Surface uplift of Tibet and Cenozoic global cooling

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Continental weathering on a global scale influences ocean chemistry and imposes a net drawdown of atmospheric CO_2 that modulates global climate (Walker et al., 1981; Berner et al., 1983). This observation, in addition to seawater Sr records that suggest an increase in continental weathering after ca. 40 Ma, led researchers to suggest that the uplift and erosion of the Himalayan-Tibetan orogen over the past 40 m.y. has drawn down atmospheric CO_2 and cooled the globe, leading to the glacial climate that persists today (e.g., Raymo and Ruddiman, 1992; Edmond, 1992). Modeling of tectonic-climate feedbacks associated with increased weathering of the Himalaya and Tibet suggests that two primary biogeochemical processes, silicate weathering and organic carbon burial, can account for the lowering of atmospheric CO_2 necessary to force global cooling (Raymo et al., 1988; Zachos and Kump, 2005). At the time of these inferences, accurate records of both atmospheric pCO_2 and the surface uplift history of the Himalaya and Tibet were lacking. Now, in light of a growing body of atmospheric pCO_2 reconstructions and paleoelevation records, we can test the theory that increased weathering associated with growing mountain belts leads to the drawdown of atmospheric CO_2 and global cooling.

The Eocene-Oligocene transition (EOT) at ca. 34 Ma marks the first major decline in Cenozoic global temperatures and the initiation of Antarctic glaciation. Critical to the argument that continental weathering has caused the drawdown of atmospheric CO_2 is documentation of the temporal relationship between the surface uplift of the Himalayan-Tibetan orogen relative to major cooling events, such as the EOT. Dupont-Nivet et al. (2008, p. 987 in this issue) and other researchers focused on the early elevation history of Tibet (Cyr et al., 2005; Graham et al., 2005; Rowley and Currie, 2006; DeCelles et al., 2007) to provide constraints on the timing and magnitude of the early surface uplift of Tibet (Fig. 1). Rowley and Currie (2006) and DeCelles et al. (2007) use stable isotope paleoaltimetry to show that central Tibet has been at an elevation similar to its modern elevation since ca. 40–26 Ma. Precise age constraints reported by DeCelles et al. (2007) indicate a minimum age of 26 Ma at which high elevations were obtained. However, neither of these studies documents a change in surface elevation that pinpoints the timing of surface uplift in central Tibet. Another paleoelevation study based on stable isotopes in the Hoh Xil basin of north-central Tibet (Cyr et al., 2005) suggests ≤2 km paleoelevation at a loosely constrained age of ca. 35–40 Ma. However, the ability to determine the precise timing of surface uplift of the Hoh Xil basin is limited by the poorly constrained ages of Hoh Xil lake deposits, large uncertainties in applying conventional stable isotope paleoaltimetry in northern Tibet (e.g., Quade et al., 2007), and the lack of a recorded increase in paleoelevation in the Hoh Xil basin. Yet another stable isotope study by Graham et al. (2005) documents a regional trend toward more positive $\delta^{18}O$ values in Eocene to Oligocene time in the southern Tarim basin and western Qaidam basin, north of Tibet, which they attribute to aridification associated with the initial topographic growth of the Tibetan plateau. The lack of good age constraints on these Tarim and Qaidam basin deposits precludes the ability to discern whether this positive shift in $\delta^{18}O$ values preceded the EOT or simply reflects climate change associated with the EOT.

Dupont-Nivet at al. (2008) present pollen data from well-dated sedimentary deposits in the Xining basin in northeast Tibet to evaluate the regional tectonic versus global climatic influences on the flora of northeast Tibet. The value of the Dupont-Nivet et al. study is that it

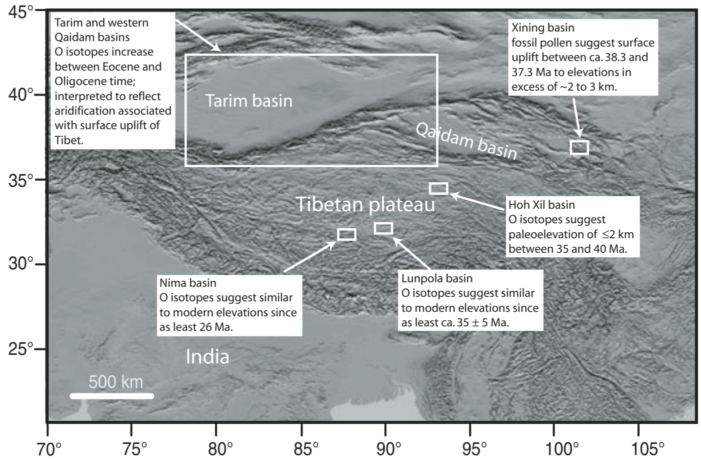

Figure 1. Shaded relief map of the Tibetan plateau and surrounding regions, showing localities of Eocene to Oligocene age basins that have yielded quantitative estimates of paleoelevation.

records a transition to cooler-climate plant taxa within a precisely dated succession of lacustrine deposits. The sudden appearance and increasing abundance of conifer pollen (in particular, *Picea*) between 38.3 Ma and 37. 3 Ma cannot be accounted for by global cooling because this appearance predates the major cooling trend observed at the EOT. Under warm climate conditions, prior to the EOT, the surface uplift of northeast Tibet provides the simplest explanation for the appearance of cool-climate plant taxa. With the knowledge that distal parts of Tibet, far removed from the collision zone between India and Asia, were significantly elevated (>2–3 km) by ca. 38 Ma, it is clear that the surface uplift of vast tracts of Tibet preceded major Cenozoic global cooling. Dupont-Nivet et al. conclude that the surface uplift of central and northern Tibet, prior to the EOT, is therefore consistent with the idea that erosion and silicate weathering associated with large mountain belts lowers atmospheric CO_2, thereby forcing global cooling.

