Did the Indo-Asian collision alone create the Tibetan plateau?

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ABSTRACT

It is widely believed that the Tibetan plateau is a late Cenozoic feature produced by the Indo-Asian collision. However, because Tibet was the locus of continental accretion and subduction throughout the Mesozoic, crustal thickening during that time may also have contributed to growth of the plateau. This portion of the geologic history was investigated in a traverse through the central Lhasa block, southern Tibet. Together with earlier studies, our mapping and geochronological results show that the Lhasa block underwent little north-south shortening during the Cenozoic. Rather, our mapping shows that ~60% crustal shortening, perhaps due to the collision between the Lhasa and Qiangtang blocks, occurred during the Early Cretaceous. This observation implies that a significant portion of southern Tibet was raised to perhaps 3–4 km elevation prior to the Indo-Asian collision.

INTRODUCTION

Although it has long been recognized that Tibet was the locus of continental collision and accretion since the early Mesozoic (Allégre et al., 1984; Şengör, 1984; Searle et al., 1987), the style and intensity of deformation produced by each accretional event remain poorly documented (e.g., Tibetan Bureau of Geology and Mineral Resources [TBGMR], 1982). To address this issue, we conducted systematic mapping of the Coqin area in the north-central part of the Lhasa block (Fig. 1), during which three thrust systems were documented (Gugu La, Shibaluo, and Emei La) along a 132-km-long north-south traverse (Fig. 2). None of these thrusts appear to have involved metamorphic basement, and thrusts in their hanging walls are cut by plutons that are in turn overlain by essentially flat-lying tuff deposits. Although the ages of sedimentary sequences in the mapped area have been broadly constrained as Paleozoic and Mesozoic by using index fossils (Tibetan Bureau of Geology and Mineral Resources, 1982), the igneous rocks were not previously dated. In this paper we briefly summarize the structural relationships and age constraints for the three thrusts and, in conjunction with allied data, conclude that the southern Tibetan plateau had begun to form during the Early Cretaceous and remained elevated until the Indo-Asian collision began.

GUGU LA THRUST SYSTEM

The north-dipping Gugu La thrust places Cretaceous strata (Gugu La sequence) over Cretaceous (?) conglomerate and volcaniclastic rocks (Burial Hill sequence; Fig. 2a). The thrust has a maximum stratigraphic throw in its central part. Fault slickensides indicate a S10°–20°W transport direction.

The lower part of the hanging wall consists of ~1-km-thick volcanic breccias and volcaniclastic sandstones. Paleocurrent measurements of crossbeds in the sandstone indicate a north-directed paleoflow. The top of the lower section (~800 m thick) is marked by a laterally extensive limestone layer, which contains abundant Early Cretaceous rudist bivalves (TBGMR, 1982). Above it is an ~500-m-thick sequence of fluvial sandstone that records a change upsection from north-directed to south-directed paleoflow. We interpret these paleocurrent measurements to indicate that the early north-directed paleoflow was related to development of the Shibaluo thrust south of the Gugu La thrust (Fig. 2), and the younger south-directed paleoflow was related to the development of a thrust north of the Gugu La thrust.

