

## Amphibious Seismic Survey Images Plate Interface at 1960 Chile Earthquake

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The southern central Chilean margin at the site of the largest historically recorded earthquake in the Valdivia region, in 1960 ( $M_w = 9.5$ ), is part of the 5000-km-long active subduction system whose geodynamic evolution is controversially debated and poorly understood. Covering the area between 36° and 40°S, the oceanic crust is segmented by prominent fracture zones. The offshore forearc and its onshore continuation show a complex image with segments of varying geophysical character, and several fault systems active during the past 24 m.y.

In autumn 2001, the project SPOC was organized to study the Subduction Processes Off Chile, with a focus on the seismogenic coupling zone and the forearc. The acquired seismic data crossing the Chilean subduction system were gathered in a combined offshore-onshore survey, and provide new insights into the lithospheric structure and evolution of active margins with insignificant frontal accretion.

In this article, the first images are presented of the predominantly land-based components of SPOC in southern central Chile, which was a collaborative effort of several German and Chilean institutions. These new seismic data provide constraints on the continuation of fault structures at depth, on deep crustal structures, and on Moho depth. Finally, the plate interface of the 1960 rupture event is evident in the near-vertical incidence reflection section and calibrated with results from the wide-angle velocity model, suggesting the relocation of the 1960 earthquake at 73°05'W.

### Aims and Motivation

Convergent continental margins are the Earth's principal locus of important earthquake hazards. Some 90% of global seismicity and all interplate megathrust earthquakes with  $M > 8$  occur in the seismogenic coupling zone between the converging plates. However, the processes that shape the coupling zone and

its relation to surface deformation are poorly understood. Seismogenic coupling zones occupy a limited depth range between 5–10 km depth at the updip end, and 30–60 km at the downdip end (Figure 1, inset). Stronger asperities or material-state variations are supposed to control the strength of the seismogenic coupling zone and subduction channel [Ruff, 1999; Pacheco *et al.*, 1993], while extent and degree of seismic coupling play a major role in great interplate earthquakes [e.g., Oleskevich, 1999].

The long-term vision of our integrated study is a quantitative understanding of mega-thrust earthquake seismicity in subduction zones, and its relation to processes at depth and at the surface. We have started with a series of experiments in the area of the 1960 Chile earthquake that is designed to (1) image the plate interface from the updip to below the downdip end of the seismogenic part, in order to (2) yield key petrophysical and mechanical properties with (3) their variation along different along-strike segments of the plate interface which are at different stages of the seismic rupture cycle, and (4) determine their effect on surface deformation.

### Regional Setting

The southern central Chilean convergent margin provides a first site for our studies (Figure 1). Here, the largest instrumentally recorded earthquake occurred in 1960 ( $M_w = 9.5$ ). The ruptured zone, starting at 38°S at a hypocentral depth of some 30–40 km below the continental forearc, extended progressively toward the south for approximately 1000 km [Cifuentes, 1989] with a co-seismic slip of up to 40 m, up to 2 m vertical displacement, and a tsunami up to 15 m high that affected the entire Pacific [Kanamori and Cipar, 1974; Pflafer and Savage, 1970]. Recent GPS data reveal this part of the upper plate to be still in the post-seismic relaxation stage [Klotz *et al.*, 2001].

### Experiment Components of SPOC

The first component of the study, the shipborne geophysical experiment SPOC with the R/V

*SONNE*, took place in fall and winter 2001/2002, and was operated by the BGR, GEOMAR, and the Berlin-Potsdam Andes research group, SFB 267 (Figure 1). It will yield a near-three-dimensional image of the offshore forearc, including the updip parts of the seismogenic coupling zone of the 1960 Chile earthquake segment, and the seismic gap segment to the north [Reichert and SPOC, 2002].

Between 36° and 39°S, a predominantly land-based combined onshore-offshore, active-passive seismic experiment was carried out, operated by the GFZ Potsdam and the FU Berlin, linking the marine profiles to the subduction features observed onshore. It comprised (1) a pilot near-vertical incidence reflection (NVR) seismic experiment covering the onshore-offshore transition along a WE line to test the structural and reflectivity potential along the seismogenic plate interface, and (2) a three-dimensional-wide angle reflection/refraction component with the aim of comparing different segments of the Chilean continental margin.

