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Investigating Subduction Zone Processes in Chile

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The highly active subduction zone of southern Chile was the source region of the 1960 Valdivia megathrust earthquake ($M_w = 9.5$), the largest earthquake ever recorded. This region is currently under investigation by the multidisciplinary TIPTEQ (From the Incoming Plate to Mega-Thrust Earthquake Processes) project, which is studying the structure, state, and deformation of the subduction zone lithosphere.

Over 90 days, from December 2004 to February 2005, TIPTEQ scientists on cruise SO181 of the German research vessel (R/V) *Sonne* acquired a broad variety of geophysical and geological data in the research area offshore Chile between 35°S and 48°S (Figure 1). These data include active and passive source seismics, heat flow probing, magnetics, magnetotellurics for studying Earth conductivity, high-resolution multibeam bathymetry, and sediment probes from gravity cores.

New results from this data set compare the incoming Nazca plate at different ages, hence at different thermal states, and provide clues as to why the 1960 earthquake ruptured over a length of 800 kilometers through thermally strongly varying structures. The results show that remarkable similarities appear in lithospheric structure at varying thermal states, with differences existing in the respective seismicity at these states.

In addition to marine data, the TIPTEQ campaign also acquired land data in the same region [*Rietbrock et al.*, 2005], including both seismics and magnetotellurics that were acquired as combined onshore-offshore data.

TIPTEQ Aims

The TIPTEQ project investigates subduction zone processes, in particular the thermal structure of the oceanic plate and subduction zone, the rheological behavior of the subducting sediment, seismic activity and nucleation of large subduction-related earthquakes, and the role of water and hydrothermal circulation in all of the above.

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The temperature at the subduction interface has been proposed as a key parameter controlling seismogenic behavior and other subduction zone processes. Interface temperature is closely linked to the thermal structure and thus the age of the incoming plate. In southern Chile, the oceanic Nazca plate, the oceanic Antarctic plate, and the continental South American plate join at the Chile Triple Junction, at 46.5°S (Figure 1). Within 8° latitude to the north, the age of the subducting Nazca plate changes from 0 to 25 million years old (Ma) across several fracture zones [*Tebbens et al.*, 1997].

This segmentation along the Chilean margin enables data acquisition along corridors of distinct ages within a relatively small area. A simple plate motion environment exists with a constant convergence rate between the Nazca and the South American plates, similar spreading rates at the spreading centers, and a homogeneous plate motion vector subparallel to the fracture zones and perpendicular to the trench, thus establishing a favorable natural laboratory for subduction zone process studies.

Five major data corridors are the focus of the marine component of TIPTEQ, with ages of the incoming plate at the trench ranging from 25 Ma (TIPTEQ corridor 1/SPOC profile 1, Figure 1) down to 3 Ma (TIPTEQ corridor 4, Figure 1). The data along these transects comprise seismic wide-angle refraction and vertical incidence reflection data; heat flow
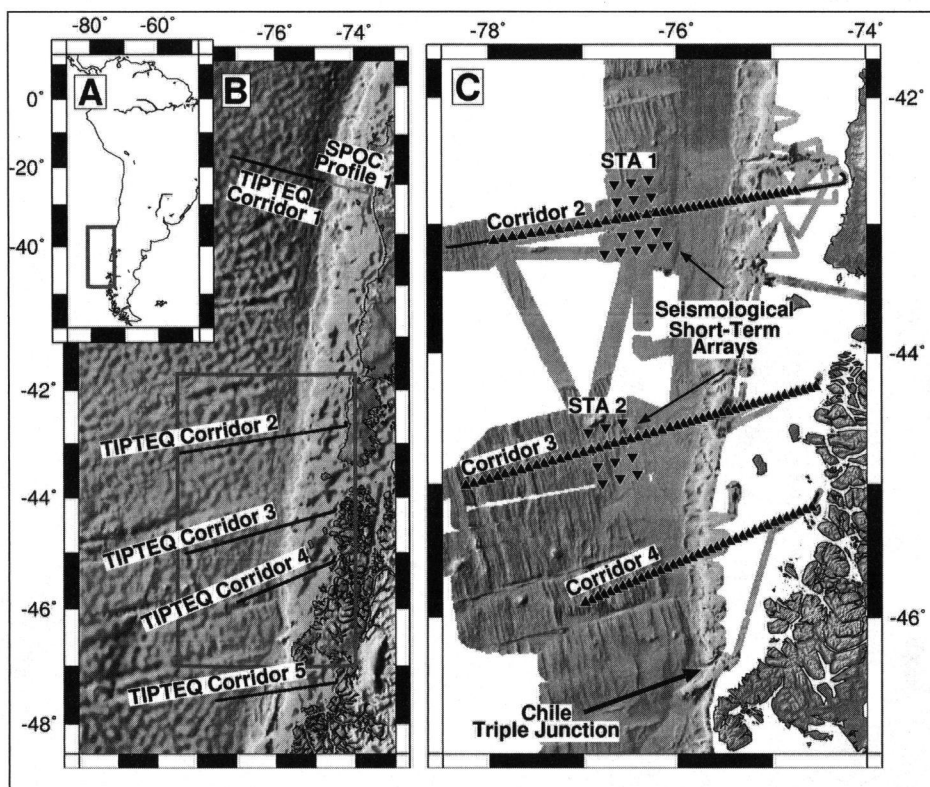

