Nyainqentanglha shear zone: A late Miocene extensional detachment in the southern Tibetan Plateau

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ABSTRACT

A major low-angle ductile shear zone containing S-C mylonites involves metamorphosed granitic rocks at the southeastern edge of the Nyainqentanglha mountain range, southern Tibet. Prominent triangular facet geomorphology is developed by valley erosion of the detachment surface, defined by the top of the southeast-dipping mylonitic shear zone. Kinematic criteria consistently indicate a top-to-southeast sense of shear. The ductile shearing deformation is inferred, from isotopic cooling ages, to have occurred during the interval 11-5 Ma (late Miocene). We interpret the shear zone as a regional extensional detachment; its development indicates when the extensional tectonics in this area started, which in turn may mark the time when the maximum sustainable surface elevation, and perhaps crustal thickness, was reached in southern Tibet.

INTRODUCTION

Since the Indian and Asian continents began colliding at about 40–50 Ma, Tibet has been uplifted and its crust thickened, most likely by interior shortening strain induced by north-south compression (Dewey and Burke, 1973). However, the modern tectonic style in this plateau is marked by east-west–trending strike-slip structures that prevail in northern Tibet and by normal faults and grabens accommodating east-west extension that prevail in southern Tibet (e.g., Molnar and Tapponnier, 1978). The change in tectonic style is inferred to mark the time at which maximum sustainable crustal thickness was reached and the crust started to spread under gravitational stresses, perhaps accompanied by eastward tectonic escape movement (e.g., Mercier et al., 1987). In the Basin and Range province of the western United States (Coney and Harms, 1984; Wernicke et al., 1987), in the Variscan belt in central Europe (Ménard and Molnar, 1988), and in the Caledonian belt of western Norway (Norton, 1986; McClay et al., 1986), late orogenic crustal extension subsequent to crustal thickening in convergent or collision belts has also been explained by partial collapse of a thickened crust. In these areas, especially the Basin and Range province, large-scale low-angle ductile shear zones or detachments that show normal faulting shear sense are related to the early stage of extension (e.g., Davis and Lister, 1988; Malavieille et al., 1990). We present here observations from a mylonitic shear zone in southern Tibet, and propose that it is an exceptionally young and lofty example of this kind of low-angle ductile extensional shear zone; the timing of the shearing deformation puts a constraint on when the extension in southern Tibet began.

