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1 Interaction between forearc and oceanic plate at the
2 South-Central Chilean margin as seen in local seismic
3 data

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We installed a dense, amphibious, temporary seismological network to study the seismicity and structure of the seismogenic zone in southern Chile between 37° and 39° S, the nucleation area of the great 1960 Chile earthquake. 213 local earthquakes with 14,754 onset times were used for a simultaneous inversion for the 1-D velocity model and precise earthquake locations. Relocated artificial shots suggest an accuracy of the earthquake hypocenter of about 1 km (horizontally) and 500 m (vertically). Crustal events along trench-parallel and transverse, deep-reaching faults reflect the interseismic transpressional deformation of the forearc crust due to the subduction of the Nazca plate. The transverse faults seem to accomplish differential lateral stresses between subduction zone segments. Many events situated in an internally structured, planar seismicity patch at 20 to 40 km depth near the coast indicate a stress concentration at the plate's interface at 38° S which might in part be induced by the fragmented forearc structure.

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1. Introduction

The largest earthquakes are being generated at convergent plate boundaries, where oceanic plates subduct beneath other tectonic plates [*Pacheco et al.*, 1993]. More precisely, these earthquakes are being generated at the relatively shallow portions of the interface between both plates, the coupling zone or seismogenic zone, where the (moving) plates are locked for considerable periods of time thus accumulating elastic stresses [e.g. *Hyndman et al.*, 1997]. Large interplate earthquakes result from successive ruptures of subsequent segments of these coupling zones following stick-slip frictional behavior [*Scholz*, 2002].

The coupling, which is a measure of the seismogenic mechanical interaction between the plates and decisive for the occurrence of large earthquakes, seems to be highly nonuniform (both along strike and in comparison with other subduction zones). Even during large earthquakes, regions along these plate boundaries with large coseismic slip and moment release, known as asperities, alternate with sectors characterized by relatively small slip [*Lay and Kanamori*, 1981].

However, there is much discussion about the physical properties of those observed asperities, which ultimately are the controlling factors of plate coupling and the occurrence of megathrust earthquakes. Many studies focused on the lower plate and discussed parameters such as the plate roughness, the sea floor age, the trench sediment fill, the convergence velocity/obliquity, the temperature field [*Oleskevich et al.*, 1999], the history [*Kanamori*, 1977], and other parameters [e.g., *Kanamori*, 1986, and references within]. Less attention had been paid to potential controlling parameters related to the upper plate [*McCaffrey*, 1993; *Collot et al.*, 2004; *Song and Simons*, 2003; *Fuller et al.*, 2006].

Here, we use high-resolution local observations of the "minor" subduction zone seismicity occurring during the interseismic cycle to characterize the coupling zone and the forearc of the southern Chilean convergent margin (37° - 39° S) and the interplay between the upper and lower plate.

At this location at May 22, 1960 the worldwide largest instrumentally observed earthquake ($M=9.5$) nucleated and ruptured the almost 1000 km long segment from the Arauco peninsula (AP) southward down to the triple junction [Plafker and Savage, 1970; Barrientos and Ward, 1990; Cifuentes, 1989, Figure 1]. The southern Central Chilean subduction zone, in which the oceanic Nazca plate dives beneath South America, is considered to be strongly coupled, and the rupture plane of the 1960 earthquake is today almost devoid of seismicity. However, international earthquake catalogs [Engdahl *et al.*, 1998; Engdahl and Villaseñor, 2002] and regional networks [e.g., Bohm *et al.*, 2002] list many earthquakes in a patch of increased activity just South of the AP in which many larger earthquakes in the last century nucleated (Figure 1). The northward adjacent segment ruptured in 1835 and is considered a recent seismic gap [Campos *et al.*, 2002]. The forearc in this region is cut by several NW-SE trending faults [e.g., Melnick and Echtler, 2006].

