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Earth and Planetary Science Letters 269 (2008) 41–55

EPSL

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Seismicity in the outer rise offshore southern Chile: Indication of fluid effects in crust and mantle

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Received 24 July 2007; received in revised form 17 January 2008; accepted 22 January 2008
Available online 16 February 2008
Editor: R.D. van der Hilst

Abstract

We examine the micro-earthquake seismicity recorded by two temporary arrays of ocean bottom seismometers on the outer rise offshore southern Chile on young oceanic plate of ages 14 Ma and 6 Ma, respectively. The arrays were in operation from December 2004–January 2005 and consisted of 17 instruments and 12 instruments, respectively. Approximately 10 locatable events per day were recorded by each of the arrays. The catalogue, which is complete for magnitudes above 1.2–1.5, is characterized by a high *b* value, i.e., a high ratio of small to large events, and the data set is remarkable in that a large proportion of the events form clusters whose members show a high degree of waveform similarity. The largest cluster thus identified consisted of 27 similar events (average inter-event correlation coefficient >0.8 for a 9.5 s window), and waveform similarity persists far into the coda. Inter-event spacing is irregular, but very short waiting times of a few minutes are far more common than expected from a Poisson distribution. Seismicity with these features (high *b* value, large number of similar events with short waiting times) is typical of swarm activity, which, based on empirical evidence and theoretical considerations, is generally thought to be driven by fluid pressure variations. Because no pronounced outer rise bulge exists on the very young plate in the study region, it is unlikely that melt is accessible from decompression melting or opening of cracks. A fluid source related to processes at the nearby ridge is conceivable for the younger segment but less likely for the older one. We infer that the fluid source could be seawater, which enters through fractures in the crust. Most of the similar-earthquake clusters are within the crust, but some of them locate significantly below the Moho. If our interpretation is correct, this implies that water is present within the mantle. Hydration of the mantle is also indicated by a decrease of P_n velocities below the outer rise seen on a refraction profile through one of the arrays [Contreras-Reyes, E., Grevemeyer, I., Flueh, E.R., Scherwath, M., Heesemann, M., 2007. Alteration of the subducting oceanic lithosphere at the southern central Chile trench-outer rise. Geochem., Geophys. Geosyst. 8, Q07003.]. The deepest events within the array on the 6 Ma old plate occur where the temperature reaches 500–600 °C, consistent with the value observed for large intraplate earthquakes within the mantle (650 °C), suggesting that the maximum temperature at which these fluid-mediated micro-earthquakes can occur is similar or identical to that of large earthquakes.

PACS: 91.30.Dk; 91.30.Ga; 91.30.Ye; 91.50.Wy; 91.55.Tt
Keywords: subduction; outer rise; seismicity; fluids and earthquakes; serpentinisation

1. Introduction

The outer rise forms an integral part of the subduction system with regard to both material fluxes and stress distribution. The oceanic lithosphere is stressed by bending and remote loading from the subduction zone or possibly other nearby plate boundaries, so that crustal and even mantle earthquakes occur. Faulting at the outer rise is thought to provide pathways for water into the lithosphere, both its crustal part (Kirby et al., 1996) and probably also into the mantle (Ranero et al., 2003; Ranero and Sallares, 2004; Grevemeyer et al., 2007); it

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doi:10.1016/j.epsl.2008.01.044

therefore exerts a strong influence on melt generation and rheology further down the subduction system. Hydration of the mantle lithosphere at the outer rise can potentially more than double the amount of water carried by the downgoing slab (Rüpke et al., 2004). Dehydration of serpentinised mantle has also been proposed to account for the lower plane of double seismic zones (Peacock, 2001). The stress field at the outer rise is a superposition of bending stresses and regional horizontal stresses (Christensen and Ruff, 1988). Because the latter varies through the seismic cycle of the interplate megathrust (e.g. Taylor et al., 1996), with trench-perpendicular compression late in the cycle and tension early in the cycle, Christensen and Ruff (1988) proposed that an increased number of outer rise thrust events indicates an interplate-thrust close to the rupture limit, whereas many normal faulting events are expected to follow great interplate earthquakes. However, actual mechanisms also depend on the loading history (Mueller et al., 1996), such that the relationship is likely to be more complicated than suggested by this simple idea.