### The NVR Seismic Experiment

The NVR land component at 38°15'S covers the near-shore part of the subduction zone between the South American and Nazca plates along the westernmost part of a longer refraction line (Figure 1). The 54-km-long WE line was set up in three spreads, and recorded a series of 14 shots fired at 10 different locations (Table 1). This resulted in a single-fold CDP coverage along a 71-km-long profile encompassing a 45-km-long portion with two-fold CDP coverage. In addition, the airgun shots of the offshore profile SO161-38/42 were recorded with the first 18 km of the onshore NVR spread.

### The Wide-angle Seismic Experiment

The wide-angle seismic experiment simultaneously recorded the airgun pulses from R/V *SONNE* with 30 three-component stations deployed in an array, 52 stations along three consecutive WE profiles, 22 OBH/OBS stations along the offshore part of the profile at 38°15'S, and 6 three-component broadband stations along a profile at 39°S (Figure 1). Furthermore, eight chemical shots were fired, mainly at the ends of the three WE profiles (Table 2). Teleseismic, regional, and local events were recorded by the array and broadband stations, contributing to the passive component of the experiment.

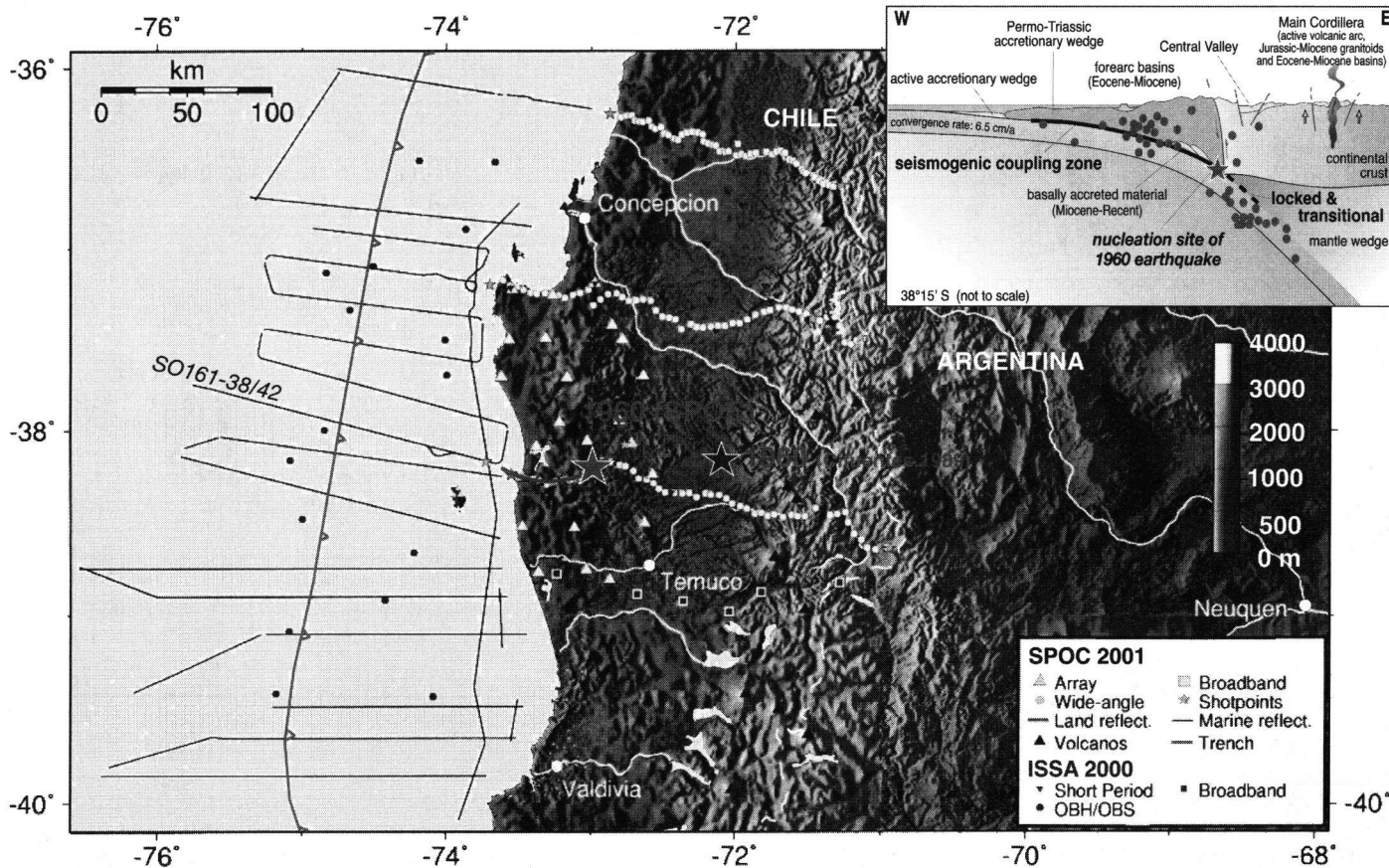


Fig. 1. Map of investigated area with SPOC profile locations. The inset shows a schematic illustration of the conceptual model of crustal structure of the southern Chilean subduction zone at 38°15'S. The blue asterisk marks the 1960 Valdivia earthquake location from Cifuentes [1989]; the red asterisk marks the suggested relocation. Original color image appears at back of volume.

First Results

All land data first underwent different processing and modelling procedures (Tables 1 and 2), eventually providing a migrated section and a velocity model along the profile at 38°15'S (Figures 2 and 3).

The offshore profiles [Reichert and SPOC, 2002] reveal that the upper plate is split into many segments, with pronounced forearc basins and a strikingly narrow accretionary wedge. A thick subduction channel (up to 2 sec TWT) seems to take down the relatively thick trench fill, thereby suggesting a non-frontal accretionary subduction type here.

The onshore NVR section gives an image of different reflection bands in the upper and middle crust (Figure 2). On the entire profile, a subparallel, 3-km-thick strong reflection band is observed between 8 and 11 km depth. Different mainly eastward dipping prominent reflection bands are imaged between 5 and 25 km depth. These bands are interpreted to describe the internal structure of the Permo-Triassic accretionary wedge integrating metabasitic and meta-ophiolitic structures in a dominantly meta-sedimentary, basally accreted nappe pile.

Finally, in the western part of the seismic reflection profile, some reflections which weaken eastwards are found between 18 and 30 km depth (Figure 2). All these eastward dipping reflection bands between 20 and 45 km depth correlate with Wadati-Benioff seismicity, and