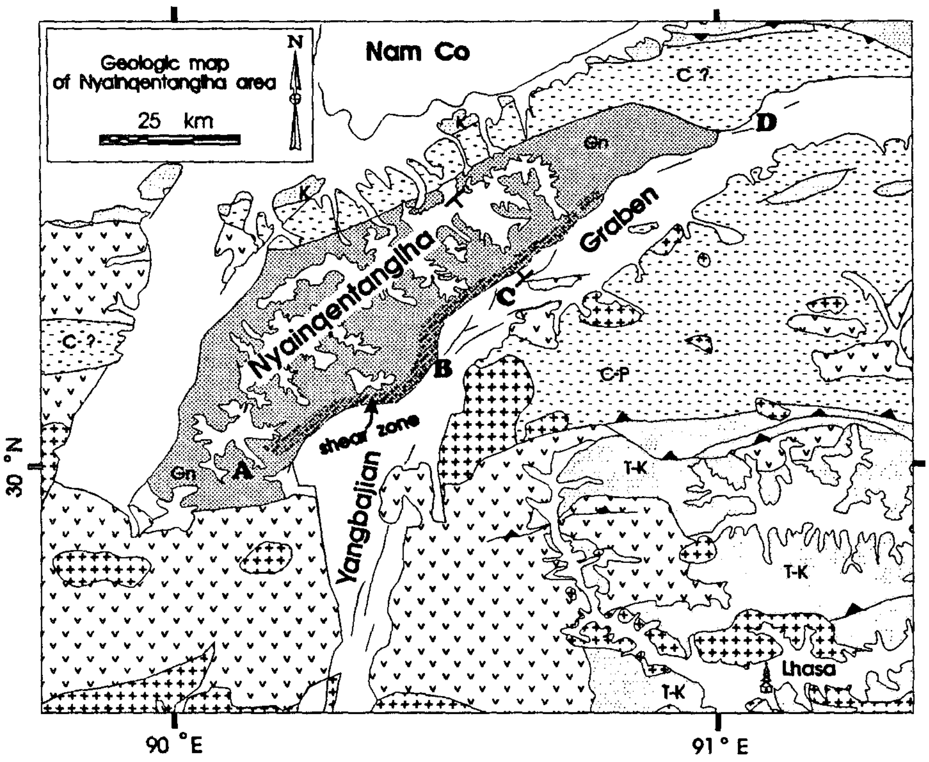

Figure 1. Geologic map (after Kidd et al., 1988) of Nyainqentanglha area, southern Tibet. Plus pattern = Gangdese batholiths, v pattern = Cenozoic volcanic rocks, Gn = orthogneiss, C? = possible Carboniferous sedimentary strata, C-P = Carboniferous-Permian sedimentary strata, T-K = Triassic-Cretaceous sedimentary strata. Lines with teeth are thrusts. Darker band on southeast boundary of area of orthogneiss represents Nyainqentanglha shear zone. Blank areas are either Quaternary sediments or ice cover in Nyainqentanglha Range. A, B, C, D are field locations visited.

SETTING

Series of Quaternary grabens and normal faults are present in the southern Tibetan Plateau (Armijo et al., 1986). The average trend of these structures is north-south, but there is considerable variation. The Yangbajian graben is part of the Gulu-Yadong rift system, the longest rift system in southern Tibet. The Nyainqentanglha Mountains bound the northwest side of the Yangbajian graben and are parallel to it (Fig. 1). The average elevation of the Nyainqentanglha Mountains is about 6000 m; the highest peak is 7162 m, in sharp contrast to the Yangbajian graben, the floor of which is about 4500 m in average elevation. The southern part of the graben is bounded to the east and west by two major faults of opposite dip, while the central and northern parts have a steep southeast-dipping master fault that developed on the southeast margin of the Nyainqentanglha Mountains (Armijo et al., 1986).

The Yangbajian graben cuts across Paleozoic to Cenozoic stratified rocks of the Lhasa block. These contain east-trending folds and thrusts, most of which predate 60–65 Ma, but there are also some south-verging thrusts that disrupted Paleogene (50–60 Ma) volcanic rocks (Coward et al., 1988). To the south and southeast of the Nyainqentanglha Mountains, the Gangdese magmatic belt, containing rocks with ages between

~110 and 40 Ma, crops out to the north of the Zangbo suture zone. These plutons and the Paleogene volcanic rocks are products of northward subduction of the Tethyan ocean prior to the India-Asia continental collision (Xu et al., 1985).

Rocks from the central and southwestern Nyainqentanglha Range consist predominantly of granitic orthogneiss. Peak metamorphic conditions in these rocks reached about 5 kbar and 700 °C, and the rocks have been brought to the surface from depths greater than 12 km (Harris et al., 1988). Xu et al. (1985) reported a zircon U-Pb age of about 50 Ma, with an inherited component of 1.2–2 Ga, which suggests that the plutonic protolith of the rocks was also created by subduction of the Tethyan ocean.

FIELD OBSERVATIONS

A major low-angle shear zone, at least several hundred metres thick, termed here the Nyainqentanglha shear zone, is found at the southeastern edge of the central section of the Nyainqentanglha Range, facing the Yangbajian graben (Fig. 1). This shear zone is truncated by the steep master fault of the Yangbajian graben (see Coward et al., 1988). Highly strained mylonites and ultramylonites of the shear zone are derived mainly from gneissic granitic rocks; major mineral phases present are plagioclase, K-feldspar, quartz, biotite, muscovite, and minor garnet. Two foliations are recognizable in outcrop; one of them is defined by flattened and layered quartz and feldspar; the other is defined by shear surfaces that crenulate and transect the mineral fabric. Similar foliations have been described in tectonites defined as type I S-C mylonites (Lister and Snoke, 1984). The mineral fabric is highly metamorphosed and in many places mylonitic, with quartz ribbons.

