nature geoscience

LETTERS

PUBLISHED ONLINE: 8 APRIL 2012 | DOI: 10.1038/NGEO1447

Abrupt change in the dip of the subducting plate beneath north Chile

E. Contreras-Reyes[1]*, J. Jara[1,2], I. Grevemeyer[3], S. Ruiz[1]* and D. Carrizo[1,2]

No large tsunamigenic earthquake has occurred in north Chile since 1877 and the region has been largely recognized as a mature seismic gap[1–9]. At the southern end of the seismic gap, the 2007 M_w 7.7 Tocopilla earthquake ruptured the deeper seismogenic interface, whereas the coupled upper interface remained unbroken[4,6,7]. Seismological studies onshore show a gently varying dip of 20° to 30° of the downgoing Nazca plate[3,6], which extends from the trench down to depths of 40–50 km. Here, we study the lithospheric structure of the subduction zone of north Chile at about 22° S, using wide-angle seismic refraction and reflection data from land and sea, complemented by hypocentre data recorded during the 2007 Tocopilla aftershocks[7]. Our data document an abrupt increase in the dip of the subducting plate, from less than 10° to about 22°, at a depth of approximately 20 km. The distribution of the 2007 aftershocks indicates that the change in dip acted as a barrier for the propagation of the 2007 earthquake towards the trench, which, in turn, indicates that the subduction megathrust is not only segmented along the trench, but also in the direction of the dip. We propose that large-magnitude tsunamigenic earthquakes must cross the barrier and rupture the entire seismogenic zone.

The Chilean subduction zone is an extremely active convergent margin producing large earthquakes ($M_w > 8$) about every ten years and capable of generating at least one tsunamigenic megathrust earthquake per century. These earthquakes occur in the seismogenic contact between the subducting oceanic Nazca and overriding continental South American plates. In particular, north Chile (19°–23° S) has been identified as a mature seismic gap not having experienced a tsunamigenic megathrust earthquake since the Iquique event in 1877 (M_w 8.8; refs 1–9). The rupture zone of this historic event is bounded in the north and south by the 1868 (M_w 8.8; ref. 2) and 1995 (M_w 8.1; ref. 3) earthquake rupture areas, respectively (Fig. 1a). An important portion of the southern Peru 1868 earthquake rupture area broke in 2001 with the Arequipa megathrust earthquake (M_w 8.4; ref. 10) releasing a considerable amount of slip accumulated during >130 years. In contrast, only a few events with $7 < M_w < 8$ have occurred in north Chile since 1877, and they were not large enough to release a significant part of the slip accumulated in the region during the past ~130 years, which is at present largely or completely coupled[4,5,9]. This was the case of the 2007 Tocopilla event (M_w 7.7) which ruptured the southern region of the seismic gap (Fig. 1). Seismological and geodetic data indicate that the earthquake rupture is confined in the deeper part (30–55 km) of the thrust interface[4,6,7] whereas the upper plate contact remains unbroken. Furthermore, the Tocopilla event presents low coseismic slip (<3 m) and released only 2–4% of the moment deficit accumulated in the thrust interface during the past ~130 years[4,9]. An earthquake with similar characteristics occurred in 1967 (M_w 7.4), which ruptured at 46–48 km depth just north of the 2007 event[8]. Both the 1967 and 2007 events should be considered as precursors of an expected larger tsunamigenic earthquake that could partially or completely rupture the ~550-km-long seismic gap in north Chile.

The Tocopilla epicentre underlies a spectacular coastal scarp, a major trench-parallel morphological feature of the leading edge of the forearc, which extends >1,000 km along the northern Chilean coast with an average height of 1,000 m. This coastal scarp forms part of the Coastal Cordillera; a trench-parallel morphological province formed mainly by an extinct, exhumed and uplifted Mesozoic palaeomagmatic arc. Some authors have suggested that underplating at the base of the continental crust caused by subduction erosion may be responsible for the tectonic evolution of the leading edge of the forearc[11–17].

