# Imaging a plate boundary using double-sided onshore-offshore seismic profiling

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Seismic profiling across the ocean-land transition is a known challenge that requires a combination of data collection techniques. Seismic acquisition may require the use of swamp buggies, bay cables, ocean bottom hydrophones or seismometers, and/or marine air guns. The onshore-offshore seismic profiling technique, which uses moderate-to-widely spaced land instruments to record densely spaced marine air-gun sources, undershoots the coastline to provide detailed images of subsurface regions that cannot be seen in either marine or land profiles. Intermediate to wide-angle raypath geometries are common in this technique. Useful analysis methods include arrival-time velocity tomography or wide-angle prestack migration, neither of which is based on vertical-incidence raypaths.

The creation of the IRIS PASSCAL pool of portable seismic recorders accelerated an era of investigations of continental crust using this onshore-offshore seismic profiling technique. During the past decade, the crustal seismology community based primarily in Europe and North America has used this method to improve our understanding of the 3D structure of passive and active continental margins, ocean-continent subduction zone and arc systems, and plate boundaries situated near coastlines. Recent targets include the Baltic shield, conjugate margins on both sides of the mid-Atlantic spreading system, subducting slabs at Cascadia and the Andes, the Mendocino triple junction, the San Andreas strike-slip plate boundary, and as we report here, the Pacific/Indo-Australian transpressional plate boundary in southern New Zealand.

This latter plate boundary, which has often been compared to the Big Bend of the San Andreas fault in southern California, is an example of extremely active strike-slip translation and continent-continent convergence with one of the fastest present-day exhumation and erosion rates (8-10 mm/yr) in the world. Unlike the San Andreas fault, this southern New Zealand plate boundary has suppressed levels of modern seismicity which suggest either long recurrence rates for strong episodic earthquakes or a larger role for ductile creep or fluids-enhanced aseismic slip within the plate boundary fault zone. We used the onshore-offshore technique to conduct crustal imaging of this plate boundary in order to derive crustal structure and rheological behavior.

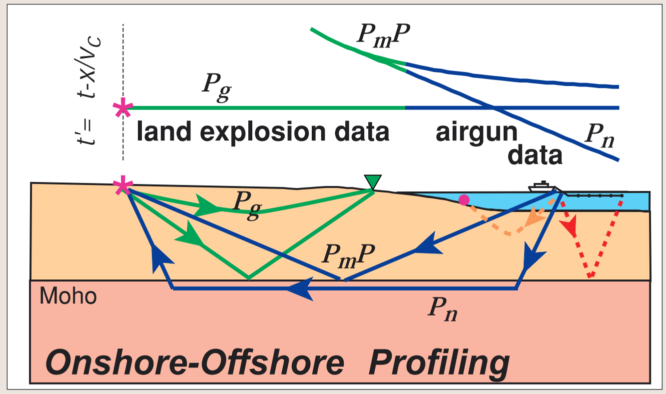


*Figure 1. The traveltime curves within an onshore-offshore common receiver gather are produced by marine air-gun sources recorded at a specified land instrument site (far offsets; blue raypaths) and by a collocated land refraction shot gather (near offsets; green raypaths) using the concept of reciprocity. Asterisk denotes site of collocated receiver gather's instrument and shot gather's explosion. Note opposite direction of raypaths from air-gun and land explosion sources. Numerous onshore instruments provide many such common-receiver gathers, which can be used in tomographic inversions and other analyses. Other acquisition phases involve recording the airgun signals by OBS instruments (pink circle) and an MCS streamer. While these additional raypaths are illustrated (orange for OBS and red for MCS), their traveltime curves are not shown.*

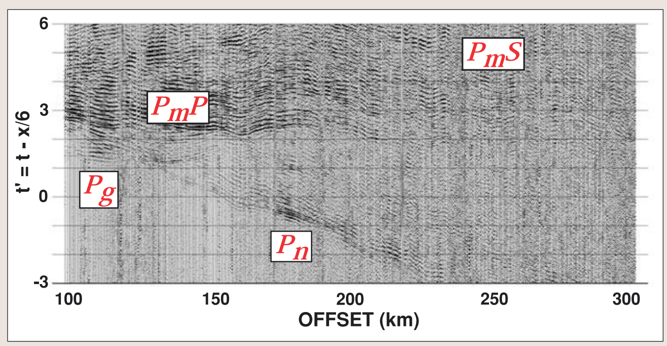


*Figure 2. Example of an onshore-offshore common receiver gather. For this gather the station location is shown in Figure 5 (red triangle) and the air-gun ship was in the Pacific Ocean. Seismic trace spacing is 50 m, an interval controlled by air-gun shot spacing. Vertical axis is reduced traveltime using 6.0 km/s. Crustal and upper mantle events are visible.*

