Geological interpretation of a deep seismic reflection profile across the Eastern Province and Median Batholith, New Zealand: crustal architecture of an extended Phanerozoic convergent orogen

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Abstract An offshore seismic reflection profile provides new information on the tectonic evolution of the Paleozoic–Mesozoic margin of southern Gondwanaland. The 550 km long composite South East South Island (SESI) profile extends from near Christchurch to near Stewart Island, New Zealand. It crosses the Eastern Province geological basement terranes and ends in the Median Batholith.

The Median Batholith and all the basement terranes appear to extend down to middle or lower crustal levels and are not minor thin-skinned fault slices. A discontinuous, but generally strong Moho reflector is observed along the profile varying from c. 22 to 32 km depth. Upper to mid-crustal reflections can be related to Murihiku Terrane bedding and Otago Schist foliation. Gravity and magnetic measurements indicate that the Maitai Terrane dips northeast beneath the Otago Schist. The SESI profile contains no evidence for stranded slabs of Mesozoic oceanic crust beneath the Eastern Province.

The Moho depth along the SESI profile, particularly under the Median Batholith and Otago Schist accretionary prism, is markedly shallower than in other circum-Pacific Mesozoic orogens. This, and the geometry of several fault-related reflectors in the SESI profile, can be attributed to significant out-of-profile Late Cretaceous extension related to Gondwanaland breakup. Three regions of strong, deep crustal reflectivity are present, and their association with thinner crust suggests they may also be extension-related features.

Keywords reflection seismology; SESI profile; crustal structure; tectonics; South Island; New Zealand; Moho; Eastern Province terranes; Median Batholith; Paleozoic; Mesozoic

INTRODUCTION

New Zealand is a rifted fragment of Gondwanaland that currently lies astride the Australian-Pacific plate boundary (Fig. 1). Pre-Late Cretaceous basement rocks of the South Island can be described in terms of a number of volcanic-sedimentary accreted terranes, batholiths that intrude these terranes, and schist and gneiss overprints on the sedimentary and plutonic rocks (e.g., Coombs et al. 1976; Bradshaw 1989; Mortimer et al. 1999). The age of basement rocks varies from Middle Cambrian to late Early Cretaceous; no Precambrian strata or cratonic rocks are exposed. The
Phanerozoic tectonic history of New Zealand is generally interpreted in terms of progressive Pacific-ward growth of the Gondwanaland/Pangea supercontinent by terrane accretion and batholith intrusion at an obliquely convergent margin. Continental growth was terminated by widespread extension in southern Gondwanaland at c. 110 Ma that culminated in Tasman Sea and Southern Ocean seafloor spreading from c. 85 Ma. Post-110 Ma sedimentary rocks in New Zealand rest unconformably on the basement and are generally less indurated, less deformed, and better stratified than the pre-110 Ma rocks. The entire New Zealand basement was subjected to renewed deformation in the Neogene with inception of the modern Australia-Pacific plate margin.

The age and nature of New Zealand’s basement rock units and the position of their boundaries have been well defined by surface field mapping, but little is known about them at depth or offshore. In particular, some important specific questions about the New Zealand basement remain unanswered:

1. How do crustal thickness and the nature of the Moho change across the terranes, metamorphic belts, and batholiths?
2. Are the terranes a stack of thin thrust slices, or do they occupy substantial thicknesses of the present day crust? If the former, is there deep-seated vergence towards the continent or the ocean?
3. Are stranded, subducted slabs of Paleozoic–Mesozoic age present beneath the terranes and batholiths?
4. To what extent has 85–110 Ma extension modified the geometry of the earlier convergent orogen?

Similar questions could also be asked of many circum-Pacific and Gondwanaland orogenic belts; these issues are important because they provide insights into how continents grow and deform. The main aim of the present study was to try to answer these questions by acquiring and interpreting new multichannel seismic data in a profile across part of the New Zealand basement.

**SCOPE AND PURPOSE OF STUDY**

In 1995–96, a joint United States - New Zealand group undertook a study of the deformation associated with continental collisional orogens. This work comprised two onshore–offshore, wide angle reflection-refraction transects across the central South Island of New Zealand (SIGHT, or South Island Geophysical Transect; Davey et al. 1998). As part of this study, a number of additional multichannel seismic (MCS) lines were shot in coastal waters around the South Island (Fig. 2). Four of these lines (4e, 25e, 5e, and 6e) were combined to form a composite, 550 km long seismic reflection profile from near Banks Peninsula to near Stewart Island. This is here termed the SESI (South East South Island) profile (Fig. 1, 2, 3) and forms the main topic of this paper. The main SIGHT lines were shot across the Southern Alps to image the crustal structure of the actively convergent plate margin. In contrast, the location and orientation of the SESI line were intended to image the geometry of the pre-110 Ma basement units, as the line ran basically perpendicular to basement terrane boundaries, enabling ready extrapolation of onland structures to the offshore line (Fig. 3). Furthermore, Neogene deformation (faulting, oroclinal bending) is at a minimum along the SESI line, which is >200 km from the Alpine Fault (Fig. 1, 2). The SESI line thus had the potential to shed light on the geometry of terrane (fossil plate) boundaries preserved in close to their pre-Cenozoic configurations.

The purpose of this paper is to present, for the first time, the MCS, gravity, and magnetic measurements along the SESI profile. We integrate these data to make interpretations of crustal structure of the New Zealand basement, to test existing tectonic models and to formulate new ones, and to highlight some important issues in the deep geology of New Zealand in particular and orogenic belts in general. This is a companion paper to Godfrey et al. (2001) in which the velocity structure along the SESI line is addressed. Other work resulting from the 1995–96 offshore MCS experiments has been published by Davey et al. (1998). Interpretations of MCS lines near the southern end of the SESI profile have been given by Mellhuish et al. (1999), Cook et al. (1999), and Sutherland & Melhuish (2000).

**GEOLOGY ALONG THE SESI PROFILE**

**Cover units**

The geology of the post-110 Ma cover strata along and near the SESI line (Fig. 3) has been summarised by Carter (1988), Field et al. (1989), Bishop & Turnbull (1996), Cook et al. (1999), and Forsyth (2001). Insofar as they relate to the present study, cover units (in order of decreasing age) can be described as:
(1) Albian–Santonian (c. 110–85 Ma) half-graben sedimentary deposits of conglomerate, sandstone, and coal. Extensional tectonism led to the development of distinct basins and highs, mainly in the northeastern third of the SESI line, but also in the Great South Basin; fault movements locally exceeded 4000 m but were generally <500 m.

(2) Cretaceous volcanics. These are represented by rare 100–110 Ma ignimbrites and silicic tuffs as in Albian–Santonian strata along the Waihemo Fault, 85–90 Ma andesites, dacites and rhyolites at Mount Somers, and 70–80 Ma basalts in offshore oil exploration drillhole Galleon-1.

