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RESEARCH ARTICLE

Quaternary shelf structures SE of the South Island, imaged by high-resolution seismic profiling

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Along the south-eastern coast of New Zealand’s South Island, observations and characterisations of shelf geology are complicated by numerous possibly active faults (e.g. the coast-parallel Akatore and coast-perpendicular Waihemo and Castle Hill faults), a Miocene-aged volcanic edifice (i.e. the Dunedin volcano) and incision from an extensive submarine canyon system. Conventional marine seismic data do not adequately image the basin beneath the shallow shelf here. However, six recently digitised high-frequency single-channel boomer seismic surveys have enabled the investigation of unique local geological structures and their relationships to the tectonic and sedimentary development of the region. These structures have significant control on active processes such as: (1) the localisation of sedimentation and submarine erosion; (2) the instigation of canyon channel incision; and (3) the distribution of fluid migration pathways on the shallow shelf. Future data acquisition will further constrain these processes and help to evaluate earthquake risk in this region.

Keywords: active faults; neotectonics; New Zealand; Otago; Quaternary faults; seismic imaging; seismic reflection; shallow continental shelf; South Canterbury; sub-bottom profiling

Introduction

The seafloor off the south-eastern coast of New Zealand’s South Island between the Waitaki and Clutha rivers (Fig. 1) is characterised by a narrow (15–30 km wide) shallow (<150 m deep) continental shelf overlaying the eastward-thinning continental crust of the Campbell Plateau. Locally the shelf has undergone progressive uplift during the Pleistocene, resulting from convergence of the Pacific and Australian plates, and in places the coastline is currently subject to a gentle uplift of <0.1 mm a⁻¹ (Wellman 1979; Gibb 1986; Litchfield & Lian 2004). A coastal escarpment has consequently developed, with incised rivers emerging at the coastline to deliver sandy terrigenous sediments to the inner shelf.

Despite over 150 years of geological mapping in the provinces of Otago and Canterbury that has constrained the three-dimensional geometry of coastal rocks and sediments (e.g. Benson 1968; Bishop & Turnbull 1996; Litchfield & Norris 2000; Forsyth 2001), their expression and extent on the adjacent continental shelf and basins is still poorly understood and is largely limited to petroleum industry multi-channel seismic (MCS) surveys (e.g. Field & Browne 1989; Cook et al. 1999). Although these MCS surveys have provided insight into the large-scale basin geology, resolvable with high-energy and low-frequency seismic acquisition systems, only high-frequency single-channel seismic studies at specific sites can resolve the fine-scale features required to interpret Quaternary processes (e.g. Carter et al. 1985; Carter & Carter 1986; Carter 1986b; Browne & Naish 2003).

In the last two decades, a series of high-resolution single-channel seismic reflection surveys (Fig. 1) has been undertaken on the shallow shelf and upper slope (<250 m water depth) off the coasts of Otago and South Canterbury to address a range of structural, sedimentological, stratigraphic and hydrogeological aims (Allan 1990; Johnstone 1990; Orpin 1992; Gray 1993; Orpin 1997; Wilson 1998; Osterberg 2001, 2006). These surveys underpin a substantial body of mostly unpublished research conducted as part of a series of postgraduate theses. Regional geological mapping projects have made use of the results of these surveys (Bishop & Turnbull 1996; Forsyth 2001); however, the full potential of the datasets collected for this work has not been realised or integrated regionally due to the inadequacy of the data archiving process in the early years of computing. Recent advances in technology have enabled these analogue data to be recovered, converted to digital signals and enhanced for use in further investigations of the shelf. In particular, these data can be critical in the characterisation of Quaternary faults, most of which can be regarded as active, on the shallow shelf off Otago.

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Figure 1 Position of sub-bottom profile surveys presented in this paper. Numbers refer to MSc theses of (1) Wilson (1998), (2) Allan (1990), (3) Gray (1993), (4) Osterberg (2001), (5) Orpin (1992) and (6) Johnstone (1990) for which the data were collected. Lines presented within this paper are identified by dotted lines and labelled with their line numbers; line numbers are unique only within a particular survey. Shaded topographical relief map on land. Offshore contoured colour bathymetry courtesy of NIWA. Contour interval 100 m. Inset map shows location of main map in relation to New Zealand and the regional plate boundary.
In this paper, we highlight three case studies from these data to highlight the control that such geological structures have had – and continue to have – on sedimentation, submarine erosion, canyon incision and fluid flux. However, the ability of the technique to image evidence of these geological processes varies through the region depending on the modern sediment cover on the seafloor and the nature of the underlying bedrock. An additional aim of this study is not only to assess these earlier data, but to recognise where new studies could address outstanding questions for the continental shelf SE of the South Island.

