Orogenic-wedge deformation and potential for great earthquakes in the central Andean backarc

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Subduction of the Nazca plate beneath South America has driven the growth of the Andes Mountains. Subduction has routinely generated earthquakes larger than magnitude 8.0 along the western margin of the mountain belt[1], but the potential size of less frequent earthquakes in the eastern, backarc margin is unknown. Continued support of the high Andean Plateau at the centre of the Andes can be explained only if deformation of the backarc margin is ongoing[2–4]. Here we present GPS data that record surface motions in the Subandean ranges that are part of the backarc margin. We find that the velocity of surface movement decreases sharply from west to east across the Subandean ranges. We suggest that a subhorizontal fault underlying the ranges slips freely at depth in the west, but is locked for up to 100 km in shallower sections further east. Analysis of fault scarps formed where the subhorizontal fault intersects the surface indicates that the fault has generated repeated large earthquakes. We suggest that rupture of the entire locked section of the fault could generate an earthquake of magnitude 8.7–8.9. We attribute the large seismic potential to the unusual width of the Subandean ranges, and suggest that deformation of the Subandean ranges, at a rate unmatched by erosion, causes the mountain range to widen.

The central Andean Plateau (AP) is a bilaterally symmetric plateau of $\sim$4,000 m average elevation (Fig. 1). Although AP uplift scenarios are currently debated[5,6] it is generally accepted that the backarc orogenic wedge on the AP's east flank, comprising the Eastern Cordillera (EC), Inter-Andean zone (IAZ), and Subandes (SA), has contracted by more than $\sim$250 km since $\sim$45 Myr ago (refs 7–9). Wedge deformation has been facilitated by the presence of weak, subhorizontal decollement horizons in a 6–12 km thick pile of Palaeozoic marine sediments[7], the along-strike continuity of which gives the southern SA (SSA) its long, narrow anticline-cored ridges (Fig. 1b). Across-strike, the SSA is more than 100 km wide and workers have appealed to coupled tectonics and erosion models to suggest that a dry climate over millions of years promoted the relatively large width[10].

Modern geodetic studies document $\sim$63 mm yr^{-1} of Nazca–South America convergence at the latitude of the AP, a rate that has decelerated over the past 10–20 Myr (ref. 11). Near the Chile trench, ephemeral locking and release of the main plate interface as part of the subduction earthquake cycle dominates the surface displacement field[12,13]. In the backarc, plate boundary locking also significantly contaminates the velocity field along much of the Andes[14]. The AP's east flank in Bolivia, however, is located $\sim$500 km inland, far enough that plate boundary locking contributes less than 10% to the measured velocity ($<\sim$1 mm yr^{-1}), allowing the orogenic wedge's velocity field to be isolated[13]. Because the early GPS measurements in the backarc were spatially sparse, interpretation with respect to wedge-specific processes has been limited[15].

In a South America fixed reference frame, we present a new GPS velocity field for the backarc derived from reoccupations of the network that we augmented in 2000 and 2003 (Fig. 1, Supplementary Information S1). Although the velocity magnitude decreases away from the trench and vectors are subparallel to Nazca–South America convergence, as expected, the new results demonstrate a sharp backarc velocity decrease from $\sim$10 to $\sim$2 mm yr^{-1} over $\sim$25–100 km (Fig. 2). The velocity gradient is offset by $\sim$100 km to the west from the topographic front of the SSA and we model it as a single dislocation in an elastic half-space that approximates a frictional stability transition on the basal decollement from freely slipping (towards the mountain interior) to fully locked (towards the craton). We compare model and data using Monte-Carlo based methods and do not model fault geometry variations in the trench parallel direction, allowing reduction of the number of free parameters to six: width of the locked zone (W_L, equivalent to distance from the deformation front), depth to the lower boundary of the locked zone (Z), dip (dip), strike ($strike$), strike-slip (U_1), and dip-slip (U_2) (Supplementary Information S2). Because we use only horizontal velocities in our inversion, Z is more poorly constrained than if vertical velocities were used[16]. We mitigate this by using balanced cross-sections from the region[7–9] to assign an a priori constraint on Z of 10 ± 5 km.