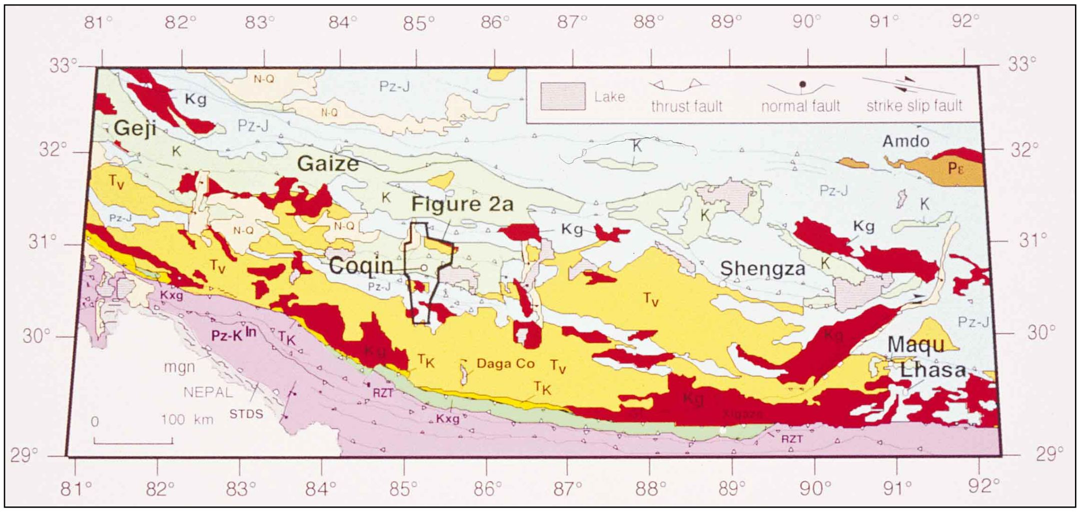


Figure 1. Geologic map of southern Tibet based on mapping published in Tibetan Bureau of Geology and Mineral Resources (1992) and our observations. N-Q—Neogene-Quaternary, T_k—Tertiary Kailas and equivalent conglomerates, T_v—Tertiary volcanic rock, K—Cretaceous rocks in Lhasa block, Kxg—Cretaceous Xigaze Group, Kg—Cretaceous granite, Pz-K^{In}—Indian shelf deposits of Paleozoic to Cretaceous age, Pz-J—Paleozoic to Jurassic sedimentary and volcanic rocks of Lhasa and Qiangtang blocks, mgn—mylonitic gneisses in footwall of South Tibet detachment system (STDS), Pε—Precambrian basement of Lhasa block. Flat-lying, Tertiary volcanic rocks (T_v) unconformably overlie deformed Mesozoic and Paleozoic strata.

Data Repository item 9743 contains additional material related to this article.

The Gugu La hanging wall exhibits south-verging fault-bend and fault-propagation folds at lower structural levels and broad folds at higher structural levels (Fig. 2b). Some hanging-wall thrusts and folds are cut by granitoids (Fig. 2, a and b). Hornblende from a crosscutting granitoid yields an ^{40}Ar/^{39}Ar isochron age of 99 ± 2 Ma, and a K-feldspar from nearby granitoid yields an ^{40}Ar/^{39}Ar age spectrum gradient consistent with a crystallization age >92 Ma.[1] These data are consistent with pluton emplacement at mid-crustal levels into deformed Upper Jurassic and Lower Cretaceous strata by ca. 99 Ma. The magnitude of post–92 Ma denudation is no more than ~6 km, consistent with the widespread greenschist metamorphism in the area. The footwall Burial Hill sequence consists of an upper conglomerate unit and lower volcaniclastic rocks. Clast composition of the ~2.5-km-thick conglomerate correlates with hanging-wall lithologies, suggesting that the deposition of the conglomerate was syn-Gugu La thrusting.

The hanging-wall folds and thrusts are overlain by essentially flat-lying tuff layers. Deuterically altered plagioclase from a sample of this tuff (sample 95-5-18-2) yields an ^{40}Ar/^{39}Ar isochron age of 65 ± 15 Ma (see footnote 1). This age, though with a large uncertainty, is similar to the age of the Linzizhong Formation, a widespread early Tertiary volcanic unit in the eastern Lhasa block (Allégre et al., 1984; Coulon et al., 1986; Pan, 1993).