Neotectonic studies reveal that the coastal scarp is a young and active feature formed during the past three to six million years[12,15,18]. However, there are controversial hypotheses explaining its origin and there is no consensus at present. Hypotheses include that the coastal scarp was formed by crustal extensional faulting and coastal uplift[15], that this feature is not tectonic related but is the result of marine erosion related to coastal subsidence[16], or that it has a tectonic-erosive origin associated with coastal active faulting and fault scarp retreat owing to marine erosion[17]. Owing to the large scale and the trench-parallel geometry of the coastal scarp, it is likely that this major feature must be related to the zone of coupling between the oceanic Nazca and continental South American plates[12,15]. However, the genesis of the coastal scarp still remains under debate due mainly to the lack of marine data.

To better understand the seismogenic contact zone and its link with the overriding crustal deformation, we studied the upper lithospheric structure of the subduction zone of north Chile at ~22° S using amphibious wide-angle refraction and reflection data. This data set is complemented by accurate hypocentre data of the 2007 Tocopilla aftershocks recorded by a local network installed in the region[7] (Fig. 1). The wide-angle seismic data were acquired in 1995 during the Crustal Investigations on- and offshore Nazca/Central Andes (CINCA) project with the German RV *SONNE* (refs 19–21). The gross seismic structure of the margin was modelled from land explosions and air gun shots recorded only at land stations[19]. However, the data from the ocean bottom hydrophones (OBHs) deployed offshore Tocopilla were not included in that modelling. Here, we included 19 OBHs deployed along the trench region and continental slope, which enabled us to image in great detail the subduction interface and inner structure of the marine forearc. Thus, we jointly used sea shots recorded in 19 marine and 30

[1]Departamento de Geofísica, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile, [2]Advanced Mining Technology Center, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile, [3]GEOMAR, Helmholtz Centre of Ocean Research, Wischhofstraße 1-3, D-24148 Kiel, Germany. *e-mail: econtreras@dgf.uchile.cl; sruiz@dgf.uchile.cl.

