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Preliminary results from a geophysical study across a modern, continent–continent collisional plate boundary — the Southern Alps, New Zealand

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Abstract

The Southern Alps of South Island, New Zealand, is a young transpressive continental orogen exhibiting high uplift rates and rapid transcurrent movement. A joint US–NZ geophysical study of this orogen was carried out in late 1995 and early 1996 to derive a three-dimensional model of the deformation. The measurements undertaken include active source and passive seismology, magnetotelluric and electrical studies, and petrophysics. Preliminary models for the active source seismic measurements across South Island confirm, in general terms, a thickened crust under the Southern Alps, a high-velocity lower crustal layer, and a major crustal discontinuity associated with the Alpine fault. The anisotropy in physical properties of the rocks of the plate boundary zone is clearly demonstrated in the preliminary results of laboratory seismic velocity measurements, shear wave splitting and resistivity. The mid-crust under the Southern Alps coincides with a major electrical conductivity high, which possibly corresponds to fluid in the crust. The top lies at about 15 km, close to the base of shallow seismicity east of the Alpine fault. Offshore the marine reflection data have consistently imaged a reflective lower crust adjacent to South Island. These data are showing complex structure, particularly off western and southeastern South Island. The complexity in structure, high-quality data and consistency in results from several techniques indicates that the South Island experiment will contribute significantly to our knowledge of transpressive plate boundaries in particular, and the continental lithosphere in general.

Keywords: seismic reflection; seismic refraction; seismicity; magnetotelluric; continental convergence; New Zealand

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1. Introduction

The deformation of continents at convergent plate boundaries at present or in the past has been the focus of significant research effort: e.g. the European Geotraverse (Pfiffner et al., 1988), Pyrenees (Choukrome and ECORS Team, 1989), INDEPTH (Zhao et al., 1993), ESRU (Juhlin et al., 1996), LARSE (Fuis et al., 1996), Wind River Mountains (Smithson et al., 1978). The motivation for these studies is to document the structure and development of major compressional mountain belts, and to understand the processes causing this deformation.

New Zealand lies across the Australian/Pacific plate boundary, which transects South Island as a transform boundary that connects the west-dipping Hikurangi subduction system in the northeast and the east-dipping Puysegur subduction system to the southwest of South Island (Fig. 1). South Island is thus being deformed by the oblique collision of the continental Pacific plate (eastern South Island, Chatham Rise and Campbell Plateau) with the continental Australian plate (northwestern South Island, North Island and Challenger Plateau) (Fig. 1). This deformation is marked by the uplift of the Southern Alps, which results from ramping up of eastern South Island along the Alpine fault, and gives rise to the distinct linear expression of the Alpine fault, and progressively higher-grade schists at the surface as the Alpine fault is approached from the east (Fig. 2). About 450 km of dextral strike-slip motion, 80 km of convergence and 20 km of uplift have occurred

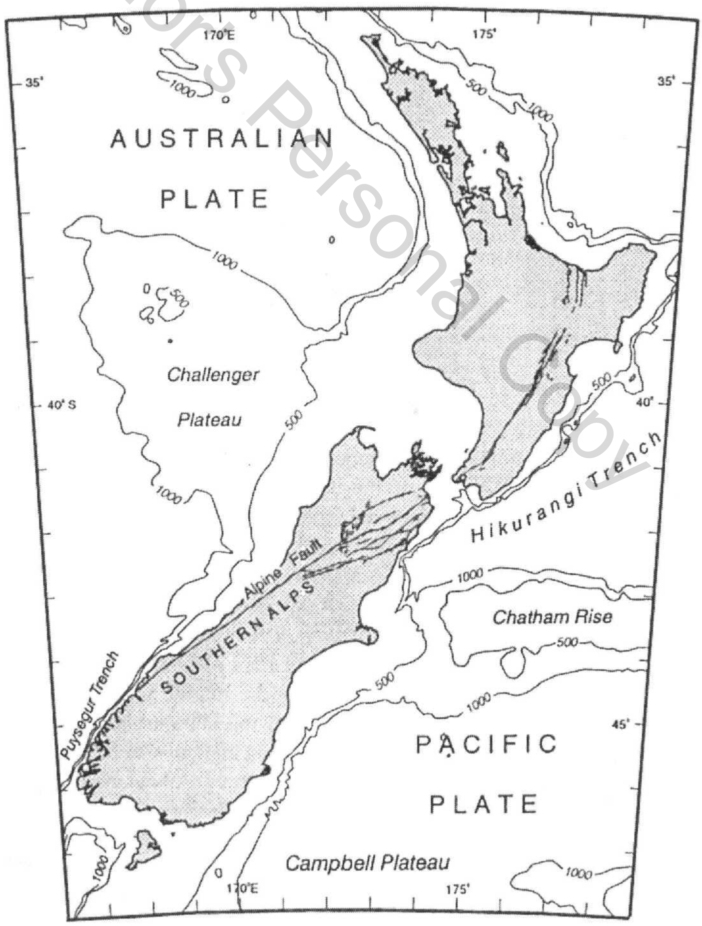


Fig. 1. Location map of New Zealand region.