Geological setting

The crustal terranes that currently strike NW–SE along the SE coast of the South Island were accreted and metamorphosed from the Jurassic to Early Cretaceous on the margin of Gondwana (Mortimer 2004). The Late Cretaceous–Early Miocene extensional tectonic regime that rifted Gondwana apart and thinned and stretched the continental crust of New Zealand evolved into the current transpressional plate boundary through New Zealand by the late Miocene (e.g. Carter & Norris 1976; Norris et al. 1990).

Tectonic inversion structures now dominate much of eastern Otago, with most of these faults trending subparallel to the major plate boundary of the Alpine Fault on the west coast of the South Island. The easternmost of the onshore mapped Otago inversion structures are the Titri Fault, which extends along the west side of the Taieri Valley SW of Dunedin, and the Akatore Fault, which crosses the shoreline (Litchfield & Norris 2000; Rees-Jones et al. 2000; Litchfield 2001; Litchfield & Lian 2004). Although there has been no historically observed seismicity on the Titri Fault, earthquakes in 1974 (Adams & Kean 1974; Bishop 1974) and 1989 have been attributed to the Akatore Fault. Even though there has been no active or palaeo-seismicity confirmed farther offshore, the basement geology also has evidence of coast-parallel structures that were possibly related to extensional tectonics (cf. Carter 1988) and are likely to be susceptible to reactivation under compression. Offshore evidence from Pegasus Bay subsequent to the 2010 and 2011 Christchurch earthquakes suggests that such basement structures along the Canterbury coast (e.g. Barnes 1996) are potential earthquake sources. Such coast-parallel offshore structures are also the subject of a current petroleum industry exploration focus in the deepwater Canterbury Basin. The area of the shallow shelf immediately seawards of the Akatore Fault was identified as being an optimal location to explore the offshore expression of coast-parallel faults.

In contrast to the coast-parallel faults, a series of regional faults lie orthogonal to the SE coast of the South Island. From SW to NE, these include the Livingstone/Castle Hill, Tuapeka, Waihemo and Waitaki fault systems (Bishop & Turnbull 1996; Forsyth 2001). The offshore coast-parallel faults identified in this work lie between the Livingstone/Castle Hill and Waihemo faults, which respectively form the south-western and north-eastern boundaries of the SW–NE-striking Otago fault system. In the NE, the Waihemo Fault is mapped onshore as an inverted normal fault where younger lower-grade textural zone II schists are uplifted to the NE over older higher-grade textural zone IV schists to the SW (Forsyth 2001). This break in the structural fabric is manifested in the NW-trending Kakanui Mountains and Shag River Valley. In the SW, the Livingstone fault zone, with a zone of deformation up to 1 km wide, is mapped as the tectonic contact between the Taiaroa and Caples terranes along the south-western edge of the Otago Schist (Cawood 1986; Bishop & Turnbull 1996). Close to the mouth of the Clutha River it possibly merges with the Quaternary active Titri Fault to form the Castle Hill Fault and runs offshore (Bishop & Turnbull 1996; Mortimer et al. 2002). Whether these coast-perpendicular fault zones extend offshore remains an outstanding question, and forms an important motivation for the current study.

The shallow modern continental shelf here lies along the NW (landwards) margin of the Great South (Carter 1988; Cook et al. 1999) and Canterbury (Field & Browne 1989) basins. Late Cretaceous to recent sedimentary units thicken greatly seawards. Although the modern shelf is narrow, the underlying sedimentary basins on the Campbell Plateau are developed on thinned continental crust that extends several hundred kilometres offshore beneath typical ocean depths of 1000–1500 m.

Superimposed on this underlying geology in the central part of the Otago coastline is the Late Miocene (16–10 Ma) Dunedin Volcano (Bishop & Turnbull 1996; Coombs et al. 2008) that grew from a base level close to present-day sea level. With an approximate diameter of 25 km centred on Otago Harbour, the resistant igneous rocks have formed a coastal promontory that has affected coastal current patterns and sediment dispersal along the shelf.