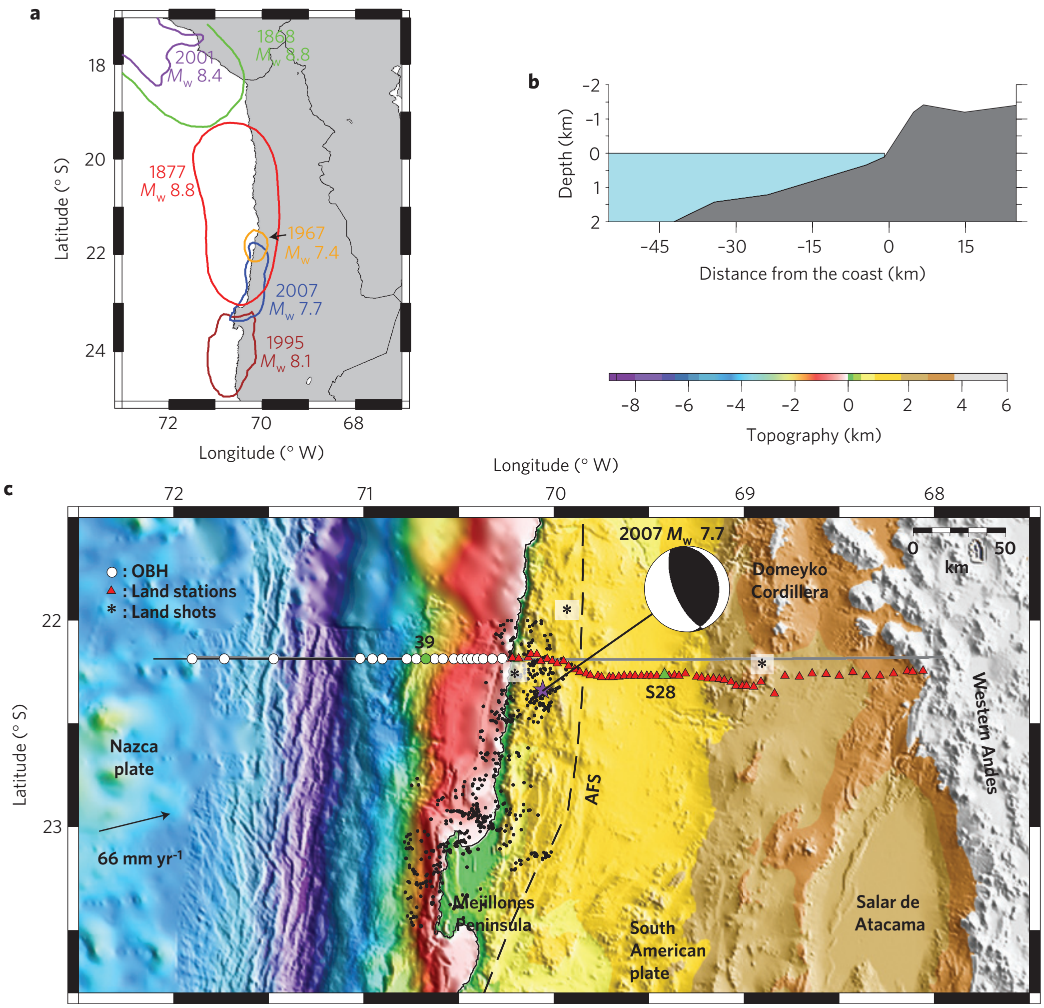

Figure 1 | Seismotectonic setting of north Chile and seismic experiment. a, Rupture areas of historic and recent earthquakes. **b**, Coastal topography along the studied seismic line. **c**, Swath bathymetry and topography[22,25], and location of the seismic experiment. The green dot and triangle indicate the seismic stations shown in Fig. 2. The purple star indicates the epicentre of the 2007 earthquake and the surrounding black dots indicate the aftershocks[7]. The dashed line denotes the Atacama fault system (AFS) that stretches linearly for ~1,100 km at an average distance of 30–50 km from the shore line[15].

land seismic stations, and additionally we included two land shots (Fig. 1c). The total length of the seismic profile is ~420 km and samples the trench outer rise, fore- and magmatic arcs. Continental crustal refractions (P_{g1}), reflections from the top of the oceanic crust ($P_{toc}P$), intracrustal continental reflections ($P_{ic}P$), oceanic crustal refractions (P_{g2}) and oceanic Moho wide-angle reflections (P_mP), were recorded with excellent quality, from which a two-dimensional velocity model was derived by tomographic inversion (Fig. 2a). Figure 2b,c shows representative examples of seismic record sections including the identified seismic phases (see Supplementary Information for modelling, uncertainties and model assessment).

The two-dimensional final velocity–depth model shows the internal structure of the erosive margin of north Chile, which is characterized by a ~30 – km-wide wedge-shaped body, with velocities ranging between 4.0 and 6.0 km s^{-1}. This body is interpreted as the front of the margin, fluid saturated, metamorphosed and disaggregated by fracturing as a consequence of subduction erosion[20]. Landward of this body, a pronounced horizontal velocity gradient is detected 30–50 km from the trench axis, from which velocities increase landward. This indicates that vigorous subduction erosion has ceased and the igneous framework is not very fractured or hydrated. Most likely, the subduction interface below the wedge-shaped body of reduced velocities is weakly coupled owing to the high fracturing degree and fluid pore pressure caused by subduction erosion[20,22].

As observed in Fig. 2a, the plate geometry landward of ~170 km and for depths >30 km is unconstrained by the wide-angle seismic data alone. We have therefore continued the geometry of the plate boundary landward by fitting it to hypocentre data of the Tocopilla 2007 aftershocks[7]. The results show that the slab dip increases abruptly from 10° to about 22° at ~85 km from the trench axis. $P_{toc}P$ reflections recorded in both marine and land stations deployed in the coastal region constrain the upper slab dip to about 10°. Near the slab-dip change, P_mP reflections recorded at land stations are consistent with the dip change (see Supplementary Information), although the resolution is low due to the lack of rays. Nevertheless, the best constraint for the slab dip at depths of 55 km < z < 20 km is the accurate hypocentre data of the 2007 earthquake[7], which in combination with the wide-angle seismic data, supports the abrupt change in slab dip. Owing to the lack of offshore–onshore seismic experiments complemented with seismological data, evidence for abrupt dip changes in other subduction zones are scarce. An exception is the Japanese subduction zone, where more than one bending point along the plate interface has been detected[23,24].