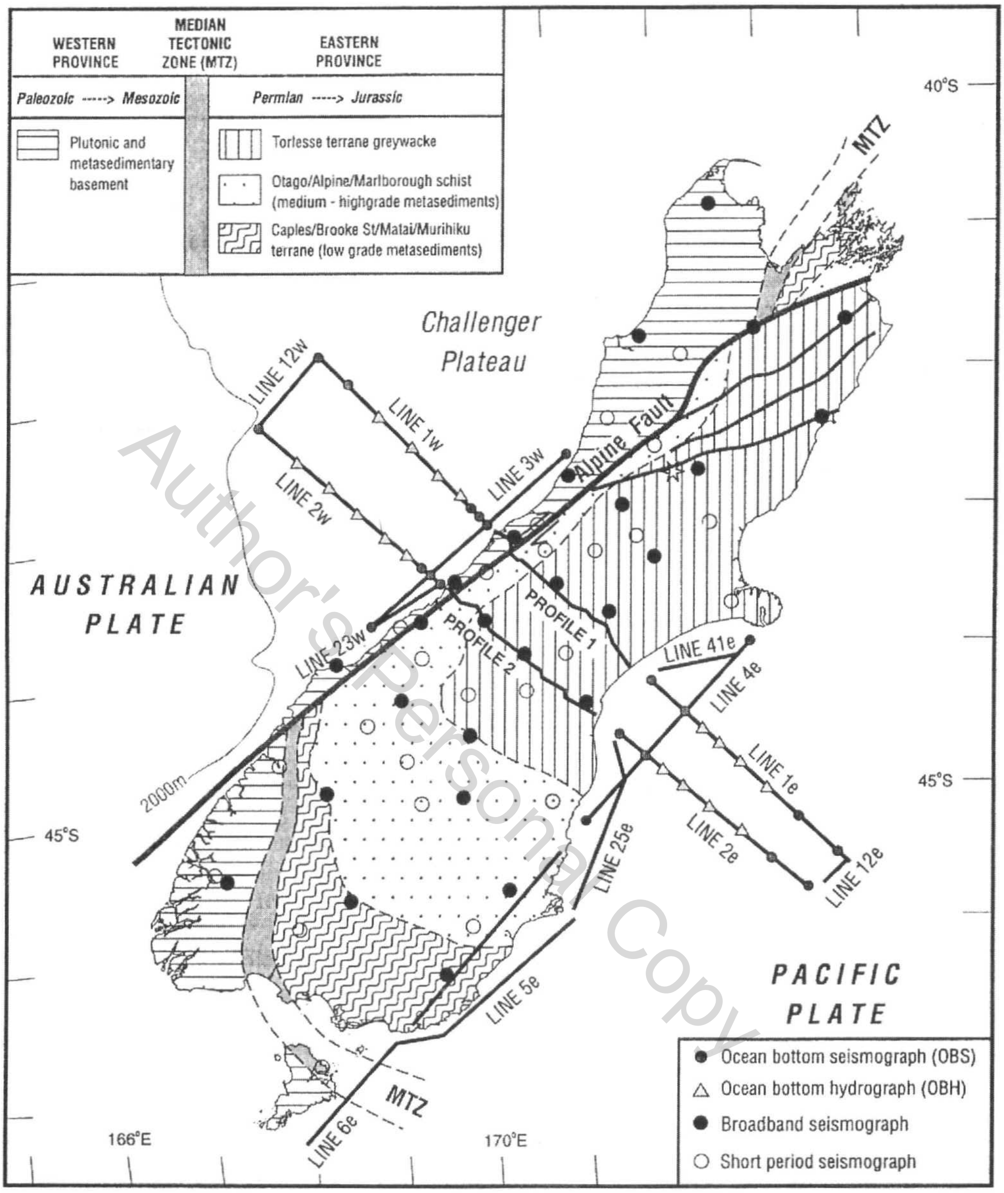


Fig. 2. SIGHT transects and OBS/H locations, and SAPSE onshore recording sites. Epicentre of the M_w 6.1 Cass earthquake is marked by an open star. Simplified geology showing the two main crustal terranes (Western Province and Eastern Province) and the offset of the Eastern Province across the Alpine fault.

across this plate boundary since the Oligocene, but most of the convergence is thought to have occurred in the past 5 m.y. (e.g. Allis, 1986).

Several conceptual models (Fig. 3) have been developed for the structure under South Island, based on surface geology (Wellman, 1979; Norris et al., 1990), gravity (Woodward, 1979; Allis, 1986), seismicity (Reyners and Cowan, 1993; Eberhart-Phillips, 1995), and limited active source seismic (Smith et al., 1995) and heatflow measurements (Shi et al., 1996). The basic models have two common components: the plate boundary suture is marked by the

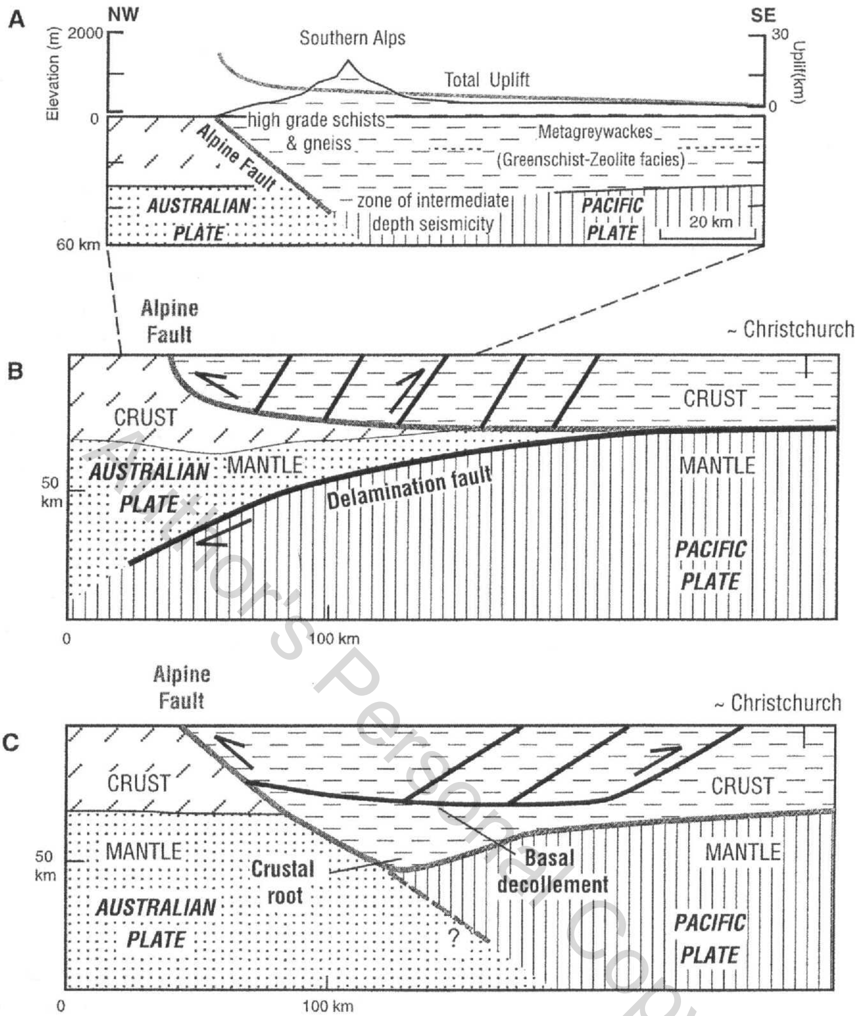


Fig. 3. (A) Summary features of a transect across the Southern Alps (after Koons, 1990). (B, C) Cross-sectional structure models of the South Island after (B) Wellman, 1979 and (C) Norris et al., 1990.

