A seismic stratigraphic model for understanding
the sedimentary and tectonic evolution of
Solander Trough, offshore Fiordland, New
Zealand

By

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Abstract

Solander Trough is located offshore and south of Fiordland, New Zealand, adjacent to the geologically young Pacific-Australian plate boundary. Petroleum industry exploration was restricted to the near-shore. This thesis presents the first stratigraphic analysis of Solander Trough south of $\sim 46.5^{\circ}\text{S}$, using 2D seismic reflection data acquired and processed onboard the R/V Marcus G. Langseth in 2018 (voyage MGL1803). The only pre-existing high-quality line, which was acquired onboard the R/V Maurice Ewing during voyage EW9601a in 1996, was reprocessed.

The study area is divided into northern and southern sub-basins by Tauru High. Four megasequences and eight sequences are identified in the northern sub-basin (SLN). In the southern sub-basin (SLS), three megasequences and seven sequences are mapped. Biostratigraphy from the Parara-1 exploration well enabled age determination in the northern sub-basin. High resolution (~ 10 m) swath bathymetry data collected along seismic reflection lines provide insight into modern sedimentary processes.

Solander Trough formed in the Eocene, but most sediment is young ($< \sim 15$ Ma). Puysegur Ridge formed in the Miocene during subduction initiation and now shelters Solander Trough from the Antarctic Circumpolar Current, which affects depositional architecture. The oldest megasequences, SLN1 and SLS1, relate to normal-faulted basement with irregular relief. An increase in sediment supply from the north created megasequence SLN2, but it is thin and not recognised in the southern sub-basin. Megasequence SLN3 signals reverse reactivation on the Parara Anticline and Tauru High; its equivalent (SLS2) marks the first sediments rapidly deposited in southern Solander Trough, and is also linked in the south to initial growth of Puysegur Ridge. SLN4 is a product of Pliocene-Quaternary reverse reactivation of Solander Anticline, and its correlative, SLS3 in the southern sub-basin, is related to folding and widening

of the eastern margin of Puysegur Ridge.

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Chapter 1

Introduction

1.1 Motivation

New Zealand is located on the boundary between the Pacific and Australian plates, where changing plate boundary dynamics have affected the distribution, sedimentation and tectonic histories of New Zealand's onshore and offshore sedimentary basins. Basin stratigraphy provides a wealth of information about the overarching plate dynamics, with implications for natural resource distribution.

Sedimentary patterns reflect the interplay of plate dynamics with local deposition effects such as current flow, sediment supply and accommodation space. Solander Trough is strategically located toward the southern end of the plate boundary through New Zealand (Sutherland, 1995), and at the northern edge of the Antarctic Circumpolar Current (ACC), the largest ocean current on Earth (Barker et al., 2007).

This thesis presents the first stratigraphic analysis of Solander Trough, offshore southwest Fiordland, New Zealand (Fig. 1.1). This is achieved using newly acquired 2D seismic reflection data onboard the R/V Marcus G. Langseth (voyage MGL1803), in accompaniment with previously acquired petroleum industry data.

Fig. 1.1: (Caption on next page)

*Fig. 1.1: Location of New Zealand (Panel A), outlining the study area (Panel B). Panel B shows the location of 2D seismic reflection data in the area. Dark-grey lines show the seismic data used in this paper, with MGL1803, Line P1 from EW9601a and S86-34 lines labelled; light grey lines show locations of pre-existing seismic data. Black circles show offshore petroleum wells (see Chapter 2). F=Fiordland, BB=Balleny Basin, SB=Solander Basin, SI=Solander Island, ST=Solander Trough, SZ=Snares Zone, PTr=Puysegur Trench and PR=Puysegur Ridge. Faults are outlined in red, where (*italicised*): PaF=Parara Fault, SF=Solander Fault, MFZ=Moonlight Fault Zone, WB=Western Boundary Fault, EB=Eastern Boundary Fault, TF=Tauru Fault and PFs=Puysegur Fault splays, where thrust direction is showed by the red teeth. The dashed arrow shows the location of Solander Channel. Bold lines are 1000 m bathymetric contours (1000–6000 m contours labelled); thin lines are 500 m intervals*

1.2 SISIE Objectives

SISIE (South Island Subduction Initiation Experiment) is a multi-national collaboration aimed at constraining the geophysical nature and reconstructing the geological history of the Pacific-Australian subduction thrust (Gurnis and Stock, 2017). This was an active source experiment involving acquisition of 2D seismic reflection and seismic refraction data during voyage MGL1803 from 19th February 2018 to 19th March 2018. The main research axis involves determining whether the Puysegur-Fiordland subduction (an example of incipient subduction zone initiation) is transitioning from a forced to a self-sustaining state (e.g. Stern, 2004). The study area is one of the few locations in the world where subduction is young and associated sedimentary and tectonic patterns are not overprinted by later stage activity, as is the case with older examples like the Izu-Bonin-Mariana and Tonga-Kermadec subduction zones (Stern, 2004). I participated in voyage MGL1803, and my contribution to the broader project is to analyse the stratigraphy of Solander Trough.

1.3 Geologic and Geographic Setting

1.3.1 Geologic setting

New Zealand was once part of the supercontinent Gondwana. At around 100 Ma, the continent of Zealandia started to rift from Gondwana (King, 2000). Separation from Gondwana was manifested as Tasman seafloor spreading, which lasted from ~ 85 –52 Ma (Laird and Bradshaw, 2004; Gaina et al., 1998). Post-rift, New Zealand’s basins were subject to marine transgression as a result of post-rift thermal subsidence (e.g. McKenzie, 1978). To the southeast in Emerald Basin, an emergent plate boundary began to develop as a spreading centre at around 45 Ma (Sutherland, 1995; Wood et al., 1996; Sutherland et al., 2000), probably initially as a pre-existing fracture zone (Collot et al., 1995; Barker et al., 2008).

Ongoing subsidence occurred through the Oligocene, when maximum transgression was reached in New Zealand (King, 2000). In the Oligocene, global cooling led to the establishment of permanent Antarctic Ice Sheets and development of the ACC (Carter et al., 1996b). Subduction northeast of New Zealand began in the late Oligocene (Ballance, 1976). By the early Miocene, this northeastern subduction zone had linked to the south-eastern spreading centre, where the Alpine Fault became the dominant accommodating fault for plate boundary movement (Sutherland et al., 2000). Plate motions became more convergent during the Neogene (Walcott, 1978), due to Australian-Pacific plate pole migration Sutherland (1995); Cande and Stock (2004). Changing plate motions facilitated development of an incipient subduction zone during the Miocene (Collot et al., 1995; Gurnis et al., 2004; Sutherland et al., 2006), which saw rapid uplift of the New Zealand continent and a corresponding increase in clastic sediment supply (e.g. Turnbull et al., 1993; Sutherland, 1996).

Today, New Zealand is located on the boundary between the Pacific and Australian plates (Panel A, Fig. 1.1). The Pacific plate overrides the Australian plate south of New Zealand at the Puysegur Trench, and the opposite occurs north of New Zealand at the Hikurangi Margin. In between these subduction zones, plate boundary motion is accommodated by the oblique dextral-reverse slip Alpine Fault.

1.3.2 Geographic setting

Solander Trough is a bathymetric low and sedimentary depocentre, south of Fiordland, south-west New Zealand. It is bound to the west by the Puysegur Ridge and to the east by the Campbell Plateau. Solander Trough gently slopes to the south and merges with the relatively flat floor of Emerald Basin (Carter and McCave, 1997), beyond the extent of the study area.

The main sedimentary basins in the offshore region are the Solander and Balleny Basins (Fig. 1.1). Solander Basin is bound to the west and east by the Western Boundary (WB) fault and Eastern Boundary (EB) fault, and is bifurcated into the upper and lower Solander sub-basins to the south by Tauru High at the Tauru Fault (TF, see Fig. 1.1 for locations and Sutherland and Melhuish, 2000, for fault nomenclature). Balleny Basin is located to the west of Solander Basin between the Puysegur Thrust and Moonlight Fault Zone, and has onshore outcrops limited to the southern edge of Fiordland. The Waitutu, Hautere and Parara sub-basins are smaller depocentres constrained by the Moonlight Fault Zone, Solander High and Parara Fault (Turnbull et al., 1993, Fig. 1.2).

Onshore sediments are deposited in the Te Anau and Waiau Basins, both comprising mostly Eocene-Recent strata with Cretaceous coal measures in the Waiau Basin (Uruski and Turnbull, 1990). Te Anau Basin is constrained to the north by the Hollyford Fault System, and to the west and south by the Moonlight Fault Zone. The Waiau Basin is similarly constrained by the Moonlight Fault Zone to the west, and in the north, a splay off the Hauroko Fault separates the Monowai and Blackmount sub-basins. It is bound to the east by the Longwood Range (Turnbull et al., 1993, Fig. 1.2).

Along the axis of Solander Trough is Solander Channel (Fig. 1.1). It extends from the Stewart Island continental shelf to beyond the study area, where it merges into the relatively flat floor of the Emerald Basin. Bathymetry data acquired during MGL1803 reveals the channel incises up to 220 m.

Fig. 1.2: Onshore and offshore locations of sedimentary basins and faults (adapted from Turnbull et al., 1993). Faults are shown in black (faults mentioned in text are italicised), and petroleum wells are shown by orange crosses. MFS=Moonlight Fault System, MTZ=Moonlight Tectonic Zone, HFS=Hollyford Fault System, HF=Hauroko Fault, HR=Hump Ridge, BSB=Blackmount sub-basin, MSB=Monowai sub-basin TM=Takitimu Mountains, LR=Longwood Range, WSB=Waitutu sub-basin, HSB=Hautere sub-basin, PaF=Parara Fault, SH=Solander High and PSB=Parara sub-basin. The red box shows Solander Islands (Fig. 1.3)

The only subduction related volcanism on the Puysegur Margin is represented by Solander Island and Little Solander Island (Fig. 1.3, Panel A). Located 40 km south of the Fiordland coast and 60 km WNW of Stewart Island, they are extinct adakitic (Reay and Parkinson, 1997) volcanic remnants of a larger edifice (Mortimer et al., 2013). Solander Island is important for understanding the relationship between incipient subduction and arc volcanism (Mortimer et al., 2013). Radiometric dating from Mortimer et al. (2013) determined the age of volcanism at Solander Island to be 350–100 ka, and at Little Solander Island to be 50–20 ka.

Further to the south lies the Macquarie Ridge Complex, which extends from western offshore Fiordland to just south of 60°S (Frohlich et al., 1997; Conway et al., 2012, Fig. 1.3, Panel B). It is a 1400 km long (Carter and McCave, 1997) arc shaped system of ridges and troughs that has a major influence on Southern Ocean circulation and deposition patterns (Schuur et al., 1998). The northernmost section of Macquarie Ridge, between 51°S and 47°S, is Puysegur Ridge (Fig. 1.3). This structure is 3–5 km high, and is flanked to the west by the Puysegur Trench, and to the east by Solander Trough. Collot et al. (1995) divide Puysegur Ridge into a deeper, more complex, asymmetrical northern segment and a shallower more linear southern segment, which widens to the south. The contrast in depths is related to differential uplift and subsidence along an incipient plate boundary (Collot et al., 1995; Lebrun et al., 1998; Mao et al., 2017). Subsidence along Puysegur Ridge is manifested in the Snares Zone, a complex deformation zone from 47°S to 48°S (Delteil et al., 1996, Fig. 1.3, Panel C).

Beyond 50°S, Deep Sea Drilling Project (DSDP) holes 277, 278 and 279 were drilled in 1973 on the Campbell Plateau, in the south Emerald Basin and southern Puysegur Ridge, respectively (Fig. 1.3, Panel D). Site 277 drilled to mid Paleocene, Site 278 to mid Oligocene, and Site 279 drilled to early Miocene (Kennett et al., 1975a,b,c). There are no seismic ties to any of these sites.

Fig. 1.3: Location of Solander Islands (Panel A, see red square in Fig. 1.2, and Mortimer et al., 2013), Macquarie Ridge Complex (Panel B1) and Puysegur Ridge (Panel B2), Snares Zone (Panel C, see Lamarche et al., 1997, for sector division), and DSDP sites 277-279 (Panel D, with MGL1803 lines M18-23ab and M18-14 for context). Panel C: STr=Snares Trough; other abbreviations as per Fig. 1.1. 1000 m bathymetric contours are labelled; thin lines are 500 m intervals

1.4 Oceanographic Setting

New Zealand's modern oceanographic setting is shown in Fig. 1.4. Southern Ocean waters in the study area include sub-tropical waters (STW), and sub-antarctic waters (SAW). These waters affect the productivity and pelagic sedimentation of the study area, and currents are a major control on sedimentary deposition patterns in Solander Trough. The sub-antarctic front (SAF) represents the northern front of the ACC, and it is deflected by Macquarie Ridge and the Campbell Plateau (Schuur et al., 1998; Carter and McCave, 1997).

Fig. 1.4: Modern circulation patterns around New Zealand (modified from: Carter et al., 1998). TF=Tasman Front; EAUC=East Auckland Current; WAUC=West Auckland Current, ECC=East Cape Current; DC=Durville Current, WC=West coast current, STF=sub-tropical front, ACC=Antarctic Circumpolar Current, SAF=sub-antarctic front. Warm currents are shown in purple, cool currents are shown in blue. Current strength is indicated by arrow size. The extent of Fig. 1.1 is shown by the black box

Elevated chlorophyll-a (enabling photosynthesis in phytoplankton) concentrations exist along the sub-tropical front (STF), which occurs due to mixing of warm, saline, macronutrient-deficient and micronutrient-rich STW, with cool, less saline, macronutrient-rich yet micronutrient-poor sub-antarctic water (SAW; Deacon, 1982; Smith et al., 2013). This combination of waters leads to high Southern Ocean biologic productivity. Tasman Sea to the west (Fig. 1.4) is also highly productive (Jitts, 1965; Hassler et al., 2014), though sedimentation patterns differ either side of the plate boundary due to current flow (see Chapter 6).

1.5 Petroleum Exploration

Discoveries of economically viable oil and gas fields in the Taranaki region, such as the Maui gas field in 1969, led to exploration of New Zealand's frontier basins, including Solander Basin. Several hundreds of thousands of kilometres of 2D seismic reflection data are publicly available under New Zealand's open-file system. In the offshore Fiordland area, two petroleum wells were drilled (Parara-1 in 1974/1975 and Solander-1 in 1985, see Chapter 2 for further discussion). This section summarises previously acquired seismic reflection data in the study area. In the appendices, Tables 1A-1 and 1A-2 summarise acquisition parameters for these data.

1.5.1 Vintage seismic data: 1960s–1970s

"Vintage" seismic data were shot in five separate surveys from 1969 to 1973.

Hunt PR556

The Hunt PR556 survey was shot in 1969 by Hunt International Petroleum Company, and provided the first insight into offshore stratigraphy of the region. Documentation of this survey is poor: any information presented is sourced from Petroleum Report 556 and associated enclosures (Hunt International Petroleum Company, 1970).

NZPET70

The NZPET70 survey was acquired in 1970 by New Zealand Petroleum Co. Ltd in Te Wae

Wae Bay (Fig. 1.2). Further information can be found in Petroleum Report 538 (New Zealand Petroleum Exploration Co. Ltd., 1970).

Mobil72

The Mobil72 seismic survey covered western and eastern offshore North Island, offshore eastern South Island, Great South Basin and Solander region. Like the Hunt PR556 survey, acquisition data are sparse and have been sourced from Petroleum Report 738 (Mobil International Oil Company, 1979).

Hunt A, B and D

These Hunt data were part of a survey covering the Solander and Great South Basins. Data were acquired by Western Geophysical Company of America: Hunt A was acquired from 1970–1971 (Hunt International Petroleum Company, 1971; Seahawk Oil International Inc., 1982), Hunt B in 1972 (Hunt International Petroleum Company, 1974) and Hunt D from 1972 - 1973 (Hunt International Petroleum Company, 1974; Seahawk Oil International Inc., 1982).