**Onshore-offshore profiling.** Crustal onshore-offshore transects cross tectonic targets that are often approximately parallel to coastlines. This profiling takes advantage of an air-gun ship's ability to shoot at 50-100 m intervals for hundreds of kilometers surrounding a tectonic target. This is coupled with onshore deployment of portable seismic recorders that are able to continuously record for at least 12 to 24+ hours. An individual instrument will collect the many air-gun signals to provide a broad aperture of source-receiver offsets within a "common-receiver" gather (Figure 1). The offset range of the air-gun data is in part determined by the location of the instrument relative to the coastline (e.g., more inland instrument sites produce farther offsets). Because instruments in onshore-offshore profiling are not rolled or redeployed during a set of air-gun ship tracks and are spaced a few kilometers apart, the onshore field effort is less intensive than standard CDP profiling.

Reduction of onshore-offshore data requires the use of GPS-based air-gun shot times to extract seismograms from the continuously recorded data. The resulting common receiver gather is rich in resolution in that seismogram spacing is based on the air-gun shot interval; this spatial density greatly improves phase identification and traveltime picking. Seismic events that appear in many crustal-scale experiments are refractions through the crust and upper mantle (Pg and Pn, respectively), the Moho reflection (PmP) at the base of the crust,

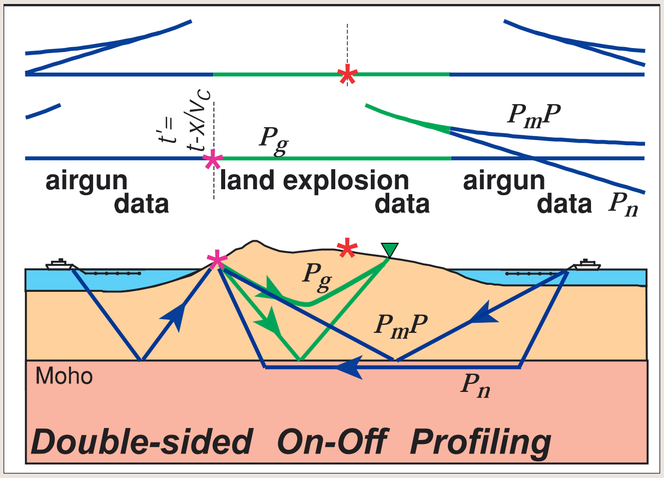


*Figure 3. Imaging using onshore-offshore profiling on each side of a narrow island. This double-sided profiling can produce very wide aperture traveltime curves and is required to properly image crustal structure beneath narrow landmasses such as islands or peninsulas. Pink asterisk denotes site of collocated receiver gather's instrument and shot gather's explosion for the lower traveltime curve. Blue raypaths and traveltime curve branches are from air-gun sources; similarly, green is from a land explosion source. Red asterisk denotes the zero-offset site of upper composite traveltime curve whose raypaths are not shown. Additional acquisition phases of air-gun recording by OBS instruments and the MCS streamer occur within each marine side but are not illustrated here.*