In a valley that crosses much of the range at a right angle (Fig. 1, location C), a stack of strongly foliated granitic rocks, ~300 m thick, crops out on the sides of the mouth of the valley, and a strain gradient is clearly visible. The top is a few tens of metres of very fine grained ultramylonites containing quartz ribbons; structurally lower, the intensity of foliation decreases, and the rocks are porphyroclastic S-C mylonites. S surfaces strike ~N40°E and dip southeast about 12°–22°; C surfaces have the same strike but dip 24°–26° to the southeast, giving a top-to-southeast sense of shear. There is strong fabric lineation in the dip direction of the S foliation. The rocks are only weakly foliated about 4 km up the valley from its mouth (structurally ~1 km farther down the section).

In another valley to the south (Fig. 1, location B), which leads to the Goring-la pass, S surfaces strike 035° and dip 10°–15° to the southeast, and the C surfaces dip more steeply, 20°–30° southeast. An upward-increasing strain gradient is observed, but it is less clear than at location C because the very intensely foliated fine-grained mylonites are not present. A down-dip lineation is also well developed here. The normal fault sense of shear is supported by asymmetric intrafolial folds seen in outcrops.

The slope of the southeast mountain front along much of the Nyainqentanglha Range displays prominent low-angle triangular facets, dipping shallowly to the southeast, parallel or subparallel to the orientation of the mylonitic foliation. This is a prominent feature in the geomorphology of the Nyainqentanglha area (Fig. 2). A cross section perpendicular to the range (Fig. 3) is based on topographic maps and field observations. The triangular facets at the top of the shear zone are interpreted to represent an exhumed brittle detachment fault surface developed parallel or subparallel to the shear zone, judging from the smooth and planar feature (only partially dissected), and its spatial relation to the shear zone. A similar but better preserved exhumed detachment surface is described in the very young dome structures in Papua New Guinea (Davis and Warren, 1988).

At location D (Fig. 1), Paleozoic dark phyllites contain a cleavage that strikes about N100°E, dips moderately to the south at about 25°–35°, and is cut by the same high-angle master normal fault as in areas to the southwest. Kink bands in the main cleavage (strike N20°E and dip 75°–80° northwest) indicate a normal faulting sense of shear. This may have resulted from the same extensional stress field that produced the graben.

MICROSTRUCTURES AND QUARTZ c-AXIS FABRIC

All the quartz and some of the feldspar within the shear zone have features characteristic of intracrystalline plastic deformation. The strong strain gradient, with the intensity of deformation gradually increasing up section, is indicated by progressive reduction in grain size.

In the structurally lowest section examined, relatively weakly foliated granite contains feldspar that remains mostly in large grains and shows little evidence of plastic deformation within grains. However, a weak preferred orientation of grain shape is present and defines the S foliation. Quartz shows strong plastic deformation, expressed by common undulose extinction, deformation bands, subgrains, and dynamic recrystallization, with localized preferred orientation of grain shapes. Sutured boundaries suggest grain-boundary migration. Shear surfaces (C) are not well developed.

At a structurally higher position in the section, mylonites have a better developed mineral foliation. Quartz grain size is greatly reduced; feldspar grain size is somewhat reduced. C surfaces are developed along mica-rich zones, and quartz and feldspar within these zones have much finer grain size than adjacent areas. These surfaces transect elongated feldspar and quartz aggregates, displaying a top-to-southeast sense of shear (Fig. 4A).

Structurally farther up the section, shearing

Figure 2. Looking north from near Yangbajian village across Yangbajian graben at Nyainqentanglha Mountains. Low-angle triangular facets formed by dissection of Nyainqentanglha shear-zone dip slope are prominent in geomorphology of southeastern margin of range. High-angle master normal fault of active graben is present in moraines forming edge of the mountains.