(3) Campanian–Recent (c. 85–0 Ma) well-stratified, passive margin sedimentary rocks and unindurated sediments, including Pleistocene strata. Paleogene rocks consist mainly of sandstones and mudstones, with a distinct Oligocene limestone/hardground facies that gives rise to a prominent seismic reflector over most of the New Zealand region.

(4) Cenozoic volcanics. A variety of Paleocene–Pliocene (mainly Miocene) mafic alkaline rocks and tuffs occur in a number of centres in or near the northeastern half of the area. The most prominent centre along the SESI line is the Dunedin Volcano; Banks Peninsula Volcano, though volumetrically larger, is just off the northeast end of the line.

**Basement units**

Onshore, close to the SESI line, a batholithic complex, six tectonostratigraphic terranes, and a schist belt are exposed at the surface (Fig. 3; Watters et al. 1968; Bishop & Turnbull 1996; Turnbull 2000; Forsyth 2001). Rakaia, Caples, Maitai, Murihiku, and Brook Street Terranes constitute the so-called

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Fig. 3  Geology in the vicinity of the composite SESI line. Data and names from Carter (1988), Field et al. (1989), Mortimer (1993), Mortimer et al. (1999) and references therein. Depth to igneous and metamorphic rocks (seismic basement) in the seven oil exploration wells is as follows: Resolution-1 sill at 1925 m, Clipper-1 schist at 4685 m, Endeavour-1 basement >2741 m, Galleon-1 gabbro at 3044 m, Takapu-1A schist at 869 m, Tara-1 near granite at 4680 m, Toroa-1 basement >4700 m.
Eastern Province of New Zealand, and the Takaka Terrane belongs to the Western Province. Regional tectonic syntheses of the basement rocks have been given by Coombs et al. (1976), Bradshaw (1989), and Mortimer et al. (1999). Units along the SESI profile are described in northeast–southwest order with numbers corresponding to the notation on Fig. 3:

(1a) **Rakai (Older Torlesse) Terrane**, a tectonically imbricated, weakly metamorphosed sequence of main marine, Permian–Triassic greywacke and argillite that is interpreted to have been deposited and/or deformed in an accretionary prism adjacent to a continental margin (e.g., MacKinnon 1983). Minor chert, limestone, and basalt represent oceanic crust; they are interbedded with, and tectonically imbricated into, the steeply dipping greywacke pile on a scale of 1–10 km and cannot simply stratigraphically underlie the greywacke pile as depicted in some models (e.g., by Smith et al. 1995). Rakai sandstones are feldsarenitic, indicating a mainly granitic source area.

(2a) **Caples Terrane** is a tectonically imbricated, weakly metamorphosed sequence of marine volcaniclastic Permian–Triassic greywacke and argillite that have a different provenance from the Torlesse and adjacent terranes (MacKinnon 1983; Roser et al. 1993). Lava, cherts, and limestones are present but are generally more rare than in the Rakai Terrane. A particularly chert- and melange-rich part of the Caples Terrane (Chrysalis Beach Complex) is exposed on the Otago Coast. Caples stratigraphic sequences, where measurable, are c. 5–7 km thick. Deposition occurred as submarine fan deposits in lower trench-slope basins and on a trench floor adjacent to an island arc, before juxtaposition with the Rakai Terrane. The contact with the Rakai Terrane is within the Otago Schist.

(1b/2b) **Otago Schist** is a two-sided pumppellyte-actinolite to greenschist facies metamorphic belt that has overprinted the Caples and Rakai Terranes (Mortimer 1993 and references therein). The Otago Schist antiformal axis represents the locus of maximum exhumation of the Jurassic–Cretaceous Rakai-Caples accretionary prism. Schist is present in offshore wells Takapu-1A and Clipper-1 and probably underlies at least some of the Rakai greywackes to the north and northeast. Estimates for conditions of Jurassic peak metamorphism of rocks now at the surface along the schist axis are 350–410°C and 30–35 km depth (Mortimer 2000). The presence of high-grade schist clasts in Albian–Santonian basin fill deposits indicates significant exhumation of Otago Schist by this time (Bishop & Turnbull 1996; Forsyth 2002 and references therein).

(3) **Maitai Terrane** consists of two lithologic associations (Coombs et al. 1976; Bishop & Turnbull 1996): (i) Dun Mountain Ophiolite Belt (DMOB), interpreted to be the tectonically disrupted remnants of a 275–285 Ma (Permian) mafic–ultramafic igneous complex that developed near an oceanic arc (Coombs et al. 1976; Kimbrough et al. 1992); (ii) stratigraphically overlying Late Permian to Early Triassic Maitai Group greywacke and argillite. Metamorphic grade reaches lawsonite-albite-chlorite facies, but near the Otago coast conodont colour and clay mineral species indicate that the rocks have never experienced temperatures in excess of c. 100°C (Paull et al. 1996). The Livingstone Fault, a zone of melange-like deformation up to 1 km wide (Cawood 1986), marks the tectonic contact between the Maitai and Caples Terranes.

(4) **Murihiku Terrane** in southeast South Island consists of a 9–10 km thick sequence of essentially conformable marine and non-marine Permian–Jurassic basin fill; rock types are mainly zeolite facies volcaniclastic sandstones and mudstones, with numerous tuffs (Ballance & Campbell 1993; Campbell et al. 2001). The Murihiku Terrane is folded into a long-wavelength asymmetric fold—the Southland Syncline—with a subvertical north limb and a subhorizontal to gently dipping south limb that has parasitic folds. About 4 km of Jurassic section is exposed in the south limb, along with isolated localities of shallow intrusive and/or volcanic rocks (Park Volcanics of Coombs et al. 1996, marked as 4* on Fig. 3). The Hillfoot Fault marks the tectonic contact between the Murihiku and Maitai Terranes (Bishop & Turnbull 1996).

(5) **Brook Street Terrane** comprises interbedded subaerial and submarine lavas and volcaniclastic rocks of Permian age. Volcaniclastic rocks dominate and lavas are mainly of basaltic composition (e.g., Houghton & Landis 1989). The Brook Street Terrane is interpreted as a low latitude intra-oceanic island arc and basin complex (Haston et al. 1989). Some 14 km of strata are preserved in the Takitimu Mountains, but only 6–7 km in the Foveaux Strait area where they are intruded by Permian plutonic rocks of the Median Batholith. Because of the long distances involved, the extrapolated positions of the sedimentary/plutonic contact and of the Letham Fault (Brook Street/Murihiku contact; Landis et al. 1999) onto the SESI line are poorly constrained.