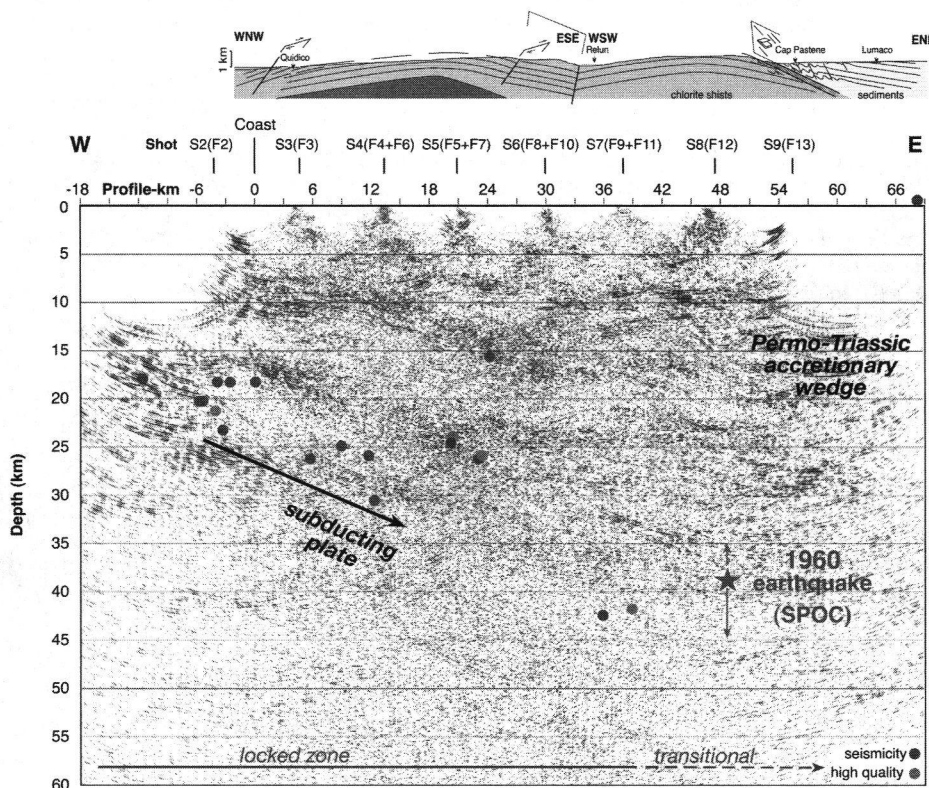


Fig. 2. Depth-migrated reflection seismic profile at 38°15'S with seismicity data (green dots from Bohm et al. [2002]). Original color image appears at back of volume.

can be interpreted as imaging the top of the downgoing plate with a change of the downdip image that approximately correlates with the downdip end of the seismogenic plate interface.

At the latitude of the NVR section, continuous wide-angle data allow the construction of a velocity model from the oceanic crust west of the trench to the continental arc. The oceanic crust is about 7 km thick (Figure 3). The oceanic Moho is constrained by PmP-reflections down to 45 km depth under the coastal cordillera. The continental crust is characterized by gradually increasing average P-wave velocities from west to east. A region of very low P-wave velocities (1.8–5 km/s) may indicate the modern accretionary wedge for about 30 km east of the trench, and further landwards may be correlated with the dominantly meta-sedimentary basement observed onshore. Under the coastal cordillera and the Longitudinal Valley, a continental Moho was not observed, indicating that here a rather smooth transition, in terms of seismic velocities, occurs from continental to oceanic crust.

The near-vertical and wide-angle reflection data provide the structural framework for the interpretation of observed seismicity and crustal deformation at the Chilean margin between 36 and 39°S. Recent seismicity [e.g., *Bohm et al., 2002*] is concentrated in the continental crust and along the oceanic/continental crust boundary beneath the coastline, and in the downgoing slab under the Longitudinal Valley and the main cordillera (Figure 3). The hypocenter of the great 1960 earthquake [*Cifuentes, 1989*] plots within the lower continental crust under the Longitudinal Valley. However, with respect to the location uncertainty of the earthquake (Figure 3), the E-W error is the largest, while the N-S and depth errors are smaller. Since the new data present for the first time the slab geometry in the region, we suggest the relocation of the 1960 Valdivia earthquake hypocenter further west at, or immediately above, the presumed slab-continental Moho boundary (Figure 3). Thus, the 1960 mega-thrust earthquake would have initiated at 73°05' W. Future relocation of seismic events and receiver function analyses for continental Moho depth determination for the region will focus on these questions.