Fig. 1. Map of the TIPTEQ working area: (a) Area relative to South America. (b) Large-scale overview with all TIPTEQ corridors and the 2001 SPOC profile [Krawcyzk et al., 2003]. (c) Central TIPTEQ transects with the locations of ocean bottom seismic recorders (triangles) of refraction profiles and the outer rise seismological networks STA 1 and STA 2. The high-resolution bathymetry in this image was acquired during the TIPTEQ cruise and by Bourgois et al. [2000]. Original color image appears at the back of this volume.
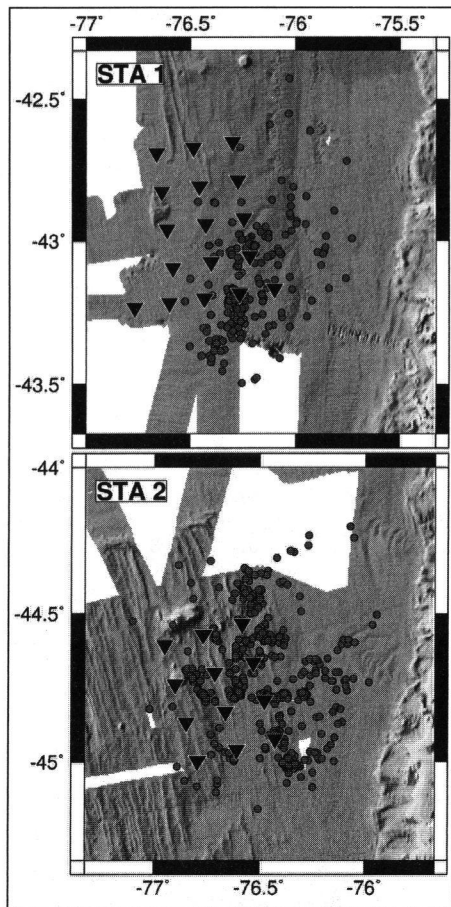
Fig. 2. Distribution of outer rise seismicity (red circles) detected during the six-week deployment of the outer rise seismological networks (ocean bottom stations marked as black triangles). Only epicenters within or close to the seismic arrays which were recorded on at least four stations are shown. Original color image appears at the back of this volume.
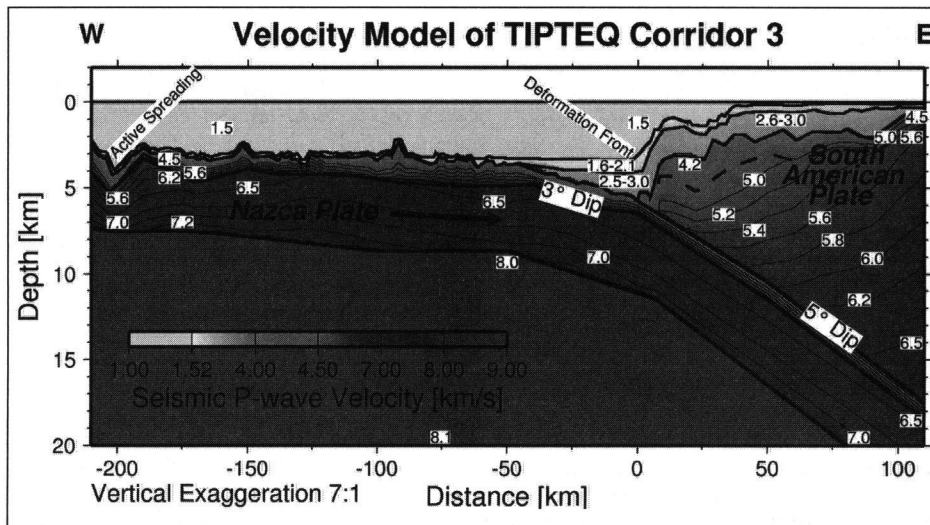