Modern sediment transport, and the geometry of the inner shelf Quaternary terrigenous sediment prism, is strongly influenced by a combination of the persistent southerly swell, north-eastwards-travelling longshore currents, winds, tidal flows and the north-eastwards flowing Southland Current (Carter et al. 1985). Fluvial sources from the Clutha, Taieri and Waitaki rivers dominate, supplying 0.39, 0.32 and 0.34 Mt of sediment per year, respectively (Hicks & Shankar 2003); note that these values are likely to be affected by major hydroelectric damming schemes on the Waitaki and Clutha river systems, but these anthropogenic effects are not considered here. At the shelf edge (approximately 140 m water depth), Carter et al. (1985) suggest that storm swells, internal waves and up-canyon currents are probable mechanisms for sediment transport. They describe four broadly shore-parallel belts of sediment from the shallow shelf off the coast of Otago, and their origin is
attributed to deposition during episodic post-glacial transgressions. These belts consist of: (1) a shore-connected wedge of highstand terrigenous sand at water depths of 0–20 m; (2) transgressive quartz gravel ridges at water depths of 20–55 m; (3) sheets and ribbons of relict transgressive sand at 55–85 m; and (4) thin veneers of outer-shelf transgressive/lowstand shell hash at water depths of 85–200 m.

A series of submarine canyons occur off the coast of the Otago Peninsula where the shelf narrows to a width of about 10 km, and feeds most sediment from this portion of the shelf to the Bounty Trough (Carter & Carter 1987; Lewis & Barnes 1999). The shelf break at roughly 140 m coincides with the seaward edge of a terrace that has its inner edge at about 120 m, in the vicinity of the Last Glacial Maximum shoreline (c. 18 ka). Note that some of the finer, suspended fractions of sediment bypass these canyons and are potentially carried a few hundred kilometres north, beyond Banks Peninsula, where they may descend via the Kaikōura Canyon System to the Hikurangi Plateau (Lewis & Barnes 1999).

Methods
In comparison to airgun-sourced multi-channel seismic (MCS) methods, boomer sub-bottom profiling techniques have limited depth penetration due primarily to the relatively low-energy levels of the seismic source. Additionally, boomer surveys are usually conducted with short receiver arrays, which results in low-fold sections that do not have the noise suppression that high-fold MCS datasets have. However, boomer datasets have several advantages over conventional MCS data. In particular, they generally have a much higher resolution in both the horizontal and vertical directions due to the shot firing rate (shot separation is often <1 m for boomer surveys compared to >20 m for an airgun survey) and the frequency content of the signal. Also, the scale of the operation is such that it can be undertaken from smaller vessels, and therefore has the potential to collect data economically over targeted regions. As a result, boomer surveys have been widely and effectively used in shallow seas and lakes to make detailed maps of the upper 50–200 m of geology (e.g. Dingle 1965; Bastos et al. 2003; Grossman et al. 2006; Upton & Osterberg 2007).

Equipment
Seismic data were collected between 1989 and 1999 on board the University of Otago’s RV Munida using a Ferranti Ocean Research Equipment (ORE) Geopulse sub-bottom profiling system (Hill 2007). The acoustic source (boomer) assembly and hydrophone array were towed approximately 25 m off the stern, with the vessel travelling at 5–8 km/h. The boomer source signal was controlled by electronics on board the research vessel (summarised in Fig. 2).

Seismic energy was received by a single-channel array (consisting of 20 piezoelectric hydrophones spaced 15 cm apart) generally deployed 5–10 m to the starboard side of the boomer. Analogue signals were amplified, filtered and plotted on board the vessel while simultaneously being recorded on a magnetic tape (VCR or DAT) system for later playback and analysis (see Fig. 2 for more details).

Digitisation of analogue data
Analogue data from the surveys presented here, combined with their associated geographical and geometrical references, have been converted to SEG-Y (Barry et al. 1975) formatted digital files. This enables digital processing methods such as deconvolution, spatial filtering and migration, in addition to archiving, facilitates presentation of the data at a range of scales for interpretation and display.

Conversion to SEG-Y format involved several steps. First, the tapes of the analogue signal were played back through the original recording system (Fig. 2) and digitised into a 16-bit stereo WAVE file, with a sample rate set to 10 000 samples/sec using the open-source Audacity program (http://audacity.sourceforge.net). The WAVE files were manually separated into files where the boomer firing rate was constant. Each of these files was then converted to SEG-Y format using a python script (Hill 2007). Data samples were written as 4-point binary IEEE floating point numbers. The trigger pulse (as recorded on one of the stereo channels) can be reliably used to indicate the start of each record trace (recorded on the other stereo channel.) The length of each trace in a particular file was generally set to be slightly shorter than the shot interval in order to allow for a consistent trace length given slight variations in the shot interval.
The header information for each trace in the SEG-Y formatted data contains co-ordinate information interpolated from original navigation files (Hill 2007). These original navigation files consist of tables of \(x\) and \(y\) coordinates, recording times and reference IDs that enabled the linking of recorded data to the navigation data. For any given trace recorded at an arbitrary time \(t\) the algorithm interrogated the navigation file, found the co-ordinates that come before and after time \(t\) and then interpolated new co-ordinates for the trace. The interpolation algorithm assumes that the vessel maintained a constant speed and heading between navigational fixes.