#### Acknowledgments

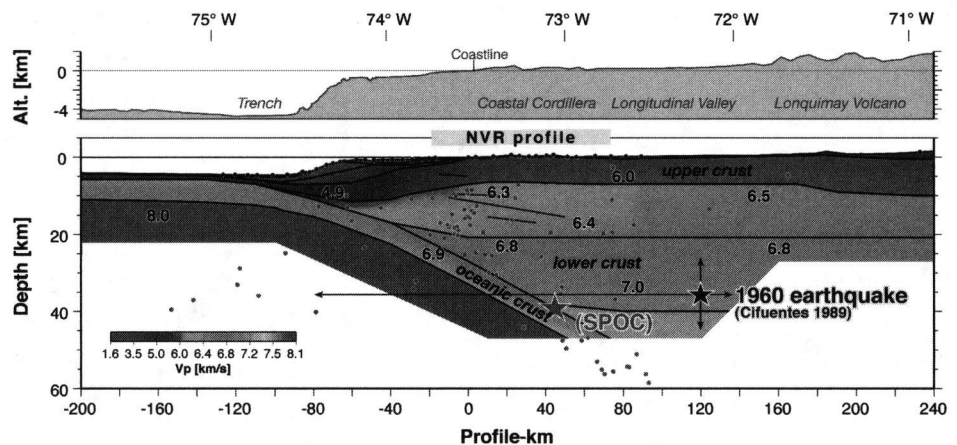
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**Table 1. Acquisition and Processing Parameters of the SPOC (Subduction Processes Off Chile) Onshore Near-vertical Reflection Component.**

Acquisition Parameters	
Recording period	9.11. - 5.12.2001
Recording systems	30 Teledyne PDAS-100 seismological recorders (6 channels, GPS-clock, 1 GByte hard disk)
Sample rate	5 ms, continuous recording
Number of profiles	1
Profile length	71 km along CDP line, 54 km along spread
Receiver Specifications	
Number of channels	30 units × 6 channels
Geophone type	Sensor SM 6, 4.5 Hz, vertical
Receiver array	6 per group, linear pattern 15 m in-line
Group spacing	100 m
Block move-up	18 km
Spread length	18 km
Number of stations	540
Source Specifications	
Explosive Charge	1 Sea: 50 kg in 190 m water depth 1 Sea: 25 kg in 40 m water depth 11 Land: 75 kg per shot in 20 m depth (1 hole) 1 Land: 150 kg in 2 holes of 20 m depth
Configuration	4 shots per set-up (-13.5, -4.5, 4.5, 13.5 km)
Shotpoint spacing	9 km + 2 far-offset shots
Number of shots	14 (at 10 different locations)
Subsurface coverage	two-fold (50 m bins)
Data amount	14 x 180 channels x 12 000 samples = 121 Mbyte
Processing Sequence	
CDP geometry	crooked-line design (50 m binning)
Amplitude correction	spherical divergence, AGC, trace equalization
Frequency filtering	DC-removal and bandpass
Static corrections	floating datum before/after NMO
Dynamic corrections	velocity model from SPOC refraction line
Deconvolution	in f-x domain
CDP stack	2-fold
Coherency enhancement	in tau-p domain
Wave-equation migration	FD method to depth



**Fig. 3. Velocity model of the two-dimensional, wide-angle seismic profile at 38°15'S, with local seismicity (red dots from *Bohm et al. [2002]*). The blue asterisk marks the 1960 Valdivia earthquake location from *Cifuentes [1989]*; the red asterisk marks the relocation suggested in this article. Arrows indicate range of earthquake locations given by different authors. Original color image appears at back of volume.**

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**Table 2. Acquisition and Processing Parameters of the SPOC (Subduction Processes Off Chile) Onshore Wide-angle Component.**

Acquisition Parameters	
Recording period	27.10.-1.12.2001
Recording systems	52 Teledyne PDAS-100; 30 RefTek 72A-07; 6 Guralp CMG-3ESPD/SAM-2 seismological recorders (3 channels + GPS-clock, hard disk: PDAS 1 GByte, Reftek 3 GByte, Guralp 4.5 GByte)
Sample rate	10 ms, continuous recording
Number of profiles	3 + array
Profile length	profiles: onshore 150-235 km, 145-180 km offshore; array: 100 x 200 km
Receiver Specifications	
Number of channels	3
Geophone type	MARK L-4C-3D, Guralp CMG-40T, Guralp CMG-3ESPD
Station spacing	2.5-4.5 km - profiles; 20-40 km - array
Source Specifications	
Explosive Charge	Sea: 200 kg in 25 kg packages Land: 50-980 kg in 1-4 boreholes
Shotpoint spacing	50 m - airgun pulses, 30-235 km - chemical shots
Number of shots	8 chemical shots + 12600 airgun pulses - profiles; 38250 airgun pulses - array
Data amount	32 GByte - profiles; 91 GByte - array
Processing/Modelling Sequence	
Frequency filtering	DC removal and bandpass
Display (plotting)	Trace-normalized amplitudes Velocity reduction of 6 or 8 km/s Water depth correction
Travel-time interpretation	2-D ray-tracing

