would, in turn, imply that the hydrogen we currently see in Titan's atmosphere has a more recent source, such as methane photolysis — a prediction that is borne out by similarities in the D/H ratio observed in hydrogen to that of methane[2].

Another constraint comes from the consideration of the ratio of the nitrogen isotopes $^{15}N/^{14}N$ in Titan's atmosphere. This ratio is higher than that of the Earth. Therefore, if Titan originated with a nitrogen isotope ratio similar to Earth's, it would have had to lose several atmospheres' worth of nitrogen to account for its present value[9]. According to Sekine and colleagues, however, only one atmosphere's worth of nitrogen could have been produced through impacts during the LHB. Thus, if this scenario is correct, the nitrogen isotopic ratio in Titan's atmosphere must have been higher than Earth's from the beginning, necessitating a large gradient in the nitrogen isotopes and distinct nitrogen sources for Earth and Titan in the Solar nebula. Measurements of the $^{15}N/^{14}N$ ratio of ammonia in comets and in the plume from Saturn's moon Enceladus would help to test this proposal.

Finally, measurements of the argon abundance of comets would also help to determine the source of Titan's atmosphere. Although the measured amount of primordial ^{36}Ar in Titan's atmosphere is low, it is not zero, with ratios of ^{36}Ar to N_2 of about 3×10^{-7}. If the scenario proposed by Sekine and colleagues is correct, and comets delivered this argon during the period of LHB, the ratio of ^{36}Ar to H_2O in comets would have to be about 10^{-8}. Argon has not yet been reliably detected in comets, but an upper limit of the ratio of argon to oxygen has been estimated at 2×10^{-4}. This is strongly depleted relative to Solar abundances and consistent with their prediction[10]. Much more sensitive measurements will be required to conclusively test the proposal of Sekine and colleagues.

At the present stage of research, the origin of Titan's atmosphere remains an open question. However, proposals such as the one introduced by Sekine and colleagues[1] provide testable hypotheses that will focus future research. The clues to the mystery lie concealed in the ices and atmospheres of the outer Solar System, and can be unveiled only with more sensitive measurements. ❒

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TECTONICS

Unexpected Andean earthquakes

Great earthquakes along the western, subduction zone boundary of the Andes Mountains in South America are expected. Measurements of surface motion along the eastern boundary highlight the potential for equally large earthquakes in the east.

Nadine McQuarrie

The western margin of the Andes Mountains marks a zone of active plate subduction. As a result, earthquakes larger than magnitude M_w 8.0 are a recurring phenomenon. By contrast, earthquakes within the South American continent along the eastern Andean margin are anticipated to be much smaller, with an estimated maximum size of M_w 7.5 (ref. 1). Writing in *Nature Geoscience*, Brooks and colleagues[2] report that a large section of the fault underlying the eastern edge of the Bolivian Andes is not slipping, despite movement along the fault to the west, and could potentially rupture in a M_w 8.7–8.9 earthquake.

The size of an earthquake is directly proportional to the area of the fault that moves during that event[3]. A fault that makes a shallow angle with Earth's surface cuts through a relatively large part of the strong, brittle crust before reaching deeper levels where the rocks are warmer, more ductile and therefore less able to store and suddenly release energy in an earthquake. As a result, shallow-angle faults have a greater potential to produce a great earthquake than steeply dipping ones whose cross section with the brittle layer of the crust is much smaller. If a fault is locked and cannot slip freely, the elastic energy created by two parts of the Earth's crust trying to move past each other is stored in this non-moving portion of the fault. A critical parameter in understanding and preparing for large earthquakes is documenting the area of a fault that is locked and understanding how much of that locked area will release, generating an earthquake.

Convergence between the Nazca oceanic plate and the South American continent over the past 40 million years or so has folded and faulted the western margin of South America, creating the Andean Mountain chain. At present this contraction is accommodated through movement of the Bolivian Andes with respect to eastern Bolivia and Brazil along a significant fault under the eastern part of the range (Fig. 1). Specifically, the southern Bolivian mountains move towards the stable interior of the continent, at a rate of 7–10 mm yr^{-1}. Although the Andes extend along the entire length of the South American continent, they are widest in northern Chile and southwestern Bolivia (Fig. 1), thus the underlying fault is probably extensive here. To assess the potential seismic hazard associated with this fault, it is critical to understand what portion of it is locked in the brittle parts of the crust.