1.5.2 Post-vintage data: 1980s–2000s

These data were shot in five further surveys from 1982 to 2006.

S82

The S82 survey was shot from 10th–30th December 1982 by The Geophysical Company of Norway for Seahawk Oil Australia Ltd in PPL38206. Weather conditions were poor and lapses in rough conditions were not long enough to allow the sea state to calm to an acceptable level. Thus, the S82 survey remained incomplete. Further information regarding the acquisition of S82 can be found in Petroleum Report 912 (Geophysical Company of Norway, 1982).

S84

The S84 survey was shot from 23rd February – 5th March 1984 by Western Geophysical Company of America for Seahawk Oil Australia Ltd in PPL38206. Further information regarding

the acquisition of S84 can be found in Petroleum Report 1027 (Geophysical Service International, 1984).

Solander-85

The Solander-85 survey was shot in 1984 by BP Oil Exploration Co. NZ Ltd. in PPL38206. Dropcore samples were also taken. The main goal was to determine suitable structures for drilling petroleum exploration well Solander-1. Full information regarding the Solander-85 survey can be found in Petroleum Report 1121 (BP Oil Exploration Co NZ Ltd, 1985).

S86

The S86 survey was shot from 6th–15th February 1986 by BP Oil Exploration Company of New Zealand Ltd. in PPL38206. Further information regarding the acquisition of S86 can be found in Petroleum Report 1165 (Clark, 1986). Line S86-34 provides a seismic tie from the Parara-1 petroleum exploration well to newly acquired seismic data during MGL1803 (Fig. 1.1).

LM06

The LM06 survey was shot from 7th–23rd May 2006 by L&M Petroleum in PEP38228. Further information regarding the acquisition of LM06 can be found in Petroleum Report 3397 (L&M Petroleum, 2006).

1.5.3 Petroleum exploration data summary

All open-access seismic reflection data are located in Fig. 1.5, which shows that there is extensive petroleum industry coverage of shallow water offshore Fiordland, but little coverage south of $\sim 46.5^{\circ}\text{S}$. Most of the regional seismic data within this area was acquired before 1975 and is of low quality. Survey MGL1803 provides the first robust basis for regional stratigraphic correlations and mapping in this previously unexplored area.

Fig. 1.5: Location of petroleum industry seismic data available from the NZPEM database. MGL1803 seismic lines are shown in dark grey. The black line indicates line S86-34, which intersects the Parara-1 well (labelled), and forms a cornerstone for correlating well strata to newly acquired seismic data to the south

1.5.4 Data quality control

Data polarity

The polarity of the S86 survey differed to that of the seismic data acquired during MGL1803 (and the reprocessed EW9601 data). As line S86-34 was pivotal to tying sequences to Parara-1, a 180° phase rotation was applied to this line. S86-34 was then saved as a new line. This phase shifted line was interpreted alongside the MGL1803 data.

Misties analysis

A mistie in seismic data is defined as a misplacement of horizons where two lines intersect. It is caused by improper static corrections or migration of either or both lines (Herron and Latimer, 2011). Migration differences occur between surveys, especially if acquisition parameters are varied within a survey. Removing misties allow for alignment of reflections between datasets. Within SeisWareTM, a -37 ms bulk shift was applied to line S86-34 to align the seafloor and other reflections at depth with line M18-17c.

1.6 Methods

This section summarises seismic acquisition, seismic processing and principles of sequence stratigraphy that were used in this thesis.

1.6.1 Seismic reflection: data acquisition

Seismic reflection surveying is a commonly used geophysical technique for imaging the sub-surface. It involves a seismic energy source and (typically) multiple receivers (hydrophones), which detect energy after it reflects off sub-surface layers (Kearey et al., 2002). Marine seismic reflection data acquisition involves towing the seismic source and a streamer comprising hydrophones behind a vessel. It is less labourious to acquire marine seismic reflection data than terrestrial data, though issues from swell and marine mammal observations can impede

acquisition.

Seismic reflection imaging works on the premise that rocks have different elastic properties (Goranson, 2002) and hence acoustic impedances (Z), which is an inherent property of a given rock dependent on the product of its density (ρ) and p-wave velocity (v) (Eqn. 1.1).

$$Z = \rho \times v \quad (1.1)$$

The greater the impedance contrast between different rock layers, the greater the amplitude of energy reflected from the layer boundary (Kearey et al., 2002). For a wave at a given angle of incidence (θ_1), energy is reflected from the interface at θ_1 and transmitted at a given angle of refraction (θ_2), according to Snell's Law (Eqn. 1.2). Zoeppritz equations can be used to determine the amplitude of reflected and refracted waves at a layer interface (Sheriff and Geldart, 1995). At normal incidence, these equations simplify to Eqn. 1.3.

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2} \quad (1.2)$$

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (1.3)$$

In Eqn. 1.3, the ratio of impedance contrasts (Z , see Eqn. 1.1) gives rise to the reflection co-efficient (R), which ranges from -1 to 1. When R is close to 0, most energy is transmitted across an interface; when closer to -1 or +1, more energy is reflected from the interface. The sign of R dictates a reflection's polarity in a seismic section, where negative values produce a reverse polarity reflection and vice-versa (Kearey et al., 2002). Reflections from rock interfaces then recorded as traces or "wiggles" by hydrophones on the streamer. The magnitude of pressure changes depends on the amount of energy received. Reflections can be primary (reflected off a single rock interface) or secondary if reflected off more than one interface e.g. "multiples" are reflected off the sea surface and seabed, and may also have reflected off a rock interface (AKA peg-leg multiples). Secondary reflections may obscure primary reflections in a seismic section,

and, during processing, are removed as best as possible.

Multiple hydrophones are often used within a streamer. This allows for data stacking, which improves image data quality by increasing signal:noise. The common mid-point (CMP) stacking method is based on sorting source-receiver pairs from different shots to image a common depth point (CDP, Fig. 1.6).

Fig. 1.6: Common mid-point (CMP) method, where, in the case of a horizontal reflector (Panel A), source (S) and receiver (R) pairs sample the same common depth point (CDP). For dipping interfaces (Panel B), the CMP method starts to break down. Adapted from Kearey et al. (2002)

Dipping reflectors are common so this needs to be accounted for in processing by applying pre-stack time migration methods. The number of raypaths that sample the same CDP is known as the fold (Eqn. 1.4, Kearey et al., 2002).

$$Fold = \frac{Receiverspacing \times \#receivers}{2 \times shotspacing} \quad (1.4)$$

During MGL1803, the nominal fold of the data was 126 for lines shot with the 12.6 km streamer, and 40 for lines acquired with the 4 km streamer (see Table 4.1).

1.6.2 Seismic reflection: data processing

1. Reformatting, resampling and geometry

Demultiplex format segd data are first converted to segy data with header information. They are then resampled from their original sample rate (frequency of data recording in time) to a lower sample rate. The resampling process optimises storage space for recording traces, and also removes some high frequency noise from the raw data. The maximum resolvable frequency (Nyquist frequency, f_N) is half the reciprocal of sample rate (δt , Eqn. 1.5).

$$f_N = \frac{1}{2 \times \delta t} \quad (1.5)$$

For seismic data acquired at 2 ms sample rate, resampling to 4 ms means $f_N = 125$ Hz, which is greater than the maximum frequency expected from reflected rays (~ 100 Hz; Onajite, 2013). Resampling also reduces processing time. Data acquired during MGL1803 were resampled from 2 ms to 4 ms (Chapter 4).

Acquisition geometry, with GPS recorded by ship and tail buoy (Fig. 4.2, Panel F) and depth and headings indicated by streamer birds (Fig. 4.2, Panel D) is necessary for spatially defining the data in terms of shot-receiver configuration for each trace, which is important for shot gathers and later processing stages such as CMP sorting.

2. Trace editing, filtering and amplitude recovery

Alongside multiple energy (see subsection 1.6.1), other unwanted energy, such as direct arrivals through water, refractions through sediment and low/high frequency noise may exist in the dataset. Noisy traces may be present, due to poor depth control, excessive swell noise, faulty equipment, etc. In Fig. 1.7, examples of unwanted energy are highlighted. Direct and refracted arrivals can be removed by muting. Some noise can be removed by frequency filtering. Noisy traces can be removed by trace editing.

Fig. 1.7: Shot 8000 from line M18-01, where the pre-processed data contain a variety of extraneous energy (labelled). The dashed yellow line shows an example of a mute that may be picked to remove unwanted energy

The amplitude of reflection events from depth are low due to energy decrease associated with spherical divergence of energy from the seismic source, and from attenuation within strata. To account for this, an amplitude gain scalar that is a function of travel time is applied (Yilmaz, 2001; Kearey et al., 2002).

3. Deconvolution and CMP sorting

A widely used method of multiple removal is predictive or gap deconvolution. This involves attempting to replicate the source wavelet to identify repetitions in the dataset (e.g. Fig. 1.7). It involves a "gap" to exclude high amplitude events, an operator length over which the trace is correlated with itself and a design/application window. Predictive deconvolution is also beneficial for improving vertical resolution (Yilmaz, 2001; Kearey et al., 2002).

As per Fig. 1.6, data can now be sorted to their assumed CDP according to the CMP method, so data may be stacked later. Sorting enables generation of a brute stack, which is a stacked section created with a crude velocity model, which allows for a preliminary view of the data (see Fig. 4.4).

4. Velocity analysis

A refined velocity model for the data is created by fitting hyperbolae to reflection events. Once picked, it means data can be stacked, which greatly increases signal:noise. Velocities that "flatten" reflection hyperbolae are known as stacking velocities, which tend to increase with depth, due to increased sediment compaction (Kearey et al., 2002). Velocity inversions do occur in nature, but may also relate to multiple energy that remains in the dataset. For onboard processing of Line P1 and MGL1803 data (Chapter 3 and Chapter 4 respectively), stacking velocity picks were made based on semblance, which is a measure of coherence within a CDP gather (Yilmaz, 2001, see Fig. 1.8). Achieving this corrects for the hyperbolic raypath of reflections, and means normal moveout (NMO) has been removed (Kearey et al., 2002). Multiple events remain hyperbolic and so, at greater offsets, will destructively stack (Fig. 1.8, Panels A & D). An inside mute at small offsets (small NMO) can aid multiple removal. Shallow reflections are corrected more (greater NMO correction) than deeper reflections (Yilmaz, 2001), resulting in an apparent change in frequency and "smearing", especially at far offsets. To prevent detrimental effects of this during stacking, an NMO stretch mute is picked.

5. Radon demultiple

Despite muting and stacking, there may still be residual multiple energy in the dataset. During MGL1803, a radon demultiple process was employed to help remove this energy. This works on the basis that primary reflections and multiple events will plot separately in terms of hyperbolic moveout when transformed into the τ -p domain using a forward transform (Yilmaz, 2001; Foster and Mosher, 1992). From this separation, multiples can be discriminated from primary events, and an inverse transformation of the multiples and subtraction from the dataset can be performed.

6. Migration

In Fig. 1.6, travel times to source-receiver combinations that are evenly spaced will differ due to the dipping reflector. Migration is the process of correctly repositioning this energy in space such that it represents a true vertical travel time to an interface (Kearey et al., 2002). Onboard MGL1803, FK migration was employed. This involves transformation of data into the

frequency-wavenumber domain, which is possible assuming a constant medium velocity. The reader is directed to Stolt (1978), Sheriff and Geldart (1995) and Yilmaz (2001) for comprehensive coverage of FK migration.

Fig. 1.8: Velocity model picking using semblance in Echos. Panel A shows a supergather of 8 CDPs and the corresponding semblance display; CDP location is shown in Fig. 4.8. Panels B and C illustrate cases where seafloor stacking velocity estimates have been overestimated (1644 m/s) and underestimated (1374 m/s) respectively. In these examples, stacking will lead to poor signal:noise. Panel D shows a suitable set of stacking velocity picks. Multiple reflection in Panels A and D (red arrow) remain hyperbolic, while primary events are flattened. Modified from Echos Velocity Analysis Tool

1.6.3 Principles of seismic stratigraphy

Processing of data acquired during MGL1803 enables seismic mapping. An objective was to map sequence and megasequence boundaries across the study area. The scientific goals were: correlation of stratigraphy from north to south of the study area; and interpretation of the depositional history of Solander Trough. Megasequence boundaries are linked to major tectonic/sediment supply changes, and are mapped as unconformable surfaces marked by stratal termination relationships and changes in stacking patterns, as shown in Fig. 1.9.

Fig. 1.9: Stratigraphic relationships used for seismic mapping. Adapted from Mitchum et al. (1977)

In Fig. 1.9, onlap and offlap are defined as up-dip truncations of strata against a basal and overlying surface respectively. Their presence defines unconformity bound depositional sequences (Christie-Blick, 1991). Downlapping is defined where strata terminate against a basal surface at a steeper dip than the surface. Christie-Blick (1991) states that a sequence may exhibit both onlapping and downlapping basal terminations.

Sequence boundaries were mapped using characteristics such as reflection amplitude, continuity and polarity (Sheriff and Geldart, 1995), in addition to the relationships shown in Fig. 1.9. The principles outlined above enabled correlation of units, in spite of several structural barriers (see Chapter 5 and Chapter 6).

1.7 Thesis Objectives

The main objectives of this thesis are:

1. Re-process Line P1 data acquired during the EW9601a survey (Chapter 3).
2. Process data acquired during voyage MGL1803 (Chapter 4).
3. Integrate well (Chapter 2) and previously acquired seismic data with MGL1803 data in order to build a seismic stratigraphy for the Solander Trough (Chapter 5).
4. Use seismic stratigraphy, well data and swath bathymetry data to develop a depositional model and basin history for Solander Trough (Chapter 6).

Note: For reference, a copy of the New Zealand Geological Time Scale is provided in Appendix 1, Fig. 1A-1.

Chapter 2

Petroleum Industry Well Data

2.1 Introduction

This chapter outlines the petroleum well data from two explorations boreholes in the offshore Fiordland region. Parara-1 was completed in 1976 and Solander-1 was drilled in 1985 (Fig. 2.1). Well biostratigraphy provides the only stratigraphic control. In this thesis, data from Parara-1 are highly important as they can be tied to the MGL1803 survey, they sample a thick Neogene sequence and complexity associated with the Solander Fault is avoided.

2.2 Parara-1: Summary

Complete data for Parara-1 are found in Petroleum Report 673: Well Completion Report (PPL 38206, Hunt International Petroleum Company, 1976). Parara-1 was drilled in 1975-1976 and is located 22 km ESE of Solander Island (Fig. 2.1) in 147.5 m of water. It aimed to test the hydrocarbon potential of the upthrown side of a reverse-fault bound anticline (Parara Anticline) that afforded >2.1 km of vertical closure, by targeting Pleistocene-Oligocene limestone and sandstone reservoirs. Having reached basement rock, no significant hydrocarbon shows were encountered, and the well was plugged and abandoned at 3800.5 m BKB as a dry hole. Paleogene sediments contained carbonaceous material, minor coal and dead oil (Fig. 2.2).

Fig. 2.1: Location of Parara-1 and Solander-1 petroleum wells. Blue lines = Solander Faults; red line = Parara Fault

2.2.1 Parara-1 stratigraphy

The Pleistocene to mid Miocene stratigraphy of Parara-1 comprises predominantly outer-shelf to bathyal clays and shales, with rare fine sands. From the mid Miocene to Oligocene, strata are fine-grained shelfal deposits with calcareous material present. All older strata are terrestrial in origin, mostly comprising sands and coal measures, with the well terminating in metamorphic basement. Table 2.1 summarises the chronostratigraphy of Parara-1.

