Shifting sources

Atmospheric concentrations of methane — a potent greenhouse gas — have been rising steadily since the Industrial Revolution. This steady rise was, however, interrupted by a plateau in methane concentrations between 1999 and 2006. The cause of this plateau is the subject of some debate as the amount of methane in the atmosphere is controlled by both the magnitude of methane emissions and the availability of reactants to break that methane down. A full account of the methane budget over this interval therefore requires an understanding of how much methane was being produced by various sources, as well as the availability of atmospheric chemicals that decompose methane.

The carbon isotopic composition of the methane can go some way to identify the sources of methane to the atmosphere; the largest sources — fossil fuel burning, biomass burning, and agriculture and wetland emissions — each produce methane with a different isotopic composition. Hinrich Schaefer and colleagues utilize measurements of the isotopic composition of methane contained in ice cores and archived air samples as well as the composition as recorded by a network of monitoring stations to isolate the factors that contributed to the methane plateau (Science 352, 80–84; 2016).

Prior to 1999, methane concentrations and isotopic composition rose in tandem, indicating increasing emissions of methane that had a relatively higher ratio of $^{13}$C to $^{12}$C. The isotopic ratio is consistent with a fossil fuel-like source. However, this trend broke down during the plateau period and, after 2006, methane concentrations started to rise again while the isotopic composition fell. This indicates that the methane being emitted had a lower amount of $^{13}$C, consistent with methane derived from biogenic sources. Box-modelling efforts confirm that the observed trend is best explained by a reduction in fossil fuel-related emissions starting between 1992 and 1993, with possible contributions by changes in atmospheric reactants, namely hydroxyls, whereas the rise in methane concentrations following 2006 is best explained by an increase in biogenic emissions.

Unfortunately, carbon isotopes are not able to readily distinguish between different biogenic sources of methane, for instance ruminant livestock, rice cultivation, tropical wetlands and Arctic permafrost. However, satellite methane measurements rule out any substantial emissions increases in the high latitudes; tropical climate changes over this time would be expected to increase wetland emissions, but not in the areas where the greatest emissions were observed. In contrast, increases in livestock inventories and rice cultivation have been reported for this interval, and methane inventories record increasing methane emissions from agriculture between 2000 and 2006. Thus, it perhaps isn’t surprising that agriculture is having such a large influence on atmospheric methane concentrations.

It is, however, surprising that fossil fuels seem to have less of a contribution, especially given the recent exploitation of both coal and unconventional gas reserves. This finding suggests that carbon budgeting — and mitigation efforts — must closely consider the expansion of agriculture, particularly if the trend towards increased global meat consumption continues.

ALICIA NEWTON

Megathrusts and mountain building

Coastlines above subduction zones slowly emerge from the sea despite repeated drowning by great, shallow earthquakes. Analysis of the Chilean coast suggests that moderate-to-large, deeper earthquakes may be responsible for the net uplift.

Rich Briggs

Charles Darwin was awed and delighted by metres of sudden coastal uplift that accompanied the Concepción earthquake in Chile in 1835. In typical fashion, he posed a startling but clear hypothesis that the high elevation of coastal islands, and by inference the Andes Mountains themselves, had been “effected by successive small uprisings”1. Indeed, it seems intuitive that massive offshore earthquakes could build mighty onshore mountains. Yet, the largest subduction zone earthquakes — great earthquakes of magnitude 8 to 9 or more — typically drown coastlines. Writing in Nature Geoscience, Daniel Melnick2...
integrates analysis of coastal uplift with seismicity records from Chile to argue for a modified version of Darwin’s idea. He suggests that permanent deformation from rare moderate-to-large-sized, deep ruptures may outweigh that from more frequent great, shallow earthquakes, leading to net uplift of the Coastal Cordillera of South America.

The coastline of western South America sits above a subduction zone. Here, the Nazca plate dives below the South American continent along a shallowly dipping fault, or megathrust (Fig. 1). The megathrust is not simply a ramp along which land rides out of the ocean. For example, slip during the monstrous magnitude 9.5 Valdivia earthquake in 1960 instantaneously drowned, rather than elevated, over 1,000 km of coastline. Similar coastal subsidence has been documented along continental coastlines adjacent to most large subduction zone ruptures. The subsidence occurs because Earth’s crust fails elastically. Slip during great megathrust earthquakes typically occurs on patches of the fault located at shallow depths offshore, resulting in a bulge of understa uplift set within a halo of shoreward subsidence. During the hundreds of years between great subduction earthquakes, the warped sea floor and ground surface slowly reverse to near their original positions through elastic and viscous processes. The fault is then primed for the next in a millennial timescale sequence of sudden lurches, during the subsequent great megathrust rupture. However, if the system is best approximated as a yo-yo over millennial timescales, it is not clear how permanent coastal uplift can accumulate.