(6) **Median Batholith** is a composite Cordilleran batholith comprising a variety of 10–15 km thick sequence Carboniferous to Early Cretaceous plutons. The northeast part of the Median Batholith was formerly known as the Median Tectonic Zone (e.g., Bradshaw 1989), but recent work in the Foveaux Strait area has emphasised its plutonic content and intrusive contacts (Mortimer et al. 1999). The age and average composition of rocks change across the batholith axis; Permian gabbrroids dominate the northeast edge, Triassic to early Cretaceous dioritoids the central part, and late Early Cretaceous granitoids the southwest margin of the batholith. These compositional changes are also matched by changes in average magnetic susceptibility and density (Hatheron 1966). A c. 3 km wide strip of latest Jurassic meta-sedimentary and metavolcanic rocks (Paterson Group, marked as 6* on Fig. 3) is enclosed within the Median Batholith on Stewart Island (Watters et al. 1968; Allibone & Tulloch 1997). Cretaceous granite is exposed at North Traps within 9 km of the southwest end of the SESI line.
(7) Takaka Terrane is present near the SESI line only as screens of cordierite- and sillimanite-bearing mica schists (Pegasus Group) c.2 km long within the Median Batholith on Stewart Island (Allibone & Tulloch 1997). Correlation of these rocks with the much less metamorphosed Cambrian–Silurian Takaka Terrane of northern South Island is made on the basis of matching metasedimentary protoliths. The sheer volume of enclosing plutonic rock means that neither the Takaka Terrane, nor its contact with Brook Street Terrane, would have any macroscopic geological expression (e.g., on the SESI line). The presence of Western Province Takaka Terrane is, however, significant as it “anchors” the southwestern end of the SESI line firmly into crust that has been part of the autochthonous Gondwanaland supercontinent since at least the Carboniferous (age of the oldest intruding plutons). High-grade metasedimentary Western Province rocks also have been drilled in the Kauaw, Hoihio, and Rakiura oil exploration wells, some 100–200 km south of Stewart Island (Cook et al. 1999 and references therein).

Post-accretionary faults

Although the position of the SESI line was chosen to avoid areas of known post-Early Cretaceous structural complexity, some faults other than the aforementioned terrane boundaries are present along it or nearby. The active Akatore Fault, and Late Cretaceous–Quaternary Titiri Fault (Fig. 3), both dip east (Bishop & Turnbull 1996) and might be expected to dip into the SESI profile plane. Off-line Cretaceous normal faulting related to formation of the Clipper and Great South Basins (Fig. 3) also might be expected to affect Moho depths on the SESI line. Galleon-1 was drilled into Cretaceous basin fill in the hanging wall of the Waihemo Fault. Both the Waihemo and Waitaki Faults are prominent linear (i.e., steep) structures that displace late Cenozoic strata. No actively subducting slabs are expected to be intersected in the SESI profile.

DATA ACQUISITION AND PROCESSING

Multichannel seismic (MCS)

The data were recorded from R/V Maurice Ewing, using a 130 litre airgun array and a 240 channel 4.0 km streamer. Navigation was by GPS. Ship’s tracks of lines with shot points are shown in Fig. 2; lines 4e, 25e, 5e, and 6e have been combined to form the composite SESI line. Acquisition and processing parameters are given in Table 1. The stacked and migrated seismic section of the composite SESI profile is shown in Figs. 4 and 5.

Gravity and magnetic

Gravity data were recorded by a Bell Aerospace BGM-3 marine gravity meter. The data were reduced to free air anomalies using location and velocity information from an integrated navigation system based on a Magnavox MX-4200D GPS receiver. ISSN71 normal field values and the WGS84 geodetic datum were used in the reductions. Bathymetry data are from the centre channel of the Atlas Hydrosweep™ D5 multibeam system. Magnetic data were recorded on a Varian V75 marine magnetometer. Data were reduced to anomaly values using IGRF 1990. Density and magnetisation for the particular rock types forming the terranes were derived from a database of rock properties held at the Institute of Geological & Nuclear Sciences. Modelling, with end corrections, was carried out using the SAKI package.

MCS INTERPRETATION

Upper crust: sedimentary cover

Along the SESI line, Campanian and younger strata are readily identified by laterally continuous reflectors shallower than 2 s two-way-travel-time (TWT) (Fig. 4, 5). These sediments vary in thickness along the line, from c. 2.0 s TWT over the Rakaia Terrane greywackes to c.0.1 s TWT over the Murihiku and Brook Street Terranes. The stratigraphic logs from Resolution-1, Galleon-1, and Endeavour-1 drillholes, and TWT from the seismic data, indicate average velocities for the cover rocks of 2.2–2.6 km/s. The thinner, younger sediments at Takapu-1 drillhole gives a much lower velocity of c. 1.8 km/s. Disturbance of sedimentary reflectors is seen in areas of previously known Cenozoic faults and volcanics, for example, Nuggets from shot point (SP) 39000–39150, Dunedin Volcano plugs (SP 36900, 36440), and Banks Peninsula Volcano plugs (SP 21750–21940) (Carter 1988; Field et al. 1989; Cook et al. 1999).

Albian–Santonian extensional basin strata have little density contrast with basement and are not prominent on the MCS line. Work by Haskell & Wylie (1998) indicates that such deposits may be more widespread in offshore South Island than hitherto realised. Near Dunedin, gently northeast dipping reflectors at SP 38300 (2 s TWT) may be graben

Table 1 Multi-channel seismic processing flow.

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<tr>
<th>Processing</th>
<th>Record length</th>
<th>Group interval</th>
<th>Far offset</th>
<th>Time-varying frequency filter</th>
<th>Whole trace balance before stack</th>
<th>Spike removal using long/short running average comparison</th>
<th>Sort to CDP domain</th>
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<tbody>
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<td>Sample rate 2 ms</td>
<td>Shot interval 50 ms</td>
<td>No. channels 152</td>
<td>Volume 495 cu in. (20 airguns)</td>
<td>Near offset 25.9 m</td>
<td>Depth 8 m</td>
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<th>Processing</th>
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<tr>
<td>Trace balance before display</td>
<td>Trace balance before display</td>
<td>2:1 trace sum and resample to 8 ms prior to migration</td>
<td>Finite difference migration (smooth stack vel. and 5 km/s for basement)</td>
<td>Trace balance before display</td>
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fill, but two graben southwest of here, mapped by Cook et al. (1999), are poorly imaged on the SESI line. In the vicinity of Galleon-1 (SP 35100–35850), a set of moderately southwest dipping reflectors occurs at 2–3 s TWT, immediately beneath the lowest laterally continuous cover reflector. These reflections almost certainly are from the coarse clastic sedimentary sequence in an Albion–Santonian extensional half graben that was partly penetrated by Galleon-1 (Field et al. 1989). The graben-bounding Waihemo Fault intersects the SESI line very obliquely, but it is not imaged. To the northeast, from SP 19600 to 20700, similar southwest-dipping reflectors are present, and we tentatively correlate these with Albion–Santonian strata. Such strata are well documented in the Clipper Basin (Fig. 3) but were not identified by Field et al. (1989) in this location along the SESI line. An alternative possibility is that the southwest-dipping reflectors could represent intra-basement reflectors.