The well-constrained parameter distributions (Fig. 2a–f) demonstrate that, at better than 95% confidence, the decollement is gently west-dipping ($<5°$), slipping at rates of 9–13 mm yr^{-1} (U_2) and 1–3 mm yr^{-1} (U_1 dextral), and that its locked width, W_L, is $\sim$85–100 km. The estimated dip-slip range agrees with Quaternary geologic shortening rate estimates of 7–10 mm yr^{-1} (refs 17,18; because the geologic estimates assume plane-strain it

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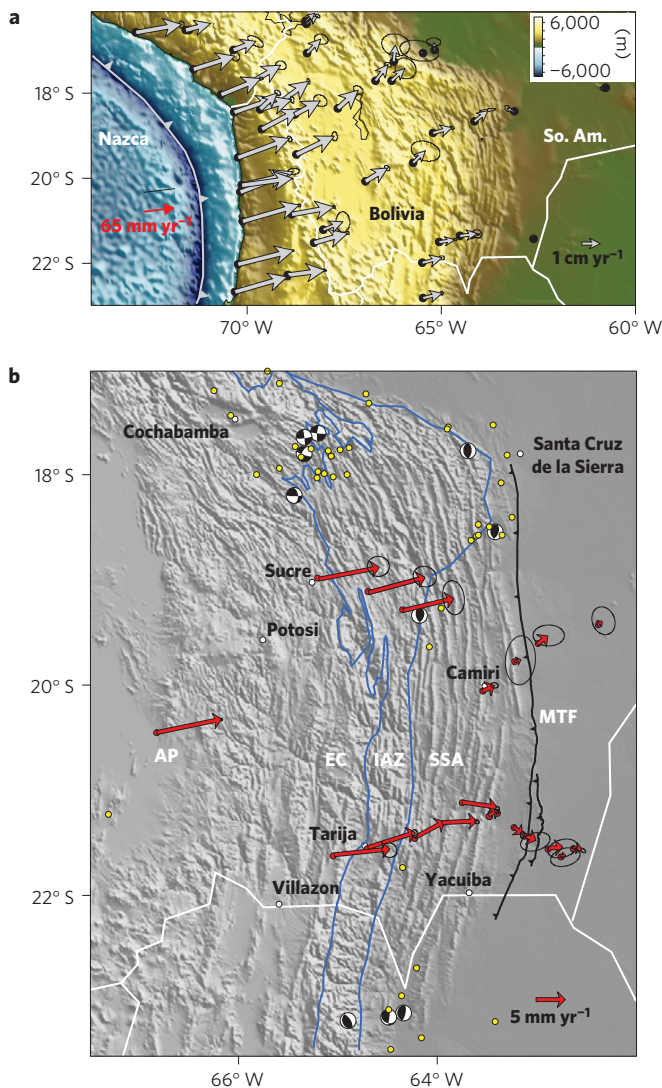
Figure 1 | GPS velocity fields in a South America-fixed reference frame.
a, Topography of the central Andes and regional velocity field (grey vectors) from ref. 13. Black arrow, Nazca–South America plate convergence vector. Grey triangles, trace of Nazca–South America subduction boundary, pointing in the down-dip direction. **b**, Shuttle Radar Topographic Mission (SRTM) topography and new velocity field from the SSA (red vectors). All error ellipses are 2σ. Focal mechanisms are for crustal events (<33 km) in the Global Centroid Moment Tensor (CMT) database with magnitudes that range from 4.9 to 6.6. Yellow circles, National Earthquake Information Center (NEIC) epicentres for crustal events. Blue lines, limits of physiographic provinces. AP, Andean Plateau; EC, Eastern Cordillera; IAZ, Inter-Andean zone; SSA, southern Subandes. Black triangles, trace of Mandeyapecua thrust fault (MTF), pointing in the down-dip direction.

is appropriate to compare only with U_2 estimates). In comparison to other active wedges, estimated W_L for the SSA is ~1.5 times as large as Taiwan, where there is a history of ~M_w 7 decollement earthquakes[19], and it is equivalent to estimates from the Himalayan wedge, where earthquakes up to M_w 8.4 have been inferred[16,20]. Furthermore, for quartzo-feldspathic rocks, the slipping-to-locked transition where frictional behaviour changes from velocity-strengthening (promoting continuous creep) to velocity-weakening (promoting stick-slip) is typically close to ~300 °C (ref. 21), and our analysis agrees well with this relation: the 300 °C contour from a recent comprehensive determination of the SSA geothermal gradient[22] intersects the decollement

within the 95% confidence region of the estimated slipping-locked transition (Fig. 2g).