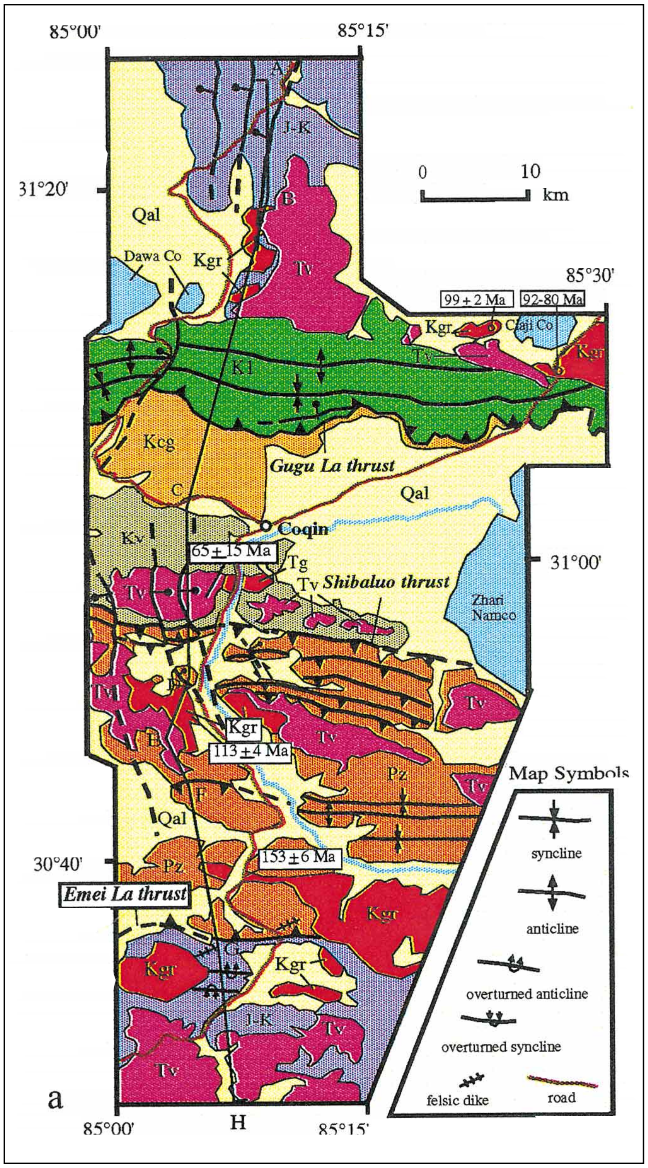
SHIBALUO THRUST SYSTEM

The south-dipping thrust places Carboniferous-Permian strata over the Burial Hill sequence (Fig. 2b). The upper Carboniferous strata is locally repeated by imbricate thrusts between 14 and 20 times in the hanging wall (Fig. 2b). *Glossopteris* foliage was identified in the Lower Carboniferous strata during our mapping.

The hanging-wall imbricate thrusts and folds are north directed and north verging in the north and south directed and south verging in the south. These structures are cut by undeformed granitoids and are overlain by flat-lying tuffs. This tuff unit can be correlated with those in the hanging wall and footwall of the Gugu La thrust to the north on the basis of their similar lithology and flat-lying attitude. A sample (CH-2) collected from a crosscutting granodiorite (Fig. 2) yields a concordant U-Pb ion microprobe zircon age of 153 ± 6 Ma (see Quidelleur et al., 1997, for analytical details; see footnote 1).

EMEI LA THRUST SYSTEM

The south-directed Emei La thrust shares the same hanging wall with the north-directed Shibaluo thrust (Fig. 2b). This thrust juxtaposes the Carboniferous-Permian strata over a Jurassic-Cretaceous sedimentary sequence (TBGMR, 1982). The fault is cut by a granitoid (sample CH-3) that yields a U-Pb ion microprobe zircon age of 113 ± 4 Ma (see footnote 1). The footwall consists of sandstone, siltstone, and mudstone interbedded with monolithologic conglomerates consisting of quartzite cobbles. The footwall strata are either isoclinally folded or repeated by imbricate thrusts. The folds and