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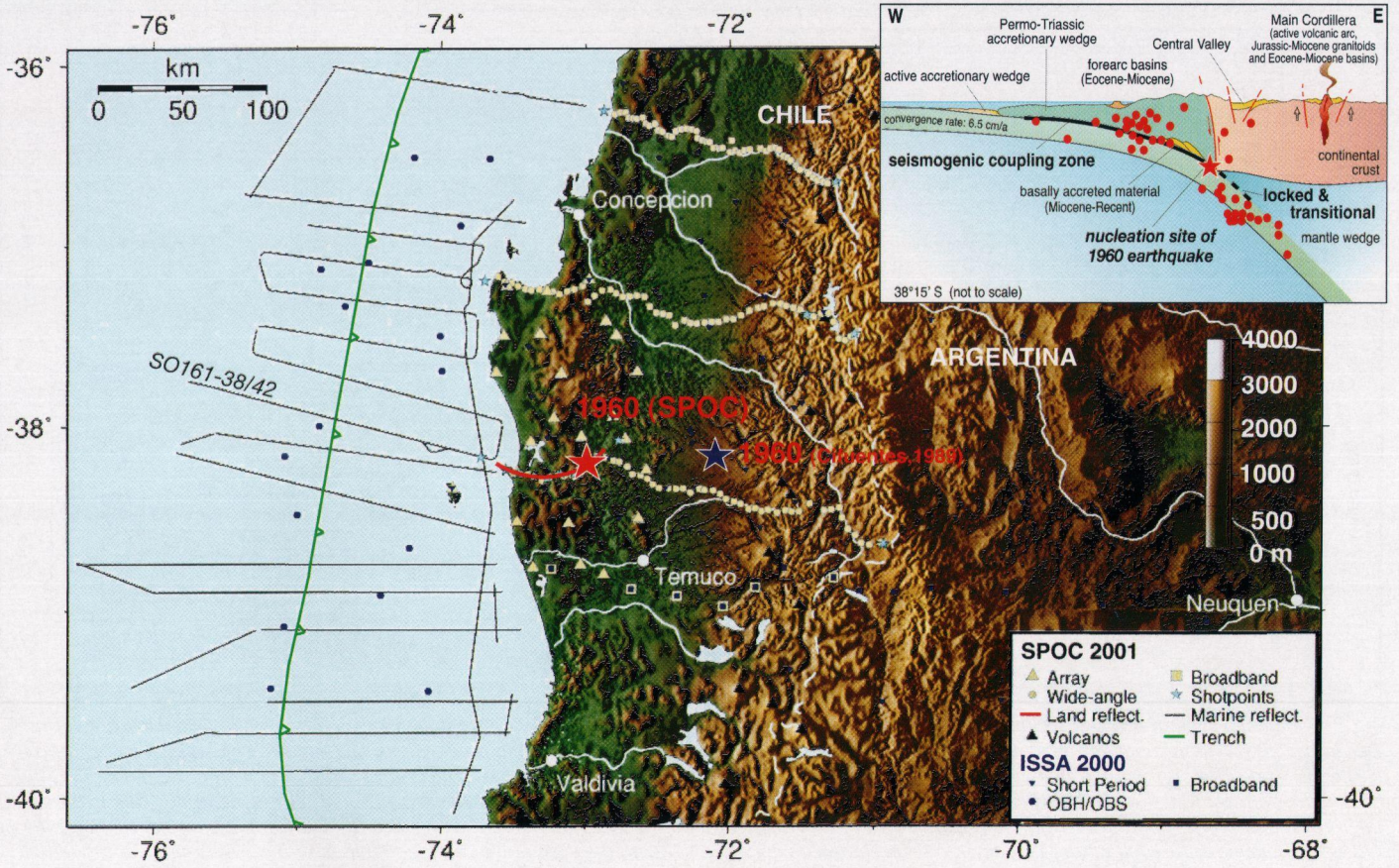