Fig. 3. Preliminary structural velocity model of TIPTEQ corridor 3 (plate age 6.5 Ma at the trench), exhibiting the plate geometry and plate boundaries at depth. Distances are relative to the deformation front. This model may change as detailed data analysis is still in progress. Another four such models will be available along the southern central Chile trench for oceanic plate ages at the trench of 3, 14.5, and 25 Ma north of the Chile Triple Junction (Nazca plate subduction), and 9.5 Ma south of the Triple Junction (Antarctic plate subduction). Original color image appears at the back of this volume.

was measured along the northern four transects either on or near the lines. The northernmost transect on the oldest plate included offshore magnetotelluric stations, extended by an onshore deployment, to map fluids in the subduction zone.

All transects extend far onto the incoming plate (at least 100–200 kilometers from the deformation front), and thus allow a well-controlled characterization of the structure and temperature of the incoming plate as it enters the subduction zone. Data on the continental shelf then give evidence for the influence of the incoming plate on the overriding South American plate.

Throughout the entire survey area, the seafloor was mapped using a Simrad multibeam system (EM120). In addition, sediment cores were taken to provide constraints on chemical composition and physical properties, in particular the rheological behavior of trench sediments to assess at what conditions they will undergo brittle failure.

Outer Rise Seismicity

Two short-term arrays of ocean bottom seismometers (OBS) and ocean bottom hydro-

phones (OBH) were deployed on the outer rise where the oceanic plate flexes upwards prior to being subducted on TIPTEQ corridors 2 and 3 (Figures 1 and 2). These networks detected microearthquakes in the outer rise, which presumably accommodate the bending of the oceanic plate. Several large, normal faulting events have occurred near the northern area (corridor 2) in the last 30 years, but none is listed in the global catalogs for the southern area (corridor 3). Nevertheless, during the six-week recording period, the southern region was far more active, with over 1000 locatable events, whereas just over 500 events could be located in the northern region during the experiment.

Figure 2 shows the epicenters of good events with clear arrivals on at least four stations and not too far from the array. Note that the northern array was situated just off the main microseismicity, and so the locations for these events are not as well determined as the locations for the events of the southern array.

The outer rise seismicity observed along the two corridors appears to show differences in depth and spatial distribution and in the statistics of the relative number of small earthquakes. In the southern part, where the oceanic crust is only 6.5 Ma old at the trench, most events are located in the crust and the uppermost one to two kilometers of the mantle. Furthermore, many earthquakes here are grouped along the NNW-SSE oriented spreading fabric, and an excess of small compared with large earthquakes is indicated.