Chronostratigraphic interval	Depth range (m BKB)	Thickness (m)
Pleistocene/Wanganui	493.7 - 835	341.3
Pliocene/Wanganui	835 - 1557.5	722.5
Miocene/Taranaki	1557.5 - 1841	283.5
Miocene/Southland	1841 - 2659.6	787.6
Miocene/Pareora	2659.6 - 2834.6	206
Oligocene/Landon	2834.6 - 2993.7	159.1
Eocene/Arnold	2993.7 - 3179	185.3
Eocene/Dannevirke	3179 - 3358.8	179.8
Paleocene?/l. Dannevirke to Maastrichtian?/Mata	3358.8 - 3779.4	420.6
Paleozoic	3779.4 - 3800.5	21.1

Table 2.1: Parara-1 chronostratigraphic divisions. *m BKB* = metres below kelly bushing

Unit 1: Quaternary – Pleistocene (493.7–835 m BKB)

Highly fossiliferous deepwater clays and siltstones with little induration were common. Carbonaceous material was present near the base, with methane gas observed in the mudstream.

Unit 2: Pliocene – Wanganui (Wm, Wp, Wo, 835–1557.5 m BKB)

The entire Pliocene section comprises mid-deep shelf deposits of highly fossiliferous clays and siltstones with little induration. The lower half of this unit contains rare loosely cemented fine sand lenses. Carbonaceous material was determined to be the source of minor methane readings.

Unit 3: Late Miocene (Taranaki, Tk – Tt, 1557.5–1841 m BKB)

This unit comprises deep shelf clays and siltstones with rare sand lenses, where soft shales indicate more induration. Carbonaceous materials were the assumed source of methane in the mud stream. The Tongaporutuan is thinner than expected, where the Kapitean is well defined, potentially due to a period of erosion or non-deposition. Increased glauconite indicates “...a break in the sedimentary sequence.” (Hunt International Petroleum Company, 1976, pg. 18). An unconformity identified on seismic line S86-34 at the top late Miocene which is “...reasonably be assumed to be early Kapitean to Tongaporutuan in age.” (Hunt International Petroleum Company, 1976, pg. 18).

Unit 4: Mid Miocene (Southland, Sw, Sl, Sc, 1841–2659.6 m BKB)

Outer shelf to bathyal clays and siltstones grade downhole to mid-outer shelf shales, indurated

clays, well cemented fine sandstones and rare microcrystalline limestones. Traces of lignite and coal are present in very thin lenses.

Unit 5: Early Miocene (Pareora, Pl, Po, 2659.6–2834.6 m BKB)

This unit comprises mid–outer shelf deposits of soft–medium firm shales with rare sandstone and limestone lenses and continuous scattered carbonaceous material. Methane gas was present.

Unit 6: Oligocene (Landon, Lw, Ld, Lwh, 2834.6–2993.7 m BKB)

Very shallow water deposits grade to deep water outer shelf deposits, comprising soft shales and clays with increased sand inclusions at depth. Limestones grade to marls, with minor coal inclusions. A hiatus at this time may mark Solander Basin flooding, as all older rocks are terrestrial. Glauconite and pyrite increase, and clays become more kaolinitic toward the base of this unit. Basal sandstone has a kaolinitic and limey matrix with thin coal inclusions. Gas readings were slight to nil. Logs indicate these sands are water bearing.

Unit 7: Eocene (Arnold, Ar, Ak, Ab, 2993.7–3179 m BKB)

This unit contains sandstones with kaolinite and rare marl, where the basal 30 m is nearly entirely coal measures. Materials ranged from soft brown peat to black brittle coal interbedded in sands and shales. No gas was recorded, with slight gas odours from sidewall cores. Sandstone porosities were 15–25%, but electric logs indicated they were water bearing.

Unit 8: Eocene (Dannevirke, unknown stages, 3179–3358.8 m BKB)

The upper 31 m of continuous sandstones contained a few dense microcrystalline limestone inclusions. Sands are very kaolinitic with occasional shale inclusions and abundant carbonaceous zones but become coarser with depth. Secondary mica traces increase with depth. The entire interval has sporadic zones of carbonaceous materials and adjacent stained sand with dull orange fluorescence. No gas was recorded, though sidewall cores have good gas odour, with methane - pentane detected. Porosities range from 20% down to 5% at the base of the interval, and electric logs indicate total water saturation.

Unit 9: Paleocene? – Maastrichtian? (l. Dannevirke to Mata, 3358.8–3779.4 m BKB)

Coarse kaolinitic sandstone grades down to a granitic wash set in a kaolinitic matrix. The upper

zone of the granitic wash is coloured with ferrigenous staining which gradually disappears with depth. Metamorphic alterations were noted. Biotite, chlorite and occasional hornblende suggest secondary mineralisation. The entire interval contained inclusions of red and green waxy shales. Sonic log indicated low porosities of $\pm 5\%$, with occasional thin zones of 10–12% porosity. The entire section was water bearing.

Unit 10: Paleozoic (Wet Jacket/Bradshaw formation (3779.4–3800.5 m BKB))

This unit comprised dark green to black gneiss with evidence of weathering. After 6 m of gneiss, a highly weathered, 3 m zone of pink kaolinitic granite wash and gneiss was encountered. The remainder of the rock drilled was dark green gneiss with some signs of weathering.

2.2.2 Parara-1 downhole observations

Fig. 2.2 summarises the wireline log data obtained from Parara-1. In summary, bit size, caliper width, bulk density, borehole sonic, gamma ray, neutron porosity, resistivity and spontaneous potential logs were run. Data were plotted from the .las file for Parara-1, also from NZP&M. A checkshot survey was also conducted. Using the Parara-1 well summary sheet provided by NZP&M, these checkshot data were plotted and one way travel times (OWT) from the seafloor were calculated, using a KB datum elevation of 31 m, water depth of 147.5 m, horizontal shot-well offset of 37.9 m and a shot depth of 10.6 m. Results are shown in Table 2.2.

Fig. 2.2: Digitised wireline log data for Parara-1, sourced from NZP&M. One-way travel times to checkshot data below the seafloor are plotted. Also shown is lithologic data with New Zealand stages and international age constraints provided from fossil records (note that these time scales were accurate at the time of data acquisition). A 3rd order polynomial (Eqn. 2.1) has been fitted to checkshot data, which provides a time to depth relationship for strata in Parara-1 and strata mapped in Solander Trough. Tt* indicates poor representation of the Tongaporutuan

From checkshot data one way travel times from the seafloor, a third order polynomial representing a depth-OWT relationship (Eqn. 2.1) and its derivative representing a velocity function (Eqn. 2.2) was calculated:

Depth (m, BKB)	OWT (s)	Depth (m, bsf)	OWT (s, bsf)	Incidence angle (°)
310	0.180	131.5	0.09	8.1
616	0.324	437.8	0.23	3.8
919	0.479	740.5	0.39	2.5
1219	0.618	1040.7	0.53	1.9
1381	0.685	1202.2	0.59	1.6
1533	0.744	1354.9	0.65	1.5
1678	0.798	1499.4	0.71	1.3
1829	0.855	1650.3	0.76	1.2
1981	0.908	1802.7	0.82	1.1
2134	0.960	1955.1	0.87	1.0
2286	1.009	2107.5	0.92	1.0
2438	1.056	2259.9	0.96	0.9
2591	1.103	2412.3	1.01	0.9
2743	1.149	2564.7	1.06	0.8
3048	1.229	2869.5	1.14	0.7
3200	1.266	3021.9	1.17	0.7
3353	1.300	3174.3	1.21	0.7
3505	1.330	3326.7	1.24	0.6
3658	1.359	3479.1	1.27	0.6
3725	1.371	3546.2	1.28	0.6

Table 2.2: Calculated OWTs below the seafloor from the Parara-1 checkshot survey

$$Depth_{\text{bsf}} = 663.1(t^3) - 193.4(t^2) + 1906.9(t) \quad (2.1)$$

$$\frac{\partial Depth_{\text{bsf}}}{\partial t} = 1989.3(t^2) - 389.8(t) + 1906.9 \quad (2.2)$$

In Eqns. 2.1 and 2.2, t = OWT below seafloor in ms. Eqn. 2.1 can be used to infer depth to interfaces below the seafloor. Eqn. 2.2 allows for interval velocities to be computed; these are shown in Table 2.3. The difference in observed and calculated depths is plotted in Fig. 2.3.

Depth (m bsf)	OWT (s bsf)	Depth (m bsf, calc.)	Δ Depth (m obs. - proj.)	V_{int} (m/s, calc.)
131.5	0.09	166.5	-35.0	1888
437.8	0.23	441.4	-3.6	1925
740.5	0.39	748.9	-8.4	2056
1040.7	0.53	1047.7	-7.0	2255
1202.2	0.59	1202.8	-0.6	2379
1354.9	0.65	1346.8	8.2	2502
1499.4	0.71	1485.2	14.2	2627
1650.3	0.76	1639.0	11.3	2772
1802.7	0.82	1789.8	12.9	2918
1955.1	0.87	1945.5	9.6	3072
2107.5	0.92	2099.8	7.7	3227
2259.9	0.96	2255.2	4.7	3385
2412.3	1.01	2418.2	-5.9	3552
2564.7	1.06	2585.5	-20.8	3724
2869.5	1.14	2895.9	-26.4	4042
3021.9	1.17	3048.4	-26.5	4198
3174.3	1.21	3193.6	-19.3	4346
3326.7	1.24	3326.0	0.7	4480
3479.1	1.27	3457.8	21.3	4614
3546.2	1.28	3513.5	32.6	4670
std. dev. = 17.0 m				

Table 2.3: Calculated interval velocities for the Parara-1 well using Eqn. 2.2

Fig. 2.3: Residual plot of observed less calculated depths from Eqn. 2.1

A standard deviation of 17.0 m and Fig. 2.3 indicate that the depth model created using the checkshot data is sound. This modelled relationship can be used to infer time-depth relationships for strata to the south of Parara-1.

2.3 Solander-1: Summary

Complete information for Solander-1 is found in Petroleum Report 1149: Well Completion Report (PPL 38206, Engmann and Fenton, 1986). Solander-1 was drilled in 1985, 31.5 km NNE of Solander Island and aimed to test for hydrocarbons in a fault bound anticline with a forecasted Eocene reservoir. The well reached a TD of 2017 m BRT in igneous basement after 24 days of drilling. There were no shows and logs showed that sandstones were water bearing. The well was plugged and abandoned as a dry hole.

2.3.1 Solander-1 stratigraphy

Table 2.4 summarises the chronostratigraphy of Solander-1, which is followed by lithologic descriptions. Fig. 2.4 outlines the well lithostratigraphy, chronostratigraphy and wireline logs.

Chronostratigraphy	Thickness (m)	Tops (m BRT)
Pliocene-Miocene		
Kapitean	689	178
Miocene		
Waiauan	172	867
Lillburnian	210	1039
Clifdenian	25	1249
Altonian	82	1274
Otaian	16	1356
Oligocene		
Waitakian?	455	1372
Waitakian-Whaingaroan?	144	1827

Table 2.4: Solander-1 chronostratigraphic divisions. *m BRT* = metres below rotary table

Pliocene – Miocene (178–1372 mBRT)

This sequence consists of mostly calcareous mudstone and siltstone with an unconformity bound sandstone/conglomerate interval from 867–1039 mBRT. Mud and silt sequences above sands provide adequate seal rocks. Log analysis shows that the sands and conglomerates have good porosity and show evidence of permeability.

Oligocene (1372–1971 mBRT)

The upper succession is a thin sandy limestone overlying a thick, pebbly sandstone sequence, the contact of which is probably conformable. Logs and cores indicate this sequence is very poor reservoir with low log porosities and negligible permeability. This sequence was deposited in a restricted shelf marine environment.

The lower succession comprises siltstone overlain by coal measures and basal conglomerate. Geochemical analysis suggests gas and condensate prone coals with some source potential, but the thin 2.75 m interval makes it insignificant. This sequence was deposited in a transitional environment with intermittent marine connection and includes reworked Eocene deposits.

Basement (1971–TD)

The upper part of the sequence consists of granite-granodiorite which shows evidence of weathering. At TD, the basement is dioritic.

2.3.2 Solander-1 downhole observations

Fig. 2.4 summarises the wireline log data obtained from Solander-1. Bit size, caliper width, cable tension, resistivity, sonic and spontaneous potential were plotted from the Solander-1 .las file; gamma ray and bulk density were digitised from well log sheets. Similar to subsection 2.2.2, the Solander-1 well summary sheet compiled by NZP&M enabled checkshot data (relative to the seafloor) to be calculated. A rotary table elevation of 26.8 m, water depth of 79.4 m, horizontal shot-well offset of 60 m and a shot depth of 10.6 m were used. Results are shown in Table 2.5.

Fig. 2.4: Digitised wireline log data for Solander-1, sourced from Petroleum Report log enclosures of Engmann and Fenton (1986) and NZP&M. Travel times to checkshot data below the seafloor are plotted. Also shown is lithologic data with New Zealand stages and international age constraints provided from fossil records (note that these time scales were accurate at the time of data acquisition). A 3rd order polynomial (Eqn. 2.4) has been fitted to checkshot data

Depth (m BRT)	OWT (s)	Depth (m bsf)	OWT (s bsf)	Incidence angle (°)
106.2	0.064	0.0	0.025	38.9
582	0.285	475.8	0.236	6.2
655	0.309	548.8	0.260	5.5
745	0.346	638.8	0.297	4.8
765	0.353	658.8	0.304	4.7
890	0.4	783.8	0.351	4
950	0.42	843.8	0.370	3.7
960	0.423	853.8	0.374	3.7
1016	0.441	909.8	0.391	3.5
1041	0.448	934.8	0.398	3.4
1110	0.471	1003.8	0.421	3.2
1235	0.513	1128.8	0.463	2.9
1359	0.556	1252.8	0.506	2.6
1390	0.565	1283.8	0.515	2.5
1510	0.597	1403.8	0.547	2.3
1625	0.626	1518.8	0.576	2.2
1745	0.652	1638.8	0.602	2
1834	0.672	1727.8	0.622	1.9
1894	0.687	1787.8	0.637	1.8
2017	0.718	1910.8	0.668	1.7

Table 2.5: Calculated OWTs from the Solander-1 checkshot survey

A third order polynomial measuring OWTs from the seafloor is shown in Eqn. 2.3, and its derivative representing an interval velocity function below the seafloor (Eqn. 2.4) was calculated.

$$Depth_{\text{bsf}} = 1610.4(t^3) + 331(t^2) + 1925.7(t) \quad (2.3)$$

$$\frac{\partial Depth_{\text{bsf}}}{\partial t} = 4831.2(t^2) + 662(t) + 1925.7 \quad (2.4)$$

As above, a time to depth conversion comparison, as well as interval velocities, are shown in Table 2.6.

Depth (m bsf)	OWT (s bsf)	Depth (m bsf, calc.)	Δ Depth (m obs. - proj.)	V_{int} (m/s, calc.)
0	0.03	0.0	0.0	1656
475.8	0.24	492.0	-16.2	2462
548.8	0.26	549.4	-0.6	2553
638.8	0.3	641.3	-2.5	2694
658.8	0.3	659.3	-0.5	2721
783.8	0.35	784.4	-0.6	2901
843.8	0.37	839.4	4.4	2976
853.8	0.37	848.8	5.0	2989
909.8	0.39	900.7	9.1	3057
934.8	0.4	921.3	13.5	3084
1003.8	0.42	990.5	13.3	3172
1128.8	0.46	1123.5	5.3	3333
1252.8	0.51	1269.0	-16.2	3497
1283.8	0.52	1300.7	-16.9	3531
1403.8	0.55	1417.3	-13.5	3654
1518.8	0.58	1528.2	-9.4	3765
1638.8	0.6	1632.1	6.7	3864
1727.8	0.62	1714.9	12.9	3941
1787.8	0.64	1778.8	9.0	3998
1910.8	0.67	1915.8	-5.0	4117
std. dev. = 9.8 m				

Table 2.6: Calculated interval velocities for the Solander-1 well using Eqn. 2.4

The difference in observed and calculated depths is plotted in Fig. 2.5. A standard deviation of 9.8 m and Fig. 2.5 indicate that the depth model created using the checkshot data is sound. However, structural complexities associated with Solander Anticline means the Parara time-depth model is preferred.