Alpine fault zone which dips at 40º to the southeast to at least the base of crust, and the spatial change in metamorphic grade in the surface rock exposures inferred to be caused by the uplift of mid-lower crustal rocks along the Alpine fault from a mid-lower crust detachment under South Island. The rocks under this detachment are either inferred to underplate central South Island, giving a crustal root and associated negative gravity anomaly (e.g. Woodward, 1979; Allis, 1986; Shi et al., 1996), or are subducted into the mantle to the west under the western South Island/Tasman sea (e.g. Wellman, 1979; Stern, 1995). Theoretical models for this continental collision deformation have been developed based on critical wedge theory; the indentor and two-sided critical wedge model of Koons (1990), and geodynamic modelling of Beaumont and Quinlan (1994) and Beaumont et al. (1994).

The geology of the South Island can be divided into two main crustal terranes: a Western Province and an Eastern Province, separated by the Median Tectonic Zone (MTZ) (Fig. 2). The oldest rocks known in New Zealand are Paleozoic rocks of the Western Province, which are a remnant of Gondwana. They are found in Northwest Nelson/West Coast, Fiordland, and offshore on the Challenger

Plateau and Campbell Plateau (Fig. 1) and consist of metamorphic and intrusive igneous rocks, which were intruded by granites in the Cretaceous. The Eastern Province comprises a number of terranes of largely low-grade metasediments (greywacke to schist) which were accreted during plate convergence and subduction in the Mesozoic. These are the rocks which are being upthrust along the Alpine fault.

The characteristics of the Southern Alps orogen, the relatively simple geology, the young deformation, clear link between erosion and uplift, and high strain and uplift rates (5–10 mm/y), provide several reasons for studying this example of continental collision. In addition, the relatively narrow South Island allows the use of onshore–offshore seismic techniques to study both sides of a continental orogen (Fig. 2).

A joint US–NZ project is studying the lithospheric deformation of this continental collisional orogen in order to understand the processes involved in continental collision and how the active deformation is accommodated, particularly in a three-dimensional (3-D) situation resulting from transpressive plate motion. The project measurements include active source and passive seismology, magnetotelluric and electrical studies, petrophysics and geological mapping, and gravity measurements. In this paper, we outline the scope of the study, and present preliminary results from the various phases of the work which were completed during the austral summer 1995/96.

2. Experimental measurements and preliminary results

The principal field activity during 1995/96 was an integrated onshore and onshore–offshore seismic refraction and wide-angle reflection experiment, carried out across the South Island and extending about 200 km offshore (Fig. 2). Measurements focused on two main transects across the central part of the island and a third transect was completed along the southeastern margin of South Island. Passive seismology, petrophysical and magnetotelluric experiments were also carried out, centred on central South Island and the two main transects. These geophysical projects are also linked to a joint programme of repeated GPS surveys across South Island that are designed to establish the crustal kinematics within the plate boundary zone (Pearson et al., 1995).

2.1. The active source vertical and wide-angle reflection–refraction seismic experiment, SIGHT (South Island GeopHysical Transect)

The experiment had two main components. The first was a wide-angle reflection–refraction experiment along two land transects (Profile 1 (north) and Profile 2 (south), Fig. 2) across central South Island. 23 chemical explosives (350–1200 kg) in boreholes up to 60 m deep were used as sound sources onshore, spaced equally across South Island with sixteen shots on the northern transect and seven shots on the southern transect. 420 recording instruments (single-channel and 3-component Refteks and EDAs) were deployed along each transect, at a nominal spacing of 400 m, to record the data. The second experiment consisted of three offshore–onshore transects, two along the land transects noted above, and a third across southeastern South Island. The third transect forms a tie line across the eastern part of the former two transects and provides information on the same terranes that are now being deformed and upthrust within the Alpine fault zone (Fig. 2). During the second experiment, data were recorded by 225 Refteks on land, spaced at about 1.5 km along the two profiles used in the land work and about 10 km intervals along the third transect and tie lines. Twenty ocean-bottom seismographs/hydrophone instruments (OBS/H) were deployed offshore. The R/V *Ewing* fired shots at ~50-m intervals, using a 139-l airgun array, along eight main profiles, each about 200 km long. It also recorded vertical incidence multichannel seismic data to 16 s two way travel time (twt) along these profiles. The survey first deployed the OBS/Hs and shot the profiles on the west of South Island and then redeployed the OBS/Hs and shot the profiles on the east of South Island (Fig. 2).

Preliminary results from the onshore work show P_g and a strong lower crustal reflected arrival clearly detected out to the maximum range (160 km) (Fig. 4). The *Ewing* airgun signals were detected to ranges of at least 300 km on the onshore–offshore data, and P_n can be seen on these data to ranges of at least 240 km (Fig. 5). The 45000 (approx.)

