TECTONICS

Reanimating eastern Tibet

The high eastern Tibetan Plateau was thought to have formed from an inflow of material from the lower crust. The cooling histories of rocks exposed at the plateau margin, however, reveal protracted, episodic growth, suggesting that faulting also played a role.

Michael E. Oskin

The Longmen Shan — Chinese for 'Dragon's Gate Mountains' — rise abruptly along the western edge of the Sichuan Basin. They form one of the steepest edges of the vast Tibetan Plateau[1] and are partly built by active faulting: the devastating 2008 M7.9 Wenchuan earthquake bears witness to such activity[2]. However, both to the north and south, the plateau slopes gradually decrease toward the sea with little hint of fault-controlled topography. This led to the controversial idea that the high topography in eastern Tibet formed when lower crustal rocks from central Tibet flowed east, starting 15 to 10 million years ago, and thickened the plateau from below[3]. Cold crust and upper mantle beneath the neighbouring Sichuan Basin are thought to have resisted the inflow and caused the Longmen Shan to rise up. Writing in *Nature Geoscience*, Wang *et al.* document an earlier phase of mountain building in the Longmen Shan that precedes lower crustal flow, with a pulse of rapid exhumation in the Oligocene epoch that rivals modern rates[4].

The history of mountain building can be reconstructed by dating episodes of rock cooling: rocks get colder as they move towards Earth's surface, their exhumation driven by the combination of faulting and subsequent erosion that removes overlying layers. As they cool, damage tracks and alpha particles generated by natural fission and radioactive decay are retained, rather than annealed or lost (as happens in hot material). The density of these markers can then be used to date the onset and rate of cooling, and thus to reconstruct the history of erosion and infer topographic growth.

Wang *et al.*[4] sampled granitic rocks from the steep slopes within the highest part of the Longmen Shan. They assembled an exceptionally long sample profile spanning nearly 3 km of elevation, and model the cooling history recorded across the suite of the rock samples. Rocks presently exposed at the surface, near the range crest of the Longmen Shan, have early Cenozoic cooling ages, implying that exhumation of the rocks began at this time. Altogether the cooling record shows that about 10 km of overlying rock must have been removed through erosion of the Longmen Shan to expose rocks with such old cooling ages at the surface today. This exhumation occurred largely during at least two rapid pulses. The first pulse beginning in the Oligocene, about 30 to 25 million years ago, rivals modern exhumation rates. A second pulse that began in the Miocene epoch, about 15 to 10 million years ago, continues today. Wang *et al.* use empirical relationships between the steepness of rivers and erosion rate to infer that about 1 km of topographic relief existed across the mountain range before the two exhumational pulses. The elevations must have been higher — perhaps up to 5 km in altitude, like today — during the Oligocene, when exhumation rates were greater.

This protracted history of faulting and erosion conflicts with the view that the eastern Tibetan Plateau and the Longmen Shan rose together in the past 15 to 10 million years as a result of lower crustal flow alone. For the crust to flow, it must become warm and ductile. Such conditions require millions of years of heating within over-thickened crust, and could not have been present in the early Cenozoic, during the initial stages of the collision between India and Asia[1]. Instead, the first topography at the Longmen Shan appears to have formed significantly earlier, before India collided with Asia, and high topography was present soon after collision began, well before the hypothesized flow of the lower crust. The early mountains probably formed by the more conventional means of

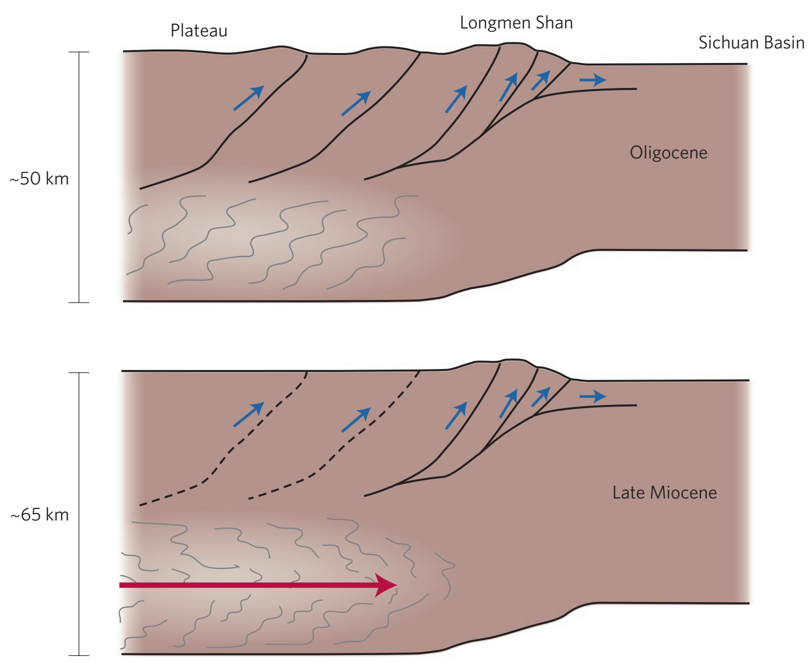

Figure 1 | Schematic cross-sections of the Longmen Shan margin of the eastern Tibetan Plateau. Wang *et al.*[4] document two pulses of rapid uplift and exhumation in the Longmen Shan. The earlier pulse, beginning in the Oligocene (top), was caused by faulting and overthrusting, and occurred at the same time as overthrusting elsewhere in this part of the plateau (blue arrows). This episode of faulting may have made way for the later pulse of uplift (bottom) that started in the Late Miocene and is ongoing today. In this later pulse, it has been suggested that the topography was inflated as a result of lower crustal material flow from central Tibet (red arrow) that could not penetrate past the Sichuan basin and therefore drove uplift of the Longmen Shan[1]. Vertical exaggeration about 2:1.

faulting and overthrusting, where one block of rock is thrust on top of another. Only the latest pulse of topographic growth is likely to have formed commensurate with lower crustal flow.