Fig. 2.5: Residual plot of observed less calculated depths from Equation 2.3

2.4 Chapter Conclusion

This chapter has covered the petroleum borehole data available in the offshore Fiordland region, where lithostratigraphy, chronostratigraphy and wireline log data have been summarised for both Solander-1 and Parara-1. For this thesis, data provided by Parara-1 well is integral to providing stratigraphic and chronostratigraphic correlations to MGL1803 seismic. Data from Solander-1 are less critical as correlations from this well along the newly acquired data are poor.

Chapter 3

Voyage EW9601a

3.1 Chapter Purpose

This chapter details the acquisition parameters and re-processing sequence for “Line P1” of seismic research voyage EW9601a. Because Line P1 runs sub-perpendicular to the axis of Solander Basin, it allows for a cross-sectional view of the basin stratigraphy, when combined with seismic line M18-17b. Line P1 is the only previous high quality seismic line across Solander Trough, south of Stewart Island.

Firstly, background information regarding the acquisition of EW9601a is outlined. Pre-voyage processing using GLOBE Claritas and onboard processing using Echos by Paradigm Geophysical is covered. Lastly, the result of this processing sequence is compared to the original processing provided by Melhuish et al. (1999). Acknowledgement is made to Wanda Stratford of GNS Science, who facilitated access to the raw data from EW9601a, and the science party members onboard MGL1803, who contributed to the additional onboard processing.

3.2 Introduction to EW9601a

The 640 km long survey EW9601a (Fig. 3.1) was conducted aboard the R/V Maurice Ewing in 1996. EW9601a aimed to constrain the crustal and upper mantle structure of the

offshore region and to investigate plate motion partitioning (Melhuish et al., 1999). EW9601a is comprised of segments P1, P2 and P3 (Fig. 3.1). Line P1 is 302 km long and begins on the southern Stewart Island continental shelf and continues across the Solander Basin. The line then traverses the Puysegur-Fiordland subduction zone. Then, Line P2 continues along Resolution Ridge, and Line P3 concludes the survey west of Dagg Sound on the Fiordland coast. For this thesis, Line P1 will be used, as Lines P2 and P3 extend beyond the study area. Acquisition parameters for EW9601a are shown in Table 3.1. The processing sequence employed by Melhuish et al. (1999) is summarised in Appendix 2, Table 2A-1.

Fig. 3.1: Location of seismic survey EW9601a (black line), which comprises lines P1, P2 and P3. Line P1 is shown in orange (data prior to Line P1 were unavailable); this is the portion of EW9601a processed in this thesis. Solander Basin, Resolution Ridge and Dagg Sound are labelled for context. PTh=Puysegur Thrust, AF=Alpine Fault, PuF=Puysegur Fault

Parameter	Value
Record length	16 s
Sample rate	2 ms
Number of channels	160
Near offset	25.9 m
Far offset	4000.9 m
Group interval	25 m
Shot interval	25 m
Source array	20 airguns
Source volume	8495 in ³
Streamer tow depth	8 m

Table 3.1: Acquisition parameters for EW9601 (see Sutherland and Melhuish, 2000, for full details)

3.3 Pre-MGL1803: EW9601a Data Processing

Line P1 raw data comprised individual segd files. Wanda Stratford of GNS Science provided these data. Also provided by Stratford were: a summary Excel sheet “4008923 DATA LIST.xls” containing reel numbers, start & end FFIDs, and start & end shot point numbers for each tape reel; and the cruise report for EW9601a. Transcription errors from the cruise report, where shot point ranges for certain reels were incorrectly documented, were identified and fixed. The cruise report outlined that Line P1 comprises reels 0603–0746. Though only reels 0637–0746 were available, they provide sufficient coverage for the aims of this thesis.

As part of initial data quality control, trace header information for segd files for Line P1 was examined. As per the acquisition parameters, there should only exist a maximum of 160 traces per shot (see Table 3.1). It was found that for a single shot, more than 160 channels were present in the dataset. This is illustrated in Fig. 3.2, where a GLOBE Claritas shot gather and associated header information are shown.

Fig. 3.2: Reel 0637 of Line P1 showing shots 1790-1791. Firstly, the total number of channels exceeds 160, as shown by the red circle. Data for channel numbers >160 may contain excessive noise (orange box). Some channels appear "normal"; however they have dubious trace header information such as CDP coordinates (see Channel 3222290840 – blue line; inset blue box). The black circle represents "spikiness" in Channel 94

This initial reading of shots shows that there are spurious auxiliary channels in the datasets. Similar flaws are present throughout other tapes. Therefore, before combining each tape into a single segd file, seismic job "EW9601_prevoyage.job" was created in GLOBE Claritas to minimise this issue.

3.3.1 Seismic job EW9601_prevoyage.job

EW9601_prevoyage.job was applied to tape reels 0637–0746 for bad trace removal (see Table 3.2). With the knowledge that only 160 channels should exist for each reel, channels 2-161 were identified and kept (03 TREMOVE). Using header information for each shot and by examining each trace, any "non-data traces" were removed (04 TREMOVE). Running EW9601_prevoyage.job produced segd files (07 WRITESEG), with the naming convention "Puysegur_xxxx_converted.sgy", where "xxxx" refers to the tape reel number.

To identify further bad channels in the datasets, each rewritten segd file (i.e. Puysegur_XXXX_converted.sgy) was read into EW9601_prevoyage.job with only data reading jobs active (01 SEISJOB; 02 READSEGY and 06 XVIEW). Within each shot of a tape reel, "spiky" and noisy channels were identified. These channels, such as Channel 94, Fig. 3.2, were examined and logged. This process was repeated for tape reels 0637–0746. These channels were flagged for later removal during MGL1803.

After completing channel identification, the terminal command "ls *.sgy > Line_P1.sfl" inserted each segy file into an .sfl file (a Claritas readable list file). This command enabled all tapes to be read by Claritas simultaneously. Subsequently, these reels were run through a job "EW9601_shot_writeseggy.job" (see Table 3.3). This job first reads in the list comprising each tape reel, then produces the segy file "EW9601_p1_shots.sgy". This file is the final version that was processed during MGL1803.

Job: EW9601_prevoyage.job	
Module name	Module description
01 SEISJOB	Defines project name, line name etc.
02 READSEGY	Reads in Line_P1.sfl
03 TREMOVE	Keeps traces 2–161
04 TREMOVE	Removes traces where trace type $\neq$ 1
05 SETLASTTR	Sets last trace flag for the last trace of a shot as ShotID
06 XVIEW	Interactive seismic display
07 WRITESEGY	Writes a segy output as "Puysegur_XXXX_converted.sgy"

Table 3.2: Explanation of modules employed in EW9601_prevoyage.job. See Table 2A-2 for module parameters

Job: EW9601_shot_writesegy.job	
Module Name	Module Description
01 SEISJOB	Defines project name line name etc.
02 READSEGY	Reads segy formatted recording data from list file
03 WRITESEGY	Writes a combined segy output as "Line_P1.sgy"

Table 3.3: Explanation of modules used in EW9601_shot_writesegy.job. See Table 2A-3 for module parameters

3.4 Line P1: MGL1803 Processing Sequence

During MGL1803, EW9601_p1_shots.sgy was processed with Echos software by Paradigm Geophysical. Processing was completed with shell scripts compiled by Steffen Saustrup of UTIG. In some cases, including velocity analysis, scripts were run manually. Each script created an Echos processing job that could also be run manually. The following sections outline the processing steps.

3.4.1 Geometry and GIN

The job "ew9601_geometry.dat" reads in segy data and assigns geometry to the dataset. In this job, the "MKDATA" module records the sample rate and record length. Furthermore, the "MARINE" module accounts for 2D seismic marine geometry and records the survey's acquisition parameters. These modules are summarised in Table 3.4.

Further trace information is read in by "GIN" within the job "ew9601-p_gin.dat". The module "DSOUT" writes the data in shot format. This job is shown in Table 3.5.

3.4.2 Trace editing, deconvolution, sorting

In addition to trace editing in Section 3.3.1, further trace editing is achieved in the job "ew9601_p1c_edit_decon_sort.dat" using the "EDIT" module. This next step of trace editing is more rigorous, where each shot for Line P1 was examined and spurious channels identified.

Job: ew9601_geometry.dat	
Module Name	Module Description
MKDATA	Reads in data recording parameters (record length, trace offsets, receiver/shot spacing etc.)
MARINE	Assigns acquisition geometry to data (channel #, channel spacing, shot spacing etc.)

Table 3.4: List of modules in the geometry job. See Table 2A-4 for module parameters

Job: GIN	
Module Name	Module Description
GIN	Reads in trace information of seismic data from tape reels
DSOUT	Writes a segy shot output "ew9601-plc_shots.segy"

Table 3.5: List of modules in the GIN job. See Table 2A-5 for module parameters

This is particularly important as this job also involves deconvolution and sorting, which are heavily affected by poor traces. Table 3.6 details modules of note within this job; a full list of modules is shown in Table 2A-6.

Using "FILTER", a Butterworth filter was applied to the data. Data were then resampled ("RESAMP"). "GAIN" allows for amplitude recovery at depth. Two iterations of gap deconvolution (gap lengths of 75 and 24 ms provided suitable results) are then implemented using "MCDECON". Data could then be sorted into CDPs using "SORT". A segy file containing these sorted data was then produced using "DSOUT".

Job: ew9601_p1c_edit_decon_sort.dat	
Module Name	Module Description
DSIN	Inputs seismic data from "ew9601-p1c_shots.segy"
EDIT*	Flags and removes channels for a given shot, or removes channels for a given CDP
FILTER	Applies a 5–85 Hz Butterworth filter to the data, with 2 db/octave tapering
RESAMP	Resamples the data from 2 ms to 4 ms
GAIN	Applies a $t^{1.5}$ spherical divergence correction to the data
MCDECON	Applies predictive deconvolution, with a gap length=75/24 ms, operator length=450 ms, design window=3500 ms and application window of 0–16 s
SORT	Sorts data to CDPs, with 200 traces/CDP
DSOUT	Writes a segy sorted output "ew9601-p1c_decon_cdps.segy"

Table 3.6: Explanation of key modules used in "ew9601_p1c_edit_decon_sort.dat" job. *The "EDIT" module removes numerous shot-channel and channel-CDP pairs - see the link in Table 2A-6 and for module parameters

Fig. 3.3 shows an example of bad channels in a shot gather. If bad traces are not removed, they produce unwanted artefacts that appear as vertical "stripes" in a migrated section (Fig. 3.4), which obscures primary reflections. This results in a lower quality migrated section.

Fig. 3.3: Examples of spiky and noisy channels for CDP 1630 on Line P1. Spiky and noisy channels are circled and arrowed (channels 2, 96, 116, 134 and 154)

Fig. 3.4: FK migrated section of seismic Line P1 showing artefacts in the stacked section (ar-rowed). A zoom in on these artefacts is shown inset. These artefacts result from improper trace removal, indicating that there are still suspect traces present in the data

Though the artefacts in Fig. 3.4 appear minor, they affect imaging at depth and also present a problem when scaling the data and for later migration. In Echos, traces were able to be removed for certain CDPs e.g. channel 154 in Fig. 3.3; they could also be removed from all CDPs in the dataset e.g. channel 116 in Fig. 3.3. Random noise like channel 154 was cause for removal from specific CDPs, whereas consistently damaging traces like channel 116 warranted complete removal. Table 2A-6 in Appendix 2 provides a URL to a file containing all traces removed.

3.4.3 Velocity picking

A robust velocity model for stacking purposes was then produced. The job "ew9601-p_velocity.dat" reads in 15 CDPs simultaneously and calculates a single semblance plot ("DSIN"), increasing the signal:noise and allowing for greater confidence in picks. Picks were made every 200 CDPs, or every 2.5 km. A Butterworth filter ("FILTER") and an automatic gain control ("AGC") were employed to aid picks. The job then saves the velocity model picked ("VELDEF"). This information is shown in Table 3.7. Fig. 3.5 shows the velocity model picked.

Job: ew9601-p_velocity.dat	
Module Name	Module Description
DSIN	Inputs 15 CDPs from "ew9601-p1c_decon_cdps.sgy"
FILTER	Applies a 5–35 Hz Butterworth filter to the data, with 3 db/octave tapering
AGC	Applies a scaling gain to the dataset
VELDEF	Allows for velocity model picking, and outputs a velocity file "stacking_stef"

Table 3.7: Explanation of modules used in "ew9601-p_velocity.dat". See Table 2A-7 for module parameters

Fig. 3.5: Velocity model picked for Line P1, using the job `ew9601-p_velocity.dat` (adapted from *Echos velocity picking tool*)

3.4.4 Radon demultiple

Multiple attenuation can be attempted with radon demultiple. A complementary multiple removal method, it is particularly useful if any multiples are not removed by stacking. Radon demultiple is achieved with the job `"ew9601-radonstack.dat"`. In this job, `"DSIN"` inputs `"ew9601-p1c_decon_cdps.sgy"`, and `"NMO"` reads in the stacking velocity model. NMO is applied using `"NMO OVCAPP"`, with an overcorrection applied (OVCAPP) to aid multiple removal. NMO is required by Echos prior to forward radon parabolic transformation, which is applied using `"RADNPAR"`. `"DSOUT"` then outputs `"EW9601_p1_radon_cdps"`. Table 3.8 details the modules and parameters used to achieve this. Note that stacking is completed in the subsequent migration job.

Job: ew9601-radonstack.dat	
Module Name	Module Description
DSIN	Inputs "ew9601-p1c_steffen_decon_cdps.segy"
NMO	Input velocity model "stacking_stef"
NMO OVCAPP	Applies NMO, and an overcorrection to aid multiple removal
RADNPAR	Applies forward radon demultiple
GOUT	Outputs a segy file "EW9601_p1.radon.cdps.segy"

Table 3.8: Explanation of modules used in "ew9601-radonstack.dat". See Table 2A-9 for module parameters

3.4.5 Migration

The job "ew9601-steffen_radonstack.dat" applies an FK migration. Firstly, the spherical divergence correction was removed with the "GAIN" module. The velocity model was then applied and the data stacked using "STACK". The "FILTER" module applied a series of Butterworth filters, with different time ranges and frequency bands. Next, the "MIGDMO" module applies an FK migration to the dataset. This form of migration applies a constant velocity (in this case 1500 m/s) in the FK domain. A 1000 ms AGC was then applied to the data to scale the final output, which is then written to a segy file "EW9601-p1c.decon.radon.fkmig.agc.segy" with the "GOUT" module. These parameters and values are shown in Table 3.9.

Job: ew9601-steffen_radonstack.dat	
Module Name	Module Description
DSIN	Inputs "EW9601_p1.radon.cdps.segy"
GAIN	Removes and applies spherical divergence correction
NMO	Input velocity model"stacking_stef"
MUTE	NMO stretch and inside mute application
STACK	Stacks traces in the dataset
MUTE	NMO stretch and inside mute re-application
FILTER	Applies Butterworth filters, for a range of frequencies and time windows
MIGDMO	Post-stack FK dip moveout migration
AGC	1000 ms sliding window AGC, for final scaling
GOUT	Outputs a final segy file "EW9601-p1c.decon.radon.fkmig.agc.segy"

Table 3.9: Explanation of modules in "ew9601-steffen_radonstack". See Tables 2A-9, 2A-9 and 2A-9 for module parameters

3.5 Comparison of Processing Results

A key difference between the processing results from Melhuish et al. (1999) and MGL1803 processing is the marked improvement in data quality in the newly processed line. Reflections in the Melhuish et al. (1999) section (Fig. 3.6) suffer from relatively low amplitudes, making small scale features more difficult to resolve. For example, at CDP 4500-4900 in Fig. 3.6, at approximately 2.5 s TWT, strata appear to be continuous and of similar amplitude. However, the equivalent location from MGL1803 processing (Fig. 3.7) reveals that these strata are actually more chaotic and more variable in amplitude. The same comparison can be made to the east of the basin, where internal stratigraphy is much better resolved in Fig. 3.7 than Fig. 3.6. Migration also resolves steeper dips more accurately with less diffracted energy in the MGL1803 section. However, one aspect where the original section is slightly better than the newer section is that multiple energy is more suppressed. Despite this, the section processed onboard MGL1803 is an overall superior quality output.