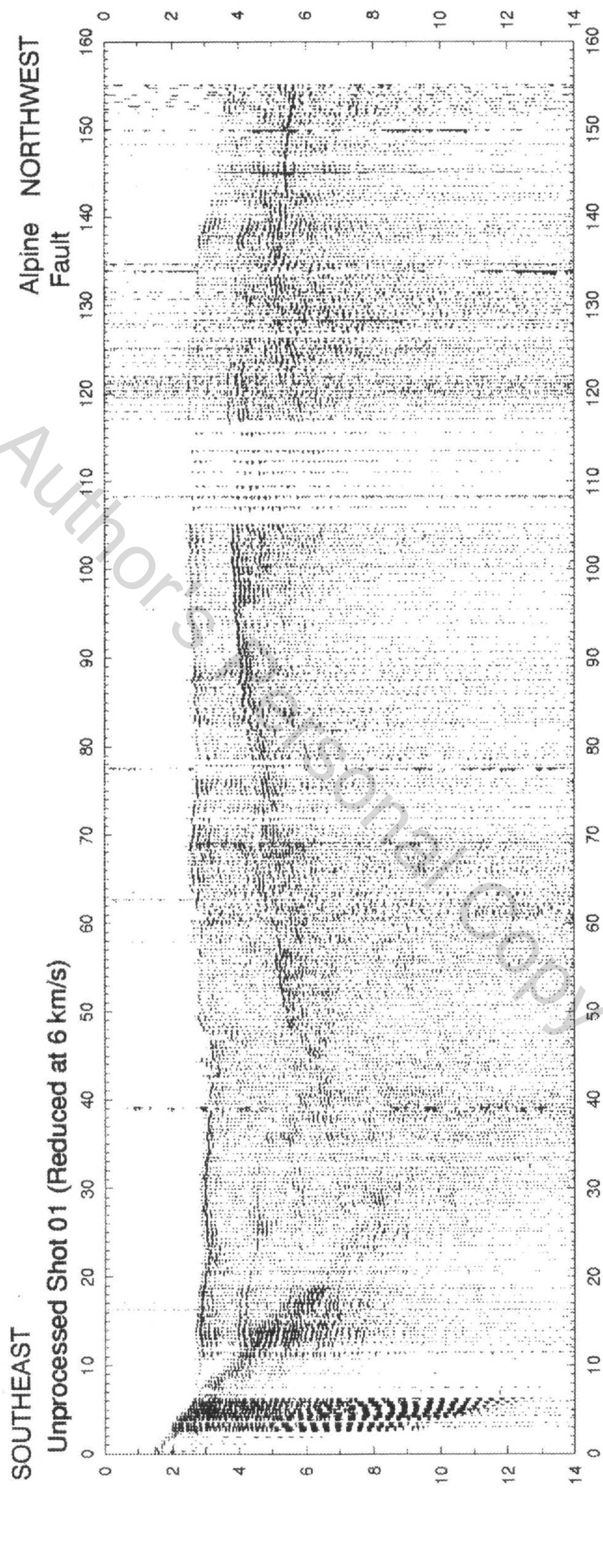


Fig. 4. Onshore seismic refraction record for shot 1 at the southeast end of Profile 1. Reduced travel times (v = 6.0 km/s) are plotted. Note the clear P_g and lower crustal reflector, and the delay in arrivals west of the Alpine fault (140 km).

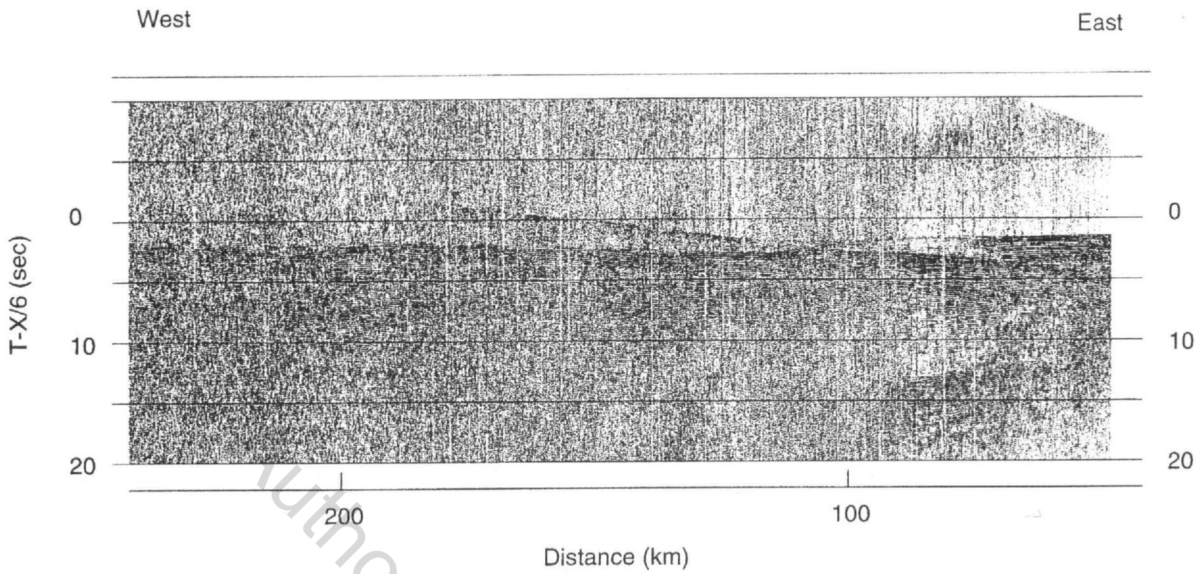


Fig. 5. Offshore/onshore seismic data for line 2E and a recorder on Profile 2. Reduced travel times ($v = 6.0$ km/s) are plotted. P_g, P_mP and P_n are well observed to ranges of 240 km.

airgun shots were recorded on most of the Refteks, and also on many of the broadband and short-period seismographs deployed concurrently for the passive seismology experiment.

Preliminary modelling of both explosion and onshore–offshore data indicate a crust of fairly constant P-wave velocity (5.9–6.2 km/s) overlying a lower crustal layer with seismic velocity of about 7 km/s and 5–10 km thick (Fig. 6, see also Stern and McBride, 1998). The total crustal thickness varies from about 30 km at the east coast to about 42 km under the Southern Alps. The deeper crustal layer may correspond to the old (Cretaceous?) oceanic crust, which is thought to lie beneath the greywacke

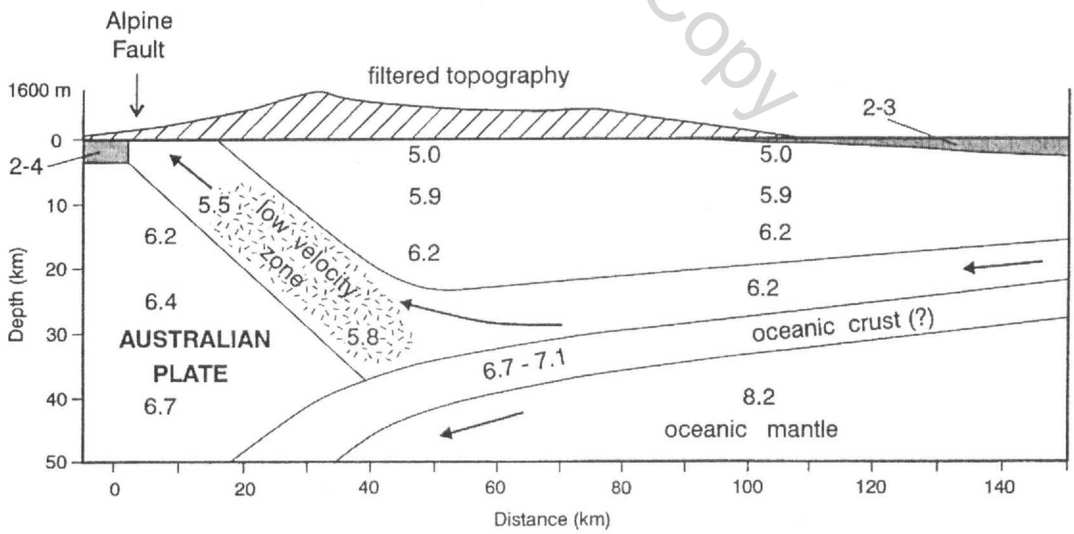


Fig. 6. Preliminary crustal model along Profile 2, derived from the onshore wide-angle seismic data (after Stern and McBride, 1998). Seismic velocities on the model are in km/s. The crustal velocities for the Australian plate are assumed.