How continuously accumulating slip is released along the locked portion of the decollement is critical in determining the wedge's seismic potential. Owing to their velocity weakening properties, fully locked fault patches typically exhibit stick-slip behaviour[21], leading us to expect that, as in other seismically active wedges, earthquakes in the SSA could episodically relieve the accumulated slip[16,19]. Along the Himalayan front, for instance, where the geodetically estimated accumulation rate is equivalent to the Holocene slip rate in the frontal Siwalik hills[23], the total amount of accumulated slip is apparently transferred to the wedge front in earthquakes that rupture the entire locked width and cause shallow fault-related folding and/or surface ruptures[20]. Along the SSA front, because there is no suitable Holocene chronostratigraphy with resolving power at the 100–1,000 yr repeat times of typical seismic cycles, we cannot quantify the relative probability of accumulated slip propagating to the thrust front versus activation of any other structure in the locked zone. Identification of multiple ~N–S trending fault scarps associated with the mapped trace of the ~500 km long Mandeyapecua thrust fault (MTF; ref. 24; Figs 1, 3), however, combined with the lack of surficial neotectonic evidence associated with any of the other SSA structures, strongly suggests that the most recent events have seismically ruptured the wedge front.

Closer examination reveals that the MTF surface expression is divided into five topographic segments (Fig. 3a), exhibiting relief profiles characterized by central maxima tapering towards ~zero-valued inflection points that may indicate persistent rupture segmentation (Fig. 3b, Supplementary Information S4). For each segment we consider a range of rupture aspect ratios and use standard scaling relations[25] to estimate that potential earthquake magnitudes range from M_w 7.2–8.3 (Fig. 3b, Supplementary Information S5). Given the small spatial scale of the segment boundaries, it is likely that they are not substantial enough to act as barriers for all dynamic ruptures[26] and it is reasonable to consider that a single earthquake could rupture the entire MTF. In this endmember scenario, if the entire locked width, W_L, of the decollement were to rupture, we estimate a maximum slip of ~10 m (Fig. 3c) and M_w values as high as 8.7–8.9 (Fig. 3d). These are probably conservative estimates: 10 m may be a low value for coseismic slip given the recent interpretation of much larger single-event slip magnitudes from palaeoseismic investigations of the Himalayan thrust front[20]. Furthermore, it is possible that coseismic rupture could extend below the lower boundary of the locked zone[21]. For both segmented and non-segmented rupture scenarios, the amount of time needed to accumulate the necessary amount of fault slip ranges between ~150 and 1,000 years (Fig. 3b,e), although if as-yet-undetected slow slip events occur on the decollement then recharge estimates could be longer. Considering the complicated way in which stress from accumulating slip and before-slip events is distributed on the decollement, we cannot determine how close to failure the MTF system is, although we can make valuable estimates. The earthquake catalogue is expected to be complete for M_w 7–8 since 1886 and 1700, respectively[27], and no events this size have been reported. Thus, it is likely that enough slip has accumulated since 1886 for a ~M_w 7 rupture.