The navigation data stored within trace headers vary in quality, both in terms of the method used to measure the coordinate positions and in the number of points used to describe a particular survey track. Early methods involved radar triangulation, which could provide coordinates that were accurate to within 290 m (Allan 1990; Johnstone 1990; Orpin 1992). These were superseded by GPS measurements which in the early 1990s were quoted as being accurate to within 50 m (Gray 1993) and, more recently, are expected to be accurate to within 5 m (Wilson 1998; Osterberg 2006).

**Seismic processing and analysis**

All data processing was undertaken using the Globe Claritas seismic processing package (Ravens 2001). The foremost of the processes applied was one to remove the effect of ocean swell on the data. Boomer data collected on the open sea are affected by ocean swell that can often have an amplitude of as much as \(3-4\) m and a period of several seconds (note that if the average swell was above \(2\) m, data acquisition was usually suspended).

Data presented here have had a simple swell filter applied through a static correction to the data as follows. The seafloor reflection was manually picked for all lines. This was then smoothed by mixing the picks from 30 adjacent traces. The smoothed picks were then subtracted from the unsmoothed picks and the result was assumed to be the component resulting from ocean swell. This result was then applied as a static shift to the appropriate trace. Note that this assumes that the seafloor will have few features on the scale of the swell. Some editing is required at locations on the seafloor where there are significant features that do not meet this assumption.

A Butterworth filter with trapezoidal cutoffs defined at 100, 180, 1500 and 1900 Hz has been applied to all data. An automatic gain correction (AGC) with a short time window (dependent on the water depth of the particular dataset) was used.

**Seismic imaging of shallow shelf structures**

The geology of the shallow shelf offshore from Otago and South Canterbury varies considerably along the coast due to the underlying crustal-scale structures and patterns of ongoing sedimentation. Two of the most obvious differences observed along the coast are the rate of crustal subsidence or uplift and the corresponding sediment accumulation rates. Off South Canterbury, in the Canterbury Basin, accumulation has been rapid through the Quaternary (Field & Browne 1989; Browne & Naish 2003). This has led to the preservation of numerous prograding sedimentary sequences as the shelf has built outwards (e.g. Fig. 3). Off Otago, basin subsidence and sediment accumulation has been considerably slower. In places, incised channels and canyons have been eroded into the shelf at sea level lowstands during the Pleistocene and partially infilled during periods of higher sea level (Fig. 3). For much of this south-western part of the shelf, especially closer to the shore, a net uplift has occurred that has resulted in the erosion of underlying Tertiary (or older) bedrock that can be clearly imaged with boomer seismic methods at several locations (e.g. Figs 4–7).

Boomer seismic surveys in the Otago region show that a smooth, hard, fluid-saturated and well-cemented seafloor will generally result in deeper penetration and higher resolution than one that is particularly soft, rugged, gas charged or organic rich. The reason for this is that the latter group of conditions tends to scatter or absorb seismic energy much more than the former group of conditions. For example, regionally limited deposits of post-glacial sand and gravel that occur on the modern shelf off Otago (Carter et al. 1985) can obscure images of the underlying Quaternary lithological units and geological structures below. However, for much of the inner and middle shelf (<60 m water depth) off the coast of Otago, little sediment is deposited on the scoured bedrock. This is particularly so along the coast between Taieri Mouth and Brighton, off the coast of Karitane and offshore from Shag Point (Fig. 1), permitting high-resolution imaging of the underlying sedimentary rocks. The barren seafloor off Brighton and Karitane appears to be affected by the interplay between the SW–NE-running longshore drift and promontories in the coastline (i.e. the Akatore block and Otago Peninsula, respectively). Basement rocks off the coast of Shag Point are not draped by sediment because they are locally higher than the surrounding shelf, probably as a result of active uplift on the north side of the Waihemo Fault.