The dip change is located 25–30 km seaward of the coastal scarp and probably marks the transition from the subsided

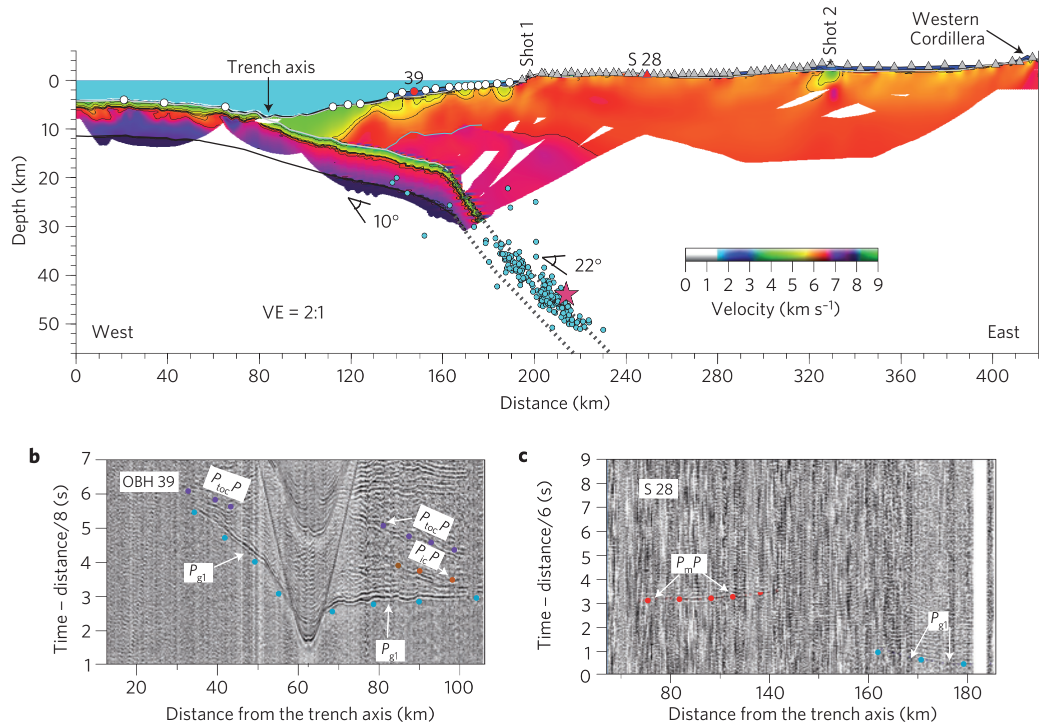

Figure 2 | Seismic velocity structure of the upper subduction zone of Tocopilla, north Chile and data example. a, Two-dimensional velocity–depth model obtained from tomographic inversion of travel times. Pink star denotes the Tocopilla 2007 hypocentre; white dots and grey triangles represent the sea and land stations, respectively. VE, vertical exaggeration. The light blue circles indicate the seismicity distribution of the Tocopilla earthquake (21.5°–22.5° S; ref. 7). **b**,**c**, Examples of wide-angle seismic data with identified travel times: **b**, OBH 39 and **c**, land station 28 (S 28). Purple, orange and red dots are example of travel-time picks.