The relation of surface uplift histories to records of continental weathering and pCO_2 is important in understanding the role of mountain belts in the drawdown of atmospheric CO_2. Specifically, does the new constraint on the timing of surface uplift of northeast Tibet from Dupont-Nivet et al. (2008) correspond with an increase in continental weathering and a concomitant decrease in pCO_2? Over the Cenozoic, seawater $^{87}Sr/^{86}Sr$ shows a marked increase, beginning after ca. 40 Ma (Fig. 2), that has been commonly attributed to erosion of the Himalayan-Tibetan orogen (Edmond, 1992; Richter et al., 1992). Interestingly, the greatest change in the rate of $^{87}Sr/^{86}Sr$ increase occurs at ca. 38 Ma at the precise time that northeast Tibet experienced surface uplift based on the appearance of conifer pollen (Fig. 2). Over the entire Cenozoic, multiple proxies for atmospheric pCO_2 indicate a decrease over the middle Cenozoic, from values of several thousand ppmV in the early Cenozoic to values of <500 ppmV by ca. 25 Ma (Fig. 2). During the time period of 40–25 Ma, the only proxy for atmospheric pCO_2 comes from alkenones, and these data suggest the most dramatic decline in pCO_2 occurred between ca. 37 and 25 Ma (Pagani et al., 2005). The close

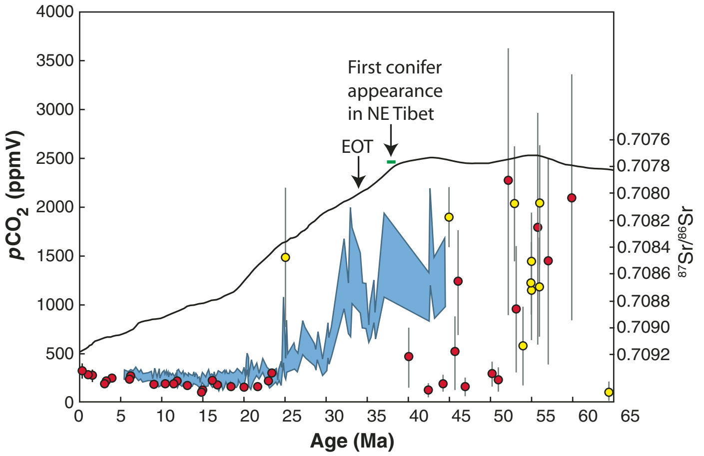

Figure 2. Cenozoic seawater Sr and paleoatmospheric CO_2 in ppmV (parts per million by volume). Sr curve is shown as black line (McArthur et al., 2001) inverted for comparison to the *p*CO_2 curve. Compilation of Cenozoic atmospheric *p*CO_2 proxy records (modified from Tipple and Pagani, 2007). Red circles with error estimates are from boron isotope records (Pearson and Palmer, 2000), yellow circles with error bars are from pedogenic carbonate records (Ekart et al., 1999; Royer et al., 2004), and the blue field shows the upper and lower estimates from alkenone records (Pagani et al., 1999, 2005). Timing of the Eocene-Oligocene transition (EOT) is labeled, and timing of the first appearance of conifers (inferred to reflect surface uplift) in northeast Tibet is labeled with a green bar.

correspondence between the seawater Sr curve and *p*CO_2 supports the inference that continental weathering imparts a significant effect on the drawdown of atmospheric CO_2. The observation that at least northeast Tibet had attained moderate to high elevations by ca. 38 Ma implicates the Himalayan-Tibetan orogen as the source of continental erosion.

What additional information can help to resolve the question "What is the role of the surface uplift and erosion of Tibet on the drawdown of atmospheric CO_2 over the Cenozoic?" Additional paleoelevation studies aimed at understanding both the timing and spatial extent of early surface uplift of the Himalaya-Tibetan orogen are critical to evaluating the role of Tibet in Cenozoic global cooling. Better resolution of the sedimentation records in marginal marine basins will provide more accurate reconstructions of the sedimentary flux from the Himalaya and Tibet (e.g., Clift, 2006) to evaluate whether long-term erosion rates were sufficiently high to impart a global effect on atmospheric CO_2. Recent studies of riverine Sr flux (Bickle et al., 2005, and references therein) have established a solid understanding of the relative contribution of silicate weathering versus carbonate weathering to the riverine flux of Sr to the oceans, and the conclusion for the Himalaya is that approximately half of dissolved Sr in Himalayan rivers is derived from silicates (Bickle et al., 2005). A remaining challenge is to understand the relative contribution of silicate weathering in the Himalayan-Tibetan orogen within the global silicate weathering budget.

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