2. Experiment, Data

Between Nov. 2004 and June 2005 a dense, amphibious, seismological network was installed in southern Chile, covering the entire forearc between 37° and 39° S [Rietbrock *et al.*, 2005]. In the first 2.5 months the network constituted out of 70 PDAS and REFTEK datalogger, running at 50 and 100 Hz sample rate, respectively. In the second phase of the project (February - June 2005) we used 120 Earth Data Logger running at 100 Hz

sample rate. All recorders were equipped with Mark L4-3D short period sensors, and they were running continuously. Between February and October 2005 ten ocean bottom seismometers/hydrophones (OBS/OBH, six of them producing data) complemented the network off-shore (Figure 1). Finally, 20 land stations and ten OBS/OBH stations remained in the region until October 2005. OBS/OBH data could be used for the first time for seismological studies in this region. Average station spacings were very small in the center (around 7 km) and larger in the outskirts of the region of interest (40 km). On average the network observed 2 to 3 local events per day.

3. Analysis and Inversion

Events were detected by applying an automatic STA/LTA trigger together with a downstream temporal coincidence check. Arrival times of the compressional (P) and shear (S) waves were manually picked with the GIANT/PITSA software code [Rietbrock and Scherbaum, 1998]. In total we located 544 local events with magnitudes between 1 and 5.2 M_L . A high quality subset based on 213 events with 8.988 P and 5.766 S picks was used for a simultaneous inversion for accurate hypocenters, 1-D velocity model and station corrections [Kissling *et al.*, 1994]. We first inverted for the v_p model assuming a constant average v_p/v_s ratio of 1.77 (based on Wadati diagram analysis) and using a wide range of starting models. In a second step we used the final v_p model (from the first step) and varying constant v_p/v_s values as starting models in subsequent inversions [Husen *et al.*, 1999]. Inversions based solely on P picks resulted in almost identical hypocenter positions in the central parts of the network (i.e. shallower than 50 km depth). The finely-layered minimum 1-D model starts with rather high crustal v_p of 6 km/s at the surface, increasing

gently to about 7 km/s at a depth of 30 km (Figure 2). Due to the dense network and also uppercrustal earthquakes even the uppermost layers are well constrained and model the velocity gradient. Above 20 km depth, v_p is slightly higher compared to *Bohm et al. (2002)* reflecting higher velocities beneath the coastal ranges. Mantle velocities are reached at a depth of 50 km. v_p/v_s decreases from high values of around 1.8 at the surface to lower values of about 1.75 between 30 and 70 km depth. Station corrections of neighboring stations are very consistent and follow regional trends (Figure 2).

4. Accuracy of earthquake locations

In order to estimate the accuracy of the hypocenter locations we located chemical explosions of an accompanying active source seismic experiment [*Krawczyk et al., 2005*] in the same way as we located the earthquakes. These shots were not part of the data used for the inversion described above. The comparison between actual and inverted locations suggests that the uncertainty in horizontal and vertical direction of earthquakes beneath central parts of the network is better than 1 km and 500 m, respectively (Figure 3). Uncertainties in absolute hypocenter position for deeper earthquakes are considered to be smaller than the estimates deduced from the shots since the travel times of the corresponding raypaths are less affected by the expected heterogenous velocity structure close to the surface (not accounted for in the 1-D velocity model) [*Kissling, 1988*].

5. Results in Discussion

Seismicity is found from the surface down to 115 km depth. The earthquakes can now be clearly associated with locations within the oceanic plate, the continental plate, and the interface between them (E and F, B, C, and D, and A in Figure 4).

5.1. Intraplate seismicity - upper and lower plate

A surprisingly large number of earthquakes is found in the continental crust and can in most cases be associated with mapped faults (B, C, and D in Figure 4).

In the coastal area a crustal M_L 5.2 event occurred at February 4, 2005 (73.47° W/37.92° S/12.2 km depth) followed by a large number of aftershocks (B in Figure 4). These and several other smaller events are related to NNW-SSE striking reverse faults close to the coast South of the AP (although the large event has mainly strike-slip character). These, deep-reaching faults, which were also imaged by industry seismic reflection profiles, accommodate the margin-normal forearc shortening, which is in part responsible for the local uplift of the AP [e.g., *Melnick et al.*, 2006].