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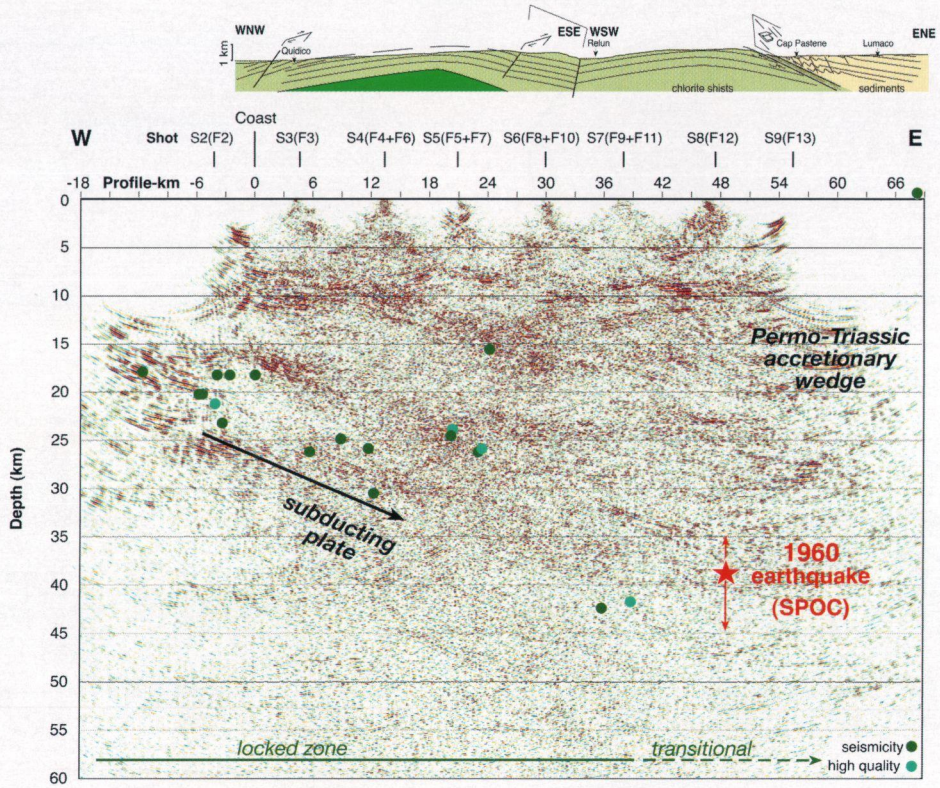


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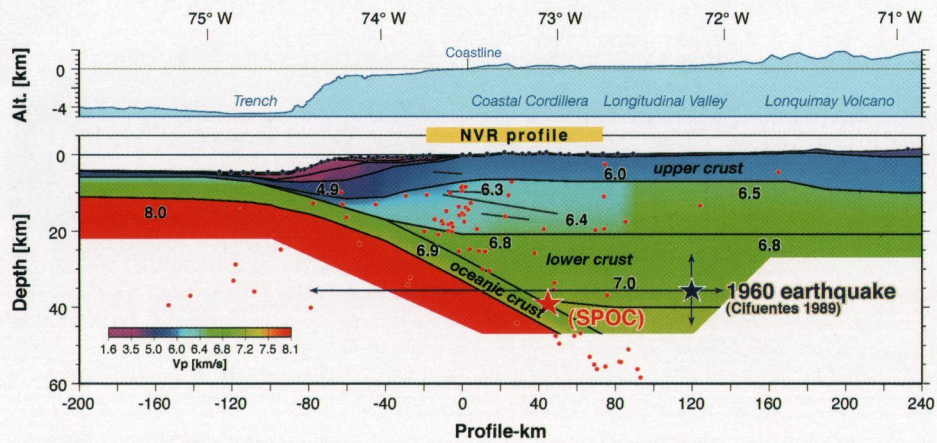


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