In contrast, seismicity in the northern array, on oceanic crust 8 Ma older than the southern counterpart, is more diffuse. Both the crust and mantle appear to be seismically active here, too, but the deepest earthquakes appear to occur at depths greater than in the south. A more typical magnitude distribution here is consistent with the absence

of large, teleseismically located events within the region of the southern array in spite of a larger number of recorded microearthquakes.

Wide-Angle Seismic Data

For the seismic wide-angle data acquisition, some 200 deployments of OBS and OBH were carried out along the TIPTEQ transects, each line with 30 to 50 stations at a nominal spacing of 5.5 kilometers. The seismic source was a 64-liter air gun array. A short seismic streamer was towed behind the air gun during most of the seismic surveying. Figure 1c shows the locations of central corridors 2, 3, and 4. Corridor 5 is the only corridor south of the Chile Triple Junction, where the spreading ridge is already actively subducting. Corridor 1 lies at 38°S and forms an extension of a previous line shot in 2001 as part of the Subduction Processes Off Chile (SPOC) project [Krawczyk et al., 2003].

The main purpose of analyzing these wide-angle seismic data is to determine the structure of crust and upper mantle by applying seismic ray-tracing methods. The resulting models show crustal thickness and also the dip of the subducting slab, among other geometric properties, and in particular help to detect anomalous zones as seismic velocity anomalies.

One such structural model is shown in Figure 3, along the same corridor on which the southern outer rise seismic array was located (Figures 1 and 2). This image shows how the incoming oceanic Nazca plate subducts beneath the continental South American plate.

When comparing the preliminary models of central TIPTEQ corridors 2–4, the salient features appear to be that the oceanic crust is around five kilometers thick, and the thickness of the sediments at the trench is about

two kilometers on all lines. A slight decrease in middle and lower crustal seismic velocities trenchward probably indicates fracturing and possibly crustal hydration due to plate bending. Seismic velocities in the oceanic upper mantle systematically increase with plate age, though on corridor 2 they locally decrease trenchward, perhaps due to serpentinized mantle rocks [*Ranero and Sallares*, 2004].

In conclusion, the lithospheric structures of both incoming and overlying plates appear relatively homogeneous along the Chile margin, despite the strong difference in age. Moreover, homogeneity also appears in the distribution of the incoming sediments (trench fill ~2 kilometers in the TIPTEQ area). One may speculate that the reason for the 1960 great Chile earthquake to rupture right through all age segments was because the structures in this region are so remarkably similar.

The information gained through the TIPTEQ project will help to further characterize the earthquake hazard for this area, and will provide a framework to study other subduction zone areas. More information about TIPTEQ can be found at: http://www.gfz-potsdam.de/pb3/pb31/tipteq

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Creating Effective Flood Mitigation Policies

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Hurricane Katrina in 2005 increased awareness of the vulnerability of people and property in flood-prone areas of the United States, particularly repetitively flooded properties. Prior to Katrina, repetitive loss properties cost the United States over $200 million annually [*General Accounting Office (GAO)*, 2004].

The U.S. Congress passed the Bunning-Bereuter-Blumenauer Flood Insurance Reform Act of 2004 (FIRA) to maintain the fiscal soundness of the National Flood Insurance Program (NFIP) and ease the burden of repetitive loss properties on NFIP. Federal calculations indicate that every dollar spent on mitigation activities creates a $3.65 savings in future disaster recovery costs, and the U.S. Federal Emergency Management Agency (FEMA) estimates that over $1 billion are spared annually through flood mitigation and floodplain management programs [*GAO*, 2005a].

Despite the availability of existing flood mitigation programs, many property owners decline mitigation offers, increasing potential future costs and their own personal vulnerability.

Since the success of flood mitigation programs such as FIRA depend on large-scale voluntary participation, it is important to understand the drivers of human decision-making at the household level, and embed this analysis in an examination of the realities of actual mitigation policy implementation. An ongoing study being conducted by the University of North Carolina has been focusing on this issue of why some repetitive loss property owners accept offers of mitigation while others make the decision to decline such offers. Results to date show that individual participation in mitigation activities hinges in part on the availability of nonfederal matching funds, building local capacity to sustain mitigation programs, creating an efficient and effective project application and review process, and the development of effective relationships between mitigation officials and local communities. While program adjustments may be made at each level of government, an overall conclusion from the study is that a community-based approach toward program implementation is needed to develop sustainable mitigation initiatives across the United States.