Boomer surveys have successfully been used to characterise three contrasting types of structural systems in the study area: (1) coast-parallel faulting associated with the outboard edge of the Otago fault-fold belt is apparent on an offshore portion of the Akatore Fault, along the Brighton coast south of the Dunedin volcanic complex (survey 6 in Fig. 1); (2) an orthogonally striking fault system is seen in the Shag Point region where the Waihemo Fault System runs offshore from the Kakanui Mountains (survey 2 in Fig. 1); and (3) shelf edge faulting possibly linked to lowstand hydrogeological fluid flow systems is seen near...
the present-day shelf break off the coast of the Otago Peninsula (survey 5 in Fig. 1). Details of these structural systems are described in the following sections.

Offshore continuation of the Akatore Fault System
The coastline of South Otago is roughly parallel to the strike of the tectonically inverted range and basin system found through the interior of the province. The onshore fault closest to the coast involved with this system is the Akatore Fault, which runs between the villages of Taieri Mouth in the north and Toko Mouth in the south and extends offshore to the NE and SW (Bishop & Turnbull 1996; Litchfield & Norris 2000). Detailed boomer data from the adjacent shelf (Johnstone 1990), acquired within about 12 km of shore and in water depths of 15–60 m, images the upper 50 ms (roughly 50 m) of sub-seafloor sediments and sedimentary rocks (Fig. 4). Most of the shelf has little Quaternary cover in this region (cf. Carter et al. 1985). Seismic profiles are characterised by numerous gently SE-dipping reflections that are distinct and continuous. They correlate to the Late Cretaceous–Tertiary sedimentary sequences that outcrop onshore, but no direct correlation (by sampling or mapping) has been undertaken between specific reflections and onshore formations. The single-channel boomer dataset recorded in this region has remarkably good penetration (i.e. >100 m), which in many cases was limited first by the occurrence of the seafloor multiple. In a few locations (e.g. as indicated by white arrows in Fig. 4), more rugged seafloor outcrops are indicated by strong seabed reflections and poor penetration. These outcrops are most likely metamorphic basement rocks, volcanic extrusions, eroded igneous intrusions or organic communities that have developed on outcropping hard substrates.

Besides the very regular reflections from sedimentary units, the most striking features identified in these data are faults (Figs 4 & 5) with distinctive folding and deformation on the hanging walls and footwalls (e.g. Line 1, Fig. 4). Unfortunately, the landward extent of the Akatore Fault could not be imaged in water depths >5 m due to operational limitations with the vessel. Previous suggestions have had the fault coming back onshore at the approximate location of the Kaikorai Stream estuary (Fig. 5) and perhaps running up the length of Otago Harbour. However, on multiple profiles, at least two other significant faults are interpreted to run roughly parallel to the Akatore Fault, approximately 3 and 10 km farther offshore (Faults A and C in Figs 4 & 5). These faults appear to displace post-glacial
Figure 4  Boomer profiles 1, 2, 5 and 4 from the nearshore shelf south of Dunedin showing reflective units of the Cretaceous–Tertiary sedimentary sequence (Johnstone 1990). In particular, coast-parallel faults and related deformation is imaged well in the upper 50 ms (roughly 50 m) of the seafloor. Faulting is indicated using black lines (solid and dashed, with solid having a higher degree of confidence). Labelled faults A, B and C are mapped in Figure 5. Fault displacement is indicated where apparent. Note possible seafloor displacement by faults on Line 1 (trace 3200) and Line 2 (trace 2800). Non-penetrative seafloor (regions indicated by white double-arrowed bars) is rare on this margin. Line positions as indicated in Figure 5.
sediment cover in places, suggesting that they have been active in the Holocene. Given their proximity to each other, either of these faults could be considered alternative sources of the 1974 (Adams & Kean 1974; Bishop 1974) and 1989 earthquakes attributed to the Akatore Fault. Anticlinal features on the SE and synclinal features on the NW sides of the fault support uplift to the SE, but the seismic images do not convincingly provide information on the dips of these faults. In some cases, deformed strata are suggestive of a system of NW-dipping normal faults or, alternatively, SE-dipping reverse faults.

The latter interpretation is preferred due to observations of the fault onshore through the Akatore block (Litchfield & Norris 2000). Offshore, measurements of throw on the faults are not possible because chronostratigraphic correlations cannot be convincingly made across the faults.