The cause of such widely disseminated overthrusting early in the evolution of the Tibetan Plateau is unclear. Strain transferred from plate margins into the continental interior through large-scale strike-slip faulting probably played an important part[1,5]. Early episodes of faulting and overthrusting may have even helped prepare eastern Tibet for the final pulse of uplift driven by injection of mobile lower crust[1], by thickening and weakening the crust.

The total amount of faulting and overthrusting documented in the Longmen Shan is substantially smaller than required to account for the volume of thick crust that underlies the eastern Tibetan Plateau. However, the Longmen Shan are not the only mountains that contribute to the high topography in eastern Tibet. Oligocene overthrusting was widespread to the south and west[1], and faulting of a similar style is recognized within the plateau, westward of the Longmen Shan[6]. Together, each of these areas of overthrusting could add considerably to the observed plateau thickness and extent.

The fault structures formed during the early phase of Oligocene overthrusting are cross-cut by the vast expanse of the plateau surface. This cross-cutting implies that the faults formed before an episode of erosion that created the plateau's current low-relief and that the present-day topography largely reflects a younger phase of uplift[7], unrelated to the faulting. Deep incision of large rivers into the plateau surface starting 10 to 15 million years ago also suggests that uplift of much of the plateau occurred simultaneously over length scales too great to be explained by faulting. These observations support the idea that the plateau was later passively uplifted in the Miocene, due to thickening of the lower crust[1,3].

However, Wang *et al.* show that topography did exist on the plateau margin before the Miocene, and thus the view that the plateau surface formed first as a low-elevation peneplain[7] and was then uplifted needs to be revisited. Much of eastern Tibet, including the Longmen Shan, could be a palimpsest of early Cenozoic crustal thickening and mountain growth. Processes that destroy mountainous relief at moderate to high elevations, such as internal drainage[5,8] and glaciation[9], may have played an important role in forming the low-relief plateau surface we see today.

Wang *et al.*[4] show that uplift and exhumation of the Longmen Shan occurred during two distinct and rapid pulses, beginning in the Oligocene and the Late Miocene. The findings add to an emerging picture of early, broadly distributed overthrusting across east Asia in areas presently within or adjacent to the eastern Tibetan Plateau[10], and implies that two distinct mechanisms for topographic growth — faulting and lower crustal flow — together contributed to eastern Tibet's high topography. ❐

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ARCHAEAN BIOGEOCHEMISTRY

Unexpectedly abiotic

Sulphur cycling on early Earth is commonly linked to microbial activity. However, sulphur isotope values from 3.2–3.5-billion-year-old rocks indicate a central role for the breakdown of volcanic sulphur dioxide by ultraviolet radiation instead.

Boswell Wing

The cycling of sulphur on early Earth is thought to have been the domain of microbes. Isotopic reconstructions of sulphur dynamics therefore inform the chronology of microbial evolution[1] and the origins of gene families[2]. The isotopic compositions of sulphur minerals that formed early in Earth's history have led to suggestions that microorganisms that gain energy through sulphate reduction were the primary contributors to sulphur cycling at this time, with possible contributions from elemental sulphur metabolizers[1,3,4]. The main source of sulphur to the biological cycle was the fallout of sulphur species produced in an oxygen-free atmosphere[5]. However, writing in *Nature Geoscience*, Philippot and colleagues[6] report sulphur isotope systematics in 3.2–3.5-billion-year-old rocks that allow for the possibility of a purely atmospheric, and abiotic, sulphur cycle during this time.

In modern anoxic environments, some microorganisms gain energy by coupling the reduction of aqueous sulphate to the oxidation of organic molecules or hydrogen. The ultimate product of this metabolic pathway — hydrogen sulphide — is familiar to anyone who has had a whiff of rotten eggs after sinking their foot into swamp mud. As so many sulphur–oxygen bonds are broken during the transformation, the process is exceptionally sensitive to the relative masses of the reacting species. The hydrogen sulphide produced by microbial sulphate reduction is enriched in the faster-reacting, lightest isotope of sulphur, ^{32}S, relative to the heavier sulphur isotopes — ^{33}S, ^{34}S and ^{36}S. The resultant hydrogen sulphide is highly reactive with iron-bearing compounds, allowing this microbial signature to be preserved in iron sulphide minerals such as pyrite. Strong enrichment of ^{32}S in pyrite is therefore generally taken as an indicator of biological sulphur cycling[1].

Whether the cycling is chemical or biological, the resultant sulphur isotope signatures are expected to follow the same trend, in which $^{33}S/^{32}S \approx (^{34}S/^{32}S)^{0.5}$ and $^{36}S/^{32}S \approx (^{34}S/^{32}S)^{2}$. This is known as mass-dependent fractionation. However, there are a select few processes that do not follow this rule, and produce what is known as mass-independent fractionation. The best-studied mass-independent process is the photolysis of sulphur dioxide gas (SO_2) by ultraviolet light[7]. This photochemical process produces anomalous $^{33}S/^{32}S$ and $^{36}S/^{32}S$ values similar to those found in rocks formed more than