Flood Mitigation Programs and Repetitive Loss Properties

Of all natural hazards, flooding causes the greatest economic losses and loss of life within the United States, and 90% of all natural disasters in the United States include flood events
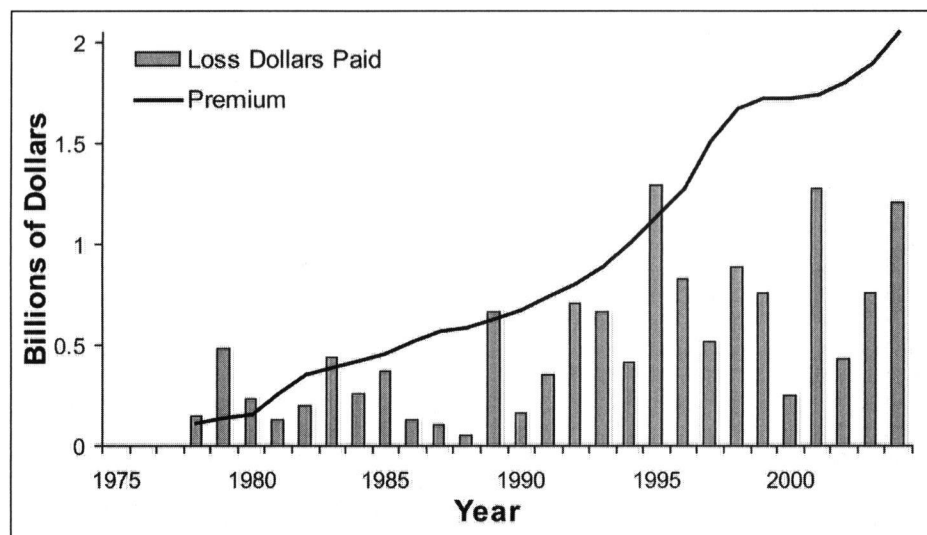