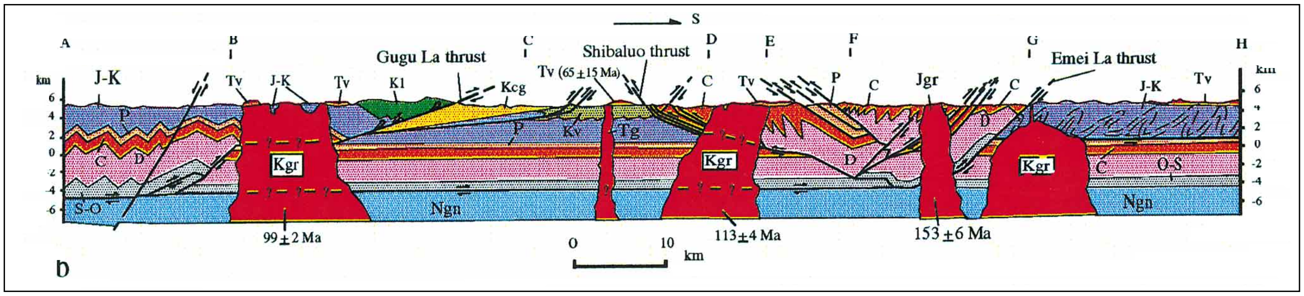


Figure 2. a: Geologic map of Coqin thrust belt based on our mapping at scale of 1:100 000. Locations of geochronologic samples are shown. Fault symbols are as in Figure 1. Qal—Quaternary alluvial deposits, Tv—Tertiary tuff, Kcg—Cretaceous conglomerate, K1—Cretaceous Gugu La sequence, Kv—Cretaceous Burial Hill sequence, J-K—Jurassic-Cretaceous strata, Pz—Paleozoic strata, Tg—Tertiary granite, Kgr—Cretaceous granite. b: Cross section across Coqin thrust belt. Paleozoic strata have been subdivided into Permian (P), Carboniferous (C), Devonian (D), and Ordovician-Silurian (O-S). Thicknesses of strata are derived from both our measurements and those published in Tibetan Bureau of Geology and Mineral Resources (1983). Rocks beneath Carboniferous strata are assumed to be similar to those exposed near Shengza.

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[1] GSA Data Repository item 9743, Ar and U-Pb data tables, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

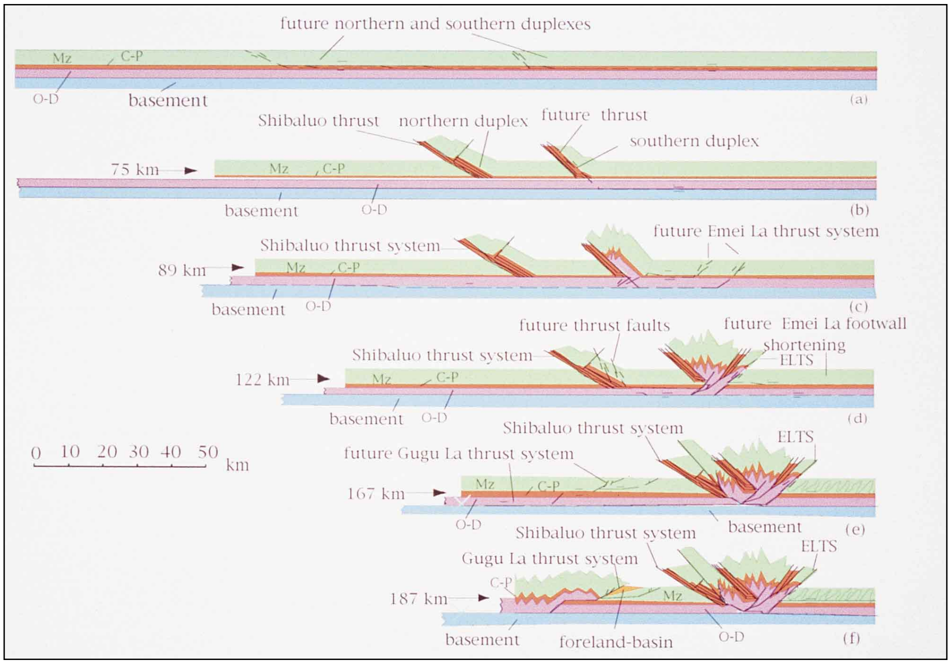

Figure 3. Sequential development of Coqin thrust belt. Strata has been divided into (M) Mesozoic, (C-P) Carboniferous-Permian, and (O-D) Ordovician-Devonian. Basement is assumed to subduct northward beneath Qiangtang block. a: Original length of section is 317 km. b: Development of Shibaluo hanging-wall duplexes. c: Development of a north-directed thrust along south side of southern duplex. d: Development of Emei La thrust system (ELTS). e: Deformation of Emei La footwall and development of north-directed thrusts on south side of northern duplex. f: Development of Gugu La thrust system and deposition of sediment in its footwall. Total shortening strain in this model is ~60%.

faults have accommodated at least 50% shortening. The folded strata are unconformably overlain by flat-lying to gentle-dipping (<12°S) tuff and tuffaceous sandstone (Fig. 2).