Melnick approaches this problem by analysing the long-term uplift rate of the central Andean rasa — a 2,000-km-long, elevated and abandoned marine platform in central Chile and southern Peru. This platform is a geomorphologist’s dream because it is preserved at a continental scale, but the sparse and conflicting age data that constrain the timing of formation of this surface mean it can also be a nightmare. Employing an elegant landscape model that accounts for erosion caused by oscillating sea levels, Melnick first establishes that uplift along this coastline has been slow, at less than 0.2 mm per year, steady and broadly uniform since about 3 million years ago. However, he also finds that a non-linear relationship exists between the rate of uplift and the elevation of the central Andean rasa. As in most coastal settings, platform ages and elevations do not simply convert to uplift rates.

Melnick argues that episodic slip along smaller crustal faults in the South America plate, changes in sediment supply and slow contraction of the upper plate between great earthquakes cannot be the root cause of the slow, sustained uplift of the Andean coast. Instead, he highlights the role of an overlooked class of moderate-to-large, deeper earthquakes, such as the 1995 magnitude 8.0 Antofagasta, 2007 magnitude 7.7 Tocopilla and 2012 magnitude 7.1 Constitución events. These ruptures all occurred between 40–45 km depth, directly beneath the coast, well landward of typical great subduction earthquakes (Fig. 1). Each earthquake caused tens of centimetres of coastal uplift. Melnick shows that slip during deep, moderate-to-large ruptures every 1,000 to 2,500 years and affecting 20 to 60 km of coast — values consistent with modern seismic data — would generate the uplift rates recorded by the central Andean rasa. The nagging question, then, is whether coastal uplift from these earthquakes is permanent or reversible.

The key to permanent coastal uplift may lie in the frictional behaviour of the subduction interface. Megathrust frictional properties vary with depth: shallow portions of the plate boundary are termed unstable because they tend to spend centuries locked and then fail in spectacular, large ruptures. By contrast, the deeper interface region beneath and just landward of the coast is termed conditionally stable, because it typically exhibits a rich suite of slip styles including stable aseismic creep, slow deformation and unstable earthquake stick–slip. Failure of the deep, conditionally stable domain during rare moderate-to-large earthquakes may not represent localized strain accumulation and release; if so, these ruptures may cause permanent uplift of the overlying coastline. To borrow a powerful metaphor, earthquake ruptures in this conditional-slip domain may be able to tap into a reservoir of elastic strain energy maintained elsewhere. That is, these earthquakes may convert energy stored at shallow levels in the subduction system into deep, focused deformation. If so, common notions of elastic rebound may require careful reconsideration.

Darwin also speculated that the South American coast is raised by an “insensibly slow rise”, a reasonable description of postseismic slip or afterslip. Afterslip is decaying, aseismic fault motion in the regions surrounding recent ruptures, and is a ubiquitous phenomenon. Deep afterslip following great, shallow earthquakes may play a key role in coastal uplift. If

**Figure 1** | Oblique view of the South American subduction zone at approximate latitude 17.5°S. At the Peru–Chile Trench, the Nazca plate subducts beneath the South America plate. The frictional properties of the plate boundary fault vary on average with increasing depth, leading to different plate slip conditions. The unstable portion (blue) of the megathrust plate boundary fault tends to fail in great ruptures that cause the coastline to subside. However, using a combined analysis of coastal platform uplift and recent seismicity, Daniel Melnick shows that slip on the deeper, conditionally stable (red) part of the plate boundary may lift the coastline, generating net uplift over geological timescales. Dashed portions of the interface denote transitions between average frictional properties. Plate interface depths from the Slab 1.0 model. Map image: Google, Landsat (USGS).
so, deep afterslip and deep moderate-to-large ruptures may both help to reverse subsidence caused during great megathrust earthquakes. This line of thinking can also be applied to continental subduction. For example, deep rupture and afterslip may also contribute to long-term uplift of the Himalaya, despite subsidence in events like the 2015 magnitude 7.8 Gorkha earthquake.12,13

Melnick’s assessment of continental-scale uplift and subduction zone seismicity in Chile implies that over geological timescales the coastline gradually uplifts in response to earthquakes on the deep subduction plate boundary. This counterintuitive result invites careful reappraisal of where and how megathrust strain energy is accrued and spent.

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