometric dating suggesting that the high relief is younger than 12 Ma (Kirby et al., 2002).

To test this model we use zircon and apatite U-Pb, monazite U-Th-Pb, and muscovite and biotite $^{40}$Ar/$^{39}$Ar dating in combination with structural and petrographic observations to constrain the ages of deformation and metamorphism in central Longmenshan. We demonstrate the existence of a previously unknown region of ca. 65 Ma Barrovian-type metamorphism, implying that the Longmenshan crust was already thick at the time of the India-Asia collision and that only minor postcollisional deformation is needed to account for the present thickness.

METAMORPHISM AND DEFORMATION IN THE DANBA REGION

The Longmenshan consists of Triassic flysch and older sediments deposited on the western fringe of the Proterozoic Yangtze craton. This sequence has undergone strong subhorizontal shortening to form a major cleaved fold and thrust belt (Dirks et al., 1994; Burchfiel et al., 1995; Fig. 1). Metamorphism locally reaches amphibolite facies, but is generally low grade. The Longmenshan is intruded by a large number of plutons (Fig. 1).

Figure 1. Simplified geological map of Longmenshan region (after Burchfiel et al., 1995). LS = Longmenshan, SB = Sichuan Basin, TB = Tarim Basin. Letters in rectangles are sample localities.

The Danba area is in the central part of Longmenshan (Fig. 1) and consists mainly of Sinian to Triassic metasediments (BGMRSNP, 1991). The whole region has undergone Barrovian-type metamorphism with progressive changes from chlorite-grade slates into sillimanite-K feldspar schists (Fig. 2A) and estimated peak conditions of ~8 kbar and 700 °C (Huang et al., 2003). Deformed plutonic rocks appear at the lowest structural levels in several culmination (Fig. 2A).

The Danba region has undergone a phase of penetrative ductile deformation, D1 (Figs. 2B, C), with a NNW-SSE-oriented stretching lineation (Fig. 2B). Asymmetric pressure shadows and quartz lenses show a consistent top-to-the-S sense of shear. The alignment of metamorphic minerals shows that the D1 deformation is peak- to postpeak metamorphism.

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The closure temperature for U and Pb in apatite is 500±800 °C (Adachi, 1991) of monazite from sillimanite-bearing pelitic schist (DBT-63). The closure and Adachi, 1991) of monazite from sillimanite-bearing pelitic schist (DBT-63) within the sillimanite zone (DBT51; Suzuki et al., 1994). Ovals give locations and numbers of samples used in dating. B: D1 stretching lineation (N = 114). C: Poles to D1 foliation (N = 211) with best-fit great circle and implied late-stage fold axis. D: D3 fold axes (N = 32) and poles to D3 axial planes (N = 37). A, B, and C are equal-area lower-hemisphere plots produced using Stereonet and contoured at 3σ levels.

Figure 2. A: Geological map of Danba area with stratigraphic boundaries after Xu et al. (1992). Ovals give locations and numbers of samples used in dating. B: D1 stretching lineation (N = 114). C: Poles to D1 foliation (N = 211) with best-fit great circle and implied late-stage fold axis. D: D3 fold axes (N = 32) and poles to D3 axial planes (N = 37). A, B, and C are equal-area lower-hemisphere plots produced using Stereonet and contoured at 3σ levels.

in age. D2 deformation is only locally developed. A stronger phase of deformation, D3, formed folds with N-S-oriented axes and steep axial planes (Fig. 2C). Locally a penetrative axial planar fabric, S3, is developed. Outcrop-scale fold profiles suggest an E-W shortening during D3 of 10%–50%, consistent with the weak development of S3.