Middle crust
Most of the middle crust is acoustically transparent. A weak set of reflectors occurs near Timaru at 5–6 s TWT (SP 36200–36600). Prominent reflectors from SP 36200 to 38900 between 3 and 7 s TWT define a broad arch, compatible with the Otago Schist antiform onshore. These terminate in the south against the single-most prominent reflector on the whole SESI line: a subhorizontal one at c. 7 s TWT between SP 38100 and 38800. The simplicity and continuity of this c. 35 km long reflector is unlike any other on the line, as is its subhorizontal attitude in a region of otherwise dipping events. The subhorizontal reflector merges with the zone of lower crustal high reflectivity (see below) at SP 38100, suggesting that these features may be genetically related.

Sets of gently northeast dipping spaced reflectors at 1–5 s TWT depth from SP 40600 to 39400 plausibly correspond to bedding in the Murihiku Terrane. Stratified rocks in the Brook Street Terrane are not obviously imaged, though some of the deeper Murihiku reflectors described above could be from the Brook Street Terrane. There is a south-dipping zone of reflectivity at mid-crustal depths (6 s TWT) from SP 39600 to 39900 beneath the Murihiku Terrane. Other mid-crustal reflectors that similarly rise from, or merge with, zones of lower crustal reflectivity are a series of southwest-dipping reflectors near Stewart Island at 2–5 s TWT (SP 43050–42300).

Lower crust
Three kinds of lower crustal reflectivity are present:

1. weakly reflective or acoustically transparent zones (e.g., at the northeast end of the profile near Banks Peninsula Volcano);
2. highly reflective zones with 1–10 km long continuous, closely spaced reflectors in packages 1–2 s TWT thick. These are present in the profile near Stewart Island (SP 41750–43084), near Dunedin (SP 37100–38300), and near Timaru (SP 19600–20100). Individual reflectors within each zone dip southwest and are apparently truncated by the prominent Moho reflector (see below);
3. moderately reflective with shorter, more diffuse reflections than in the highly reflective crust, and in 2–5 s TWT thick zones. These can grade laterally and vertically into (1) or (2) above. The tops of the zones can be stepped, suggesting faulting. Examples are from SP 40450 to 42800 and northeast of the highly reflective zones near Dunedin and Timaru.

Moho and mantle reflections
Prominent reflections from 8 to 11 s TWT are imaged along most of the SESI line, and are interpreted as coming from the crust mantle boundary (see below for discussion of supportive gravity and velocity modelling results). Where present, the character of the Moho is of two (end-member) types:

1. a single, simple strong reflector, with few breaks (e.g., SP 21700–34600, 34900–35200, 35400–35650, and 36000–39200). This can be present beneath zones of highly reflective crust (e.g., near Dunedin);
2. as a diffuse but distinct lower limit of zones of moderately reflective deep crust (e.g., SP 36000–38400, 39500–39750, 40100–40800, and 41400–43084).

The Moho is deepest underneath the Murihiku Terrane at SP 40800 (11 s TWT, c. 32 km). It is shallowest near Stewart Island at SP 42800 (7.5 s TWT, c. 22 km) but appears to deepen again to the southwest. Relief on the Moho is greatest in the southwest end of the line from SP 40900 to 42850, but because it is not represented by individual reflectors here, we cannot be sure if the Moho is stepped (faulted) or continuous and dipping. Another possible (c. 1 s) step in the Moho occurs across the non-imaged zone from SP 34600 to 39900. Changes in Moho character at SP 40000 and 40880 coincide with bends in the profile line and may reveal significant horizontal anisotropy. The change in dip of the Moho at the course alteration in line 6e indicates a northwesterly dip, towards land (discussed below). The absence of Moho reflectors in parts of the northeast half of the line is probably due to dispersion/reflection of energy off near-surface Cretaceous–Cenozoic volcanics and the Waihemo and Waitaki Faults.

Some sub-Moho reflectors are recognisable. A prominent single reflector at 10 s TWT, from SP 20100 to 19350, is the same depth beneath the Moho as the Oligocene limestone is below the water surface, and we interpret this as a multiple. At 12–15 s TWT from SP 42800 to 43050 (the southwest end of the SESI line), sub-Moho reflectors dip moderately northeast and are the deepest recognised on the profile. While these may be true intramantle reflectors, it is possible that they could be out of plane reflections (Melhuish et al. 1999).

MCS VERSUS VELOCITY INTERPRETATIONS
In a parallel investigation, Godfrey et al. (2001) have made interpretations of the velocity structure along a transect partly coinciding with the SESI line. Their key results are:

1. good agreement of the mid and upper crustal velocity model with surficial geology except for a thin (2 km) modelled Murihiku Terrane and a high-velocity region at 9–18 km depth near Dunedin, which they interpret as Caples Terrane. In general, average mid-crustal velocities are lower to the north of Dunedin than to the south;
2. anomalously low velocities for mantle and deep crust (7.7–7.9 and 5.2–5.9 km/s, respectively) near Dunedin, as compared with the rest of the line. The position of these anomalies coincides with surface volcanics, high heat flow, and He anomalies and is interpreted by
Fig. 4
Stacked and migrated offshore South East South Island (SESI) seismic reflection profile. The 550 km long profile is a composite of four shorter lines shown in Fig. 2. AC. The course...
Fig. 5  A. Seismic reflection profile showing the locations of course alterations, joins in lines 6e, 5e, 25e, and 4e to make the composite line, and the projected positions of geographic features, exploration wells, and major magnetic anomaly peaks and structural features.  B. SESI profile shot points and projected near-surface basement geology.  C. Line drawing of the major reflectors.  Note that some reflectors are not especially visible in the profile presented in Fig. 4, and were picked from plots processed to enhance the contrast of shallow features.  Light and dark grey areas are zones of moderate and pronounced deep crustal reflectivity, respectively (see text for discussion).
Godfrey et al. (2001) to be caused by thermal anomalies related to volcanism;

(3) that the prominently reflecting Oligocene limestone and/or condensed sequence horizon was deposited horizontally and can be used as a reference surface to track buoyant uplift around the Dunedin Volcano.

As discussed by Godfrey et al. (2001), there is, in general, a good correspondence between their modelled velocity change discontinuities and the presence of reflectors in the MCS data. For example, the highly reflective lower crust near Dunedin matches the region of anomalously low velocity. Estimates of crustal thickness (discussed in more detail below) between the velocity and MCS interpretations are also in agreement.

GRAVITY AND MAGNETIC INTERPRETATIONS

Gravity and magnetic observations collected along the SESI line are shown in Fig. 6A, B. The magnetic field is flat and low over the Rakaia Terrane and Otago Schist. In contrast, high amplitude, short wavelength anomalies from the Maitai Terrane to the Median Batholith (Stokes Magnetic Anomaly System) are probably caused by the presence of near-surface magnetic rocks. The sharp magnetic peak between SP 40900 and 41000 is interpreted to mark the northeastern extent of Brook Street Terrane near the seafloor. Moderate wavelength anomalies are present over the central Murihiku Terrane and over the Maitai Terrane, as recognised onland by Hatherton (1966) and Woodward & Hatherton (1975).