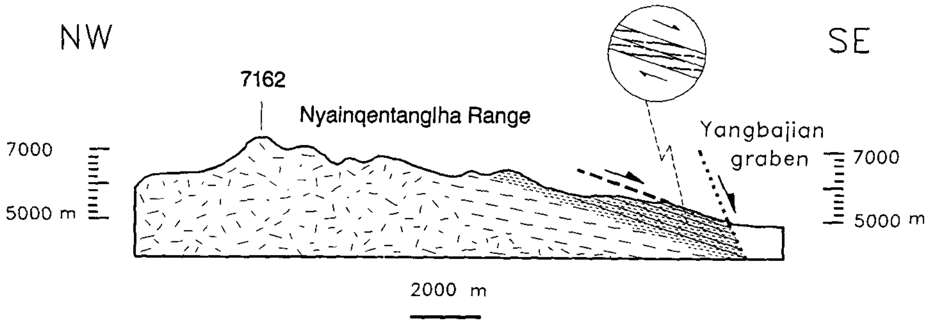

Figure 3. Cross section perpendicular to Nyainqentanglha Range (Fig. 1, location C), looking northeast. Fine-dash pattern = Nyainqentanglha shear zone; heavy dashed line = ultramylonites and detachment surface at top of shear zone; detail shows S-C foliation relations that indicate normal faulting shear sense.

foliations become even stronger, and grain size is further reduced. Quartz aggregates form long bands or layers. They are closely spaced, and parallel or subparallel to the S foliation; the shape-preferred orientation of quartz grains or subgrains is oblique to these bands or layers and forms "downstream imbrication" with respect to a top-to-southeast shear sense. Some K-feldspar grains have plastic deformation features—i.e., deformation bands and mantle-core structures, but subgrains within the host are absent. However, most other feldspars, especially plagioclase, show brittle fractures. The sense of offset shown by fractured grains is consistent with a top-to-southeast shear sense for the zone.

At the exposed top of the shear zone, ultramylonites contain extremely fine grained quartz showing much evidence of dynamic recrystallization. Many feldspar grains have sigma-type tail structures (Fig. 4B) that yield the same sense of shear as other indicators. S and C are parallel or subparallel to each other, but the grain or subgrain boundaries within quartz layers are still preferentially aligned at an acute angle to the elongation of the ribbons, indicating top-to-southeast shear sense. The sense of shear criteria we use was discussed by Simpson and Schmidt (1983) and Cobbold et al. (1987). Quartz c-axis fabrics in mildly deformed samples show a weakly developed cluster. In mylonitic samples, quartz c-axis patterns display moderately to strongly developed type II crossed girdles (Fig. 5). The c-axis maximum is near the center of the net, suggesting that prismatic slip was dominant.

TEMPERATURE AND TIMING OF THE SHEARING DEFORMATION

The shearing deformation in the Nyainqentanglha shear zone most likely occurred in the temperature range 300 to ~500 °C, for the following reasons. (1) Subgrain and deformation bands and preferred orientation of quartz grain shapes suggest temperatures of 300–350 °C (Hirth and Tullis, 1992). (2) Quartz c-axis patterns of naturally deformed quartz commonly show either type I or type II crossed girdles, and the transition from type I to type II occurs at ~300 °C (see Takeshita and Wenk, 1987). Our results show a type II c-axis pattern. (3) The predominant prismatic slip system indicates that the deformation occurred at high temperatures (300–500 °C?; see Takeshita and Wenk, 1987). (4) Most feldspar grains show brittle fractures, whereas some feldspar grains have begun to show plastic deformation without dynamic recovery (lack of subgrains), indicating temperatures of 400–500 °C (Tullis and Yund, 1985, 1987). (5) Large-scale ductile shearing in the crust must occur above 300 °C, as predicted by flow laws for quartz and confirmed by observations (Carter and Tsenn, 1987).