**Offshore continuation of the Waihemo Fault System**

The Shag River, approximately 50 km north of Dunedin, delivers 0.060 Mt a$^{-1}$ of sediment to the coast (Hicks & Shankar 2003). At the river mouth, the NW–SE-trending Waihemo Fault System heads offshore where a series of boomer lines running parallel to the coast has helped to constrain the offshore extent of this fault system and its associated deformation (Allan 1990). Three coast-parallel lines shot in water depths of 35–45 m image the seafloor sediments of, primarily, the hanging wall of the Waihemo Fault. At least three fault traces within the Waihemo Fault System are imaged seismically in this region (Fig. 6).

The main Waihemo No. 2 Fault trace interpreted at the SW end of the three lines in Fig. 6 shows the reflective Cretaceous–Tertiary hanging-wall sequences to the NE juxtaposed against seismically transparent sediments to the...
SW, interpreted to be the Holocene deposits of the Shag River. To the south, signal penetration was not sufficient to image the base of the channel at the mouth of the Shag River. In contrast, north of Waihemo No. 2 Fault, very little modern sediment overlies the Cretaceous–Tertiary sequence.

The seafloor expression of the fault coincides with the transition from strong irregular seafloor reflections to the north (on the hanging wall) to a flat-lying planar seafloor to the south. The rough seafloor reflections are interpreted to correspond to indurated rock outcropping as strike ridges (associated with Waihemo No. 1 and Waihemo No. 2 faults in Fig. 7) that extend approximately 8 km offshore (between Lines 3 and 4). However, the underlying seismic character in the deep profile (Line 4, Fig. 6) shows that the fault system continues seawards as a blind fault.

Identification and correlation of particular units within the offshore seismic sequence has been attempted by Allan (1990), but is tenuous because the survey line spacing is too wide and lacks a tie line (Figs 6 & 7). However, strong contrasts in the internal reflectivity characteristics of the units are consistent with the sedimentary formations (primarily clastic nearshore units) observed in outcrop on shore. For example, a hanging-wall anticline is clearly observed in sea cliffs along the coast at Shag Point, within the fault zone. A hanging-wall anticlinal feature is also observed on all three seismic lines, with the crest of the anticline converging with the main fault trace as the shelf deepens. Sedimentary units on the NE limb of the anticline are observed to dip to the NE at 8°–16°.

**Shelf edge faulting and fluid flow**

On the uppermost part of the slope off the coast of the Otago Peninsula, between the Papanui and Saunders canyons, the otherwise regular margin is interrupted by a < 1 km² bench at a water depth of roughly 200 m (Figs 1 & 8), about 60 m in depth below the regional shelf break. Fishermen dredging for scallops on this bench discovered a collection of chimneys and irregularly-shaped carbonate concretions (Orpin 1992, 1997) that have been linked to distinctive vent phenomena observed elsewhere around New Zealand (Lewis & Marshall 1996). Radiocarbon dating has determined that the chimneys are relict features with a maximum age of 33 000 ± 550 years and a stable oxygen and carbon isotope composition consistent with a predominantly marine origin for the fluid that would have flowed through shallow organic-rich sediments at a time when sea level was considerably lower than present (Orpin 1997).

Two high-frequency single-channel seismic profiles (survey 5 in Fig. 1) image up to 150 m of sedimentary section within the lowered bench feature on which the chimneys are found (Orpin 1992, 1997). Line 1 (Fig. 8)
shows a series of reflections that generally dip gently seawards (maximum 8° dip), representing the prograding system of Late Cretaceous–Quaternary sediments seen along the outer shelf of the SE South Island. As shown by the truncated east-dipping beds at the seafloor (e.g. reflection A in Fig. 8), the present-day outer part of the shallow shelf is starved of modern sediment (Carter et al. 1985; Orpin et al. 1998).

A geological cause for the bench and the focusing of chimney features in this region has not been determined, but shelf-edge faulting or large-scale slumping of the shelf margin is a possible mechanism. Potential evidence for small-scale slumps is supported by a cemented ridge observed in close proximity to the zone of carbonate cementation and chimneys by a camera mounted on a remotely operated vehicle (Orpin 1992, 1997). However, a larger-scale slump mechanism for the overall formation of the 1 km² bench is complicated by the observation of relatively continuous subsurface reflections (e.g. reflections B–E in Fig. 8) that broadly mirror the modern stepped geometry of the shelf break. Evidence of erosional surfaces that truncate dipping reflections is common, especially on shallower portions of reflections B, C and E. Reflections immediately above the erosional surfaces appear to infill channels. In addition, Reflection B is conspicuous because it has an apparent landwards dip below the bench containing...
the chimneys. Weaker reflections that drape over Reflection B appear to mirror this attitude. The repetition of this geometric pattern is consistent with glacio-eustatically controlled sedimentation on the outer shelf throughout the Late Tertiary (cf. Osterberg 2006), suggesting that the bench has been a stable geomorphic feature through successive cycles, perhaps augmented by longstanding fluid-flow processes. If slumping did control the initial geometry of the bench, the base of the slump is now deeper than can be readily imaged in the seismic data.