Negative anomalies in the gravity profile over the Rakaia Terrane, Otago Schist, and Median Batholith can be explained by the variable thickness of cover sediments and/or water depth (e.g., Karitane Canyon at SP 36000). Sharp gravity peaks over the Maitai and Brook Street Terranes correspond to high-density mafic rocks near the surface.

Modelling of the gravity and magnetic profiles provides constraints on some mid and deep crustal features that are not imaged by the MCS data. The positive anomalies over the Maitai Terrane (Junction Magnetic Anomaly) are caused by mafic-ultramafic rocks of the Dun Mountain Ophiolite Belt and are modelled as highly magnetic slabs dipping at 60°NE and extending between 2 and 15 km depth (Fig. 6C). This is somewhat steeper than the 30° dip modelled by Hatherton (1966) a few tens of kilometres inland. We agree with Hatherton (1966) that the positive magnetic anomaly over the Murihiku Terrane is probably caused by the more magnetic rocks of the Park Volcanics Group and its intrusive equivalents, being far more extensive at depth than at the surface; our modelling indicates that the magnetic body has to be <7 km deep, which probably rules out a source in the Brook Street Terrane (cf. interpretation of Cook et al. 1999).

The broad gravity and magnetic gradients across the Murihiku Terrane are modelled as a dense, magnetic, underlying Brook Street Terrane with the contact increasing in depth to the northeast. The gravity and magnetic modelling is consistent with crustal thinning near Stewart Island (Fig. 5, 6).

DISCUSSION

Unequivocal correlation of all but the shallowest reflectors with specific geological units or their contacts is difficult. The geological history of the basement rocks along the SESI line is one of major Cambrian to Early Cretaceous convergent margin magmatism and tectonics, followed by Early–Late Cretaceous extensional magmatism and tectonics, and then by intraplate Cenozoic magmatism and tectonics. The reflectors on the SESI profile are thus the product of a variety of geological processes of varying age and style, some or most doubtless reactivated. Crosscutting relationships between reflectors help in assigning relative ages and making geological interpretations.

Cover strata

Campanian–Pliocene strata are known to thicken offshore, particularly towards the Clipper and Great South Basins (Field et al. 1989; Cook et al. 1999). Godfrey et al. (2001) relate the depth of the prominent Oligocene seismic reflector to buoyant uplift around the Dunedin Volcano. However, Miocene uplift was widespread throughout the whole of onshore Otago (I. M. Turnbull pers. commun.), not just restricted to the doming around the Dunedin Volcano. Furthermore, the depth of the basement/cover contact and of the Oligocene limestone horizon along the SESI line is strongly controlled by differential subsidence related to post-rift thermal relaxation, and the angle between the SESI line azimuth and paleoshorelines has perhaps contributed to only an apparent upwarping of the prominent reflector in the vicinity of Dunedin. This issue needs to be more closely examined using shallow seismic datasets.

Moho and crustal thickness

Smith et al. (1995) presented an interpretation of a two-layer crustal model near Timaru consisting of c. 25 km of Rakaia Terrane upper crust (5.8–6.2 km/s), 10 km of lower crust (7.2 km/s), and Moho at c. 35 km above mantle (8.0 km/s). Similar results were obtained for the East Otago area by Wilson & Eberhart-Phillips (1998). The velocity model along the SESI line (Godfrey et al. 2001) refines these values: upper crust of 5.0–6.6 km/s extends down to c. 22 km under the Rakaia Terrane and to c. 28 km under the Murihiku Terrane. The change to a >7.2 km/s velocity layer (the Moho) is modelled at 25 km under the Rakaia Terrane and 32 km under the Murihiku Terrane.

The good agreement between the MCS interpretation, the above velocity models, and our gravity models on a 50–100 km length scale gives us confidence that the MCS data can be used to examine the finer Moho structure (e.g., on a 10–50 km length scale). Crustal thickness is greatest under the Murihiku Terrane and shallowest under Stewart Island; between SP 40880 and 42800, the Moho shallow from c. 32 to 22 km (an apparent dip of 6°). The difference in Moho reflectivity either side of the bend at SP 40880 suggests significant lower crustal anisotropy. The bends in the SESI line are too obtuse to enable confident calculation of true Moho dip, but crustal extension in the Great South Basin must be suspected as a probable cause of Moho shallowing along this part of the SESI line.

It is likely that the less extreme shallowing of the Moho from Dunedin towards a region offshore of Timaru and Oamaru can be similarly explained by the offline influence of the Clipper Basin. Eberhart-Phillips & Bannister (in press) show that, in general, the crust along the east coast of the South Island thins in an easterly direction.
Fig. 6  A. Magnetic profile.  B. Gravity profile.  C. Magnetic and gravity model along the SESI line. Numbers within bodies refer to densities (Mg/m$^3$) with magnetisation parameters $>0$ (A/m) shown in square brackets. Petrophysical properties of the six highly magnetic bodies shown in black are (from southwest to northeast): Median Batholith $2.75$ Mg/m$^3$ [4.4 A/m], Brook Street $2.77$ [2.2], Murihiku volcanics $2.75$ [8.3]. Maitai Terrane ophiolite slices $3.00$ [1.1], $2.95$ [1.6], and $2.95$ [1.6]. Density and magnetisation values were chosen to approximate known properties of the units onland.
Rakaia Terrane and Otago Schist

The Rakaia Terrane is characterised by a transparent mid–upper crust c. 20–25 km thick. There are at least three possibilities for the irregular zone of moderate reflectivity at 6–8 s TWT between SP 19600 and 20700: (1) Rakaia Terrane schist (as found in the nearby Clipper-1 well); (2) tectonic imbrication of Permian–Cretaceous oceanic crust underplated onto the base of the Rakaia accretionary wedge, which could also be schistose; (3) an underplate of Mesozoic volcanic rocks, similar to the onland Mount Somers Volcanics or (largely inferred) offshore Galleon volcanics (Fig. 3). The apparently stepped nature of the upper contact of the zone of reflectivity, and downlapping of reflectors against the Moho (Fig. 4, 5), suggests later truncation of the unit.

The lack of mid and lower crustal reflectivity beneath Rakaia Terrane from SP 19300 to 36100 can be explained by the lack of penetration caused by the Galleon volcanics (disturbances just above the basement/cover contact) and/or steeply dipping schist that would not be imaged (e.g., between the Waihemo and Waitaki Faults). Reay & Sipiera (1998) reported xenoliths of quartz-rich granulites with accessory graphite from an Oligocene diatreme deposit 30 km WNW of SP 32000 (i.e., near Endavour-1 well on Fig. 5). Crystallisation pressures are consistent with the lower crust, but their bulk chemical composition does not clearly equate with a simple Rakaia Terrane greywacke protolith. Granulite facies assemblages would not be expected to crystallise in the trenchward part of an accretionary prism: their presence may instead support the existence of a major Cretaceous extensional-related recrystallisation, the products of which were sampled by the diatreme.