Brooks *et al.*[2] use global positioning system (GPS) data to measure the surface movement of the southern Bolivian

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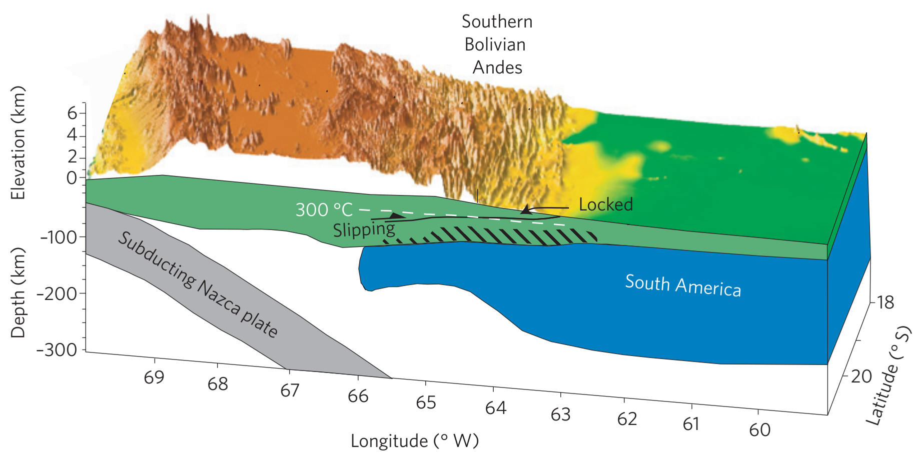

Figure 1 | The southern Bolivian Andes. The western Andes mark the boundary of plate tectonic subduction and are therefore expected to produce great earthquakes. In contrast, the eastern Andes, located closer towards the stable interior of the continent, are not generally associated with large destructive earthquakes. However, Brooks and colleagues[2] show that an 85–100 km section of the fault underlying the southern Bolivian Andes is locked at present and is storing elastic energy that could potentially rupture in a M_w 8.7–8.9 earthquake. Figure modified with permission from ref. 9, © 2002 AGU.

Andes as they move eastward towards stable South America. They show that the measured GPS velocities are best modelled by a fault that dips at a shallow angle of less than five degrees towards the west. They find that the fault is slipping at rates of 9–13 mm yr^{-1} in the west, but is locked over a distance of 85–100 km in the east and is storing elastic energy. The distance over which the fault is locked is an essential parameter in determining the size of any potential earthquake. For comparison, this distance is about 1.5 times larger than locked fault segments measured in Taiwan where earthquakes reach M_w 7 (ref. 4), and is equivalent to estimates from the Himalaya where earthquakes of up to M_w 8.4 have been inferred[5,6].

Another dimension critical to understanding the size of potential earthquakes is the length along the fault that may rupture. If a fault is divided into many segments, instead of producing a single large quake, individual parts may rupture separately in smaller earthquakes. Brooks *et al.* use high-resolution topographic data to identify the surface expression of the locked fault, the Mandeyapecua thrust fault. They propose that areas of high relief mark segments of the fault that move during earthquakes (with individual segments moving during different earthquakes) whereas regions of low relief mark segment boundaries. Through this analysis of topography, Brooks and colleagues find that the fault is divided into five distinct segments. With both a length and width estimate for each segment of the fault, it is possible to use earthquake scaling relationships[7] to assess the potential earthquake size for each fault segment. Brooks *et al.* estimate that individual segments of the fault in the eastern Andes could rupture in earthquakes of M_w 7.2–8.3. However, the largest possible earthquake permitted on the fault — if the entire locked width were to rupture across all fault segments — could be as large as M_w 8.7–8.9.

How often a fault slips is crucial to understanding its seismic potential. If it slips regularly, the stresses are gradually released as small earthquakes rather than in one large, destructive event. Unfortunately there are no data along the eastern front of the Bolivian Andes that provide an age of when the fault last moved. No earthquakes greater than M_w 7 have been recorded in the region[1], thus strain has been accumulating since at least 1700, when observations started. Such a long accumulation period increases the potential of an earthquake of M_w 7 or greater.

Two significant factors could contribute to the unusually large width of the locked fault zone beneath the southern Bolivian Andes, according to Brooks and colleagues. First, the Andes Mountains started off from horizontally layered sedimentary rocks that become folded and faulted as the Andes are built. In this environment, faults develop along the horizontal sedimentary layers, thus there are few natural boundaries — usually vertical discontinuities — that could inhibit slip during an earthquake. Second, Brooks *et al.* suggest that more new rock is added to the mountain range as a result of faults growing and moving the Andes eastwards, than is removed by erosion. This mismatch requires the mountain range to expand outwards, and promotes a widening range underlain by a long, gently dipping fault at its base. In contrast, in the northern Bolivian Andes high precipitation rates and more rapid erosion limit the width of the mountain range[8] and may help to reduce the seismic potential here. Further GPS data in this region could test the contribution of erosion to potential earthquake magnitude.

Brooks *et al.*[2] demonstrate that some parts of the Andes Mountains that are generally not associated with high earthquake risk could potentially rupture in large, catastrophic events. In light of recent earthquakes in Haiti and Japan, these findings should prompt a re-evaluation of other regions that may have great, but underestimated, seismic potential. ❐

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