Discussion and implications
Active structures on the shallow shelf off the coast of Otago affect a wide range of geological and hydrodynamic processes. These include the localisation of sediment accumulation and erosion, the establishment and maintenance of fluid migration pathways through the shelf and possibly the initiation and focusing of shelf-margin canyons. Each of these is addressed in the following sections.

Structural controls on sedimentation
Seismic data collected off Shag Point (Allan 1990) show the strong role that active structures can have on sedimentation. At this location, the seafloor geology changes significantly across the NE-dipping Waihemo Fault System of reverse faults. However, the seismic data support the possible termination of the fault zone just a short distance offshore. The surface expression of this faulting ceases about 8 km from the coast, and basement faulting is not visible in conventional marine seismic data a further 7 km offshore (Allan 1990; Mortimer et al. 2002). Immediately NE of the seafloor expression of the Waihemo Fault System, the structure consists of the SE-plunging Shag Point Anticline.

The juxtaposition of basement units against Tertiary sedimentary rocks in the footwall of the offshore Waihemo Fault presents a geometric conundrum. To address this problem, Allan (1990) inferred an extension of the coast-parallel Titri–Akatore Fault System NE of the Otago Peninsula, trending subparallel and close to the present coastline, terminating at the Waihemo Fault (Fig. 7). Southeast of this hypothetical junction of the Waihemo and Titri fault systems, displacement across the Waihemo Fault System would be relatively small. The termination of these structures can be accommodated by linking the motion of the blocks on the south-eastern side of the Titri Fault System and the north-eastern side of the Waihemo Fault System. These structures are presently insufficiently imaged to allow a more detailed and quantitative analysis, but this style of fault termination is consistent with several other central Otago faults such as the Taieri Ridge, Rock and Pillar, Rough Ridge and Raggedy Faults (Norris 2004; Norris & Nicolls 2004), which all have north-eastern terminations in the Waihemo Fault System. These offshore data suggest that the major tectonic boundary between the SW–NE-striking range and basin inversion structures of Otago and the NW–SE-striking faults of South Canterbury has an equivalent expression on the adjacent shelf where it is overlain by Quaternary sedimentation.
Structures within the Tertiary and older sedimentary units on the Otago margin, and especially those that traverse the coastline and adjacent continental shelf, have the potential to influence the position of river and drainage channels. For example, on land, the Shag River follows the line of the Waihemo Fault System. Offshore, the Shag Point anticline and extension of the Waihemo Fault System deform Late Cretaceous–Moocene deposits, exposing them as strike ridges and reefs on the seafloor that can be observed in the seismic data (Fig. 6) and sidescan sonar (Allan 1990). These units were sub-aerially exposed during Quaternary glacial periods, and scarps would have influenced topographical drainage in a similar way to the on-land section. For example, evidence of a buttress unconformity is seen in seismic section (e.g. Line 4, Fig. 6) with Holocene marine sediment deposited against deformed Tertiary sedimentary rocks. Furthermore, buried channels are observed to traverse the present-day inner shelf with braided or meandering cut-and-fill channel patterns (Gray 1993) and link with other tributaries further towards the shelf break. These fluvial networks presumably drained into an ancient manifestation of the Karitane Canyon.

**Structural influence on fluid flow within and on the shelf**

Fluid migration pathways on the Otago margin are poorly understood, but the carbonate chimneys between the Papanui and Saunders canyons provide conclusive evidence of Late Quaternary fluid flow in the system (Orpin 1997). At active marine settings elsewhere along the eastern margin of New Zealand, migration pathways can be linked to large-scale contractional faulting associated with a basal décollement (e.g. Barnes et al. 2010), consistent with occurrences elsewhere in the world (Moore & Vrolijk 1992). Even though the Otago Margin is classified as passive, the coast-parallel NE-trending thrust faults in the region (Beanland & Berryman 1989; Norris et al. 1990; Jackson et al. 1996) might be expected to provide similar migration pathways for deep fluids. Offshore, such features have been proposed farther south in the Waipounamu Fault System (Johnstone 1990). However, no large-scale imbricate thrust systems originating from a deep master fault have been confirmed along the shallow shelf east or north of the Otago Peninsula (Orpin 1992; Gray 1993; Osterberg 2006).