Fig. 3.6: Processed segment of Line P1, processed by (Melhuish et al., 1999, see Table 2A-1 for processing sequence). Labelled are areas of comparison to Fig. 3.7

Fig. 3.7: Processed segment of Line P1, processed aboard MGL1803 (see section 3.4). Labelled are areas of comparison to Fig. 3.6

3.6 Chapter Conclusion

This chapter has summarised pre-voyage and onboard processing of Line P1 from EW9601a. Pre-MGL1803 trace editing was employed, with onboard processing including geometry definition, further trace editing, resampling, filtering deconvolution, stacking, migration and scaling for final output. This reprocessing has yielded an output of higher quality than that of the original processing by Melhuish et al. (1999).

Chapter 4

Voyage MGL1803

4.1 Background Information

A key objective of voyage MGL1803 was the acquisition and processing of 2D seismic reflection data. These data are beneficial for providing the first stratigraphic correlations from Solander Trough to the shallow water petroleum industry seismic reflection and well data in the north. Interpretations of these data will also assist researchers at UTIG and CalTech for further research such as subduction zone initiation. This section outlines the acquisition and onboard processing of these MGL1803 seismic reflection data. I thank fellow science party members for their contribution to processing.

4.1.1 Summary of MCS data

Locations of all seismic reflection lines are shown in Fig. 4.1 below. Highlights included lines M18-17c, M18-17b, M18-01, M18-23ab and M18-14, which provided a tie from Parara-1 to strata at Puysegur Ridge at the western edge of line M18-14. This map also shows the proposed 2D survey versus actual coverage of MGL1803 seismic data. In total, 1265.21 km of data were acquired.

Fig. 4.1: Actual (Panel A, coverage=1265.21 km) vs. proposed (Panel B, coverage=4348.89 km) location of 2D seismic lines for voyage MGL1803. For comparison, actual seismic acquired is shown in red in Panel B. Labelled are Parara-1 and Solander-1, both dry and abandoned petroleum wells (see Fig. 2.1). M18-23ab*: indicates this line was acquired as two separate lines (M18-23a and M18-23b), and has been processed as a single line

The proposed 2D MCS lines totalled 4934 km. The 70% reduction in seismic data coverage was mostly due to weather, amid fears of equipment damage and health and safety concerns. The first weather delay occurred on 24-02-2018, where ~ 18 hours were spent on the lee side of Auckland Island. The most significant weather delay was spent from 11-03-2018 to 16-03-2018, sheltering behind Stewart Island from 4–11 m swells and 25–40 knot winds. Though depleted, the seismic reflection data acquired provide unique downdip imagery of Solander Trough; ties to Puysegur Ridge enable a new stratigraphic and tectonic history to be defined (see Chapter 6).

4.2 Seismic Data Acquisition Parameters

The following sections outline acquisition parameters for each of the seismic lines shot in Fig. 4.1 above.

4.2.1 Seismic source

Source for MGL1803 consisted of four sub-arrays, each containing 9 active guns and one backup gun. Each sub-array comprised 1,650 in³, for a total of 6,600 in³ for all 36 guns. For M18-17b however, shotpoints 29466–29718 were only shot with arrays 1 & 2, totalling 3120 in³. Shot interval was 50 m, with a 14-16 s record length allowing for deep crust and upper mantle imaging. The seismic source was towed at 9 m depth with the aid of flotations. This was monitored using depth indicators, as well as acoustic transponders on each sub-array. To help maintain this depth, vessel speed was kept at 4-5 knots; this speed also minimised cable tension. The source array was towed at a distance of 220 m from the stern. The array and flotations are shown in Fig. 4.2, Panels A and B.

Fig. 4.2: Seismic acquisition equipment used during MGL1803. Air gun array flotation devices (Panel A), air gun array (Panel B), seismic streamer (Panel C), streamer bird (Panel D), streamer weights (Panel E) and tail buoy (Panel F)

4.2.2 Seismic streamer

A single streamer cable was run during MGL1803. This cable was either 12 km or 4 km long, where a 4 km streamer was used after M18-23b due to inclement weather, which would have severely damaged the cable. A 4 km streamer takes much less time to deploy and recover, given an average deployment and recovery rate of 1 km/h. Streamer depth was changed from 9 m to 18 m to reduce swell noise (Table 4.1). Each streamer contained compass birds and weights, for maintaining streamer depth and providing weight to prevent resurfacing of the streamer respectively. A tail buoy attached to the end of the streamer provided flotation but also provided positioning via GNSS, and contained an acoustic transponder to communicate with the guns and the ship's bridge. The above equipment is shown in Fig. 4.2.

4.2.3 Summary acquisition parameters

This section outlines the source and streamer acquisition parameters for MGL1803. Fig. 4.3 summarises the source-streamer configuration for MGL1803. Table 4.1 shows source and streamer acquisition parameters for each of the 2D seismic lines acquired on MGL1803.

Fig. 4.3: Source and streamer configurations for acquired seismic data. NRP= Navigation Reference Point, COS=Centre of Source, CNG=Centre of Near Group, ShD=Shot depth (9 m), StrD=Streamer depth (10-18 m). MSL=Mean Sea Level. For 12 km streamer: NRP-COS=220.0 m, NRP-CNG=422.0 m, COS-CNG=202.0 m. For 4 km streamer: NRP-COS= 220.0 m, NRP-CNG=405.2 m, COS-CNG=185.2 m

Line name	Number of channels	Channel spacing (m)	Streamer length (km)	Streamer depth (m)	Record length (s)	Source volume (in ³)	Line length (km)
M18-01	1008	12.5	12.6	10, 12	16	6600	281.6
M18-03a	1008	12.5	12.6	12	16	6600	121.25
M18-14	1008	12.5	12.6	18, 14	16	6600	206.2
M18-17a	324	12.5	4	14	14	6600	10
M18-17b	324	12.5	4	14, 18	14	6600*	83.95
M18-17c	324	12.5	4	14, 18	14	6600	96
M18-19a	324	12.5	4	14	14	6600	122.85
M18-23a*	1008	12.5	12.6	12, 18	16	6600	174.85
M18-23b*	1008	12.5	12.6	18	16	6600	76.3
M18-T01	1008	12.5	12.6	12	16	6600	63.35
M18-T03	324	12.5	4	14	14	6600	15.75

Table 4.1: Summary acquisition parameters for all 2D seismic lines acquired during voyage MGL1803. *Line M18-17b was partly shot at 3120 in³. **Lines M18-23a and M18-23b were later combined into line M18-23ab

4.3 MGL1803 Shipboard Processing Sequence

This section details the onboard processing sequence that was undertaken using Echos by Paradigm Geophysical. Processing steps were implemented as shell scripts written by Steffen Saustrup of UTIG. These scripts created Echos processing jobs that were run using terminal commands. MGL1803 provided an ideal opportunity to process 2D seismic data as they were being acquired. Each processing job will be explained in detail, with examples shown.

4.3.1 Pre-processing of M18-03a and M18-23a

During acquisition of lines M18-03a and M18-23a (the former to become M18-23ab), marine mammal sightings required source power-downs as part of marine mammal protection. This involved lowering source volume from 6600 in³ to 40 in³. This is reflected in shot gathers where reflections are comparatively less prominent than previous shots. The 40 in³ shots are known as mitigation shots, where low volume shots are meant to encourage mammals to migrate away from the mitigation radius as defined by marine mammal observation guidelines.

After the initial 40 in³ mitigation shot, the guns are all slowly warmed up to full volume. This is called the ramp-up sequence, which takes around 20 minutes to complete. For some shots during the ramp up sequence, there were 2 FFID values assigned to a single shot. An example of this is shown in Fig. 4.4. Trace header information revealed that both shots had the same shot number but different FFID values and time stamps. It was suspected that though shots are recorded at 50 m increments, during the ramp up sequence the ship's recording system changes to record shots every 20 s. Thus, whenever a 50 m shot recording coincided with a 20 s recording, a gather will appear to comprise 2 shots. Further evidence of this is that both shots contain the same reflections in a shot gather, which suggests that they correspond to the same surveying location. This phenomenon only occurs during the ramp up sequence and is only present on M18-03a and M18-23a.

Fig. 4.4: "View Data" window in Echos showing Shot 11477 for line M18-03a, where there exists two shots recorded for a single FFID, where there should be one

To determine whether or not to delete data, all shots corresponding to a double shot were removed. On an FK migrated section, this had the effect shown in Fig. 4.5 below:

Fig. 4.5: The effect of removing the shot where the double FFID problem occurred. Removal of these shots has resulted in “migration swings” where migration attempts to account for the missing data. This is similar to what occurs at the ends of seismic lines where there are insufficient data for migration. The dashed blue box outlines the extent shown in Fig. 4.7

Fig. 4.5 shows that complete removal of the entire shot was detrimental to the migration process. Therefore, the solution was to determine which FFID was best to remove from the dataset. Shot interval was 50 m, or ~ 20 s between shots. Within Echos’ View Data, trace header information showed the time of a given shot. Therefore, any shots that were 20 s apart were non-duplicates. In some cases, a good shot was preceded by two double shots; therefore the preceded good shot was examined. By calculating decimal times for shots, the “right panel” (see Panel B, Fig. 4.4) was determined to be the duplicate shot. As the two shots had different FFID values, FFIDs corresponding to the right hand panels were identified and removed in the “EDIT” module in Echos. An example of a removed shot is shown in Fig. 4.6. After all double shots were removed, the data were stacked and an FK migrated section was produced. A comparison between two migrated sections, one with and one without inclusion of the double shots, is shown in Fig. 4.7.

Fig. 4.6: Shot 11477 (refer to Fig. 4.4) showing the effect of removing the repeated "shot" from the dataset

Fig. 4.7: Comparison between FK migrated section, line M18-03a, with duplicate FFIDs removed (Panel A) and without duplicate FFIDs removed (Panel B). The extent is shown in Fig. 4.5

The comparison shown in Fig. 4.7 shows little, if any, discernible difference between two migrated sections. Therefore removal of the duplicate shot yielded no improvement to the quality of these datasets, and it was ultimately determined by UTIG processors that the doubled FFIDs should remain in the data. Despite the lack of improvement, it was important to verify for ourselves and for future processing that there would at least be no detrimental impact on data quality.

4.3.2 SEGD: data read and resample

The "SEGD" job reads in the .segd data from the ship's tape reels. These are copied from the ship's servers using the "segd_rsync.csh" shell script. This script was able to be run as the data were acquired, allowing for continuous real-time processing. The next shell script, "segdinSISIE.csh", converts the tape reel data into shot format. Using the "SEGD" module (Table 4.2), this process reads in the sample rate, record length and number of channels for a given tape reel range. The "RESAMP" module resamples data to 4 ms, and a shot file in segy format is produced ("GOUT").

Job: MCSxxx_SEGD ¹	
Module Name	Module Description
SEGD	Transforms trace from SEG-D for Echos processing
RESAMP	Resamples data from 2 to 4 ms
DSOUT	Write out shot domain data as "MCSxxx.shots" ¹

Table 4.2: Explanation of modules used in the "SEGD" job. See Table 3A-1 for module parameters. ¹ "xxx" refers to the line number

4.3.3 Marine geometry

2D seismic marine geometry is then assigned to the shot gathers using the "geometry" job, implemented with the script "geometrySISIE.csh". This job reads in acquisition parameters using "MKDATA", inputs a rough velocity model using "VFNDEF" and applies direct wave mute, brute mute and an inside trace mute to the data (Table 4.3).

Job: MCSxxx_geometry.dat ¹	
Module Name	Module Description
MKDATA	Assigns marine geometry to the data
VFNDEF	Stores time/velocity pairs into the vertical function repository
VFNDEF	Applies direct wave mute, brute mute and inside mute files

Table 4.3: Explanation of modules used in the "geometry" job. See Table 3A-2 for module parameters. ¹ "xxx" refers to the line number

4.3.4 Brute stack

A brute stack was produced with the job "MCSxxx_brutestack.dat"; modules are shown in Table 4.4. In this job, shot data are read in ("DSIN") and trace edits ("EDIT") are applied. Low and high frequency noise is filtered using a Butterworth filter ("FILTER"). The data are then sorted to CDPs ("SORT") and a rough velocity model is applied to allow for stacking ("NMO"; "STACK"). A brute stack is then produced ("DSOUT"). This brute stack shown in Fig. 4.8.

Job: MCSxxx_brutestack.dat ¹	
Module Name	Module Description
DSIN	Inputs "MCSxxx.shots" ¹
EDIT	Removes bad/noisy traces
FILTER	Applies a 5–85 Hz Butterworth filter, with 12 db/octave tapering"
SORT	Sorts data into CDPs
NMO	Inputs velocity model "brutestack_vels_seafloor"
STACK	Stacks data within CDPs
DSOUT	Writes a brute stack output "MCSxxx.brutestack" ¹

Table 4.4: Explanation of modules in "MCSxxx_brutestack.dat". See Table 3A-3 for module parameters. ¹ "xxx" refers to the line number

Fig. 4.8: Brute stack along line M18-17b produced with the brutestack job. Black circles/arrows show multiple energy and blue arrows denote diffraction energy. The blue line refers to the location of velocity model picks in Fig. 1.8

Though riddled with multiple energy and unmigrated energy, a brute stack allows a preliminary view of the stratigraphy and any potential tectonic features. It also allowed for picking of a seafloor horizon, which was useful for deconvolution in subsequent processing.

4.3.5 Deconvolution and CDP sorting

After applying geometry to the data, we now begin pre-stack processing with the "MC-Sxxx_deconcdpsort.dat" job, implemented using the shell script "sortSISIE.csh". This job reads in shot data with "DSIN" and applies trace edits with "EDIT". After filtering ("FILTER"), amplitude recovery is employed using the "GAIN". Two iterations of gap deconvolution (gap lengths of 75 and 24 ms) are then applied using "MCDECON". Traces were then sorted to CDPs using "SORT". Data were then written to a new file with "DSOUT". Table 4.5 outlines summarises key modules within this job.

Job: MCSxxx_deconcdpsort.dat ¹	
Module Name	Module Description
DSIN	Inputs "MCSxxx.shots" ¹
EDIT	Removes bad/noisy traces
FILTER	Applies a 7-85 Hz Butterworth filter, with 12 db/octave tapering
GAIN	Applies a $t^{1.5}$ spherical divergence correction
MCDECON	Applies predictive deconvolution with a gap length=75/24 ms, operator length=450 ms, design window = 3500 ms, application window=0-14/16 s ²
SORT	Sorts data to CDPs with 400 traces per CDP
DSOUT	Writes a sorted output "MCSxxx.decon.cdps" ¹

Table 4.5: Explanation of modules in the "MCSxxx_deconcdpsort.dat" job. See Table 3A-4 for module parameters. ¹ xxx refers to line number. ² see Table 4.1 for acquisition parameters

4.3.6 Velocity picking

In the job "MCSxxx_veldef.dat", a more robust and accurate velocity model is created. Final velocity models had picks made every 1000, 500 then finally 250 CDPs, or at 3.125 km resolution. Data were read in using "DSIN", and after direct wave muting ("MUTE") and filtering ("FILTER"), velocity picks could be made using semblance plots. These comprised 8 CDPs in a "supergather", producing a higher signal:noise and thus allowing for more accurate picks. A 300 ms AGC ("AGC") was also added to aid visualisation of semblance spectra. "VELDEF" then saved the completed velocity model. Modules are summarised in Table 4.6. The velocity model picked is shown below in Fig. 4.9.