Mantle xenoliths have been obtained from a number of onland East Otago volcanoes within 40 km of the SESI profile (Reay & Sipiera 1986). Rock types include lherzolites, garnet pyroxenites, clinopyroxenites, and websterites (i.e., “fertile” or unmelted mantle). Harzburgites, lherzolites, garnet pyroxenites, clinopyroxenites, and websterites might be previously melted residues derived from a subducted slab, have not been reported. None of the available geophysical datasets suggest the presence of a stranded slab beneath the Rakaia Terrane.

Despite its overall subhorizontal dip southwest of the Waihemo Fault, and marked planar anisotropy on a 1 m to 1 km scale, no reflections from the Otago Schist are visible above 2.5 s TWT. Good reflectors in the schist, dipping in the expected opposite directions on either side of the schist antiform axis, are seen between SP 36250 and 38900, mostly at 4–8 s TWT (c. 11–20 km). The shallowest observed reflectors on the antiform axis (4 s TWT) would correspond to schist structural levels seen at the surface near Mt Aspiring in West Otago (northermost end of the schist antiform trace drawn in Fig. 3). The deeper reflections would represent even higher metamorphic grade (eclogite facies?) schist and/or a relict slab of sub-accrretionary wedge oceanic crust that was warped up with the schist on cessation of subduction. This material may be equivalent to the so-called Aspiring lithologic association, a greenschist-rich subdivision of the Rakaia Terrane (Mortimer 1993; Turnbull 2000). High average mid-crustal velocities near Dunedin are better explained by the presence of Aspiring association rocks at depth rather than Caples Terrane at depth (as favoured by Godfrey et al. 2001).

Caples and Maitai Terranes

The southwest-dipping reflective sequence below SP 38500 (3 s TWT) and SP 38900 (4.5 s TWT) extrapolates to the surface position of the Caples/Rakaia Terrane boundary within the Otago Schist (Mortimer 1993). These mid-crustal reflectors are probably an image of the penetratively deformed structural top of the Rakaia Terrane parallel to schistosity. The schist reflectors dip down towards, and are truncated by, two prominent high-amplitude reflectors.

One of these is a 35 km long, subhorizontal reflector at c. 7 s TWT between SP 38100 and 38800, and is one of the single-most prominent reflectors on the SESI line (Fig. 4). We believe that this is possibly the Titri Fault, a long-lived Cretaceous–Quaternary fault that breaks the surface out of the SESI section line (Fig. 3). Near-surface dips on the Titri Fault are c. 70° east (Bishop & Turnbull 1996; Litchfield 2001 and references therein), and the fault probably becomes lenticular at depth. At the surface, both the Titri Fault and the main terrane-bounding Livingstone Fault merge with the Castle Hill Fault (dashed on Fig. 3) and head offshore. Two short northeast-dipping reflectors at 6 s and 7 s TWT beneath SP 38950 also appear to merge into the prominent horizontal reflector. The complexity of variably dipping reflectors on the MCS line suggests that faults with variable surface strike, and variable and long-lived amounts of throw, all sole into (and/or crosscut each other near) the c. 20 km deep and c. 35 km long flat reflector on the SESI profile. The base of the present-day seismogenic zone over much of the South Island is c. 12 km depth (Leitner et al. 2001) and, based on heat flow in measurements in Takapu-1, the expected temperatures at 20 km depth are c. 500–550°C (R. Funnell pers. comm.). If the prominent reflector does correspond to a long-lived Cretaceous–Recent fault, it is likely to be a ductile, greenschist-amphibolite facies mylonitic zone.

Onland surface geology between SP 39000 and 39480 consists of steeply dipping Maitai Terrane ophiolite belt melange and coherent, but also steeply dipping, Maitai and Murihiku sedimentary rocks (e.g., Cawood 1986). All of these are unsuitable for reflection seismic imaging. The position of the surface projection of the Livingstone Fault onto the SESI line is uncertain within 16 km; mapped and extrapolated surface faults (Bishop & Turnbull 1996; Cook et al. 1999) would place it at SP 39170, southwest of the observed magnetic anomaly peak. As discussed above, the Maitai Terrane ophiolite along the SESI line can be modelled as dipping steeply under the Caples Terrane.

Murihiku Terrane

Subhorizontal Murihiku Terrane strata on the south limb of the Southland Syncline are well imaged as discrete reflectors at 0.5–3.0 s TWT from SP 39550 to 40900. Subtle changes in apparent dip of Murihiku strata coincide with bends in the SESI line at SP 40000 and 40880. As shown in Fig. 6, the base of the low density, low susceptibility Murihiku Terrane is modelled by gravity and magnetic data as a northeast-dipping surface above the contrasting Brook Street Terrane. Reflectors at or close to this contact (the Letham Fault of Landis et al. 1999) include a short reflector at c. 4.5 s TWT at SP 40850 and 5 s TWT at SP 39400.

Interpretation of industry shallow seismic lines led Cook et al. (1999) to suggest that Murihiku Terrane strata extend as far south as Stewart Island. This is a radical interpretation as, elsewhere in South Island, tectonostratigraphic basement
terranes are always restricted to parallel belts. In a separate investigation, deep seismic reflection line P1 was shot southeast of Stewart Island (Fig. 2); parts of this line have been interpreted by Cook et al. (1999). P1 crosses the SESI profile at SP 42640 and, at this cross point, Cook et al. (1999) interpreted Murihiku Terrane strata at between 1 and 3 s TWT. Our own MCS data neither support nor disprove this interpretation; as with much of the nearshore Murihiku Terrane, we can see no reflections near SP 42640. However, as conceptual support for the extension of Murihiku Terrane strata across and within the Median Batholith, we note the presence of latest Jurassic Paterson Group volcanic and volcaniclastic rocks on Stewart Island. These rocks are coeval with youngest Murihiku strata and are a plausible, proximal volcaniclastic source for the more distal Murihiku rocks.

**Brook Street Terrane and Median Batholith**

Brook Street Terrane is not well imaged by the MCS data, but has a distinct high density, high magnetic susceptibility character. Gently southwest dipping reflectors at c. 6 s TWT under the Murihiku Terrane (SP 39650–39950) could be from within Brook Street Terrane, from a plutonic/sedimentary contact, or from southwest-dipping imbricate faults. The change in nature and depth of Moho reflectors between SP 39200 and 39500, coupled with the absence of imaged Moho between these points, may indicate a major lower crustal geological boundary. In short, it is still unclear what material constitutes the lower crust beneath the Maitai and northern Murihiku Terranes. Speculation is continued in the geological models section below.