^{40}Ar/^{39}Ar cooling ages from muscovite, biotite, and K-feldspar and fission-track cooling ages from apatite suggest that rocks in and below this shear zone cooled rapidly from

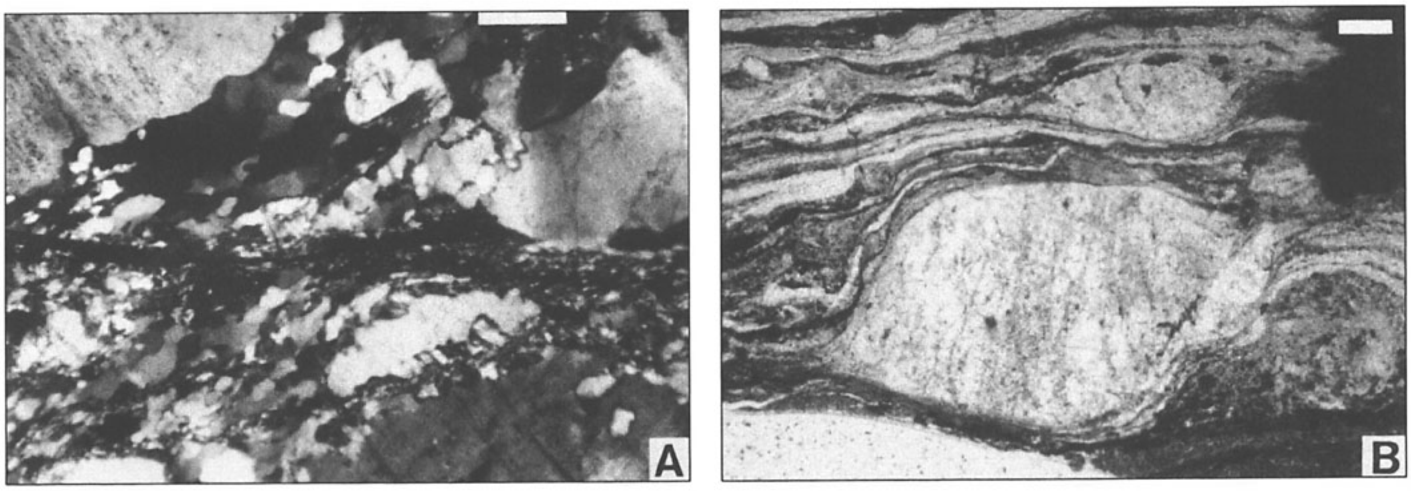

Figure 4. A: S-C relation in mylonite. B: Sigma-type tail structure of K-feldspar grain. Scale bar in each photo = 0.25 mm. Sense of shear is top to right (southeast).

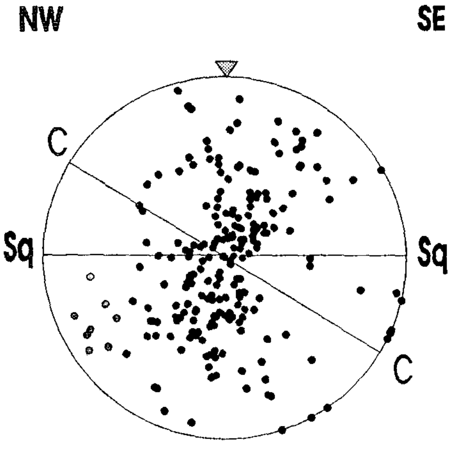

Figure 5. Quartz c-axis pattern of representative mylonite sample (220 measurements). C = shear surfaces. Triangle = pole to quartz grain-shape preferred orientation (Sq). Lower-hemisphere equal-area projection.