TIMING AND MAGNITUDE OF CRUSTAL SHORTENING

Although there are no direct crosscutting relationships between plutons and two of the major thrusts (the Gugu La and Shibaluo) in the mapped area, that the folded hanging-wall strata are intruded by the granitoids and the early Tertiary tuffs are essentially flat-lying argue that the two thrusts ceased activity prior to the deposition of the early Tertiary tuff and probably before the intrusion of the Cretaceous plutons.

Retrodeformable cross sections were constructed to constrain the magnitude of shortening (Figs. 2b and 3). We assume that (1) the Coqin thrust belt is thin skinned, (2) the unexposed strata between Carboniferous and basement rock in the Coqin area are similar to those exposed in the Shengza area (Fig. 1), and (3) the Coqin thrust belt roots into a basal detachment, following the contact between the Nyainqentaghla gneiss and the Ordovician carbonate rocks. The observed fault-bend fold and kink-bend fold geometries are used in the reconstruction. Estimates of stratigraphic thickness were derived from both our own measurements and those previously reported (TBGMR, 1982). We estimate the minimum depth to detachment to be 10 km, on the basis of the thickness of the Paleozoic and Mesozoic strata. The estimated slip along the Gugu La, Shibaluo, and Emei La thrusts are 13, 25, and 15 km, respectively. When considering the magnitude of contraction required by folding and thrusting within each thrust sheet, the total amount of contraction across the 132-km-long Coqin transect is ~187 km (Fig. 3), yielding an estimate of ~60% horizontal shortening.

DISCUSSION

The Coqin thrust belt appears to extend along strike to the east and west. The Cretaceous Takena strata in the Maqu area of the eastern Lhasa block are shortened ~40% (Pan, 1993). The deformed strata are overlain by the gentle-dipping, early Tertiary Linzizhong volcanic rocks (Allégre et al., 1984; Coulon et al., 1986; Pan, 1993), a relationship similar to that observed in the Coqin area. We observed the same relationship in the Geji area in the western Lhasa block (Fig. 1), where Cretaceous strata are folded while the overlying Late Cretaceous to early Tertiary pyroclastic rocks are undeformed. The similarity in crosscutting relationships in the Coqin, Geji, and Maqu areas of the northern Lhasa block suggests a regionally extensive Mesozoic