The seismic character of the upper three-quarters of the Median Batholith is mainly transparent, as would be expected for a volume of dominantly plutonic rock. This transparent region merges with the Brook Street Terrane and extends under the Murihiku Terrane, so the exact north-eastern limit of plutonic rocks is unclear. Much of the lower quarter of the crust below the Median Batholith is of moderate reflectivity (Fig. 5). Moho depth shallows to the southwest from 32 to 22 km (see above), so a crustal root is not present beneath the batholith. In comparison, the Moho depth beneath the Median Batholith west of the North Island, New Zealand, is 10–13 s (c. 30–35 km) (Stern & Davey 1988). The latter is comparable to the crustal thickness of modern intraoceanic and continental arcs (Fig. 7). Crustal structure beneath the Coast Mountains Batholith and accreted terranes of the Canadian Cordillera has been investigated by Varsek et al. (1993) and Spence & McLean (1998). This region is as geologically diverse as the SESI line. A flattish Moho extends under the area at c. 11–12 s TWT, indicating a uniform crustal thickness of c. 34 km. The Moho beneath the New England Orogen of eastern Australia is also flattish and at a depth of c. 34 km (Finlayson 1993). Thus, compared to other Paleozoic–Mesozoic batholiths and accreted terranes, the crust along the SESI line is unusually thin. As discussed elsewhere in this paper, we attribute this thin crust to Cretaceous extension in the Great South and Clipper Basins.

**Origin of lower crustal reflectivity**

The ongoing debate on the origins of lower crustal reflectivity has been summarised by Mooney & Meissner (1992). It is interesting that, on the SESI line, the three zones of highest reflectivity (Fig. 4) are present in regions of thinner crust adjacent to the Great South and Clipper Basins. In all three regions, mid-crustal reflectors, interpreted by us as listric faults, merge with the zone of high reflectivity. Two of these plausibly break the surface offline as the Titri and Escarpment Faults. The Titri and Livingstone Faults were major Albian–Santonian normal faults (Carter 1988; Bishop & Turnbull 1996 and references therein); the age and kinematics of the Escarpment Fault of Stewart Island are poorly known, but it represents a major Cretaceous crustal break (Allibone & Tulloch 1997). We tentatively suggest that the three zones of high reflectivity are regions of schistose, gneissic, and/or mylonitic rocks. The gap between the two zones under the Rakaia Terrane may be due to poor signal acquisition through the Galleon volcanics and/or...
reflectivity. Origins involving Mesozoic geological features, as outlined above, cannot be ruled out for the origin of the lower crustal reflectivity.

Crustal velocity models (e.g. Smith et al. 1995, fig. 4; Godfrey et al. 2001, pl. 1; Eberhart-Phillips & Bannister in press, fig. 10) indicate a laterally extensive, high velocity lower crust at 20–25 km depth beneath the eastern South Island. Modelled velocities are c. 6.5–7.2 km/s, which are too high for metamorphosed Rakaia greywacke and too low for typical mantle velocities. It has been suggested that this high-velocity crust could possibly be oceanic crust that was subducted beneath the Rakaia accretionary prism in the Mesozoic (Smith et al. 1995; Godfrey et al. 2001, fig. 7). The MCS dataset does not provide a good test of this hypothesis, but we note that: (1) the base of the high-velocity layer is the reflection Moho, and the top is not imaged on the SESI line; (2) the high-velocity layer appears to be a New Zealand-wide feature. It is not restricted to the Rakaia Terrane, and does not deepen towards the Median Batholith, as might be predicted if it were simply a shallow, relic slab (Fig. 7); (3) the presence of lherzolite and granulate xenoliths north of Dunedin (Reay & Sipiera 1986, 1998) indicates that material other than low temperature, high pressure accretionary prism rocks and harzburgitic, subducted slab has been sampled by the Cenozoic volcanics.

The above three points are not inconsistent with an origin for at least some of the reflective, high-velocity lower crust along the SESI line resulting from Late Cretaceous igneous intrusion and/or amphibolite-granulate facies recrystallisation as the result of New Zealand-wide crustal stretching and extension.

Evidence for melting beneath the Dunedin area?

The mid-crustal antiformal schist reflectors near Dunedin are truncated downward by the top of one of the zones of reflective lower crust (Fig. 4, 5). In contrast to the other regions of reflective crust on the SESI line, this lower crustal region, and the mantle below it, are zones of relatively low velocity, accompanied by higher surficial heat flow and He anomalies, and it has been suggested that they are a region of Miocene and/or current melting (Godfrey et al. 2001). While we agree with Godfrey et al. that this is a possible explanation, we here further note that: (1) there are no clear manifestations of Dunedin Volcano-related features in the MCS data except in the top 1 s TWT at SP 36850 and 36440; (2) the zone of highest reflectivity in the lower crust is actually displaced southwest from beneath the projected centre of the Dunedin Volcano; and (3) Banks Peninsula Volcano, an even larger late Miocene volcano at the northeast end of the SESI line, has neither a reflective zone below it, nor convincingly demonstrable high heat flow or He anomalies (Cook et al. 1999, fig. 4.20).

It is unfortunate that, on the SESI line, Mesozoic and Cenozoic geological features (Otago Schist antiform, Dunedin Volcano) coincide with each other and with a bend from lines 5e to 25e. While the heat flow and He anomaly evidence do seem to point to a Neogene melt origin, other origins involving Mesozoic geological features, as outlined above, cannot be ruled out for the origin of the lower crustal reflectivity.

GEOLOGICAL MODELS

Hypotheses to test

Geological and geophysical cross-sections of the upper 5–10 km of the crust near the SESI line have been presented by a number of authors including Hatherton (1966), Woodward & Hatherton (1975), Mortimer (1993), and (near Dunedin) Bishop & Turnbull (1996). On these interpretations, the Livingstone Fault and adjacent ophiolite belt are shown to dip northeast under the Caples Terrane with an average dip of between 40 and 80°. The Brook Street Terrane (including its Permian plutonic underpinnings) is always shown as extending northeast beneath the Murihiku Terrane. The base of the Murihiku Terrane has usually been drawn as an asymmetric wedge with its “keel” as deep as 8 km, reflecting the asymmetry of the Southland Syncline. The geometry of Median Batholith/Takaka Terrane units has been depicted in a more schematic fashion, but Woodward & Hatherton (1975) have modelled the contact between the Permian–Cretaceous gabbros of Foveaux Strait and Cretaceous granites of Stewart Island as a c. 45° northeast-dipping contact.