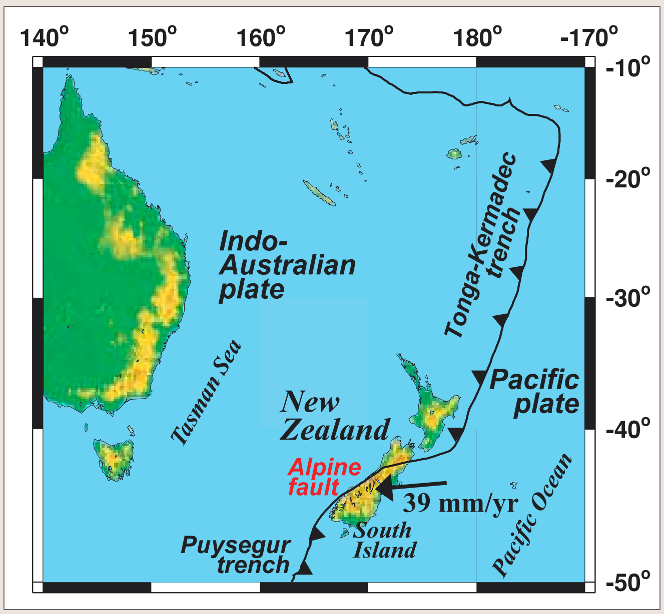


*Figure 4. Relative motion across the Pacific and Indo-Australian plates is 39 mm/year of which about 35 and 12 mm/yr are parallel and perpendicular, respectively, to the Alpine fault transpressional plate boundary. The Alpine fault forms a transition between two oppositely dipping subduction zones.*

and often intermediate crustal reflections (Figure 2). S-waves generated at the seafloor, basement, or Moho are often observed (e.g., Sg, SmS, PmS). Crustal velocity structure can be derived using first-arrival tomography or ray trace forward modeling of the numerous common receiver gathers after which prestack wide-angle migration methods can be applied to create a Moho image.

A complete onshore-offshore experiment employs three other phases of data acquisition: land refraction (explosion) profiling, ocean bottom seismometer (OBS) refraction profiling, and air-gun multichannel seismic (MCS) profiling. The OBS, MCS, and onshore-offshore recording are all performed at the same time because they record the same air-gun signals (Figure 1). Land refraction acquisition is conducted separately and normally uses additional instruments in order to achieve shot gather trace spacing of 100-400 m. The land refraction explosion sources are only recorded on land; although OBS instruments could, in theory, record the land explosions, this is seldom worthwhile due to the limited information they offer relative to the logistical efforts needed to collect this particular source-receiver combination.

Land refraction profiling provides three separate contributions. First, missing nearer offsets in the common receiver gathers can be filled in using the concept of reciprocity (Figure 1). Second, near-to-intermediate offsets within the coarsely spaced shot gathers can be processed to create a low-fold CDP stacked profile coincident with the refraction array. Third, land refraction data contribute the near-surface velocity structure which cannot be well constrained from just the onshore-offshore data. Without land refraction data, near-receiver effects such as traveltime delays could increase uncertainties at greater depths in the onshore-offshore results. For a similar reason, the OBS refraction profiling produces the offshore near-surface velocity structure, preventing offshore near-source effects from leaking into the deeper structure. Finally, the MCS profiling offers vertical-incidence images of offshore crustal structure. Data from all four acquisition phases are used during onshore-offshore data analysis. We note that this acquisition style can be scaled to image with high-resolution sedimentary basins which are situated at or adjacent to coastlines.

**Single versus double-sided onshore-offshore profiling.** Onshore-offshore profiling has an inherent ocean-to-land raypath geometry. A refraction velocity versus dip ambiguity normally arises with unidirectional shooting in conventional refraction profiling. However, when many land instruments are deployed in an onshore-offshore transect, the large number of common receiver gathers compensates for the unreversed shooting, particularly when analyzed using modern tomography and ray trace methods (e.g., Zelt and Smith, 1992; Hole, 1992). A typical crustal-scale experiment may use land instruments at 2-5 km spacing over an array length of 150+ km, all of which record the same air-gun sources. Instruments along additional transects or in a 2D array can be simultaneously deployed to collect 3D data. The numerous overlapping common-receiver gathers produced from the spatially dense arrays provide adequate ray coverage to create detailed images of subsurface structure.

The onshore-offshore technique has special application to narrow landmasses, where it must be applied to both margins. In this case, an insufficient number of onshore-offshore common receiver gathers can be collected from an air-gun ship on one side and the associated land refraction profiling will be too short to collect any events other than Pg. In order to properly image beneath the landmass and the two coastlines, a double-sided onshore-offshore experiment must be conducted. Such an experiment requires onshore-offshore shooting on each side of the landmass into the same transect (Figure 3). A composite "super"-gather can be made using common receiver gathers from opposite marine shiptracks and a cross-landmass explosion gather. The cumulative data collected in a double-sided onshore-offshore experiment will provide high-resolution refraction and wide-angle reflection imaging under the landmass and its marine-land transitions.