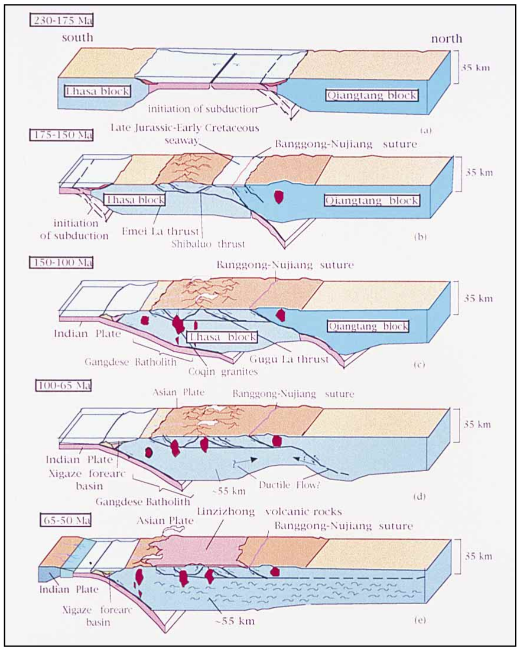

Figure 4. Schematic tectonic development of southern Tibet since ca. 230 Ma. a: Lhasa and Qiangtang blocks are separated by ocean. b: Subduction along south side of Qiangtang leads to its collision with Lhasa block, expressed by development of Emei La and Shibaluo thrusts. Existence of narrow seaway north of Coqin thrust belt has been suggested by occurrence of Upper Jurassic–Cretaceous marine strata (Yin et al., 1994), depicted in b to have formed in response to flexural loading by emplacement of thrust sheets along Banggong-Nujiang suture. c: Continued convergence between Lhasa and Qiangtang blocks leads to south-directed thrusting of Cretaceous marine strata. Shallow subduction of Indian plate beneath Lhasa block produced granitoid magmas that are emplaced into deformed strata. d: Steepening of subducting Indian plate shifts magmatism southward to position of main Gangdese batholith. Fore-arc basin develops, receiving sediments of Xigaze Group. Pure-shear thickening of lithosphere in response to thickening of upper crust. MOHO was smoothed out due to ductile flow in the lower crust, driven by topographically induced pressure gradient (e.g., Bird, 1991; Royden, 1996). e: Deposition of early Tertiary volcanic and pyroclastic rocks (Linzizhong volcanic rocks) unconformably above deformed strata.

thrust belt, which we term the *Northern Lhasa thrust belt*. Our observation of no significant Cenozoic crustal shortening in southern Tibet is consistent with the recently published *Geologic Map of Xizang Autonomous Region* (TBGMR, 1992), which shows that the early Tertiary volcanic rocks in the Lhasa block are essentially undeformed (Fig. 1).

As the Northern Lhasa thrust belt is parallel to and located immediately south of the Banggong-Nujiang suture, and the mostly south-directed thrusts developed during the Late Jurassic–Early Cretaceous, it is possible that the thrust belt developed during the collision between the Qiangtang and Lhasa blocks (Fig. 4). It is also conceivable the thrust belt developed in the back-arc region of the Gangdese magmatic arc, such as the sub-Andean thrust belt in South America (e.g., Isacks, 1988), as suggested by England and Searle (1987). However, we prefer the collisional setting because of the agreement between the timing for thrusting and that estimated for the Lhasa-Qiangtang collision (e.g., Leeder et al., 1988).

Because the Lhasa block underwent little denudation except for its southeasternmost part owing to development of the Gangdese thrust (Yin et al., 1994), the southern Tibetan plateau was mostly created and uplifted from nearly sea level in the Early Cretaceous, as indicated by widespread marine limestones in the northern Lhasa block, to ~3–4 km in the early Tertiary prior to the Indo-Asian collision. This estimate is based on our 60% shortening estimate and the assumption that upper crustal shortening was accommodated by vertically uniform thickening (pure shear), with Airy isostasy as the compensation mechanism. In contrast, if thin-skinned shortening (simple shear) of the Coqin thrust belt was accommodated by northward subduction of the Lhasa basement beneath the Qiangtang block, then a large portion of northern Tibet may have been raised to ~3–4 km with a crustal thickness of 60–65 km during the late Mesozoic. The north-dipping, thin-skinned kinematic model requires a 40 km crustal thickness for the Lhasa block in the early Tertiary and implies that 30 km of its current 70 km crustal thickness was produced either by the development of an Andean-type margin in southern Asia or by combined continental subduction and/or lower crustal injection from India. We prefer the second model because the middle Cretaceous–lower Tertiary Xigaze fore-arc deposits are suggestive of relatively low topography along the southern margin of Asia throughout this interval and an elevated hinterland (Fig. 4; Dürr, 1996).

Mass-balance calculations (England and Houseman, 1986) that assume low elevation throughout Tibet prior to the Indo-Asian collision require that the subsequent ~2000 km convergence between India and Asia be accommodated solely by crustal thickening and sedimentation. Documentation that the southern Tibetan Plateau had attained an elevation of 3–4 km by ca. 99 Ma, and maintained significant topography until the onset of collision, releases this constraint and permits the possibility of substantial eastward extrusion (Peltzer and Tapponnier, 1988), crustal delamination (Le Pichon et al., 1992), or injection and/or subduction of Indian lithosphere beneath Tibet (Argand, 1924; Powell and Conaghan, 1973; Zhao and Morgan, 1987).

ACKNOWLEDGMENTS

Supported by grants from the National Science Foundation, Lawrence Livermore National Laboratory IGPP (Department of Energy, Contract W-7405-Eng-48), and the German Research Foundation. We thank B. C. Burchfiel and M. P. Coward for helpful reviews.

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Manuscript received November 4, 1996
Revised manuscript received April 21, 1997
Manuscript accepted May 12, 1997