Job: MCSxxx_veldef.dat ¹	
Module Name	Module Description
DSIN	Inputs MCSxxx.decon.cdps" ¹ , and reads 8 CDPs over a given range at a specified CDP increment
MUTE	Applies a direct wave mute
FILTER	Applies an 8-50 Hz Butterworth filter for 0-2 s and an 8-35 Butterworth filter for 1-14/16 s ²
AGC	Applies a 300 ms sliding window AGC
VELDEF	Allows for velocity model picking and outputs a velocity file "MCSxxx_stackvels" ¹

Table 4.6: Explanation of modules in the MCSxxx_veldef.dat job. See Table 3A-5 for module parameters. ¹ xxx refers to line number. ² see Table 4.1 for acquisition parameters

Fig. 4.9: Velocity model picked for line M18-17b, using the job MCS17b_veldef.dat (adapted from Echos velocity picking tool)

4.3.7 Radon demultiple

After creating a superior velocity model, the job "MCSxxx_radonmultiple.dat" aims to remove multiple energy data using a radon parabolic transformation. "DSIN" reads in "MCSxxx.decon.cdps". Data are then NMO corrected using the velocity model produced with "MCSxxx_veldef.dat". NMO stretch is muted ("MUTE"). "RADNPAR" then employs radon parabolic transformation. FK filtering ("FKFILT") removes any residual noise. The data are then written out using "DSOUT". Modules in this job are shown in Table 4.7.

Job: MCSxxx_radon.dat ¹	
Module Name	Module Description
NMO	Inputs velocity model "MCSxxx_stackvels" ¹
MUTE	Removes NMO stretch
RADNPAR	Applies forward radon demultiple
FKFILT	Rejects traces that dip from 0.572-0.888 ms/trace
DSOUT	Outputs "MCSxxx.decon.radon.cdps" ¹

Table 4.7: Explanation of modules in the "MCSxxx_radon.dat" job. See Table 3A-6 for module parameters. ¹ xxx refers to line number

4.3.8 Stacking, migration and scaling

The job "MCSxxx_Radon_stack.dat" stacks, migrates and scales the data for final output. "DSIN" reads in "MCSxxx.decon.radon.cdps". NMO correction is applied using "NMO", NMO stretch is removed with "MUTE", and data subsequently stacked using "STACK". A Butterworth filter ("FILTER") constrains multiple frequency ranges for multiple time ranges. "MIGDMO" then employs F-K dip moveout correction and migration. For final scaling, a 1000 ms sliding window AGC ("AGC") is applied. Lastly, segy format data are output using "GOUT". Table 4.8 describes relevant modules for this job.

Job: MCSxxx_Radon_stack ¹	
Module Name	Module Description
DSIN	Inputs "MCSxxx.decon.radon.cdps.segy" ¹
NMO	MCSxxx_stackvels ¹
MUTE	MCSxxx_stackmute ¹
STACK	Stacks Data
FILTER	Applies Butterworth filters for a range of frequencies and time windows
MIGDMO	Post-stack F-K dip moveout correction and migration
AGC	1000 ms sliding window AGC
GOUT	Final segy output "MCSxxx_decon.radon.fkmig.agc.segy" ¹

Table 4.8: Explanation of modules in the "MCSxxx_Radon_stack.dat" job. See Tables 3A-7, 3A-8 and 3A-9 for module parameters. ¹ xxx refers to line number

4.4 Chapter Conclusion

This chapter has covered the acquisition and processing sequence employed aboard MGL1803 for the newly acquired seismic data. In summary, data were: resampled; assigned marine geometry; filtered with deconvolution; stacked with a refined velocity model; migrated; and lastly scaled for final interpretation.

Chapter 5

Seismic Stratigraphy

5.1 Introduction

This chapter summarises stratal correlations and relationships made using SeisWareTM. A key objective of this project is to map sequence and megasequence boundaries from the Parara-1 well in the north, to the southern-most line M18-14. This provides a framework for interpreting depositional and tectonic mechanisms in the study area. Assignment as a sequence or megasequence boundary is justified in each section.

Providing reliable correlations from Parara-1 presented a significant challenge, as sedimentary and structural barriers affect continuity of sequence and megasequence boundaries. Tauru High produced significant uncertainty for correlations due to the difference in accommodation space created on either side of the high, due to a change from Paleogene extension to Neogene compression (see Sutherland and Melhuish, 2000). Therefore, nomenclature for two sub-basins (north and south of Tauru High) are defined. For example, "U-SLN3-2a" refers to a unit in the northern Solander sub-basin, within megasequence #3, overlying sequence #2, of facies variation "a". Age inferences are discussed in Chapter 6.

5.2 Northern Sub-basin

This section details the seismic stratigraphy north of Tauru High. It focuses on mapping results from lines S86-34 and M18-17c. In this northern region, four megasequence boundaries are identified and eight seismic units distinguished. They can be mapped into the Parara and Hautere sub-basins to the north and onto Solander Anticline (Fig. 5.2).

5.2.1 SLN1-1

U-SLN1-1 comprises low continuity, high to moderate amplitude reflections. U-SLN1-1 locally thickens towards Tauru High and the Parara Fault (line M18-17c, Fig. 5.1; line S86-34, Fig. 5.2 respectively). The inferred northeastern dips of the Tauru Fault and Parara Fault, in combination with stratal fanning and unit thickening toward the faults, implies increasing accommodation space and tilting from normal faulting during deposition of U-SLN1-1.

North of Tauru High, around $\sim$ CDP 1500 (line M18-17c, Fig. 5.1), U-SLN1-1 downlaps a low continuity, moderate to high amplitude, positive polarity reflection, interpreted as seismic basement. Stratal onlap occurs further north at $\sim$ CDP 3200, and at Parara Anticline on both lines M18-17c and S86-34. North of Parara Anticline, stratal relationships are uncertain due to poor basement imaging. This is also the case west and east of Parara-1 (line S86-34, Fig. 5.2), though strata lie parallel to basement from CDP 750-1250.

This basement surface is defined as a megasequence boundary as it is overlapped/downlapped by overlying U-SLN1-1. Additionally, onlap of U-SLN2-1 is observed on line M18-17c (Fig. 5.1, subsection 5.2.2).

Fig. 5.1: Seismic stratigraphy for line M18-17c, northern Solander Basin. Stratal onlap is shown with small arrows. Stratigraphic terminations are indicated by dashed black lines. Biostratigraphic stages in the Parara-1 well (labelled in bold) are dashed, and correspond to: Seafloor, Mangapanian (Wm), Kapitean (Tk), Waiauan, Altonian, Waitakian (Lw), Whaingaroan, Teurian (Dt) and top Paleozoic. Faults are indicated by red lines. VE = vertical exaggeration, see Fig. 1.1 for line location

Fig. 5.2: Seismic stratigraphy for line S86-34, northern Solander Basin. Stratal onlap is shown with small arrows. Stratigraphic terminations are indicated by dashed black lines. Biostratigraphic stages in the Parara-1 well are dashed, and correspond to: Seafloor, Mangapanian (Wm), Kapitean (Tk), Waiuan, Altonian, Waitakian (Lw), Whaingaroan, Teurian (Dt) and top Paleozoic. Faults are indicated by red lines. The black dotted box shows the extent of the inset shown in Fig. 6.15. VE = vertical exaggeration, see Fig. 1.1 for line location

5.2.2 SLN2-1

Reflections within U-SLN2-1 are moderate to low amplitude, with high continuity. U-SLN2-1 is not present from $\sim$ CDP 4000–12400 (line M18-17c, Fig. 5.1). Thinning toward Tauru High is observed, and on line S86-34 (Fig. 5.2), U-SLN2-1 thickens west of Parara Anticline. These thickness observations contrast to underlying U-SLN1-1, which thickens in an opposite direction to U-SLN2-1 (Fig. 5.1, $\sim$ CDP 0–3500; Fig. 5.2, $\sim$ CDP 0–750).

U-SLN2-1 strata onlap basement north of Tauru High and on the southern limb of Parara Anticline (Fig. 5.1). On the northern flank of Tauru High at $\sim$ CDP 1500, strata onlap a high continuity, high amplitude, positive polarity reflection. Further onlap of U-SLN2-1 onto this reflection occurs north of Parara Anticline at $\sim$ CDP 14400 (line S86-34, Fig. 5.2). However, this reflection downlaps basement on the southern limb of the anticline. Here, the relatively planar basement surface from CDP 10000–12500 implies erosion of strata down to basement, possibly due to thinning on the footwall of the fault during its extensional phase (Sutherland et al., 2006). Therefore, south of this to $\sim$ CDP 3200, this surface was not mapped. U-SLN2-1 strata also onlap this basal reflection west of Parara Anticline, and downlap it east of Parara Anticline (line S86-34, Fig. 5.2). On line S86-34, the basal reflection is mapped as a high continuity, high amplitude reflection.

Onlap and downlap of U-SLN2-1 strata onto the basal reflection, and opposite thickening and onlap direction to underlying SLN1-1 is justification for classification of the basal reflection as a megasequence boundary.

5.2.3 SLN2-2

Unit U-SLN2-2 comprises reflections that are moderate to low amplitude and of variable continuity. Strata north of Tauru High are locally folded at $\sim$ CDP 4000 (line M18-17c, Fig. 5.1); no evidence of localised folding is observed at Parara Anticline (line S86-34, Fig. 5.2), where strata are parallel. Similar to U-SLN2-1, U-SLN2-2 thickens north of Tauru High and Parara Anticline, which implies a northern sedimentary source.

On the northern flank of Tauru High (line M18-17c, Fig. 5.1), U-SLN2-2 onlaps a moderate continuity, high amplitude, reverse polarity reflection. This basal reflection is not mapped between $\sim$ CDP 4200–12350, and on this line, has been tentatively mapped at Parara Anticline on the basis of its high amplitude and reverse polarity. Here, onlap is inferred on the southern limb of Parara Anticline. U-SLN2-2 strata are interpreted to onlap this basal reflection west of the anticline (line S86-34, Fig. 5.2), though no onlap is observed to the east. On line M18-17c, north of $\sim$ CDP 4200, U-SLN2-2 strata onlap basement.

The basal surface is designated a sequence boundary with only local onlap by U-SLN2-2, though it is regionally mappable based on continuity and seismic character.

5.2.4 SLN3-1

U-SLN3-1 has moderate amplitude, low to moderate continuity internal reflections north of Tauru High to the paleochannel beginning at $\sim$ CDP 4700 (line M18-17c, Fig. 5.1). North of this paleochannel, strata are more continuous and planar. U-SLN3-1 is a relatively thin unit on line M18-17c, though thickening occurs north of Tauru High (CDP 1350–3800, Fig. 5.1); north of this it thins against a basement high at CDP 8400. U-SLN3-1 then thickens toward Parara Anticline. Thickness variations at Parara-1 (Fig. 5.1) are unclear due to further channelisation at CDP 12000. On line S86-34 (Fig. 5.2) strata are more continuous and planar. Slight thickening occurs west of Parara Anticline; farther west of this it appears to thin, and to the east, thickening is observed.

Onlapping of U-SLN3-1 strata onto a low continuity, low to moderate amplitude, positive polarity reflection is observed on the northern flank of Tauru High from CDP 800-1300 (Fig. 5.1). Onlap is also observed at the basement high at CDP 8400. The basal surface marks the onset of a long-lived channel system north of Tauru High ($\sim$ CDP 4700–7000, Fig. 5.1), as well as adjacent to Parara Anticline. West of Parara-1, U-SLN3-1 strata onlap this basal reflection.

The basal surface is determined as a megasequence boundary. There is widespread onlap of U-SLN3-1 strata, as discussed in sub-sections 5.2.5, 5.2.6 and 5.2.7, and onlap of strata overlying U-SLN3-1 is observed on the northern flank of Tauru High (Fig. 5.1). Furthermore, U-SLN3-1

is interpreted as growth strata related to folding of Tauru High (see section 6.4, Chapter 6).

5.2.5 SLN3-2

Reflections within U-SLN3-2 are low to moderate amplitude, and mostly continuous. Amplitudes are lowest from $\sim$ CDP 1200 to $\sim$ CDP 3600, and from $\sim$ CDP 8400 to $\sim$ CDP 11000 (line M18-17c, Fig. 5.1). Slight thickening north (line M18-17c, Fig. 5.1) and west (line S86-34, Fig. 5.2) of Parara Anticline is observed. The basal boundary with U-SLN3-1 becomes indistinct due to channelisation, but is still mappable elsewhere.

From CDP 1800–2400 (line M18-17c, Fig. 5.1) U-SLN3-2 strata onlap a low continuity, high amplitude, reverse polarity reflection. South of this to $\sim$ CDP 1340, strata lie parallel to this reflection and beyond this, U-SLN3-2 onlaps the underlying megasequence boundary. Further north, onlap onto this high amplitude, reverse polarity reflection is observed at $\sim$ CDP 7300, as well as north of Parara Anticline. Poor imaging of this basal surface on line S86-34 (Fig. 5.2) makes stratal relationship inferences difficult.

There is onlap of U-SLN3-2 onto the basal surface, though this reflection is poorly imaged and does not appear to be related to any major geologic event. Therefore, it is assigned sequence boundary status.

5.2.6 SLN4-1

U-SLN4-1 consists of reflections of low to moderate amplitude that are mostly continuous. This unit thickens north of Tauru High and south of Parara Anticline (line M18-17c, Fig. 5.1), and on line S86-34 (Fig. 5.2), it pinches out west of Parara Anticline. A paleochannel feature at CDP 11500 (approx. 1.5 s TWT) is present within U-SLN4-1 (line M18-17c, Fig. 5.1). These channel deposits comprise higher amplitude reflections that dip to the south. Similar high amplitude reflections visible at CDP 1500, 1.25 s TWT on line S86-34 may be part of the same channel system (Fig. 5.2).

East of Solander Anticline (line S86-34, Fig. 5.2), U-SLN4-1 strata onlap a low continuity,

moderate to low amplitude, reverse polarity reflection. An active channel, visible in seafloor morphology, is inferred to be the modern depositional analogue of what created the high amplitude channel reflections mentioned above. It is theorised that, during its early stages of growth, uplift and folding of Solander Anticline facilitated development of this channel, thus this basal surface is related to activity on the Solander Anticline. Further onlap of U-SLN4-1 onto this reflection is observed north of Tauru High (line M18-17c, Fig. 5.1). Onlap of these strata onto the megasequence SLN3 is observed.

The basal surface is given megasequence boundary status, based on onlap of U-SLN4-1 at Solander Anticline and at Tauru High.

5.2.7 SLN4-2

U-SLN4-2 deposits underlying the modern continental slope between the northern end of line M18-17c and the intersection with line S86-34 are of variable amplitude but high continuity (Fig. 5.1). By comparison, below the modern continental shelf, reflections are moderate amplitude, with some low and high amplitude variations, and strata have moderate continuity. On line S86-34 (Fig. 5.2), reflections are moderate amplitude, with some lower amplitude events. East of Parara-1, reflections are more continuous than those west of ~CDP 1100. The unit is truncated by a modern channel at CDP 1700-1920 on line S86-34 (Fig. 5.2), and is truncated by a modern channel at CDP 2500 on line M18-17c (Fig. 5.1, see swath bathymetry in Fig. 6.5). U-SLN4-2 is thickest to the north (Fig. 5.1) and east (Fig. 5.2) of Parara-1, and thins southward to Tauru High (Fig. 5.1) and west toward Solander Anticline (Fig. 5.2).

Minor onlap of U-SLN4-2 onto a high continuity, moderate to low amplitude, reverse polarity reflection occurs north of Tauru High at ~CDP 1600 (Fig. 5.1). These strata mostly lie parallel to this basal surface; this basal relationship is also observed on line S86-34 adjacent to Solander Anticline (Fig. 5.2).

The basal surface is assigned sequence boundary status, as there is minimal evidence for significant regional tectonic change related to its occurrence.

5.2.8 SLN4-3

U-SLN4-3 is differentiated from underlying U-SLN4-2 strata on the basis of its high continuity, low to moderate amplitude reflections. It is intersected by channels that truncate U-SLN4-2 strata. Continental slope deposits of U-SLN4-2 are continuous, low amplitude reflections that grade into moderate amplitude, stacked clinoforms beneath the continental shelf (north of CDP 12500, line M18-17c, Fig. 5.1, see seismic image Fig. 6.12). These prograding shelf deposits are also imaged on line S86-34 (east of CDP 800, Fig. 5.2), where they grade westward into continuous, parallel reflections beneath the continental slope. Seabed pockmarks occur at CDP 9600–11200 (line M18-17c, Fig. 5.1). U-SLN4-3 thins to the south (Fig. 5.1), and to the west (Fig. 5.2).