The potential for great backarc earthquakes in the SSA stems from the large fault area available for seismic rupture. Along strike, fault rupture dimension is controlled primarily by the stratigraphic continuity of the Palaeozoic decollement horizons[7]. To better understand the physical controls on across-strike rupture dimension (measured by W_L) we appeal to critical taper theory[28], which states that to attain a steady-state width, a deforming
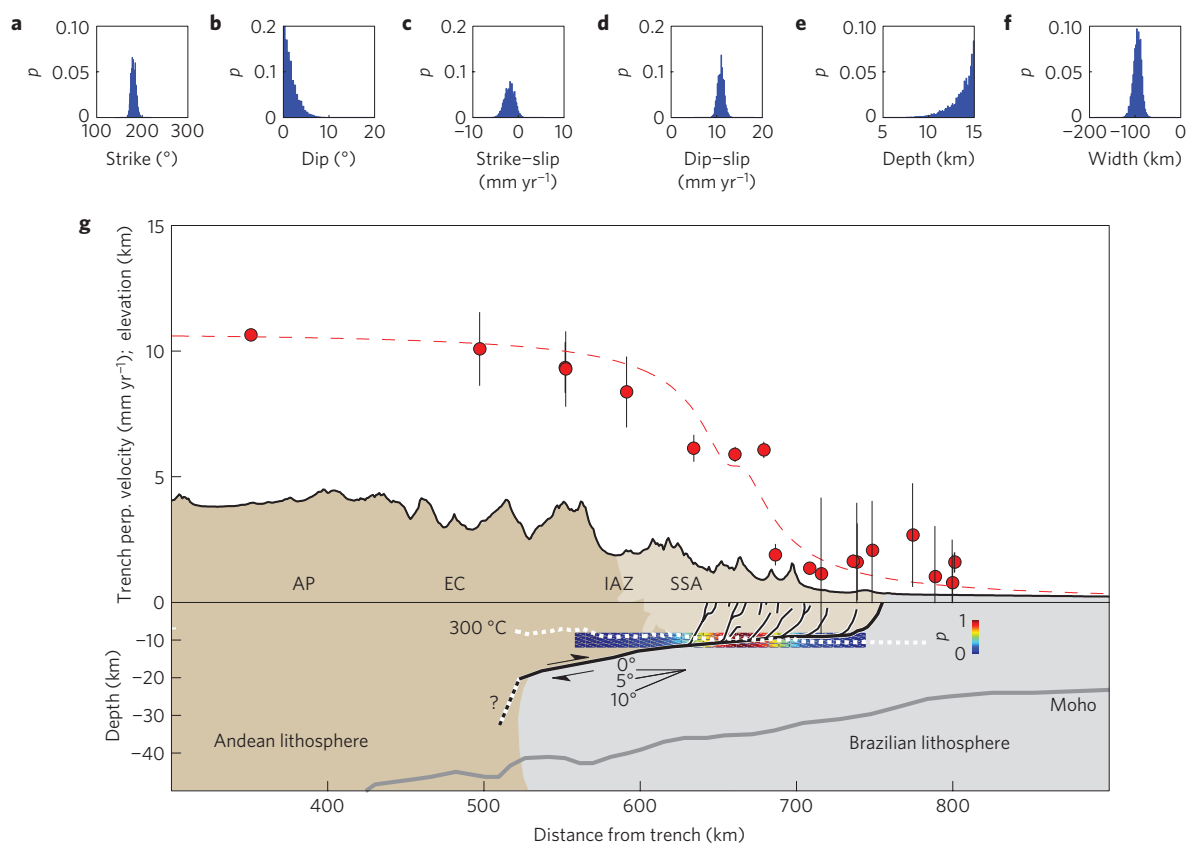
Figure 2 | Marginal posterior probability distributions (PPDs) for estimated dislocation parameters and a cross-section at 20° S. a, strike, (**b**), dip, (**c**), strike-slip (dextral, negative), (**d**), dip-slip, (**e**), depth, (**f**), locking width, W_L. **g**, Red circles, trench-perpendicular component of all new GPS velocities from Fig. 1b with 2σ error bars. Red dashed line, best model from inversion (strike, 181°; dip, 0.1°; strike-slip, -1.5 mm yr^{-1}; dip-slip, 11.1 mm yr^{-1}; depth, 14.9 km; W_L, 94 km). Black lines, topographic profile. Rainbow shading, PPD for W_L at 10 km depth. Black lines in subsurface, faults from regional cross-section[18]. White dashed line, 300 °C isotherm calculated from the geothermal gradient[22].

orogenic wedge must reach a mass balance between accretionary flux, F_A, into, and erosional flux, F_E, out of, the wedge. Non-steady wedges that have greater F_A, lesser F_E, or are underlain by lower friction decollements, will strive towards larger widths by means of cratonward propagation of the wedge tip, which will also lead to an increase in W_L. We can evaluate the mass balance in the SSA. From our geodetically estimated slip rate ($\sim$9–13 mm yr^{-1}) and published Quaternary shortening rates (7–10 mm yr^{-1}; refs 17, 18), and assuming an accretionary thickness of $\sim$10 km from the balanced cross-sections, we estimate F_A ($\sim$70–130 m^2 yr^{-1}) to be significantly larger than F_E estimates ($\sim$50 m^2 yr^{-1}) determined from SSA-wide denudation rates over similar time periods[29] (10^2–10^6 years, Supplementary Information S3). Thus, unless the excess mass is accommodated by active, as yet undetected Quaternary shortening in the IAZ or EC to the west, the SSA has been in a transient state that favours widening. The non-steady conditions have probably persisted since at least $\sim$6 Myr ago, when the wedge front began propagating rapidly towards the craton, in concert with an increase in SSA shortening rate from $\sim$1.5 to $\sim$11 mm yr^{-1} (ref. 18). During that same time, there is no evidence to suggest that F_E would have decreased: on the contrary, SSA precipitation rates (and, presumably erosion rates) seem to have steadily increased despite the generally dry climate[6,30]. We infer, therefore, that the great seismogenic potential in the SSA is attributable to some combination of an increase in accretionary flux and material properties (stratigraphic architecture and thermal gradient) that have governed the growth of the contractional wedge and the depth of the transition to velocity-strengthening behaviour.

This paper has focused on the physical processes governing orogenic wedge deformation and seismicity that are elucidated by the new geodetically defined surface velocity field and existing SSA topography. Of more pressing import, however, is that the SSA is host to a population of more than two million people and associated infrastructure that, our analysis shows, are exposed to significantly underestimated seismic hazard. Owing to its relative quiescence, the most recently published seismic hazard assessment for the SSA considers the maximum expected earthquake size to be M_w 7.5 (ref. 27), in comparison to our estimates of M_w 8.7–8.9 (Fig. 3d).