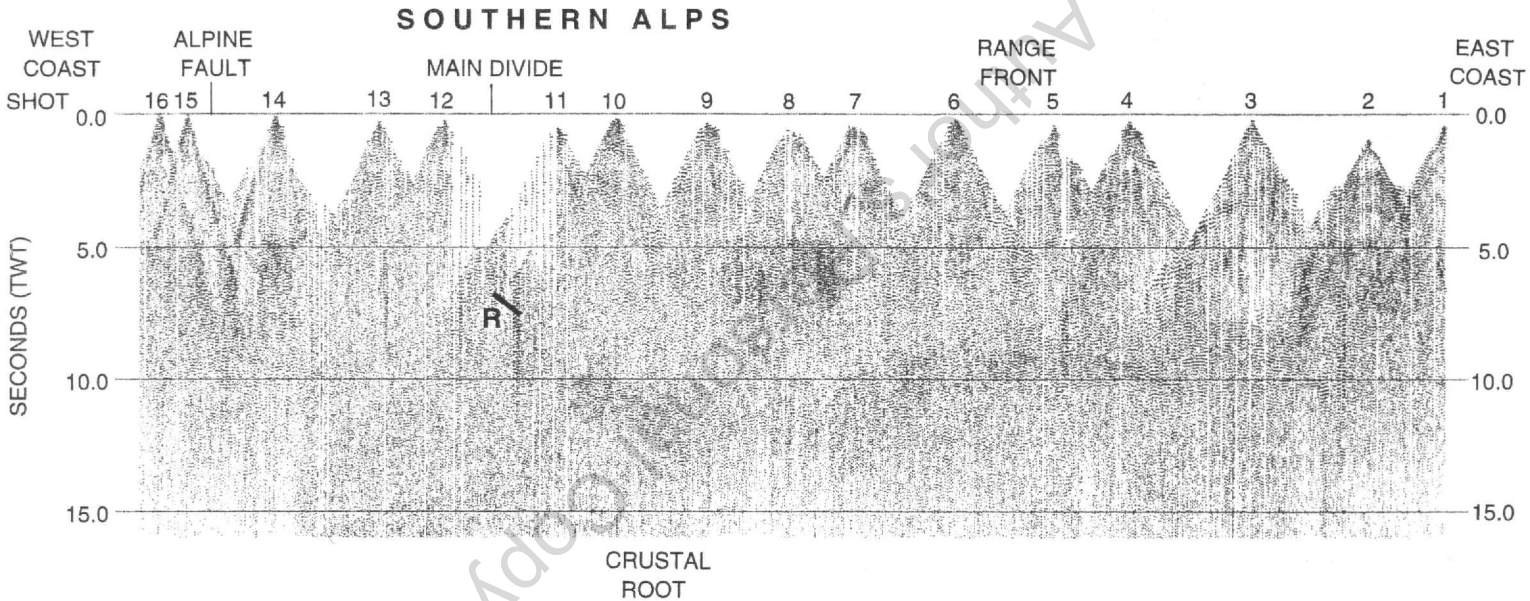


Fig. 7. Preliminary low fold CDP section along Profile 1. The stack was produced using data up to 30 km offset from each of the 16 shots. *R* marks the reflecting element inferred to be from the Alpine fault zone (Davey et al., 1995) projected onto this profile. The 'range front' marks the southeastern margin of the Southern Alps orogen.

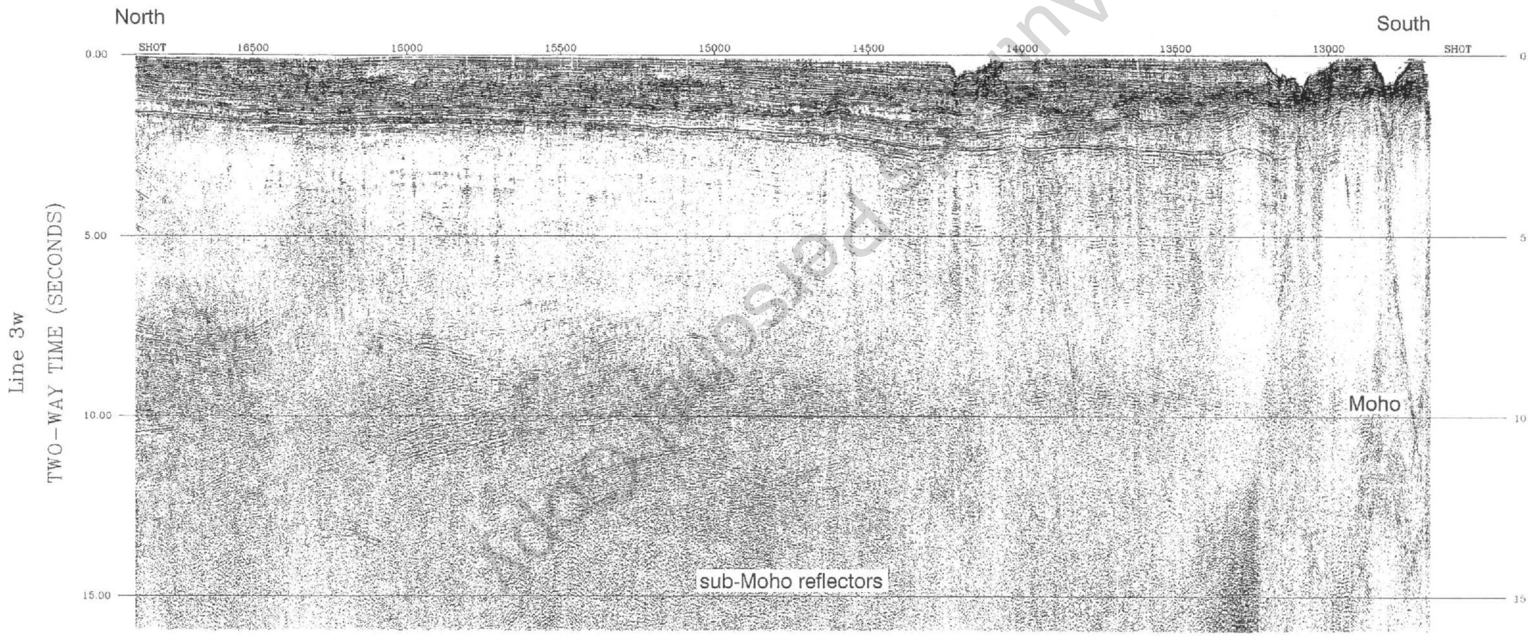


Fig. 8. MCS section for line 3W. Shots are at 50-m intervals. Moho lies at about 9.5 s twt at the southern end of the profile, deepening to about 10.5 s twt at the northern end of the profile. Short, north-dipping, sub-Moho reflectors occur at shot points 14600–14900 and 15000–15400.