In addition to its significance to the subduction system, the outer rise region also plays host to most of the world's oceanic intraplate seismicity (excluding intermediate and deep-focus earthquakes which might be controlled by different frictional laws). Intraplate earthquakes in oceanic mantle have been used to show that temperature is the dominant factor controlling the depth of brittle faulting (Wiens and Stein, 1983), with 650 °C being the maximum temperature at which earthquakes are observed (McKenzie et al., 2005). However, all previous studies of outer rise seismicity and oceanic intraplate seismicity in general exclusively utilised teleseismic and regional data (e.g. Wiens and Stein, 1983; Christensen and Ruff, 1988). This approach allows global coverage but limits the analysis to strong earthquakes (m_b>~5.5). This limitation poses particular problems for very young oceanic plates where few events of sufficient magnitude occur. Moreover, the finite source properties of the larger of these events make it hard to ascertain the maximum depth of faulting (as opposed to the hypocentre, see Tichelaar et al., 1992). Here, we take the complementary approach and use dense arrays of ocean bottom stations to characterize micro-earthquake activity in the outer rise of the Chilean subduction zone.

A number of fracture zones north of the Chile triple junction segment the Nazca plate which subducts at the Chilean margin (Fig. 1). No significant variation has been resolved in the convergence rate between the Nazca and South American plates (7.9–8.0 cm/yr, near trench-perpendicular convergence of N79E) (DeMets et al., 1994). However, the square root of time dependence of plate cooling is expected to cause large variations of thermal structure. During cruise SO181 of R/V Sonne (December 2004–February 2005) we have placed seismic arrays on the second and third youngest subducting segments (with ages at the trench of 6 and 14 Ma at the centre of the segment, respectively), which are bounded, from south to north by the Guamblin, Guafo and Chiloe fracture zones. This experiment forms part of the TIPTEQ project (Scherwath et al., 2006), so that the passive seismic data are complemented by refraction and heat flow profiles as well as swath bathymetry mapping and magnetic profiling.

2. Data and processing

The northern array consisted of 7 ocean bottom hydrophones (OBH) and 10 four-component stations (ocean bottom seismometers — OBS). The southern array consisted of 2 OBH and 10 OBS. All stations were sampled continuously at 100 Hz, except obh28 within the southern array which sampled at 50 Hz. Most stations were operational for 5–6 weeks, but two stations, one in each array, did not return any useful data (see Table S1 in the supplementary material for station locations and instrument types). The hydrophone records generally showed clear P onsets and, for most stations, could easily be picked on the unfiltered traces (Fig. 2). Strong S arrivals were visible on all seismometer components (including the vertical) but were characterized by ringing, nearly monochromatic waveforms, presumably due to resonances within the shallow sediment. The P arrivals on the hydrophone channels were usually succeeded by a strong arrival on the seismometer channels 0.5–1 s later, with the time delay varying from station to station but being similar between events. Similarly, S arrivals were preceded by precursory arrivals, which were particularly clear on the hydrophone channels, but sometimes also appeared weakly on the horizontal components, again separated by approximately 0.5–1 s from the main arrival. The delayed and precursory phases are presumably related to mode-conversions at the basement. Active source data show that sediment thickness does not exceed 500 m in the area of the array (Flueh and Grevemeyer, 2005; Contreras-Reyes et al., 2007) but the observed large delays are easily explained by extremely low S velocities (<100 m/s) in the uppermost layers of unconsolidated marine sediment (Hamilton, 1980).

2.1. Location and magnitude determination

Before any further analysis, timing and location of the ocean bottom stations were corrected as described in the supplementary material. We then carried out the following procedure.

(1) Generation of a preliminary list of events with a STA/LTA trigger algorithm that detects nearly coincident changes in the amplitude at several stations.
(2) Manually inspect all trigger events and pick arrivals, assigning a subjective weight to each pick. Remove events, which are unclear, presumably not earthquakes, or cannot be picked on at least three stations.
(3) Obtain a preliminary location for each event by linearised inversion and using a 1-D velocity model derived from the refraction data (Scherwath et al., 2006). A total of 656 events were located by the northern array, and 1114 events by the southern array.
(4) Based on preliminary locations, temporarily remove events which were recorded by less than 5 stations, have only picks for one phase type (P or S), or are far from the array (azimuthal gap >300°). This procedure leaves 240 events for the northern array, and 484 events for the southern array. In the following we will refer to these events as the restricted set or restricted events.