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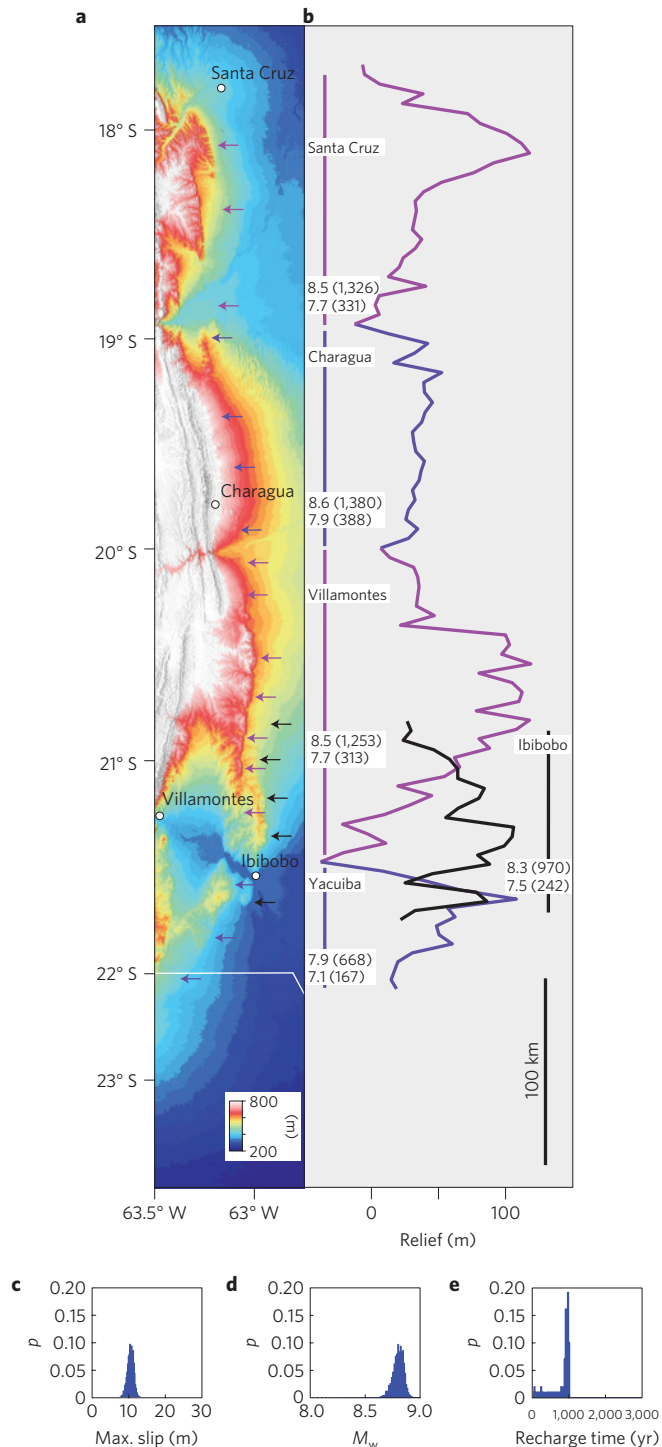
Figure 3 | Topographic analysis of the Mandeyapecua Thrust Front and estimated maximum earthquake parameters. a, SRTM Topography. Coloured arrows, segment fault traces; colours correspond to **b**. See also Supplementary Figures SI3-8. **b**, MTF relief (median hanging wall minus median footwall elevation). Vertical coloured bar indicates estimated range of M_w and recharge time, in parentheses, for each segment. **c–e**, derived parameters: maximum slip (**c**), moment magnitude, M_w (**d**), and recharge time (**e**, slip rates taken from Fig. 2d) for the case where rupture is of the entire locked width (taken from Fig. 2f) and entire length of the MTF.

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Author contributions

B.A.B. designed the study, collected GPS data, processed GPS data, performed all analyses and wrote the paper. M.Bevis contributed to the study design, GPS processing approach and data collection. K.W. and J.R.A. contributed to geomorphic analysis. J.F. contributed to the GPS processing approach. T.Z. contributed to the study design and geological interpretation. E.K. collected GPS data and contributed to the GPS processing approach. E.M. contributed to regional seismological analysis. A.E. contributed to the study design and GPS data collection. M.Blanco, P.E., M.S., and R.J.S. Jr collected GPS data. All authors discussed the results and commented on the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.A.B.