**The Pacific/Indo-Australian plate boundary.** New Zealand lies across the Indo-Australian/Pacific plate boundary (Figure 4). This plate boundary transects the South Island as the trans-

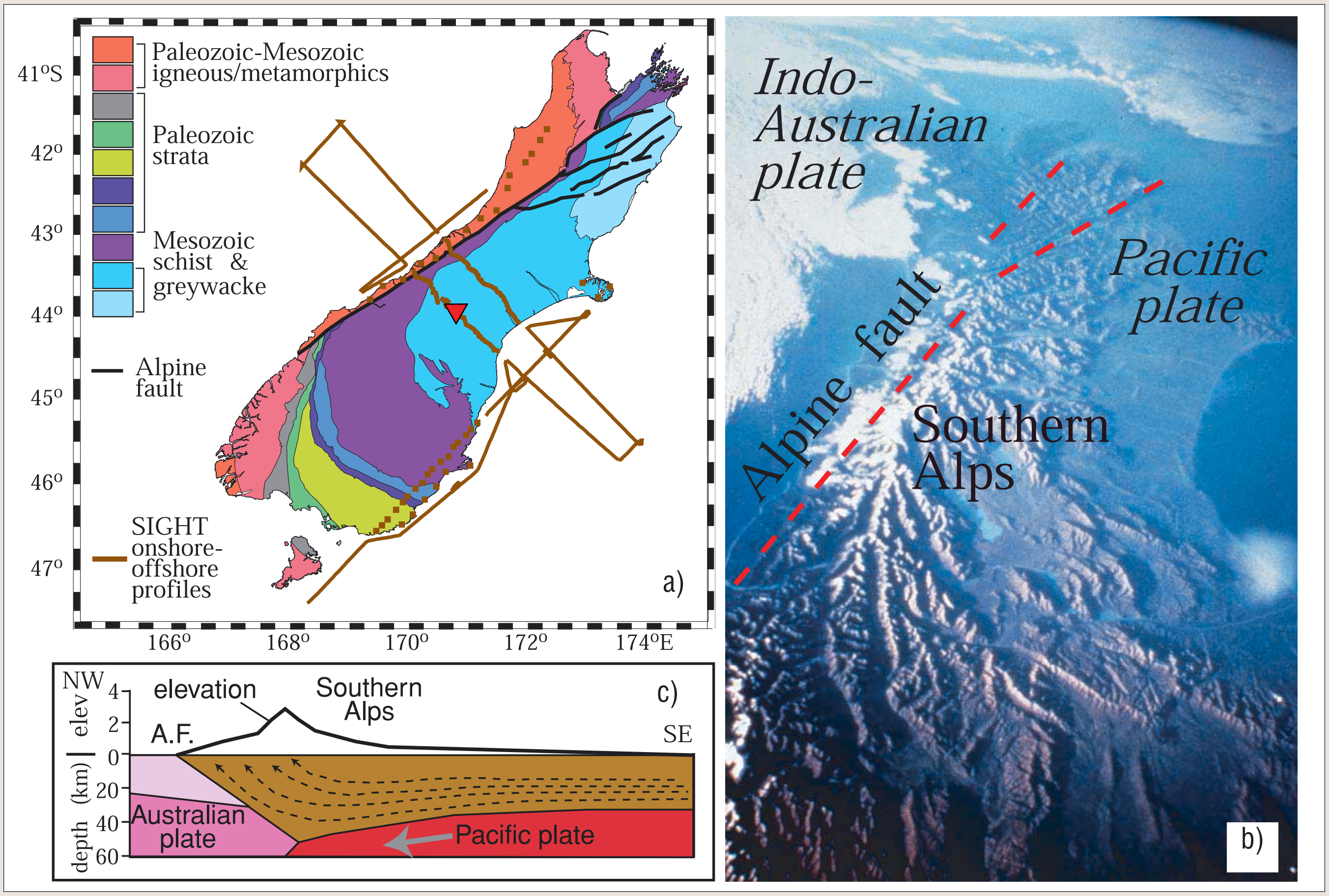


*__Figure 5.__ (a) South Island oroclinal bending of geologic belts. (b) This bending is also expressed in the geomorphology and topography. (c) Plate boundary deformation is marked by the uplift of the Southern Alps along the Alpine fault. Ship tracks and onshore profiles for the SIGHT experiment are shown in (a). The red triangle in (a) indicates the common receiver gather in Figure 2 and the combined data gather in Figure 8.*