and schists of South Island (Smith et al., 1995). The wide-angle reflection from the top of this old oceanic crust has a large amplitude and complex coda that may arise from multiple reflections within the oceanic crust. The data also provide further evidence of deep reflections from within the dipping (~40°) Alpine fault zone, similar to those found in a earlier pilot study (Davey et al., 1995), and delayed lower crustal phases for west coast seismographs from shots east of the Southern Alps (Fig. 4), which could be due to a deep low-velocity zone associated with the Alpine fault zone (Smith et al., 1995; Stern and McBride, 1998).

A low fold common depth point section along Profile 1, based on the sparse explosion data, shows a strong, but diffuse, reflective sequence interpreted as the lower crustal layer (Fig. 7). These preliminary results clearly show a crustal root, up to 8 km thick and limited in extent to the deforming Southern Alps orogen. The dipping, inferred Alpine fault zone, reflector of limited extent detected in the earlier survey (Davey et al., 1995) has been projected, relative to the Alpine fault surface trace, onto the section and is labelled R in Fig. 7. This reflective element and the western, east-dipping, margin of the crustal root are aligned approximately with the surface outcrop of the Alpine fault zone, suggesting that these features may correspond to the subsurface extension of the Alpine fault zone and hence the leading edge of the Australian plate crustal indentor.

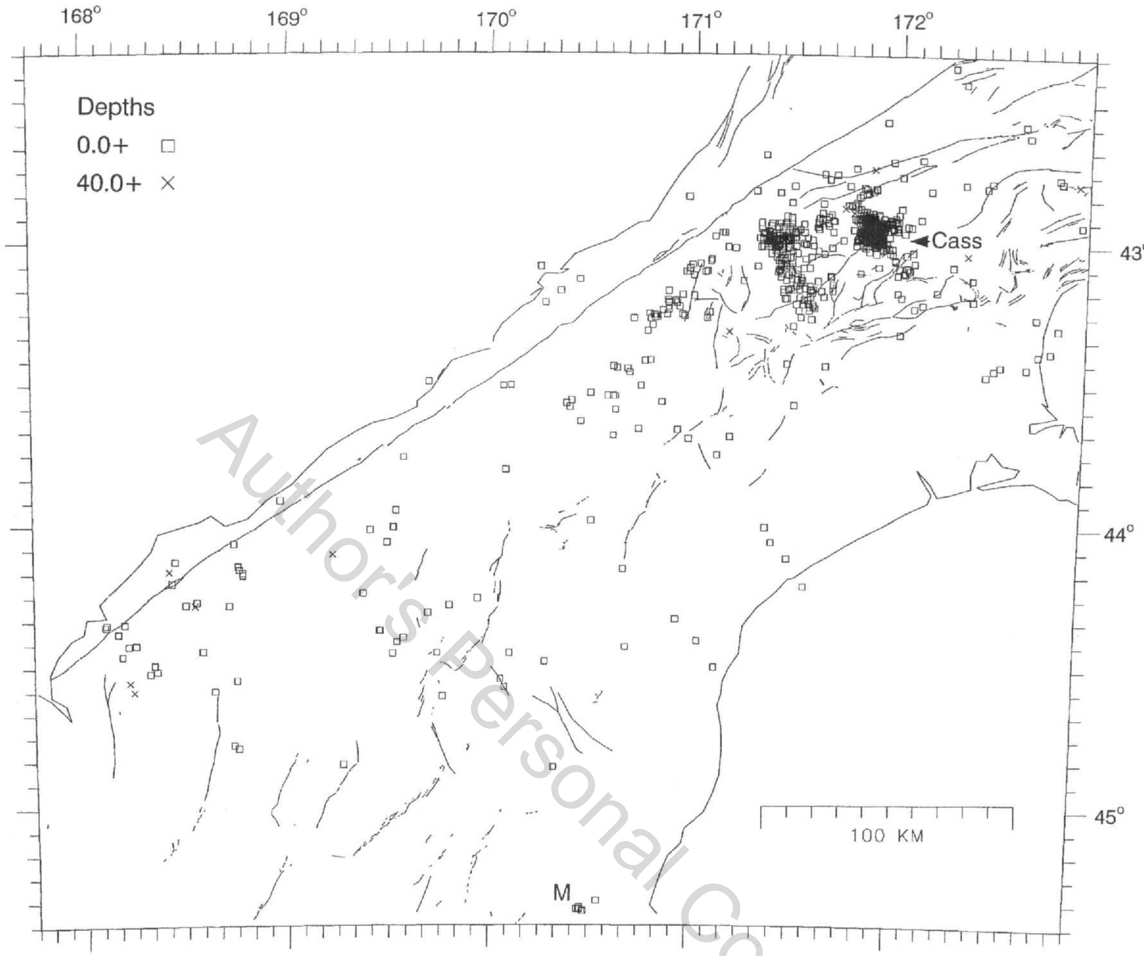
Seismic sections from the marine vertical reflection data show a well defined sedimentary section, which on the western profiles shows coastward thickening of sediments and onlap of reflectors onto basement, consistent with a foreland loading model for the west coast region (Kamp et al., 1992). In general, clear lower crustal–Moho reflections are imaged along most of the tracks, and sub-Moho reflectors of limited extent (Fig. 8) occur off the west coast (MCS Line 3W, Fig. 2). Interpreted Moho lies at about 10 s twt off the west coast and at 8 s twt off the east coast. Lower crustal reflectivity apparently fades with the inferred thinning and extension of the crust further offshore.

2.2. Passive seismology experiments, SAPSE (Southern Alps Passive Seismic Experiment)

The Southern Alps Passive Seismic Experiment (SAPSE) used stations distributed throughout the South Island (Fig. 2) to record both active (transect) and passive source data to use in a broad range of analyses to study fault geometry, inferred stress orientations, crustal velocity structure, and deeper structure using teleseismic tomography. Co-located stations will be used to calibrate the variations in crustal thickness determined from receiver functions with the SIGHT results.

