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Review Article

Outward-growth of the Tibetan Plateau during the Cenozoic: A review☆

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ABSTRACT

The surface uplift history of the Tibetan Plateau (TP) offers a key testing ground for evaluating models of collisional tectonics and holds important implications for processes ranging from global cooling to the onset of the Asian monsoon. Various models have been proposed to reveal the surface uplift history of the TP, but controversies remain. We evaluate these models using data from sedimentology and stratigraphy, structural geology, magmatism, exhumation, and paleoaltimetry studies. Structural analyses indicate that thrust belts, which spread from the central TP outward toward its surrounding margins, accommodated most of the India–Asia convergence, and facilitated crustal shortening and thickening in the central TP. Eocene adakitic rocks located in the Qiangtang and the Lhasa blocks likely were generated by partial melting of an eclogitic source. Paleogene (50–30 Ma) potassic rocks only occur in the Qiangtang block, whereas Late Oligocene–Late Miocene (26–8 Ma) potassic rocks occur both in the Qiangtang and Lhasa blocks. Low-temperature thermochronologic ages in the central TP are older than 40–35 Ma, whereas those in the margins are younger than 20 Ma (mostly Late Miocene, and Pliocene/Pleistocene in age). Independent paleoaltimetry estimates suggest that the Lhasa and Qiangtang terranes attained their current elevations during the Eocene, most likely due to the initial collision between India and Lhasa, whereas the Hoh Xil basin area to the north and Himalayas to the south were still low, even below sea level in the latter case. We argue for an inside-out growth pattern for the Tibetan Plateau. The TP grew southward and northward from a nucleus of high topography and is likely to continue expanding along the Mazar Tagh fault to the northwest, the Kuantai Shan-Hei Shan-Longshou Shan to the northeast, the Longquan Shan to the east and the Shillong plateau to the south if the northward force of India would not diminished.

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1. Introduction

The India–Asia collision and surface uplift of the Tibetan Plateau (TP) are arguably the most important geological events of the last 100 Ma in Earth's history. The collision directly resulted in the formation of the Tibetan Plateau, with an area greater than 2.5 million km^2 and an average elevation of about 5000 m (Fielding et al., 1994; Figs. 1 and 2). The Tibetan Plateau is widely accepted as a natural laboratory for studying continental collision (Allègre et al., 1984; Molnar et al., 1993) and is linked to the regional climate of Asia and Cenozoic global cooling, as well (An et al., 2001; Raymo and Ruddiman, 1992). In particular, early Cenozoic global cooling from the drawdown of atmospheric CO_2 due to an increase in chemical weathering (Raymo and Ruddiman, 1992); changes in the oceanic Sr–Li isotopic composition in the Paleogene (Misra and Froelich, 2012; Richter et al., 1992); aridification of Asia during the Eocene–Oligocene transition (Dupont-Nivet et al., 2007, 2008); and the onset and intensification of Asian monsoon in the Miocene (Molnar et al., 2010; Quade et al., 1989) have been attributed to the development of the TP. There are also proposals that the Asian monsoon attributed to the TP uplift have direct connections with human cultural evolution in sub-Saharan Africa and the greater Old World (Wang, 2003). Longitudinal river systems that eminate from the Tibetan Plateau served as incubators for the human civilizations of the Yellow River, Yangtze River, Southeast Asia, India, and Persia regions (Fig. 1). These rivers evolved during the Cenozoic time in response to the intracontinental deformation that followed the collision between the Indian and Eurasian continents. Therefore, interactions among the lithosphere, atmosphere, and ocean add significance to studies of the TP beyond continental collision and deformation (e.g., Yin and Harrison, 2000). Temporal and spatial variability of surface uplift is key for understanding TP uplift mechanisms, as well as guiding interpretation of geological processes ranging from global cooling, to the onset of Asian monsoon during the Cenozoic. Nonetheless, the tectonic, topographic, and geodynamic evolution of the TP and its relation to the climate change remain poorly understood.

The manner in which TP topography evolved before and after the onset of collision has remained a lively topic of debate for nearly 90 years (e.g., Argand, 1924; E. Wang et al., 2012; Yin and Harrison, 2000). A number of competing models have been proposed to explain the Cenozoic crustal deformation and surface uplift of the TP. These comprise four categories: (1) *Underthrusting of Indian lithosphere beneath the Tibetan Plateau*. This was first proposed by Argand (1924) and was developed by Powell (1986) who suggested that the underplating Indian continental lithosphere lead to rapid surface uplift of the TP. In addition, the injection of Indian crust into the weaker lower crust of the TP (Zhao and Morgan, 1985) and the insertion of the Greater Indian lower crust into the TP as far north as the northern Qiangtang block (DeCelles et al., 2002) have also been suggested to explain the crustal thickening and surface uplift of the TP. (2) *Rigid-block extrusion and subduction*. Block extrusions along principal strike-slip faults (Tapponnier et al., 1982, 2001) facilitate intracontinental deformation rather than surface uplift, whereas intracontinental subduction of the Asian lithosphere under the TP (Roger et al., 2000; Willett and Beaumont, 1994) provides a mechanism for surface uplift. (3) *Continuum deformation*. This type of model advocates that the north–south shortening of the entire Asian crustal column was continuous (Dewey and Burke, 1973; England and Housemann, 1986) or the entire TP thickened through the convective removal of the lower lithosphere (Molnar et al., 1993). (4) *Lower-crustal channel flow*. This mechanism has been invoked to explain low relief in the interior of the eastern TP and the steep topography between the Longmen Shan Mountains and Sichuan Basin (Clark and Royden, 2000; Royden et al., 1997). This type of model emphasizes the minimal contribution of upper-crustal deformation to surface uplift. However, none of these models uniquely explain all of the geologic and geophysical observations in the Himalayan–Tibetan orogen (e.g., crustal thickness and strength; shortening). Rather, several of these processes likely operated together throughout the orogen and changed in relative importance through time and space.

Understanding the development of high elevation in the TP provides a test for tectonic models. For example, models related to the removal of a convective instability in the upper mantle infer rapid, regional uplift during Late Miocene (e.g., Molnar et al., 1993), whereas models that build the Plateau by addition of Indian crustal material from the south predict a progressive northward increase in elevation from Late Eocene onward (e.g., DeCelles et al., 2002). Models of ductile flow of lower- to middle-crustal material call for gravitationally driven north- and northeastward expansion of the TP (Clark and Royden, 2000), a process that needs to explain the origin of the thick crust in the central TP at the onset of crustal flow. Continuum mechanical models invoking a thin viscous sheet (England et al., 1988) have been used for decades to describe the orogenic development of the Tibetan Plateau. Dayem et al. (2009) showed that for specific set of initial conditions a thin viscous sheet model exhibits substantial strain at the onset of block indentation focused well inboard of the locus of collision, consistent with strong geological evidence for deformation as far north as the Nan Shan and West