AGE OF METAMORPHISM IN DANBA REGION

To estimate the age of metamorphism and constrain the age of ductile deformation in the Danba region, we used two methods of radiometric dating: sensitive high-resolution ion probe (SHRIMP) dating of apatite from granodiorite within the sillimanite zone (DBT51; Fig. 2A) and the chemical Th-U total lead isotope ratio method (CHIME) dating (e.g., Suzuki et al., 1994), and the age of this mineral should closely date the time during the metamorphism at which the monazite grew. The results give an age of 65 ± 3 (1σ) Ma (Fig. 3B), compatible with the apatite age and clearly showing that the peak of metamorphism in this area is Cenozoic. SHRIMP analyses of the rims of apatite grains, where reequilibration is most likely to be complete, give an age of 67 ± 12 Ma (1σ) (Fig. 3A), much younger than the previously assumed Triassic age. Monazite in the high-grade schist sample contains sillimanite aligned parallel to S1 and is contained within biotite (Fig. 3C). These microstructures clearly show that the monazite is a metamorphic mineral. The closure temperature for CHIME dating of monazite is around ~700 °C (Suzuki et al., 1994), and the age of this mineral should closely date the time during the metamorphism at which the monazite grew. The results give an age of 65 ± 3 (1σ) Ma (Fig. 3B), compatible with the apatite age and clearly showing that the peak of metamorphism in this area is Cenozoic.

STUDIED PLUTONS AND RELATIONSHIP TO DEFORMATION

The discovery of Cenozoic regional metamorphism in the central Longmenshan contradicts the generally held view that the tectonic metamorphism in this region is Mesozoic and unrelated to the formation of the Tibetan Plateau. How widespread is this event? The primary constraint on the age of regional deformation and metamorphism in the Longmenshan comes from radiometric ages of posttectonic plutons. There are two major sources of uncertainty in these estimates. First, some of the plutons show moderate to strong deformation. In particular, our field studies have shown that the plutons of the Danba area are strongly deformed (Fig. 4A) and their formation ages give an older limit on deformation, not a younger limit. Second, nearly all the available age data are biotite K-Ar ages, which should give cooling ages and not intrusion ages. The ages show a large scatter from pre-Triassic to Cenozoic (Fig. 5). There has been no attempt to assess the significance of this variation.

To address these problems, we sampled eight granitic plutons from between 28° and 31°N for zircon U-Pb, mica 40Ar/39Ar dating, and structural studies. We define four distinct areas (Fig. 1).

Dahebian Area

The Dahebian area consists mainly of slates and schists locally with amphibolite-grade mineral assemblages intruded by two plutons referred to as Dahebian south (DHS) and Dahebian north (DHN). The main deformation produces a flat-lying schistosity with an E-W-oriented stretching lineation. Subsequent deformation produced a series of upright folds and a locally well-developed cleavage. Both DHS and DHN intrude across the main schistosity. DHS is affected by the upright folding (Fig. 4D).

Xinduqiao Area

In the Xinduqiao area two granodiorite plutons, Xinduqiao and Jaggai, apparently intrude across the axes of regionally developed upright folds and associated faults (Burchfiel et al., 1995). The microstructure of cordierite por-
Gongashan Area

The Gongashan area consists of a large pluton that locally has a subvertical foliation related to movement on the major Xianshui He strike-slip fault (Roger et al., 1995).

Danba Area

The three plutons studied in the Danba area are Gezhong, Dasan, and Danba. All three are locally strongly deformed (Fig. 4A).

FORMATION AND COOLING AGES OF PLUTONS

Dating Methods

In this study we combine zircon U-Pb dating with muscovite and biotite ⁴⁰Ar/³⁹Ar dating. These three methods have contrasting closure temperatures, and the age data can be used to discuss the thermal history of the plutons. Our results can also help verify the geological significance of the ages by observing if they form a predictable sequence corresponding to the order of their closure temperatures. With the exception of the Danba area and one age from the JG pluton, the ages from the three methods are in a sequence compatible with their accepted closure temperatures (Hames and Bowring, 1994; Grove and Harrison, 1996; Cherniak and Watson, 2000).

Because the closure temperature for U-Pb dating of zircon is high, these ages are interpreted as formation ages of the plutons (Table 1). We used cathodoluminescence images to help distinguish inherited cores from in situ growth and mainly measured rims of large idiomorphic grains. All the results plot on concordia and the rim data are consistent at the 1σ level. We carried out ⁴⁰Ar/³⁹Ar dating of single grains of biotite and muscovite with step heating to estimate cooling ages of the plutons (Table 1). Where plateau ages cannot be defined, ages are given as weighted means of consistent steps (Ludwig, 2001). More details of the dating results are available as archive material.