pressional Alpine fault, which connects oppositely dipping subduction systems to the northeast (Tonga-Kermadec) and to the southwest (Puysegur). South Island is being deformed by oblique collision of a small continental fragment within the Pacific plate with a continental portion of the Indo-Australian plate. During the past 46 million years, the South Island has undergone dextral shear with displacements of 850 km. About 450 km of slip along the Alpine fault has occurred with more diffuse shearing northwest and southeast of the fault. This shearing is expressed in the bending of geologic belts (Figure 5). The Southern Alps orogen is an impressive expression of how the Pacific plate deforms due to oblique convergence (Figure 6).

Although the Alpine fault plate boundary is highly active, its historical and present-day rates of seismicity are extremely low. In order to be consistent with the rates of plate motion, this quiescence suggests either episodic large magnitude earthquakes must occur at recurrence rates of over 300 years or that the plate boundary is fundamentally weak and slips aseismically. The mechanism of movement along the Alpine fault is tied closely to the physical properties within the plate boundary fault zone and in a broader context with the creation and uplift of the Southern Alps orogen, the internal geometrical configurations and rheological strengths of the Pacific and Indo-Australian crusts, and ultimately how the plate boundary is accommodated in the mantle of both plates.

A joint USA-New Zealand geophysical study of this orogen was recently conducted to understand the processes involved in transpressional continental collision and how active deformation is accommodated (e.g., Molnar et al., 1999; Stern et al., 2000). Studies included passive seismology, magnetotelluric and electrical studies, petrophysics, crustal-scale reflection profiling, and refraction/wide-angle reflection profiling. The refraction effort, titled SIGHT (South Island GeopHysical Transect), involved double-sided onshore-offshore profiling across the Alpine fault and Southern Alps in central South Island. The objective of this effort was to derive a three-dimensional model of the plate boundary geometry as expressed in crustal structure, Moho configuration, reflectivity used as strain markers, and velocity structure for indication of composition and rheological strength.

*__Figure 6.__ The Southern Alps are the result of uplift due to exhumation of the Pacific plate near the Alpine fault plus rapid erosion due to weather produced in the Tasman Sea. The northern SIGHT transect ran along the near river bank into the Southern Alps.*