5.3 Southern Sub-basin

This section describes the seismic stratigraphy of southern Solander sub-basin, south of Tauru High. It presents mapping results from lines M18-17b, M18-01, M18-23ab and M18-14. In the southern region, three megasequence boundaries and seven sequences are identified.

5.3.1 SLS1-1

U-SLS1-1 consists of low amplitude, low continuity reflections that are locally folded on line M18-17b at $\sim$ CDP 8000 and onlap basement south of Tauru High (Fig. 5.3). The intersection of line M18-17b and M18-01 occurs on a basement high with minimal sedimentary cover, so the thickness of this unit is uncertain on line M18-01 (Fig. 5.4), where reflections are low to moderate amplitude, mostly continuous and onlap basement.

Further to the south on line M18-23ab (Fig. 5.5), U-SLS1-1 is confidently mapped, where it comprises high to moderate amplitude reflections with high continuity, where basement onlap is observed. A tie to line M18-14 (Fig. 5.6) is possible, despite basement topography from $\sim$ CDP 28800–34000 on line M18-23ab (equivalent basement topography from $\sim$ CDP 4200–6500 on line M18-14, Fig. 5.6). U-SLS1-1 is mapped to Puysegur Ridge at the western edge of Fig. 5.6, where folding at $\sim$ CDP 13000 is observed (Fig. 5.7). U-SLS1-1 is variable in thickness, it thickens locally in sub-basins e.g. CDP 35500, line M18-23ab (Fig. 5.5); $\sim$ CDP 7800, line M18-14 (Fig. 5.6).

The base of U-SLS1-1 is seismic basement, which is a low continuity, moderate amplitude, positive polarity reflection. Basement is poorly imaged within Tauru High ($\sim$ CDP 9500–11500, Fig. 5.3), though it is clearly differentiable from overlying strata on the basis of its reflection characteristics and chaotic internal reflectivity. U-SLS1-1 strata onlap basement on all southern lines, and basement onlap of strata overlying U-SLS1-1 is also observed.

Fig. 5.3: Seismic stratigraphy for line M18-17b, southern Solander Basin. Stratigraphic onlap and downlap are shown with small arrows. Stratigraphic terminations are indicated by dashed black lines. Faults are indicated by red lines. VE = vertical exaggeration, see Fig. 1.1 for location

Fig. 5.4: Seismic stratigraphy for line M18-01, southern Solander Basin. Stratigraphic onlap is shown with small arrows. Stratigraphic terminations are indicated by dashed black lines. Faults are indicated by red lines. VE = vertical exaggeration, see Fig. 1.1 for line location

Fig. 5.5: Seismic stratigraphy for line M18-23ab, southern Solander Basin. Stratigraphic onlap is shown with small arrows. Stratigraphic terminations are indicated by dashed black lines. VE = vertical exaggeration, see Fig. 1.1 for line location

Fig. 5.7: Seismic stratigraphy for Puysegur Ridge, line M18-14, southern Solander Basin. Stratigraphic onlap is shown with small arrows. VE = vertical exaggeration, see Fig. 5.6 for figure location

5.3.2 SLS2-1

U-SLS2-1 comprises low continuity, moderate to low amplitude reflections on line M18-17b (Fig. 5.3). There is poor basal constraint on line M18-01 (Fig. 5.4); though where observed, reflections have high continuity and are of moderate to low amplitude. Despite volcanic basement at the northern end of line M18-23ab (Fig. 5.5), U-SLS2-1 is mappable to the south of this line, where reflections have high continuity and low to moderate amplitude. U-SLS2-1 is mapped further west onto line M18-14 (Fig. 5.6), where reflections are continuous and low to moderate amplitude. Faulting occurs at $\sim$ CDP 5750. The sequence is folded at around CDP 11500, and on the eastern flank of Puysegur Ridge from $\sim$ CDP 13000–13750 (Fig. 5.6). Correlations west of $\sim$ CDP 13850 were not made due to reverse faulting. U-SLS2-1 is thickest immediately south of Tauru High (Fig. 5.3). South of this, it tends to thin towards basement topography, with the most pronounced thinning occurring on the eastern flank of Puysegur Ridge, where it is uncertainly mapped (Fig. 5.7).

U-SLS2-1 strata downlap a continuous, low amplitude, positive polarity reflection south of Tauru High to $\sim$ CDP 8000 on line M18-17b (Fig. 5.3). South of CDP 8000, strata lie parallel to this basal reflection, though onlap onto basement occurs at the south of the line. West of the "central fault system" on line M18-01 (Fig. 5.4), U-SLS2-1 strata onlap basement where topography creates discrete sub-basins (e.g. CDP 36000; CDP 37350). East of this, strata onlap basement, though at the eastern edge of the line, basal relationships are unclear.

Further basement onlap occurs onto volcanic highs from CDP 2000–12000 and CDP 29000–33500 to the south of the study area (line M18-23ab, Fig. 5.5). Onlap onto basement occurs at CDP 4700 on line M18-14 (Fig. 5.6), and farther west at Puysegur Ridge, strata onlap the low amplitude, positive polarity reflection identified south of Tauru High on line M18-17b (Fig. 5.3).

The basal reflection is distinguished as a megasequence boundary. At Tauru High, this surface represents the onset of reverse reactivation on Tauru High, as noted by the significant amount of footwall accommodation space created as well as downlapping relationships. Additionally, onlapping at Puysegur Ridge indicates that deposition in the southern Solander Trough began

at this time, suggesting incipient growth of Puysegur Ridge (see section 6.5).

5.3.3 SLS2-2

South of Tauru High (line M18-17b, Fig. 5.3) and across the axis of the basin (line M18-01, Fig. 5.4), U-SLS2-2 consists of moderate to low amplitude reflections with high continuity. Along the axis of Solander Trough (line M18-23ab, Fig. 5.5), U-SLS2-2 comprises low to moderate amplitude reflections of low continuity. Stratigraphic pinchout occurs at a volcanic high at CDP 31000 (Fig. 5.5), though U-SLS2-2 is mapped to line M18-14 (Fig. 5.6). On this line, this unit is near reflection free: any reflections are low amplitude but have high continuity. Faulting of this unit occurs at $\sim$ CDP 5750. U-SLS2-2 is folded at CDP 11500; further folding is observed from $\sim$ CDP 13000–13750. U-SLS2-2 is not mapped west of $\sim$ CDP 13850 due to reverse faulting. U-SLS2-2 is thickest in the northeast of the basin (Figs. 5.3 and 5.4), and markedly thin on the flank of Puysegur Ridge (Figs. 5.6 and 5.7).

Downlap of U-SLS2-2 strata occurs around CDP 9000 on line M18-17b (Fig. 5.3). This downlap surface is a continuous, high amplitude, reverse polarity reflection. South of this, strata are parallel with this reflection, which becomes lower amplitude and less continuous. However, onlap of U-SLS2-2 occurs at $\sim$ CDP 40700 on line M18-01 (Fig. 5.4). Onlap onto basement is observed at the southern end of line M18-17b, as well as to the west of the basin on line M18-01 (Fig. 5.4). In the centre of line M18-01 (axis of Solander Trough, Fig. 5.4), U-SLS2-2 onlaps basement (CDP 37500–38500). Volcanics from CDP 2000–12000 and CDP 29000–33500 along line M18-23ab (Fig. 5.5) are onlapped by U-SLS2-2.

This basal surface has been assigned sequence boundary status. Though first mapped based on the downlap relationships observed on line M18-17b, there are minimal terminations of U-SLS2-2 on this basal reflection.

5.3.4 SLS2-3

Across the entire southern area, U-SLS2-3 comprises moderate to low amplitude reflections that are continuous. In the southernmost study area (line M18-14, Fig. 5.6), strata are faulted at

~CDP 5750. On the same line, folding of this unit at the base of Puysegur Ridge (~CDP 11500) and on its eastern flank from ~CDP 13000–13750) is observed. U-SLS2-3 is comparatively thin on lines M18-17b (Fig. 5.3) and M18-01 (Fig. 5.4). South of CDP 14000 on line M18-23ab (Fig. 5.5), U-SLS2-3 thickens markedly. On line M18-14, this unit thins to the east and thickens towards Puysegur Ridge, though there are uncertainties in mapping of the basal reflection on the eastern flank of Puysegur Ridge.

At CDP 9500 on line M18-17b, onlap of U-SLS2-3 strata onto a continuous, high amplitude, positive polarity reflection occurs (Fig. 5.3). Further onlap onto this basal surface occurs to the east on line M18-01 (Fig. 5.4) and at ~CDP 15000 on line M18-23ab (Fig. 5.5). Elsewhere, these strata parallel this basal reflection. South of ~CDP 15000 on line M18-23ab, this surface is low continuity and low amplitude. U-SLS2-3 onlaps volcanic basement to the south of Tauru High on line M18-17b, and to the west of the basin on line M18-01. Southward on line M18-23ab, onlap onto volcanic basement occurs from CDP 4600–9300, and although no basement onlap is observed in the southernmost study area, onlap onto the basal reflection is inferred on Puysegur Ridge (line M18-14, Fig. 5.7).

The basal surface is mapped as a sequence boundary, based on high continuity and different internal stacking patterns above (U-SLS2-4) and below (U-SLS2-2).

5.3.5 SLS2-4

U-SLS2-4 comprises low to moderate amplitude, continuous reflections across the entire southern sub-basin. In the centre of line M18-17b, channelisation geometry is first observed at CDP 6500, ~4.25 s TWT (Fig. 5.3). East of the central fault system on line M18-01 (Fig. 5.4), further channelisation of this sequence is observed from CDP 38500–39500, ~4.5 s TWT and from CDP 39000–39500, ~4.0 s TWT. Near its upper bounding surface, minor channelisation also occurs at CDP 37500, line M18-23ab (Fig. 5.5) and CDP 6000, line M18-14 (Fig. 5.6). Folding of this unit and underlying units at the base of Puysegur Ridge (~CDP 11400) ceased during deposition of this sequence (Fig. 5.6, see also Fig. 5.7), suggesting syn-tectonic deformation. Further folding of U-SLS2-4 is observed from ~CDP 13000–13750. U-SLS2-4 is thickest on the east of line M18-01, thins along the axis of Solander Trough (line

M18-23ab), and is thinnest on Puysegur Ridge.

U-SLS2-4 is largely parallel with its basal reflection, which is a continuous, moderate to high amplitude, reverse polarity reflection across the southern region. Minor onlap onto this surface occurs adjacent to the central fault system on line M18-01 (CDP 37500, Fig. 5.4), and east of Puysegur Ridge (line M18-14, CDP 11500, Fig. 5.6). Basement onlap is prominent in the south sub-basin (Figs. 5.3, 5.4, 5.5 and 5.6).

The basal surface has been demarked as a sequence boundary, with different stacking and reflection character of underlying (U-SLS2-3) and overlying (U-SLS3-1) units. Minimal stratal terminations are observed.

5.3.6 SLS3-1

On line M18-17b, U-SLS3-1 comprises moderate to low amplitude reflections of variable continuity. Within U-SLS3-1, facies U-SLS3-1a and U-SLS3-1b are identified on this line (Fig. 5.3). Facies U-SLS3-1a is mapped from CDP 35500–37400 on line M18-23ab (Fig. 5.5). U-SLS3-1a contains moderate to low amplitude reflections of moderate continuity, whereas U-SLS3-1b consists of higher amplitude reflections of lower continuity. Both have limited extent north of ~CDP 7000 on line M18-17b, and both onlap basement to the south of M18-17b. Along line M18-01, U-SLS3-1 strata are of similar amplitude to line M18-17b, with high continuity (Fig. 5.4). Farther south at CDP 39000, channelisation is observed. Along strike of Solander Trough (line M18-23ab, Fig. 5.5), U-SLS3-1 is comprised of low to moderate amplitude reflections that have low continuity. Channelisation (with seabed expression) of this unit is mapped at CDP 10200 and 13600; further channelisation is observed at the southern end of the line at CDP 39500. U-SLS3-1 is mapped to line M18-14 (Fig. 5.6), where strata are moderate to low amplitude and are continuous. A modern channel at CDP 5800 incises this unit, south of which strata are mapped to ~CDP 12500, at the foot of Puysegur Ridge (see also Fig. 5.7).

Onlap onto a basal surface was identified east of Puysegur Ridge at ~CDP 11200 and 12500 (Fig. 5.6), where reflection is variably continuous, low amplitude, and reverse polarity. It is of moderate to low amplitude and low continuity along the axis of the study area (line M18-23ab,

Fig. 5.5). Though mostly parallel with this surface, basal onlap of U-SLS3-1 is observed along line M18-23ab at CDP 23000 and 32600. Further west on line M18-01, onlap of U-SLS3-1 onto this surface occurs at CDP 35750 and CDP 41000–41500 (Fig. 5.4). Strata lie parallel to this surface south of Tauru High (line M18-17b, Fig 5.3). Overall, this unit is of relatively consistent thickness, though thickening occurs adjacent to Puysegur Ridge on line M18-14 (Figs. 5.6 and 5.7).

Across lines M18-17b, M18-01 and M18-23ab, onlap of U-SLS3-1 onto basement is observed, though notably these strata do also overlies basement topography. This is observed from CDP 1100–2200 (line M18-17b, Fig. 5.3), CDP 35000 (line M18-01, Fig. 5.4) and CDP 7200–8100 (line M18-23ab, Fig. 5.5).

Designation of this basal surface as megasequence status is justified from onlap and growth of U-SLS3-1 strata next to Puysegur Ridge. The onset of channelisation within this unit provides further evidence.

5.3.7 SLS3-2

South of Tauru High on line M18-17b, U-SLS3-2 encompasses moderate to low amplitude reflections of high continuity (Fig. 5.3), with little variation across Solander Trough (line M18-01, Fig. 5.4). At the western edge of the basin (line M18-01), active scouring by a channel occurs (CDP 33950), and immediately east of this, sediment drift deposits are present (see swath bathymetry, Fig. 6.10). To the east, strata are channelised at CDP 39400, and toward the Campbell Plateau, eroded topography of U-SLS3-2 produce irregular seafloor morphology (see swath bathymetry, Fig. 6.3). Along line M18-23ab (Fig. 5.5), U-SLS3-2 comprises low to moderate amplitude, low continuity reflections. Active channelisation of this sequence is observed at CDP 10200 and 13600 (Fig. 6.8), and to the south of the line at CDP 39500. Further channelisation occurs to the west along line M18-14 (CDP 5800, Fig. 5.6; see swath bathymetry, Fig. 6.9). On this line, reflections are low to moderate amplitude with good continuity. This unit is of variable thickness across the southern study area.

Basal onlap of U-SLS3-2 onto a continuous, low amplitude, reverse polarity reflection is

observed at CDP 11500 on line M18-14 (Fig. 5.6). Northward on line M18-23ab, onlap is observed at CDP 22900 (Fig. 5.5) and further west on line M18-01 at CDP 35850 (Fig. 5.4). Elsewhere, U-SLS3-2 strata lie parallel to this reflection. Unlike underlying strata, onlap of U-SLS3-2 onto basement is limited to the western margin of line M18-01 (Fig. 5.4). To the east of this line, despite poor mapping of the base of SLN3, U-SLS3-2 is interpreted to unconformably overlie U-SLS2-4 strata.

5.4 Chapter Conclusion

This chapter has summarised the seismic stratigraphy mapping of seismic data acquired during MGL1803. In the northern sub-basin, four megasequences are mapped, with eight sequences defined. Mapping in the southern sub-basin has identified three megasequences, with seven sequences correlated. This mapping has provided the first stratigraphic analysis from Parara-1 to Solander Trough.