Results and Interpretation of Pluton Age Data

The Dahebian plutons formed ca. 176 Ma and cooled slowly (Table 1), reaching the closure temperature for Ar in biotite 60–70 m.y. after intrusion (Fig. 5A). The slow cooling rate suggests that the pluton intruded into relatively high temperature rocks, and this is consistent with the local presence of amphibolite-grade rocks.

In the Xinduqiao area plutons formed ca. 196 Ma. Two biotite ⁴⁰Ar/³⁹Ar ages are ca. 195 Ma. Other biotite samples showing some signs of subsolidus alteration yielded similar but slightly scattered ages. These results suggest that the plutons cooled to the closure temperature for Ar in biotite within a few million years of intrusion (Table 1; Fig. 5B). Rapid initial cooling is consistent with the low grade of the surrounding Triassic sediments.

In both the Dahebian and Xinduqiao areas pluton intrusion clearly postdates the main tectonic fabrics, showing that the age of regional deformation in these areas is Triassic. The differences in cooling rates revealed here probably reflect differences in the depth of intrusion and may be the principal cause of the wide spread of biotite K-Ar ages (Fig. 5B).

Our new ⁴⁰Ar/³⁹Ar muscovite plateau age of 5.5 Ma (Fig. 5A) from the Gongashan pluton is consistent with the estimated 12 Ma formation age (Roger et al., 1995).

The Gezhong pluton in the Danba area has a U-Pb zircon age of 771 Ma (Table 1), suggesting that this is part of the Yangtze craton (e.g., Roger and Calassou, 1997). The ⁴⁰Ar/³⁹Ar mica ages range from 102 Ma to 48 Ma (Table 1) with a clear cluster around 50 Ma.

1GSA Data Repository item 2003119, Table DR1, sample locations, and Figures DR1 and DR2, details of dating, 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.
It is significant that all of the 40Ar/39Ar ages are younger than any of the results from either the Dahebian or Xinduqiao areas (Fig. 5B). The ages are too diverse over too small an area to be explained as the result of local differences in cooling rates; we propose that the spread in ages is due to incomplete degassing during the ca. 65 Ma Danba metamorphism, the cluster of ages around 50 Ma representing a cooling age (Fig. 5B). Biotite ages older than muscovite ages in sample DBW19C support this interpretation.

**IMPLICATIONS FOR TECTONICS OF EASTERN TIBET**

Our work has confirmed the conclusion of earlier studies that most of the upper crustal deformation in the Longmenshan orogen is Mesozoic. However, we have also revealed the presence of a ca. 65 Ma Danba metamorphism and related deformation in the Danba area. These results give an important test of models that suggest that thickening in the eastern margin of Tibet took place by solid-state midcrustal flow.

The Danba metamorphic rocks represent a zone of ductile flow overlying low-grade rocks deformed nearly exclusively in the Mesozoic and underlain by basement rocks of the Yangtze craton. Both the type and structural position of these metamorphic rocks are consistent with the idea of solid-state intrusion of mid-crustal material. However, deformation in the Danba area is associated with a N-S stretching direction, roughly perpendicular to the line of maximum topographic gradient and not parallel. This implies that the Cenozoic ductile deformation was not driven by gradients in the Tibetan surface topography. We cannot exclude the possibility of rotation of the lineations since their formation, but the presence of consistent Mesozoic fold and foliation trends suggests that such rotation is limited. A second important point is the age of metamorphism and deformation. The presence of high-grade Barrovian metamorphism ca. 65 Ma implies that the crust was already thick before the onset of India-Asia collision (ca. 54 Ma). D3 in the Danba region represents a significant phase of 10%–50% E-W shortening younger than 65 Ma, and we conclude that the D3 deformation is sufficient to explain most, if not all, the development of the present crustal thickness.

Midcrustal flow is a likely cause of the flat topography of Tibet. However, there is no need to invoke this process to account for either the surface geology or crustal thickness of the Longmenshan; we suggest that this process occurs on shorter length scales than those previously proposed.

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