A number of strike-slip earthquakes is delineated along NW-SE striking faults such as the Lanalhue fault (LFZ) and a northern fault strand (C in Figure 4). The seismic activity along these faults is situated between 10 and 30 km depth indicating that these faults are deep reaching and cut through almost the whole forearc crust. According to the mapped fault trace at the surface [*Melnick and Echtler*, 2006] and the hypocenters, the LFZ appears to be near-vertical. This seismic activity thus reflects the recent, brittle deformation of the forearc along crustal-scale transverse faults. It can be related to the clockwise forearc block rotation due to the obliqueness of the subduction of the Nazca plate proposed e.g. by *Echtler et al.* [2003]. Additionally, the activity along these transverse faults indicates the decoupling of adjacent margin segments (i.e. North and South of the LFZ) which could accomplish the transfer of differential lateral stresses between segments at different stages of the seismic cycle (i.e., segments associated with the 1835 and 1960

earthquakes). A pronounced post-seismic, large-scale crustal deformation in the area of (and in response to) the great 1960 earthquake differing from the deformation in the northerly adjacent segment, which is currently in the interseismic cycle, was observed by GPS studies [Khazaradze *et al.*, 2002]. It had been previously proposed that such transverse faults could also control the extent of seismogenic ruptures [Collot *et al.*, 2004].

Crustal seismicity at depth smaller than 30 km at about 71.2° W (although situated at the edge of the network) is evidence for recent activity of the almost arc-parallel Liquiñe-Ofqui fault zone (LOFZ, in Figure 4). This large right-lateral shear zone cuts the Patagonian batholith and controls the architecture of the modern volcanic arc of southern Chile thus accomplishing the lateral northward movement of a forearc sliver due to oblique subduction [Cembrano *et al.*, 2000].

At depths between 50 and 115 km intermediate depth seismicity (E in Figure 4) is found in a plane dipping easterly [see also Bohm *et al.*, 2002]. The dip is approx. 25° between 72 and 73° W. Intense intermediate seismicity was found to be dominating in the subduction zone section just north of the AP [Campos *et al.*, 2002]. These events are generally attributed to phase transformations and dehydration embrittlement within the subducting plate. Few events are found in the subducting slab off the coast (F in Figure 4).

5.2. Interplate seismicity

Beneath the coast we find a persistent patch of increased seismicity at a depth between 20 and 40 km (A in Figure 4). In map view, the events are not uniformly distributed within this patch and reflect an internal structure with often linearly aligned earthquakes.

The collocation in a very narrow ($\sigma = 1.6$ km), almost flat plane (dip 9° - 11° E, 73.75° - 73° W, 38.25° - 37.5° S) suggests that these events occur at the interface between the subducting and the upper plate. The downdip limit of this patch is around 40 km depth which is at the lower bound of the estimates for the downdip limit of the seismogenic zone based on the distribution of hypocenters of large earthquakes (40-53 km) in the region [Tichelaar and Ruff, 1991]. W of 74° W this seismicity diminishes. The width of the inclined zone is therefore 60 km which is considerably smaller than estimates of the width of the 1960 rupture plane of 120 - 150 km [Plafker and Savage, 1970; Barrientos and Ward, 1990]. We therefore conclude that the interseismic minor seismicity observed by our network predominantly occurs in the lower part of the plate interface rupturing in large earthquakes. The upper part W of 74° W, which appears almost aseismic in our data, seems to be related to a conditionally stable region experiencing brittle failure during large events and stable sliding inbetween [see e.g., Bilek and Lay, 2002].