Sketch cross-sections of inferred Late Cretaceous (c. 110 Ma) crust/mantle geometry in the vicinity of the SESI line have been presented by Landis & Bishop (1972), Coombs et al. (1976), Wood (1978), Bradshaw (1989), and Muir et al. (1995). Genetic relationships between the Permian rocks of the Brook Street and Taiitai Terranes are implied via relict, imbricated Permian oceanic crust and mantle under the Murihiku Terrane. The Otago Schist is a thick (>50 km) crustal welt which is underlain by a slab of oceanic crust subducted from the paleo-Pacific Ocean; the schist does not continue southwest of the DMOB, which is shown as a steeply northeast dipping, crust-penetrating suture. By their nature, geological cross-sections emphasise 2D geometry, but Cawood (1986), Bradshaw (1989), and Muir et al. (1995) noted the likelihood of strike-slip movement on terrane boundaries. They also depict some post-110 Ma extensional structures in Fiordland: Cretaceous crust in their sections is shown as being thickest (c. 45 km) beneath the Otago Schist, and thinnest (<20 km) under western New Zealand. Taiitai/Brook Street relations are less specific than in the modern day cross-sections, but a (relict) slab is depicted as being present under at least part of the Rakaia Terrane/Otago Schist.

Preferred model

Despite the SESI line being shot perpendicular to basement structural trends, it is clear that out-of-section features have exerted a major influence on reflector position and nature in the line. Examples of this include: (1) Moho dip indicates the thin crust near Stewart Island is plausibly related to Great South Basin rifting. Thinning under Rakaia Terrane is probably due to extension in Clipper Basin; (2) Titirangi Fault and Livingstone Faults are separate, steep, mutually perpendicular faults at the surface west of the SESI line, but possibly merge into a single, subhorizontal fault that intersects the SESI profile as the prominent subhorizontal reflector.

Major uncertainty arises in the interpretation of the three regions of deep-crustal high reflectivity, as these do not reach the surface and cannot be correlated with known geological features. Interpretation of highly reflective deep crust is
rarely unique, and has been ascribed to sill-like igneous intrusions, layered gabbroic intrusions, regional metamorphic fabrics, ductile faults and shear zones (commonly extensional) (see, e.g., Mooney & Meissner 1992). It is also important to realise that the age of reflectors, including the Moho, along the SESI line is likely to vary by hundreds of millions of years.

Our preferred model is shown in Fig. 8. The depth of features in kilometres is constrained mainly from gravity modelling, and also from the velocity model of Godfrey et al. (2001). Geological boundaries are positioned mainly by MCS reflection data. Key points are:

1. present-day crustal thickness under Median Batholith and Eastern Province terranes is now well constrained;
2. the antiformal Otago Schist extends down through most of the crust but Moho is not involved in the schist upwarp;
3. Maitai Terrane is confirmed to dip under the Caples Terrane in the mid and upper crust;
4. lower crustal geology and fault geometry beneath Maitai and Murihiku Terranes is unconstrained by MCS data but appears to consists of dense material, presumably largely of mafic igneous rock;
5. Cretaceous extension (in large part offline) has resulted in significant thinning of crust and dips on the Moho, irrespective of terranes or batholithic rocks;
6. imaged crustal faults related to Cretaceous extension may include the Titri Fault, which could sole into a zone of high crustal reflectivity; other zones of major deep crustal reflectivity are present near Stewart Island and the Clipper Basin;
7. mid and deep crustal features near Dunedin can be possibly explained in terms of Mesozoic geological events, not solely as effects of Miocene–Recent igneous activity.

In general, our new data support the crustal structure inferred from previous, geologically formulated, cross-sections.

Implications for tectonic history

The overall tectonic accretionary style is that of juxtaposition of 10–100 km size blocks, most of which extend from the surface down to the middle or lower crust. The New Zealand terranes are not thin-skinned thrust slices stacked up on the Gondwanaland margin. A comparison of the width and depth of the Paleozoic–Mesozoic tectonic elements of the SESI line with the crustal architecture of modern day convergent margins (Fig. 7) emphasises that we are not dealing with the simple case of a single Mesozoic subduction-arc complex that has been preserved intact. While the maximum crustal thickness of the Median Batholith (c. 30 km) is comparable to that of some modern day magmatic arcs (Fig. 7B, C), the crustal thickness of most of the New Zealand forearc terranes and batholith along the line is substantially less than unextended, actively accreting continental margins (Fig. 7D).

The variably dipping, but generally poorly imaged reflectors deep under the Caples, Maitai, and Murihiku Terranes suggest tectonic complexity, possibly as a result of both dip-slip and strike-slip faulting at various times. Dense lower crust is required beneath the Murihiku Terrane, and it is possible that this consists of imbricated Maitai-like and/or Brook Street Terrane-like ophiolitic/arc crust of Permian age. There is no compelling evidence for a stranded Jurassic–Cretaceous subducted slab under the Otago Schist and Rakaia Terrane; relatively high velocity middle crust near Dunedin may be Aspiring lithologic association gneisschist/amphibolite-rich material, not Caples Terrane.

Despite careful selection of the position of the SESI profile line to minimise the effects of post-accretionary tectonics, much of the crust is probably far thinner than that expected for an unextended orogen. Thin crust, and reflective lower crust, along the line corresponds with the proximity of the Great South and Clipper Basins. It is likely that many of the terrane-bounding faults have been reactivated (potentially with movement out of the plane of section). This may be a contributing factor to the complex intersection of reflectors beneath the central part of the SESI line.

CONCLUSIONS

A 550 km long multichannel seismic line offshore of southeast South Island, New Zealand, provides important new data on the crustal structure of the Median Batholith and Eastern Province terranes that formed along the margin of southern Gondwanaland. The SESI profile cross from terranes deformed in a Jurassic–Cretaceous accretionary prism, across the paleo-forearc region of Permian–Jurassic terranes, and into the Paleozoic–Mesozoic magmatic arc. The batholith and all the Eastern Province terranes appear to extend down to middle or lower crustal levels and are not minor thin-skinned fault slices. Most reflections are believed to come from faults or contacts between major geological units, although reflections from gently dipping Otago Schist foliation and Murihiku Terrane bedding are observed. Gravity and magnetic modelling shows that the Brook Street/Murihiku and Maitai/Caples Terrane contacts dip gently and
steeply northeast, respectively. There is no evidence in the SESI profile for the presence of relict slabs of Mesozoic oceanic crust beneath the Eastern Province.

Crustal thickness along the SESI profile varies from c. 22 km (beneath Median Batholith) to 32 km (beneath Murihiku Terrane), and there is no simple relationship between crustal thickness and near-surface basement geology. Along the SESI profile, the modern day crust is generally thinner, and the inferred Mesozoic arc-trench gap is greater, than that of unextended circum-Pacific orogens and modern day convergent margins; most of the elements of New Zealand’s Early Cretaceous convergent margin are probably still in their original juxtaposed positions, but have been stretched and thinned during post-accretionary Late Cretaceous extension related to Gondwanaland breakup. The origin of three regions of deep crustal reflectivity remains unresolved, although their association with thin crust suggests they are also extension-related features.

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