An examination of the shelf bathymetry (Carter 1986a) suggests that the peninsula impacts the shelf gradient out to around the 60 m isobath, inferring that post-glacial coastal flows might have been steered eastwards since the Early Holocene and during at least the highstand phases of marine isotope stages 5 (70–130 ka) and 7 (190–240 ka) (e.g. Martinson et al. 1987). Seismic evidence also supports the occurrence of enhanced longshore currents during lowstand periods on the shelf. The lowered bench feature on the uppermost slope between Papanui and Saunders canyons shows stacked, draped internal reflections that lap down onto the upper slope (Fig. 8). This regular unbroken pattern is indicative of depositional processes. Truncated or disrupted reflections consistent with a slump are not visible. The bench therefore appears to be a longstanding geomorphic feature that has persisted over several eustatic cycles and been maintained by the hydraulic regime.

**Structural controls on canyon development**

The underlying reason for the concentration of five large canyons adjacent to the Otago Peninsula (Fig. 1) remains an outstanding question. As a first-order geomorphic interpretation, the creation of submarine canyons has traditionally been linked to locations where river mouths likely incise into the shelf break during sea level lowstand (Shepard 1981). The Waitaki Canyon along the south-eastern margin of the South Island is perhaps the most compelling example of this, where the canyon head lies seawards of the modern Waitaki River (0.34 Mt a⁻¹, Hicks & Shankar 2003; Fig. 1).

Underlying coast-perpendicular crustal faulting such as the Waihemo Fault or basement structures such as the Hyde-Macraes Shear Zone or the basement arch (Mortimer et al. 2002; Mortimer 2003) may have focused channel incision across the shelf and led to canyon development, most likely at the location of the Karitane Canyon which lies directly offshore from the Waihemo Fault System. However, there are several other factors to consider with respect to the positions of the Otago canyons.

1. During highstands, longshore currents would be constrained on the shelf by the promontory of the peninsula, accelerating flows and potentially deflecting water masses, and transported sediment offshore (e.g. Herzer 1979) without the need to correlate to existing coast-perpendicular river drainage systems.
2. The isostatic and thermal effects of the adjacent Dunedin Volcanic Complex on the shelf-canyon sequence architecture are poorly known.
3. The relative balance of lowstand-driven geomorphology on highstand bathymetric features is poorly understood. For example, what is the role of geomorphic inheritance at terrestrial–marine transitions, such as the mid and outer shelf?
4. Finally, fluid flow (with or without structural controls) at the shelf edge could facilitate headwards incision and canyon development at zones of elevated fluid pressure, perhaps as a result of slumping or the development of more easily eroded surface material (Orpin 1997).

However, as stated earlier, there is no direct evidence for these processes in the data collected.

Further to point (4) above, a strong correlation appears to exist between the location of the chimneys on a bench at the edge of the continental shelf and the heads of nearby submarine canyons. The association of canyon heads, rapid
changes in slope and chimney fields has been described in detail for the Cascadia convergent margin off the west coast of North America (e.g. Moore et al. 1990; Orange & Breen 1992; Orange et al. 1997). This suggests that fluid-induced slope failure – possibly related to coast-parallel faulting – could also influence the formation and ongoing maintenance of the Otago canyon system.

**Future work**

Sea conditions and the shallow water of the shelf create seismic imaging challenges (e.g. reduced signal penetration due to multiple and soft sediments, access limitations due to ship operations in shallow water or areas of commercial fishing and inability to collect data near surf or low-tide zones). Smaller vessels such as the one used to collect the data presented in this paper provide a suitable platform for working in this environment. However, all of the topics discussed in this paper could benefit from increased data coverage both laterally (i.e. more seismic lines) and in-depth penetration. Real-time acquisition of digital seismic data at sea combined with location (e.g. Global Positioning System) information is greatly improving our capabilities to collect more detailed lateral datasets. For example, the collection and analysis of new digital datasets covering the fault systems off Shag Point (Allan 1990) and along the south Otago coastline (Johnstone 1990) in detail – at a resolution suitable for palaeoseismic and earthquake hazard analysis – is currently underway.

In the future, higher-energy sources and multi-channel systems (e.g. Missiaen et al. 2002; Bell et al. 2008) will enable the reduction of contaminating multiple energy in seismic sections and thereby greatly improve both resolution and depth penetration. Such techniques are critical to improving our understanding of shallow Quaternary processes along the Otago margin and for characterising local seismic hazard.

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