The SAPSE array consisted of 26 interspersed broadband and 15 short-period (1 Hz) temporary 3-component stations that were augmented by 17 permanent New Zealand stations. The stations were broadly distributed but centrally weighted towards the central Alpine fault and transect region (Fig. 2). After demobilisation of most of the dense South Island network in April 1996, a subset of 7 SAPSE broadband stations was left in place. These stations recorded until early 1997, as part of SUNY's extensive regional surface wave network that includes stations on Macquarie Island, in Australia, and elsewhere in New Zealand. The broadband Refteks recorded 1 sample per second (sps) and 50 sps continuous data streams and the short-period instruments recorded 100 sps event-triggered data. Triggered data streams on the broadband instruments were quickly abandoned because of the high microseism-noise level. The network data volume was about 1.4 Gbytes per day in SEGY format. In-field

Fig. 9. (a) SAPSE hypocenters from short-period data only. Events shown have six or more observations and rms residual less than 0.5 s. 900 events are shown of 3500 recorded in this region (5700 recorded in the whole South Island). These are preliminary locations. Improved hypocenters will be obtained for all events once the broadband data are included and velocity models are updated for the combined SAPSE network. *M* indicates cluster of inferred surface explosions near Macrae's Mine, *Cass* points to Cass events. The other large clusters are continued aftershocks of the 1994 Arthurs Pass earthquake. Also note that refraction shots are observed along the two profiles. (B) Cross-section showing events southwest of Arthurs Pass projected onto a section normal to the Alpine fault. The depth resolution for these preliminary partial-network hypocenters is poor, but significantly better than that indicated by the Macraes Mine cluster (*M*) which lies at the periphery of the network. Dashed line outlines the zone of higher seismicity on Fig. 11.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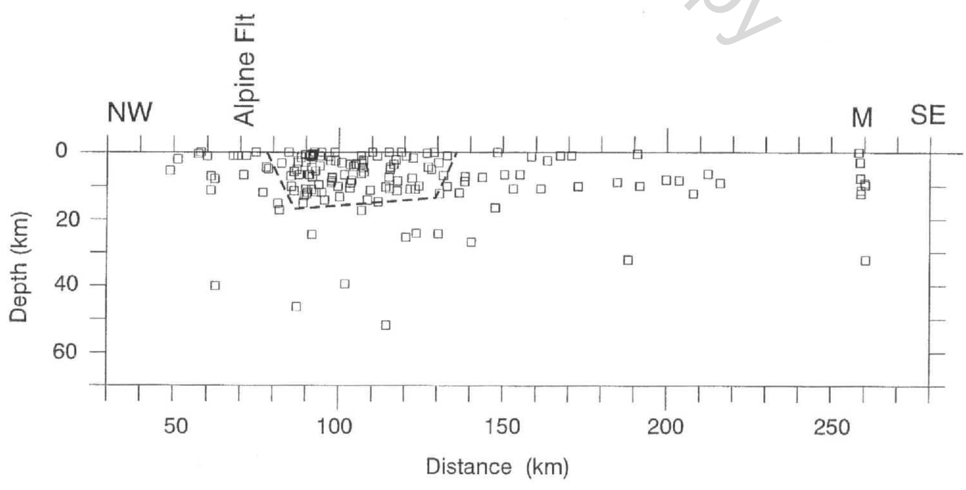
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250
Distance (km)

processing was carried out. Preliminary hypocentre location has only been carried out to date for the short-period stations. These locations indicate that crustal seismicity is concentrated under the Southern Alps at depths less than about 15 km (Fig. 9).

These data also show broad-scale features and intriguing 3-D focusing effects. Preliminary analysis indicates shear wave splitting >2 s at several sites. The November 4 Cass *M* 6.2 earthquake (Fig. 9) has a reverse fault mechanism with a strike of NNE, consistent with its location on the eastern margin of the orogen (Fig. 2). High-frequency teleseismic body waves observed at SAPSE stations hold promise for high-resolution crustal transfer functions and anisotropy analysis for definition of a 3-D structure.

2.3. Magnetotelluric and electrical studies

Forty-two wideband magnetotelluric (MT) soundings were collected to investigate the deep thermal and fluid state beneath South Island. Thirty of these lie along Profile 1 (Fig. 2), the northern transect, although a 30-km data gap remains across the Main Divide due to no road access. Preliminary results for the main line (Fig. 10) reveal 1–2 km thickness of conductive Cenozoic sediments overlying resistive basement rocks. The basement rocks are >1000 ohm-m representing cratonic rocks west of the Alpine fault and meta-greywackes overlying old oceanic crust to the east. The major feature of the MT transect is the response of a middle to lower crustal conductive zone developing in amplitude toward the west as the Main Divide is approached (Fig. 10). It has become very subdued again in the data west of the Alpine fault, indicating closure of the conductor by the point the Alpine fault trace is reached. Preliminary models indicate that the depth to the high conductivity is about 15 km. MT soundings made 50 km to the northeast and southwest of Profile 1 indicate a similar mid-crustal conductive zone (see also Ingham, 1995), suggesting continuity of a highly developed isolated mid-crustal conductor parallel and underlying the eastern flank of the Southern Alps. The most likely cause of this conductor is the development of a fluidized zone in the deep crust, the bounds of which would have profound ramifications for crustal rheology and partitioning of strain because such zones are relatively weak. The weak zone also may contribute to the low seismicity deep in the crust. There is evidence that the upper bounds of deep fluid zones may mark a crustal isotherm (Jiracek, 1995).