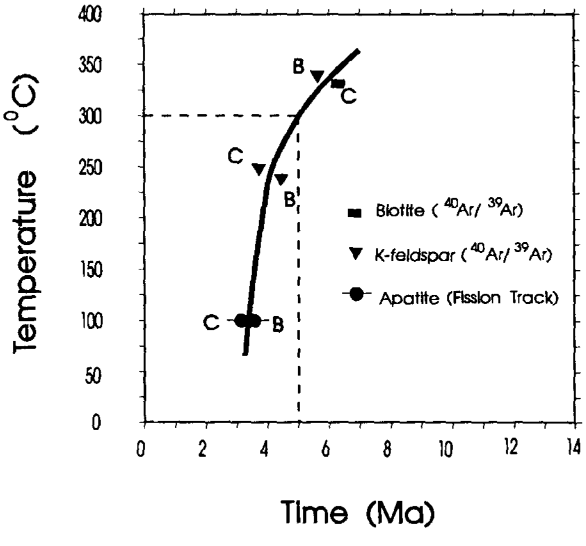

Figure 6. Cooling history of Nyainqentanglha shear zone based on mineral cooling ages and associated closure temperatures. Two sigma error range is smaller than symbol for ^{40}Ar/^{39}Ar ages and is marked for fission-track ages. Closure temperatures for biotite and apatite are taken to be 330 and 100 °C; closure temperatures for K-feldspars are derived from their Arrhenius plots. Data for ^{40}Ar/^{39}Ar ages are from Copeland (1990). B and C refer to sample locations in Figure 1. Dashed line indicates when rocks of shear zone cooled through 300 °C. See text for discussion.

>350 °C to ~ 100 °C between 8 and 3 Ma, and were above 300 °C prior to about 5 Ma, based on data from Copeland (1990) and Pan et al. (1991), the details of which are expected to be published in full elsewhere. Cooling histories of sheared rocks from location B and C are remarkably consistent with each other in the temperature range 350–100 °C (Fig. 6). Because the isotopic system records the latest time at a specific temperature, the deformation, which occurred at temperatures above 300 °C, must have started at ≥5 Ma. A leucocratic vein contained by a calc-silicate xenolith does not penetrate into the sheared rocks and therefore must have formed prior to mylonitization. Two analyses of sphene from this vein yield identical ^{206}Pb/^{238}U ages of ~11 Ma (P. Copeland et al., unpublished). We conclude that the shear zone as a ductile structure was active to ~5 Ma, and started at or later than 11 Ma.

DISCUSSION AND CONCLUSIONS

The Nyainqentanglha shear zone could be (1) a low-angle extensional shear zone that is analogous to the ductile detachment zones in the Basin and Range province and elsewhere in the world, or (2) a rotated low-angle ductile thrust fault. We strongly favor the first possibility, for the following reasons. The Nyainqentanglha Range is the footwall of the shear zone. Tectonic denudation of the footwall of a low-angle extensional fault provides a mechanism for the very young and rapid cooling recorded by the isotopic data. There is a remarkable parallelism between the shear zone and the graben which suggests that they are genetically related; otherwise it would be a curious coincidence, particularly because older shortening structures on the southeast side of the graben are strongly oblique to it (Fig. 1; see Kidd et al., 1988). Tectonites from the shear zone show no evidence of static recovery as would be the case if the zone was a thrust that was unroofed and cooled much later than the deformation. If the shear zone were a thrust fault, a root for the structure should be present on the northwest side of the Nyainqentanglha Range, and the thrust should come out at the surface to the southeast. There is no evidence that indicates the existence of an appropriately large, northeast-trending thrust zone in this general region.

We think that this ductile shear zone can be best explained as a major extensional detachment bounding the Nyainqentanglha Range, whose high-grade rocks represent an associated metamorphic core complex. The shallow-dipping triangular facets on the top of the shear zone prominent in the geomorphology of the southeast margin of the Nyainqentanglha Range are interpreted as the remnants of the tectonically exhumed surface of a detachment. The shearing deformation represents the earliest stage of extension in this region. If this extensional structure is representative, extension began in southern Tibet in the late Miocene (8 ±3 Ma). This occurred when the maximum sustainable surface elevation and, perhaps, crustal thickness, was achieved at this location. The timing is consistent with (1) the oldest sediment fill in the Thakkola graben, north of Annapurna, which is late Miocene (Mercier et al., 1987), and (2) the intensification of the monsoon in the late Miocene (Quade et al., 1989), indicating that the plateau was a large feature at high elevation by that time (Prell and Kutzbach, 1991), which is a precondition of graben formation.

ACKNOWLEDGMENTS

Supported by National Science Foundation grant EAR 87-21026 to Kidd. We thank P. Copeland and T. M. Harrison for discussions; B. Zhu, Y. Zhang, and Y. Xie for making the field work possible; W. D. Means for helpful comments on quartz c-axis fabrics; and B. C. Burchfiel and P. J. Treloar for constructive reviews.

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Manuscript received December 27, 1991
Revised manuscript received June 5, 1992
Manuscript accepted June 17, 1992