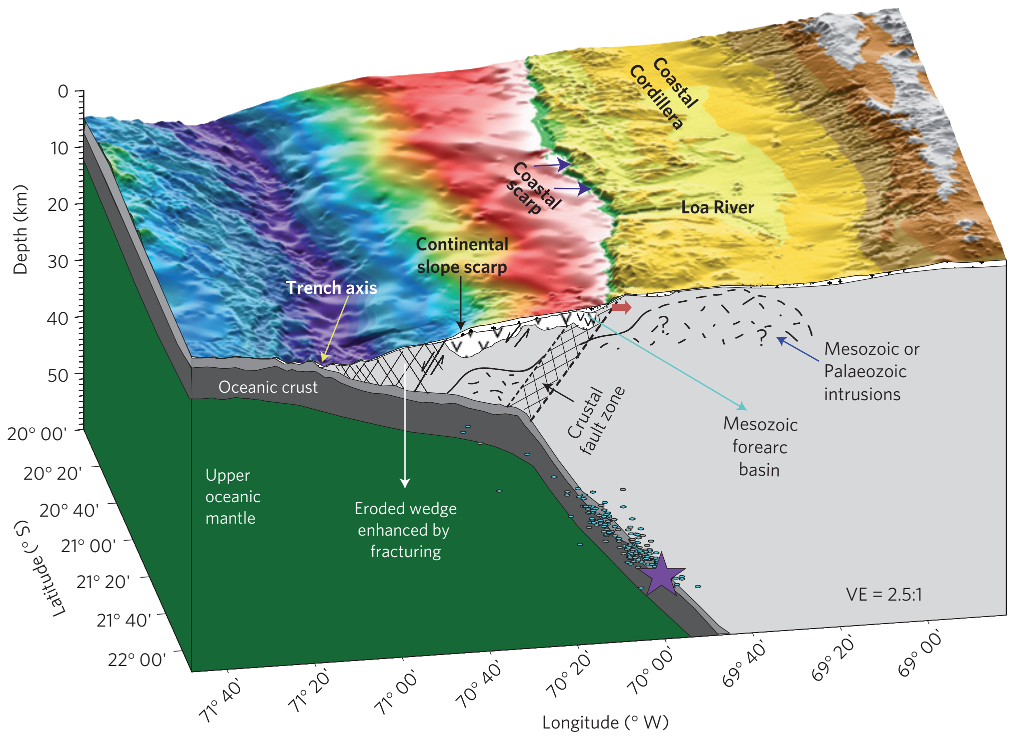

Figure 3 | Summarized interpretation of the tomographic velocity–depth model. The front of the margin is fluid saturated, metamorphosed and disaggregated by fracturing as a consequence of subduction erosion. This region spatially correlates with the continental slope scarp implying gravitational collapse of the trenchward part of the margin. The red arrow near the coast denotes the eastward scarp retreat enhanced by marine erosion[13]. The coastal zone of the upper plate is dominated by crustal faults, which are probably related to the change of plate-coupling degree around the abrupt subducting plate-dip change. The purple star denotes the Tocopilla 2007 hypocentre. VE, vertical exaggeration.

leading edge of the upper plate (marine block) to the uplifted Coastal Cordillera (coastal block; see Fig. 3). We interpret the coastal scarp as the surface expression of a crustal fault zone caused by anomalous stresses in the overriding crust generated by the strong plate-coupling gradient around the abrupt slab-dip change. An east–west extension in the marine block is evidenced by trenchward-dipping normal faulting inferred from high-resolution seismic reflection and bathymetry data[20,22,25], the morphology of the marine basins (Fig. 2a) and reported trenchward gravitational collapse of the seaward continental plate edge[14]. However, the coastal block presents less-developed extensional tectonics[12,15,18,26–29], which is expressed as faults that have been active at least since the Pleistocene epoch[26,29]. Palaeoseismological records also indicate active faulting related to shallow intraplate events $M_w \sim 6.0$–7.0 (ref. 15). Thus, the coastal scarp marks a boundary in the magnitude of deformation between the marine (gravitational collapse and high extension) and coastal (uplift and moderate extension) blocks.