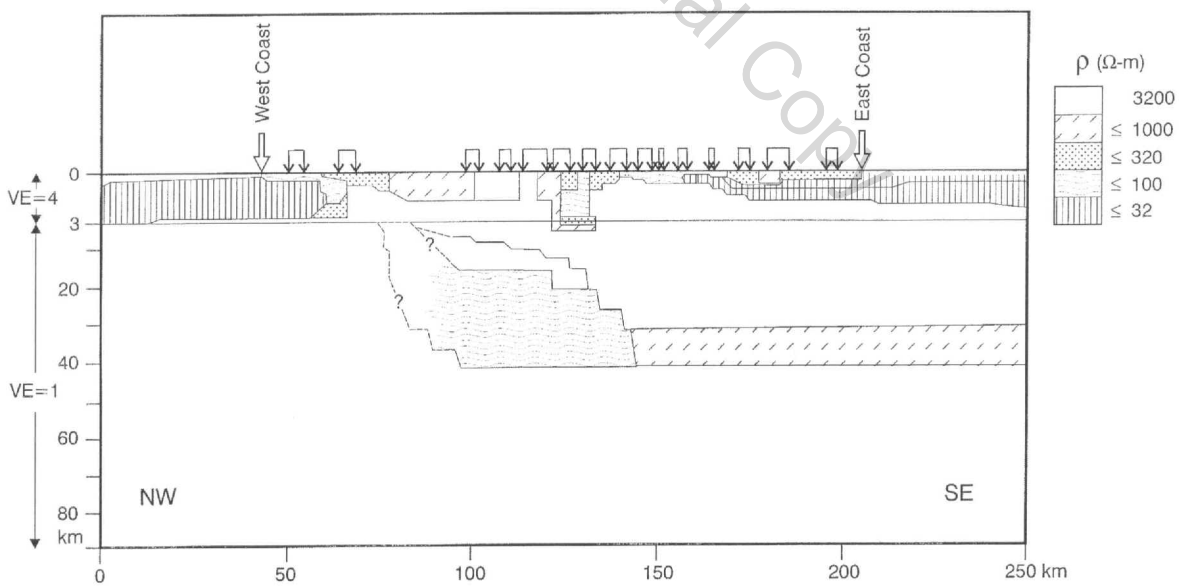

Fig. 10. MT results. Preliminary 2-D conductivity cross-section based on finite-element forward modelling of the transverse magnetic (TM) mode observations. Observation points are marked by the pairs of vertical arrows. The western margin of the mid-crustal conductivity high is poorly constrained due to a lack of observations in this region.

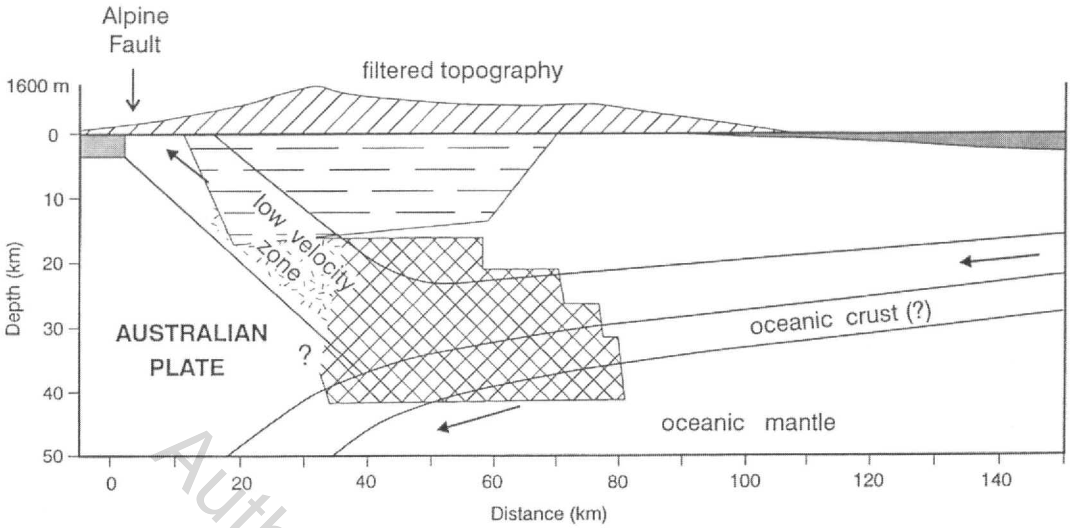

Fig. 11. Preliminary seismic section across South Island showing the depth separation of the zones of high conductivity (cross shading) and high seismicity (horizontal shading) but their close association with the region of inferred high strain from modelling studies.

In addition, a combined DC (multiple-source bipole–dipole) long offset time domain EM (LOTEM) resistivity survey was conducted across the Alpine fault on the northern transect. More than 70 measurement stations were distributed across the coastal plain and along a 20-km profile crossing the Alpine fault. Preliminary analysis indicates that the DC apparent resistivities increase from 10–20 ohm-m about 5 km west of the fault to a maximum of 700 ohm-m adjacent to the Alpine fault. East of the fault, resistivity values are in the order of 100–200 ohm-m for source receiver distances of 10–15 km. The apparent resistivity tensor ellipses change in eccentricity as the Alpine fault is crossed and indicate anisotropy associated with the schistose rocks east of the fault.

2.4. Petrophysics

The physical properties of rocks from the central South Island region provide rigorous constraints on crustal structure models of the Alpine orogen. A representative suite of rock samples from the various tectono-stratigraphic terranes present in the central South Island region has been collected for laboratory seismic velocity measurements over a range of crustal pressures, and has demonstrated that significant (~20%) anisotropy exists within the schist and mylonite terranes associated with the Alpine fault (Okaya et al., 1995). The anisotropy is present at all pressures and originates from preferred mineral orientations. Greenschist and amphibolite facies rocks of the Haast schist terrane possess similar high anisotropy. The pronounced velocity anisotropy will affect passive and active source seismic wave propagation and will be incorporated into the analysis of the seismic data.

3. Discussion and conclusion

The present paper presents preliminary results for the field experiments carried out in South Island in 1996, and much basic data processing and analysis remains to be done before robust models and interpretations can be constructed. Common features of all phases of the field work to date are the high signal-to-noise ratios of the data, and indications of structures within the crust and upper mantle that are distinctly different from normal continental lithosphere. The anisotropy of the plate boundary zone has been clearly demonstrated by the seismic velocity, resistivity and shear wave results. Preliminary models for the active source seismic measurements across South Island suggest a thickened crust under the Southern Alps and the high-velocity lower crustal layer, and support the model of a significant crustal root under the mountains and a major discontinuity associated with the Alpine fault. More comprehensive modelling will yield a better constrained and more detailed velocity model in which anisotropy must be included. Several features are associated with the mid-crust under the Southern Alps (Fig. 11). Shallow seismicity occurs only east of the Alpine fault down to a sharp limit at a depth of about 15 km (see also Eberhart-Phillips, 1995) and is considered to relate to a weak fractured greywacke. A major conductivity high underlies this region, its top lies also at about 15 km, and may correspond to fluid in the crust. No seismic discontinuity is detected at this depth on the active source data. Both high conductivity and high upper crustal seismicity coincide broadly with the region of high strain inferred from modelling studies (e.g. Beaumont et al., 1994) and there may be a casual relationship. Offshore the marine reflection data have consistently imaged a reflective lower crust adjacent to both sides of South Island. These data are showing complex structure, particularly off western and southeastern South Island.

This complexity in structure, high-quality data and consistency in results from several techniques indicates that the South Island experiment will contribute significantly to our knowledge of transpressive plate boundaries in particular, and continental lithosphere in general.

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