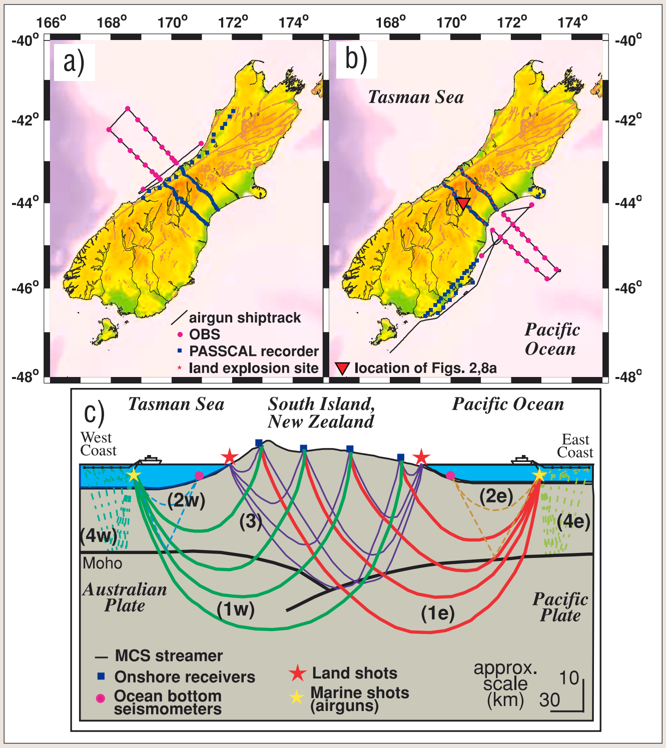


*Figure 7.* *SIGHT onshore-offshore experiments were conducted when the* R/V Ewing *collected MCS profiles in (a) the Tasman Sea and (b) the Pacific Ocean. Air-gun signals were recorded on the towed streamer and on both OBS and land PASSCAL Reftek stations. Land explosions were subsequently recorded by a separate array of closely spaced instruments. The common receiver gather in Figure 2 was collected at the red triangle when the* Ewing *was in the Pacific Ocean. The red triangle also denotes location of Figure 8a. (c) Schematic of the SIGHT double-sided onshore-offshore experiment showing the four data acquisition phases to a complete experiment: (1) onshore-offshore receiver gathers, (2) OBS receiver gathers, (3) land refraction shot gathers, and (4) multichannel seismic profiles. Phases 1, 2, and 4 use the same air-gun sources; "e" and "w" indicate when the* Ewing *was on the western and eastern sides of the South Island, respectively.*

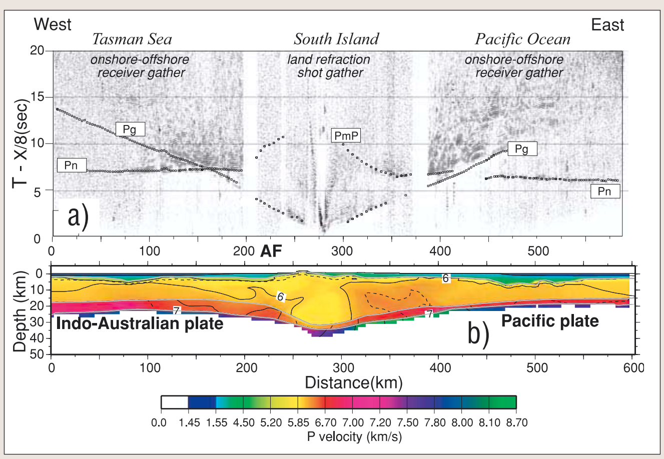


*Figure 8.* *Transect across the South Island. (a) A nearly 600-km composite "super-gather" made of onshore-offshore common receiver gathers whose air-gun sources were in the Tasman Sea and Pacific Ocean (Figure 2) plus a collocated land refraction shot gather. Location (zero-offset) of the composite gather shown in Figures 5 and 7. Vertical axis is reduced traveltime using 8.0 km/s. (b) P-wave velocity structure obtained from tomographic inversion of the onshore-offshore data. "AF" denotes location of Alpine plate boundary fault.*

**SIGHT field program.** The SIGHT experiment was designed as two parallel 600 km transects across the Alpine fault (Figure 5). These transects were at the narrowest part of the South Island where the plate boundary is nearly two-dimensional in geometry (i.e., Figure 5c) and is unaffected by the neighboring subduction systems. The SIGHT experiment used field acquisition methods of land refraction profiles using explosive sources, and on each side of the island MCS profiling with onshore-offshore and OBS recording of the MCS air-gun sources. In addition to the trans-island transects, within each plate an additional transect was collected parallel to the plate boundary fault.

The National Science Foundation ship *R/V Ewing* provided an approximately 140-liter (8600 in$^3$) air-gun array and a 4-km multichannel streamer. This research vessel deployed 20 OBS instruments and then collected 763 km of MCS profiling in the Tasman Sea (Figure 7a). Two hundred PASSCAL Reftek portable recorders were deployed by vehicle and helicopter across the two central South Island transects and along the western coastline to record these air-gun signals (see Owens and Fowler in this issue for a more complete description of the acquisition system). The *Ewing* then transited to the eastern side of the South Island while all instruments were retrieved and their data downloaded. While in the Pacific Ocean, the *Ewing* redeployed the OBS instruments and then collected 1286 km of MCS profiles (Figure 7b). The PASSCAL recorders were again deployed along the same cross-island transects and an eastern coast array at approximately 2.4-km spacing to collect these air-gun signals. After all land and OBS instruments were retrieved and downloaded, the *Ewing* departed from New Zealand. Subsequently, land refraction profiles were collected along each cross-island transect using explosion sources of 300-1200 kg (Figure 7b). Figure 7c schematically illustrates how the double-sided onshore-offshore shooting was able to image under the island coastlines.