The strong plate-coupling gradient caused by the abrupt slab-dip change also has important implications for interplate seismicity. The area around the dip change could be either a region of high stress, with an abrupt increase of plate coupling, or low stress owing to high fracturing. In both cases, this region corresponds to a barrier for trenchward propagation of earthquakes ($M_w < 8$) nucleated below the Coastal Cordillera such as the 2007 M_w 7.7 and 1967 M_w 7.4 events. This situation should be different, however, for a large tsunamigenic megathrust earthquake, which depending on where it is nucleated, would rupture either trenchward or landward of the dip change. Alternatively, a tsunamigenic earthquake might also occur by rupturing only the upper plate contact (trenchward of the slab-dip change). If a future event breaks the upper plate contact and approaches the trench, coseismic rupture would perturb deep water (>6,000 m) and produce a large tsunami.

The configuration of the forearc and plate boundary geometry discussed above also has implications for the shallow intraplate faulting triggering shallow earthquakes of moderate magnitude. Slab-dip changes play a key role in the dynamics of the plate boundary processes interfering with both interplate and intraplate earthquake ruptures, which must be considered in the assessment of seismic hazard along subduction zones. Finally, as dip changes along subducting slabs have a key influence on megathrust rupture and tsunami processes, they must be considered in new numerical modelling approaches.