Fig. 1. Annual National Flood Insurance Program dollars paid and annual NFIP premiums. Source: FEMA [2004b].
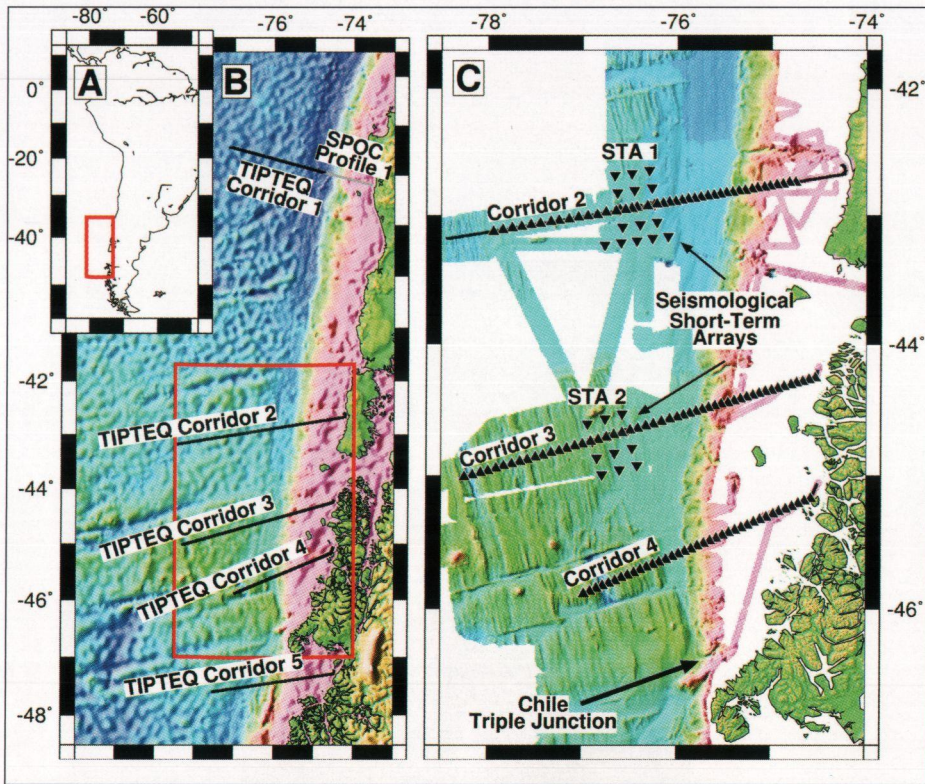
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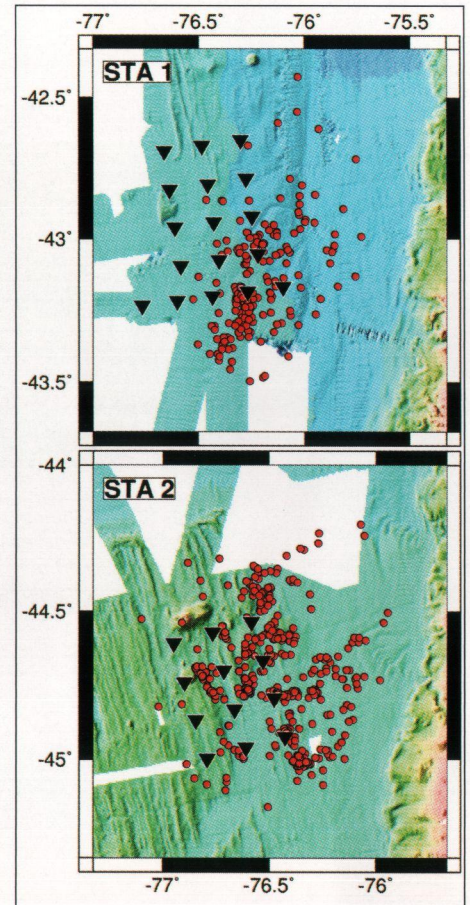
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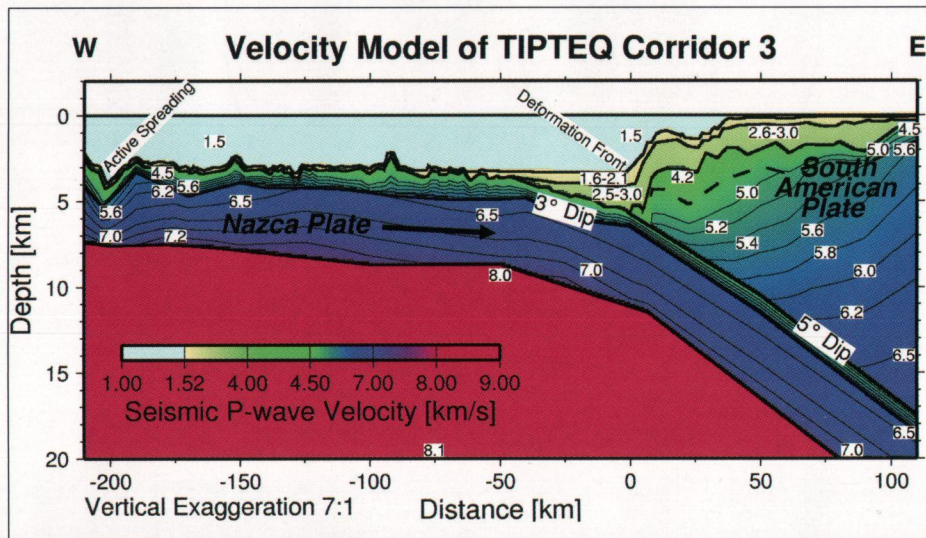
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