**Data example and results.** Figure 8a illustrates a composite gather in the center of the South Island. This gather is formed using the onshore-offshore common receiver gathers from when the *Ewing* was in the Tasman Sea and Pacific Ocean. Near offsets are provided by a land refraction gather whose shot location was collocated with the onshore-offshore portable recorder (Figure 7). This composite gather has an aperture of nearly 600 km with traveltime curves of crustal Pg, PmP, and Pn. Tomographic traveltime inversion of the combined data produces a P-wave velocity cross-section from the Indo-Australian plate into the Pacific plate, crossing the plate boundary Alpine fault. Nearly 100 common receiver and shot gathers contributed to the tomographic section in Figure 8b.

An important result of our analysis is that the Moho root under the central South Island is not directly under the Southern Alps and is excessively deep with respect to the elevation of the mountains; the Southern Alps are not in simple isostatic balance (Figures 8b and 9). Fortuitous recording of a few western Pacific teleseismic earthquakes across the South Island by the PASSCAL Reftek array during the air-gun shooting allowed Stern et al. (2000) to examine the Moho root and underlying mantle. Their study found that the Southern Alps are dynamically supported by the westward oblique convergence of the Pacific plate into the Indo-Australian plate and the Moho root is enhanced by downward pull exerted by an overthickened mantle lithosphere at the plate boundary.

In addition, the Alpine fault zone has a distinctive geophysical signature. This plate boundary fault zone is not vertical but dips eastward into the Pacific plate as evidenced by a tomographic low velocity zone to depths of 35 km (Figure 9). The nearly 9% reduction in P-wave velocity was confirmed by detailed raypath analysis of individual shot and receiver gathers plus from traveltime delays obtained from the teleseismic earthquakes described above. Magnetotelluric and crustal-scale CDP profiling studies along the SIGHT transects

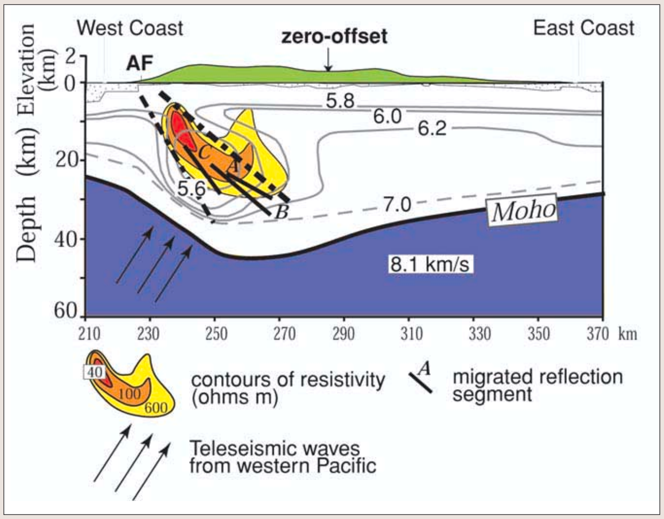


*Figure 9. Alpine fault zone and South Island velocity structure with additional fault zone properties superimposed. Resistivity and reflection segments are shown which were derived from magnetotelluric studies and crustal-scale CDP profiling, respectively, conducted with SIGHT under the same New Zealand-USA project. Note narrowing toward the surface of the Alpine fault zone (bold dashed lines) which increases the exhumation rate of fault zone rocks. The lower seismic velocities and resistivity together suggest enhanced fluid pressures are present within the fault zone.*

offered additional information about the fault zone physical properties. A low-resistivity anomaly is present (Wannamaker et al., 2002; Figure 9) and with the low seismic velocities suggest that enhanced fluid pressures are in the fault zone. Thick packages of Pacific plate greywacke and schist rocks are transported into the lower crust of the collisional zone (e.g., Figure 5) where they release water upon prograde metamorphism (Stern et al., 2002). The Alpine fault zone narrows toward the surface as is evidenced by migrated internal CDP reflectors (Figure 9); this upward constriction increases the exhumation rate of the fault zone and elevates its fluid pressures. Aseismic slip aided by the presence of these fluids helps explain the lack of seismicity that should normally be associated with a plate boundary. The Alpine fault crust and mantle geophysical behavior is fundamentally different from that of the Pacific-North American San Andreas transform fault (Fuis et al., 2001) due to differences in plate rheological strength and rates of surficial processes such as climate-controlled erosion.