The seismicity patch at the plate's interface spatially correlates with the occurrence of the forearc fragmentation by the NNW and NW striking crustal faults south of the AP (see above, and Figure 4). These deep-reaching faults could introduce stress heterogeneities at the interface which could in turn cause increased seismic activity as discussed by Hackney et al. [2006]. The internal structure of the seismicity patch with often linearly aligned earthquakes supports this hypothesis. According to high-quality hypocenter catalogs [Engdahl and Villaseñor, 2002], the hypocenter of the 1960 earthquake is at the SE limit of this patch and appears right beneath a prominent crustal fault strand. It is conceivable that the seismic events frequently occurring in this active patch can occasionally

form the nuclei for larger (or great) earthquakes, which rupture - depending on the stage of loading - adjacent asperities.

6. Conclusions

The large number of crustal earthquakes indicates a strong and still on-going interseismic deformation and fragmentation of the forearc South of the Arauco peninsula related to the subduction of the Nazca plate beneath South America. It reflects the margin-normal shortening close to the coast, strike-slip movement along NW trending transverse faults, and brittle deformation within the recent magmatic arc.

At the same latitude a pronounced, persisting and focussed patch of seismicity at 20 to 40 km depth in the coastal area, which shows an internal structure and in which several large earthquakes nucleated, give evidence for an inhomogeneous stress distribution in a localized region of the plates' interface (coupling zone). It is conceivable that the fragmented forearc with many deep-reaching crustal faults introduces these stresses triggering in turn the frequently occurring earthquakes.

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Figure 1. Tectonic Setting of the South Chilean continental margin at the Arauco Peninsula (AP) and seismological stations (inverted triangles). Thick black line show continental faults (MVZF: Mocha-Villarica Fault Zone, LFZ: Lanalhue Fault, BBFZ: Bio-Bio Fault Zone, LOFZ: Liquiñe-Ofqui Fault Zone) following *Melnick and Echtler* [2006]; MFZ: Mocha Fracture Zone, VFZ: Valdivia Fracture Zone. Young volcanos are depicted by triangles, earthquakes ($\leq M = 5.5$) since 1960 are shown by white circles. The epicenter of the M=9.5 earthquake of 1960 is shown by the black star, the approximate region of associated uplift and subsidence is shown by the dashed line [*Plafker and Savage*, 1970]. All earthquake locations following *Engdahl et al.* [1998] and *Engdahl and Villaseñor* [2002]. Areas above 700 m are shown in dark grey. Box indicates study region.

Figure 2. (Top) Minimum 1-D velocity model. Dashed lines indicate limits of starting models used, grey lines represent final models, thick black lines give final model with lowest overall rms. We only used events with $GAP \leq 180^\circ$ and at least 10 P and 5 S observations. (Bottom) P-wave station corrections corresponding to the final velocity model. The reference station is indicated by the star. For computational reasons the depths of the OBS/OBH were fixed to sea level, and the derived station delays also account for the corresponding effect [*Husen et al.*, 1999].

Figure 3. Mislocations of 44 artificial explosions to check the accuracy of the earthquake positions. Shown by circles are differences between the true positions and the relocations by the inversion, bars are histograms. Only shots with more than 14 observations and only P observations were used. The distribution suggests that the horizontal location uncertainty is about 1 km, the vertical uncertainty around 500 m. Inset shows shot locations.

Figure 4. Local seismicity observed by the temporal network (top: map view, bottom: two WE-depth sections). High-quality earthquakes used in the inversion are depicted by circles. Filled circles indicate earthquakes shallower than 17 km (W of 73° W) and 30 km (E of 73° W), respectively. Crosses depict relocated seismicity not used in the calculation of the minimum 1-D model. Black triangles indicate recent volcanoes. Faults (solid lines) after *Melnick and Echtler* [2006], dashed black line depicts inferred fault. Seismicity is unevenly distributed and can be associated to the thrust plane (A), to crustal faults with different orientation (B, C, D), and to the intermediate depth level (E). Fault plane solutions (lower hemisphere plot) are based on first motion polarities (leftmost beachball corresponds to 5.2 M_L event on February 4, 2005; date and magnitude given on top). Light grey lines indicate inferred top of subducting slab. For more information see text.