Received 16 November 2011; accepted 13 March 2012; published online 8 April 2012

References

1. Comte, D. & Pardo, M. Reappraisal of great historical eathquakes in northern Chile and southern Peru seismic gaps. *Nat. Hazards* **4,** 23–44 (1991).
2. Dorbath, L., Cisternas, A. & Dorbath, C. Quantitative assessment of great earthquakes in Peru. *Bull. Seismol. Soc. Am.* **80,** 551–576 (1990).
3. Husen, S., Kissling, E. & Flueh, E. Local earthquake tomography of shallow subduction in north Chile: A combined onshore and offshore study. *J. Geophys. Res.* **105,** 28183–28198 (2000).
4. Béjar-Pizarro, M. *et al.* Asperities and barriers on the seismogenic zone in north Chile: State-of-the-art after the 2007 M_w 7.7 Tocopilla earthquake nferred by GPS and InSAR data. *Geophys. J. Int.* **183,** 390–406 (2010).
5. Klotz, J. *et al.* Earthquake cycle dominates contemporary crustal deformation in central and southern Andes. *Earth Planet. Sci. Lett.* **193,** 437–446 (2001).
6. Delouis, B., Pardo, M., Legrand, D. & Monfret, T. The M_w 7.7 Tocopilla earthquake of 14 November 2007 at the southern edge of the northern Chile seismic gap: Rupture in the deep part of the coupled plate interface. *Bull. Seismol. Soc. Am.* **99,** 87–94 (2009).
7. Peyrat, S. *et al.* Kinematic rupture process of the 2007 Tocopilla earthquake and its main aftershocks from teleseismic and strong-motion data. *Geophys. J. Int.* **182,** 1411–1430 (2010).
8. Malgrange, M. & Madariaga, R. Complex distribution of large thrust and normal fault earthquakes in the Chilean subduction zone. *Geophys. J. R. Astron. Soc.* **73,** 489–505 (1983).
9. Chlieh, *et al.* Interseismic coupling and seismic potential along the central Andes subduction zone. *J. Geophys. Res.* **116,** B12405 (2011).
10. Robinson, D. P., Das, S. & Watts, A. B. Earthquake rupture stalled by a subducting fracture zone. *Science* **312,** 1203–1205 (2006).
11. Scheuber, E., Bogdanic, T., Jensen, A. & Reutter, K-J. *Tectonics of the Southern Central Andes* 121–139 (Springer, 1994).
12. Allmendinger, R. & Gonzalez, G. Neogene to Quaternary tectonics of the Coastal Cordillera, northern Chile. *Tectonophysics* **495,** 93–110 (2010).
13. Allmendinger, *et al.* Trench-parallel shortening in the northern Chilean forearc: Tectonic and climatic implications. *GSA Bull.* **117,** 89–104 (2005).
14. Hartley, A. J. *et al.* Development of a continental forearc: A Cenozoic example from the central Andes, northern Chile. *Geology* **28,** 331–334 (2000).
15. Armijo, R. & Thiele, R. Active faulting in northern Chile: Ramp stacking and lateral decoupling along a subduction plate boundary? *Earth Planet. Sci. Lett.* **98,** 40–61 (1990).
16. Mortimer, C. & Saric, N. Cenozoic studies in northernmost Chile. *Geologishe Rundschau* **64,** 395–420 (1975).
17. Paskoff, R. *Sobre la Evolución Geomorfológica del Gran Acantilado Costero del Norte Grande de Chile* PhD thesis, Univ. Católica de Chile (1979).
18. Gonzalez, G., Cembrano, J., Carrizo, D., Macci, A. & Schneider, H. The link between forearc tectonics and Pliocene Quaternary deformation of the Coastal Cordillera, northern Chile. *J. S. Am. Earth Sci.* **16,** 321–342 (2003).
19. Patzwahl, R., Mechie, J., Schulze, A. & Giese, P. Two-dimensional velocity models of the Nazca plate subduction zone between 19.5° S and 25° S from wide-angle seismic measurements during the CINCA95 project. *J. Geophys. Res.* **104,** 7293–7317 (1999).
20. Sallares, V. & Ranero, C. R. Structure and tectonics of the erosional convergent margin off Antofagasta, north Chile (23° 30′S). *J. Geophys. Res.* **110,** B06101 (2005).
21. ANCORP Working Group Seismic reflection image revealing offset of Andean subduction-zone earthquake locations into oceanic mantle. *Nature* **397**, 341–344 (1999).
22. Von Huene, R. & Ranero, C. R. Subduction erosion and basal friction along the sediment-starved convergent margin off Antofagasta, Chile. *J. Geophys. Res.* **108,** 2079 (2003).
23. Ito, A. *et al.* Bending of the subducting oceanic plate and its implication for rupture propagation of large interplate earthquakes off Miyagi, Japan, in the Japan trench subduction zone. *Geophys. Res. Lett.* **32,** L05310 (2005).
24. Fujie, G. *et al.* Confirming sharp bending of the Pacific plate in the northern Japan trench subduction zone by applying a traveltime mapping method. *Phys. Earth Planet. Int.* **157,** 72–85 (2006).
25. Von Huene, R., Weinrebe, W. & Heeren, F. Subduction erosion along the north Chile margin. *J. Geodynam.* **27,** 345–358 (1999).
26. Gonzalez, L., Dunai, G. T., Carrizo, D. & Allmendinger, R. Young displacements on the Atacama fault system, northern Chile from field observations and cosmogenic ^{21}Ne concentrations. *Tectonics* **25,** TC3006 (2006).
27. Delouis, B., Philip, H., Dorbath, L. & Cisternas, A. Recent crustal deformation in the Antofagasta region (northern Chile) and the subduction process. *Geophys. J. Int.* **132,** 302–338 (1998).
28. Gonzalez, G. & Carrizo, D. Segmentación, cinemática y chronología relativa de la deformación tardía de la Falla Salar del Carmen, Sistema de Fallas Atacama, (23° 40′ S), norte de Chile. *R. Geol. Chile* **30,** 223–244 (2003).
29. Marquardt, C., Lavenu, A., Ortliebc, L., Godoya, E. & Comte, D. Coastal neotectonics in southern central Andes: Uplift and deformation of marine terraces in northern Chile (27° S). *Tectonophysics* **394,** 193–219 (2004).

Acknowledgements

E.C-R. acknowledges the support of the Chilean National Science Foundation (FONDECYT) project 11090009. S.R and D.C acknowledge the support of FONDECYT project 1100429. We thank A. Fuenzalida, M. Lancieri and R. Madariaga for providing the hypocentre data. Marine data acquisition was financially supported by the German Ministry of Education, Science and Research. We also thank GeoForschungZentrum, Potsdam and the International Plate Boundary Observatory Chile for sharing the data.

Author contributions

E.C-R., J.J. and I.G. analysed and processed the wide-angle seismic data. E.C-R., S.R., D.C. and I.G. interpreted and wrote 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 www.nature.com/reprints. Correspondence and requests for materials should be addressed to E.C-R. or S.R.