**Summary.** Double-sided onshore-offshore experiments are needed in order to image the subsurface of a narrow landmass. This method can be applied to landmasses whose widths are from 1 to 3-5+ times the depth of the imaging target (Okaya et al., 2002). For crustal profiling, this translates to 50-150+ km wide regions for thin to moderate crustal thickness as is often associated with islands or peninsulas. If the landmass is too wide, air-gun energy from one side will not reach the other coast and the onshore-offshore experiments off opposing coasts become decoupled. In Figure 10, we identify a number of narrow landmasses at plate boundaries that are amenable to double-sided onshore-offshore profiling. These sites are at islands or peninsulas for which seismic air-gun energy may propagate across most of its width from offshore either coastline. In addition, the limited width of the landmasses are insufficient to properly image the crust-mantle boundary using just land profiling; marine and onshore-offshore methods are necessary. The availability of portable instruments such as the IRIS PASSCAL pool and an air-gun ship such as the *Ewing* allow for these plate boundary regions to be seismically imaged with high spatial resolution using high-confidence modern tomographic and wide-angle imaging analysis methods.

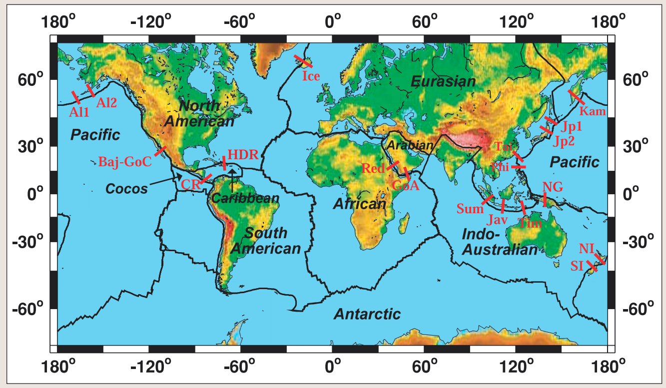


*Figure 10. Sites of plate boundaries at narrow landmasses where double-sided onshore-offshore profiling can be used for seismic imaging. Sites are primarily at subduction systems: Costa Rica (CR), Baja California (Baj), different sites within the Aleutian islands (Al1, Al2), Kamchatka (Kam), two different plate systems in Japan (Jp1, Jp2), Taiwan (Tai), Philippines (Phi), Sumatra (Sum), Java (Jav), Timor (Tim), New Guinea (NG), and the North Island of New Zealand (NI). Rifting sites include Iceland (Ice), Gulf of California (GoC), the Red Sea (Red), and the Gulf of Aden (GoA), where these last three are inverted in that they possess a narrow body of water surrounded on either side by landmasses. Strike slip sites include Haiti-Dominican Republic (HDR) and the South Island of New Zealand (SI). Major plates are labeled in black.*

**Suggested reading.** For recent examples of onshore-offshore studies throughout the world, see the special volumes associated with the biennial *International Symposium on Deep Seismic Profiling of the Continents and their Margins: Tectonophysics* (1994, 1996, 1998, 2000, 2002). More information about the IRIS PASSCAL instruments can be obtained at *http://www.iris.edu*. A new national facility similar to the PASSCAL pool of portable instruments is the U.S. National Ocean Bottom Seismograph Instrument Pool (OBSIP; *http://www.obsip.org*). Articles cited in the text are: "Crustal structure and tectonics from the Los Angeles basin to the Mojave Desert, southern California" by Fuis et al. (*Geology*, 2001); "Nonlinear high-resolution three-dimensional seismic traveltime tomography" by Hole (*JGR*, 1992); "Continuous deformation versus faulting through continental lithosphere: tests using New Zealand as a laboratory for the study of continental dynamics" by Molnar et al. (*Science*, 1999); "Super-gathers across the South Island of New Zealand: double-sided onshore-offshore seismic imaging of a plate boundary" by Okaya et al. (*Tectonophysics*, 2002); "P-wave teleseismic delays and lithospheric thickening beneath the central South Island, New Zealand" by Stern et al. (*JGR*, 2000); "Structure and strength of a continental transform from onshore-offshore seismic profiling of South Island, New Zealand" by Stern et al. (*Earth Planets & Space*, 2002); "Fluid generation and pathways beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric data" by Wannamaker et al. (*JGR*, 2002). "Seismic traveltime inversion for 2-D crustal velocity structure" by Zelt and Smith (*Geophysical Journal International*, 1992). TLE

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