Chapter 6

Discussion

6.1 Introduction

This chapter presents geological interpretations for Solander Trough. The first section covers active seabed processes in the study area, as imaged by seismic and high resolution (~ 10 m) swath bathymetry data acquired during MGL1803. In Appendix 4, Fig. 4A-1 provides a location for each image. The second section discusses the development of Parara Anticline. Similarly, the third section models the evolution of Tauru High. The final section is a regional basin synthesis, where a stratigraphic and tectonic evolution interpretation for Solander Trough is provided.

6.2 Present Day Depositional Mechanisms

6.2.1 Tasman Sea

Tasman Sea, located between Australia and New Zealand (Fig. 1.4), is an area of high biologic productivity (Jitts, 1965; Hassler et al., 2014). Despite this, ACC circulation initiation around ~ 34 Ma (Barker et al., 2007; Katz et al., 2011) means that sediments are swept eastward, localising sedimentation to small depocentres. This is illustrated in swath data at the western ends of lines M18-01 and M18-14 (Figs. 6.1 and 6.2).

Fig. 6.1: Deposition on Tasman Sea oceanic crust, line M18-01. Panel A shows depocentres in seismic (dotted lines), and Panel B shows them in swath bathymetry. Easterly ACC circulation (Panel B) localises sedimentation to accommodation space in lee of abyssal hills (e.g Buck et al., 2005). The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

Fig. 6.2: Deposition on Tasman Sea oceanic crust, line M18-14. Panel A shows depocentres in seismic (dotted lines), and Panel B shows them in swath bathymetry. Easterly ACC circulation (Panel B) localises sedimentation to accommodation space in lee of abyssal hills (e.g. Buck et al., 2005). The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

In Figs. 6.1 and 6.2, relatively thin (<400 m) of sediment accumulates in depressions in lee of abyssal hills, which are topographic features associated with normal fault blocks and/or volcanic edifices created parallel to mid-ocean ridge axes (Malinverno and Cowie, 1993). This submarine topography also trends parallel to magnetic anomalies associated with mid-ocean ridge spreading (e.g. Barker et al., 2008). It is interpreted that the ACC transports most sediment away from the Tasman Sea floor, resulting in near zero sedimentary cover in the abyssal ocean.

6.2.2 Solander Trough

Sediment Gravity Flows

Examples of active erosion in the form of sediment gravity flows occur on the eastern margin of Solander Trough, on the Campbell Plateau continental slope. Features are shown in Fig. 6.3 (line M18-01), and Fig. 6.4 (line M18-03a).

Fig. 6.3: Canyon system that has developed on the Campbell Plateau continental slope on line M18-01, shown in seismic (Panel A) and swath bathymetry (Panel B). In Panel B, dotted white lines indicate sediment gravity flow pathways, solid white lines indicate erosion by bottom currents and dashed white lines show slope failure. The grey dotted line shows the flow of Solander Channel. The black line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

Figs. 6.3 and 6.4 are located on the eastern edges of lines M18-01 and M18-03a respectively.

Fig. 6.4: Canyon system that has developed on the Campbell Plateau continental slope on line M18-03a (~12 km south of Fig. 6.3), shown in seismic (Panel A) and in swath bathymetry (Panel B). In Panel B, dotted white lines indicate sediment gravity flow pathways. The black cross marks a tributary canyon that has incised eroded topography. The grey dotted line shows the flow of Solander Channel. The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

A main canyon has been identified, with several smaller, "tributary" canyons that join the main canyon downslope of the shelf break. These canyons provide a conduit for sediment transport from the continental shelf to the deep ocean, which may be as turbidite flows (e.g. Carter et al., 1996a). If exposed during periods of low sea level, there is potential for fluvial deposition directly to canyon systems, and potentially the basin floor (e.g. Carter and McCave, 1997).

Canyons from the continental slope develop basinward into relatively flat-lying, sediment bare topography that is heavily eroded. On Fig. 6.3, these surfaces are rilled on their northern

side. This suggests that there is significant scouring of this topography by south flowing bottom currents. Lack of rilling on Fig. 6.4 suggests a weakening/redirection of bottom currents, though a tributary canyon that incises eroded topography is noted (Panel B). Other features of note on Fig. 6.3 include shelf collapse at the shelf break, and slumped material at the foot of the canyon system. In both examples, general aggradation of sediment (unrelated to canyon-derived sediment gravity flows) may be the result of north to south deposition and/or settling of material as a result of ACC flow in the lee of Puysegur Ridge.

Channelisation

Numerous channel features were identified in swath bathymetry data. These are mostly related to scouring by Solander Channel, a >450 km long, sinuous feature that extends from the Stewart Island continental shelf and terminates in the Emerald Basin south of the study area (Fig. 6.5, Carter et al., 1996a, see Fig. 1.1 for location). From the Stewart Island continental shelf, a tributary channel to Solander Channel has been identified (Fig. 6.5).

Fig. 6.5: Tributary channel to Solander Channel, line M18-17c, shown in seismic (Panel A) and in swath bathymetry (Panel B). The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

This northeast-west flowing channel is asymmetric in profile. Its eastern margin is marked by successive build-up of levee deposits. This side is slightly elevated: analysis by Carter and Carter (1988) suggests preferential levee development on the east is due to Coriolis deflection. Eastward flowing STF waters may also help aggrade these levees (see Fig. 1.4). Channel lag deposits indicate lateral migration of Solander Channel over time. Its v-shaped profile suggests a relatively high amount of vertical erosion to lateral erosion.

Fig. 6.6 illustrates a less developed channel adjacent to Solander Channel, on line M18-17b. These channels, located south of Tauru High, show a drastically different morphology and evolution history.

Fig. 6.6: Channels shown on line M18-17b, in seismic (Panel A) and swath bathymetry (Panel B). Channel (i) and Solander Channel (ii) show different morphologies and evolution histories. The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

Channel (i) in Fig. 6.6 has a gentler profile than Solander Channel (ii). It also has a less developed evolution, as evidenced by the lack of paleo lag deposits, compared to Solander Channel (ii), where extensive lateral paleo lag deposits indicate lateral migration over time (Panel A, Fig. 6.6). This suggests channel (i) is younger than Solander Channel, thus is interpreted as a tributary channel. A shared characteristic of both channels is the slightly elevated eastern margin, indicating preferential deposition on this margin (Carter and Carter, 1988).

Fig. 6.7 presents a view of Solander Channel perpendicular to the axis of Solander Trough.

Fig. 6.7: Solander Channel as shown on line MCS01, with a secondary across-basin channel to the west. Panel A shows these features in seismic; Panel B shows them in swath bathymetry. Sediment drifts (Fig. 6.10) and eroded topography (Fig. 6.3) are labelled, where dotted white lines indicate sediment gravity flow pathways. The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

Solander Channel's varied history is shown by the laterally and vertically migrating channel lag deposits, marked by high amplitude reflections (Panel A, Fig. 6.7). An elevated western margin contradicts Figs. 6.5 and 6.6 (see Carter and Carter, 1988). Here, it is proposed that the elevated central basin axis (see Fig. 5.4) is the main contributor to an elevated channel margin, rather than preferential deposition to the east due to the Coriolis force. Note that sediment drifts (Fig. 6.10) and eroded topography (Fig. 6.3) are labelled to the west and east respectively: these features are discussed in the next section.

On line M18-23ab, a two-channel system is illustrated in Fig. 6.8.

Fig. 6.8: Solander Channel (i) and a more developed channel (ii) on line M18-23ab, shown in seismic (Panel A) and in swath bathymetry (Panel B). Note channel (ii) was not recorded in swath bathymetry. The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

Though this contrast in morphologies is not as pronounced as Fig. 6.6, Solander Channel is broader in profile and has less developed channel bank deposits (Panel A). By comparison, channel (ii) is more vertically incised, has more developed channel bank deposits, and deeper paleo lag deposits. This indicates longer-lived channelisation by (ii) compared to Solander Channel. Channel (ii) was not imaged in swath bathymetry.

At the southern end of the study area, Solander Channel has been identified on lines M18-23ab and M18-14 (Fig. 6.9). In Panel B, incision of the Campbell Plateau continental shelf is observed to the east of line M18-14, facilitating sediment transport from the shelf to the deep ocean by sediment gravity flow mechanisms.

Fig. 6.9: Solander Channel as shown in seismic (Panel A) and swath bathymetry (Panel B). To the east of Panel B, incision of the Campbell Plateau continental slope is observed. Dotted white lines indicate sediment gravity flow pathways. The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

Sediment Drifts

Fig. 6.10 displays sedimentary drifts on line M18-01. These undulatory bedforms are related to moating around a topographic high (McCave and Tucholke, 1986).

Fig. 6.10: Sediment drifts on line M18-01, shown in seismic (Panel A) and in swath bathymetry (Panel B). Sediment gravity flow pathways are indicated by the heavily dotted white lines (Panel B), whereas moat scouring is marked by the lightly dotted line. ACC deflection is shown in Panel B. The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

In this example, sediment drifts are deposited adjacent to a moat. It is proposed that acceleration of strong, easterly ACC flow around a structural high has encouraged moating at its base (Fig. 6.10, Panel B), due to a topographic gap in the Snarres Zone. Here, it is theorised that the growth of Puysegur Ridge and subsequently the Snarres Zone led to development of this structural high. Deposition of sediment drifts perpendicular to moating occurs (e.g. Stow et al.,

2002). In seismic (Panel A), these drifts are somewhat lenticular, concave-up features: these drifts are a type of contourite drift defined as "elongate mound drifts" by (Stow et al., 2002).

Another example of sediment drifts is shown on line M18-03a (Fig. 6.11), approximately 22 km south of Fig. 6.10. These drifts are smaller in amplitude and wavelength. Here, a less prominent moat adjacent to the structural high (Panel B) indicates less seafloor erosion, probably due to the lower erosive energy of deflected ACC flow.

Fig. 6.11: Sediment drifts on line M18-03a, shown in seismic (Panel A) and in swath bathymetry (Panel B). Sediment gravity flow pathways are indicated by the heavily dotted white lines (Panel B), whereas moat scouring is marked by the lightly dotted line. Note the less pronounced moat compared to Fig. 6.10. ACC deflection is shown in Panel B. The red line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

6.2.3 Modern shelf and slope

Swath bathymetry imaged the continental shelf south of Fiordland at depths >70 m, showing that it dips at $<1^\circ$, landward of the shelf break. The shelf transitions to the continental slope, which is relatively steeper at around 1° . West of Puysegur Bank, the continental slope transitions to the Puysegur Trench; slopes steepen markedly from $3\text{--}4^\circ$ to a maximum of around 9° .

On the present day continental shelf on lines M18-17c and S86-34, prograding shelves have been imaged as part of sequence U-SLN4-2 (Figs. 6.12 and 6.13).

Fig. 6.12: Prograding shelf deposits on line M18-17c, illustrating a sigmoidal clinoform pattern (see Mitchum et al., 1977). See Fig. 4A-1 for location

Fig. 6.13: Prograding shelf deposits on line S86-34, illustrating a sigmoidal clinoform pattern (see Mitchum et al., 1977). See Fig. 4A-1 for location

Strata in Figs. 6.12 and 6.13 illustrate a characteristic sigmoidal clinoform geometry with relatively thin upper and lower portions at shallow dips, and a thicker central section (Mitchum et al., 1977). This prograding shelf pattern indicates deposition at $<1^\circ$ dip. The upper (topset) strata are parallel to the upper surface of the beds; according to Mitchum et al. (1977), this indicates continued aggradation of the upper portions of the beds simultaneously with middle segment progradation (see also Fulthorpe and Carter, 1991). The lower strata downlap the basal surface. Mitchum et al. (1977) state that this shelf configuration implies a combination of low sediment input, rapid basin subsidence and/or rapid sea level rise.

6.2.4 Pockmarks

Further to the south on the modern day continental slope (line M18-17c), pockmark features are evident in seismic and swath bathymetry. These oval-shaped depressions are up to 200 m wide and tens of metres deep (Fig. 6.14).

Pockmarks are typically the result of fluid (e.g. hydrocarbon, volcanic, groundwater) escaping from strata below, producing concave depressions, according to Hovland et al. (2002), who classify elongate pockmarks based on their asymmetry. Their north to south elongation (Panel B) direction indicate bottom current direction (e.g. Boe et al., 1998). These pockmarks are located ~ 18 km southeast of Solander Island, so one possibility for their existence is volcanic gas expulsion or hydrothermal dewatering (Ondréas et al., 2018). Another possibility is thermal maturation of Cretaceous coal measures present in the north by Solander-1 (Shaheen and Hutson, 1989), due to heat input from Solander Island volcano (Reay and Parkinson, 1997).

Fig. 6.14: Pockmark features shown in seismic (Panel A) and swath bathymetry data (Panel B). The black line in Panel B shows the extent of Panel A. See Fig. 4A-1 for location

6.3 Parara Anticline: Age Control of SLN Stratigraphy

Parara Anticline was initially a target for the Parara-1 exploration well (see Chapter 2). MGL1803 and S86 survey data (see Chapter 1) illustrate its development from a Paleogene extensional fault to a Miocene compressional fault. Using age control provided from Parara-1, the analysis below discusses this evolution. Findings constrain and improve on the Paleogene-Neogene evolution of Parara Anticline (e.g. Turnbull et al., 1993; Sutherland et al., 2006).

6.3.1 Pre-inversion

U-SLN1-1 growth strata show evidence of early activity as a normal fault (Fig. 6.15). Of Paleogene age, U-SLN1-1 thickens toward the Parara Fault, as a result of increased accommodation space on the hanging wall. U-SLN1-1 reaches a maximum thickness of 952 m in the footwall of the Parara Fault, with thinning and onlap onto basement to the south.

U-SLN2-1, deposited from ~23–15 Ma, overlies these growth strata. It is thickest at ~315 m at the crest of Parara Anticline. Thinning to ~250 m south of the anticline on line M18-17c indicates north to south deposition, and implies a relative lack of accommodation space on the footwall of the anticline during this time. The Parara Fault was inactive during the earliest mid Miocene.

An increase in sediment supply during the mid Miocene (Norris et al., 1978) saw thickening of U-SLN2-2, which was deposited from ~15–11 Ma (Fig. 6.15). On Fig. 6.15, north of Parara-1, U-SLN2-2 reaches a maximum thickness of >1200 m; to the south strata are only ~870 m. This indicates that accommodation space at the Parara Anticline was still greater to the north. Therefore, reverse reactivation of the Parara Fault had not occurred in the mid Miocene.

6.3.2 Inversion and post-tectonic phase

Units U-SLN3-1 and U-SLN3-2 suggest that from ~11 Ma, increased reverse throw on the Parara Fault resulted in greater accommodation space to the south of Parara Anticline. This is

evidenced by southward thickening of these strata, and relative thinning to the north. Thickening is most prominent where channelisation of strata has occurred at CDP 13000 on line M18-17c (Fig. 6.15). It is interpreted that elevation created by hanging wall thrusting allowed for initiation of this channel in the topographic low, with continual thrusting creating more accommodation space, encouraging further channel development, as well as thickening of U-SLN3-1 and U-SLN3-2.

The end of reverse movement at Parara-1 is interpreted as ~ 7 Ma. On line S86-34 (Fig. 5.2, see also inset in Fig. 6.15), U-SLN3-1 strata are non-parallel at $\sim$ CDP 800 (~ 1.8 s TWT), whereas U-SLN3-2 strata are internally parallel at the same location (~ 1.6 s TWT). Here, it is proposed that accommodation space was created during deposition of U-SLN3-1 from ~ 11 – 7 Ma; in other words, U-SLN3-1 is syn-tectonic with reverse movement on the Parara Fault. U-SLN3-2, deposited from ~ 7 – 5 Ma, represents sedimentary infill of this accommodation space after deposition of U-SLN3-1 i.e. after reverse movement on the Parara Fault. This therefore constrains timing of reverse movement on the Parara Fault as ~ 11 – 7 Ma. These age estimates improve on previous analyses of Parara Anticline growth (e.g. Turnbull et al., 1993; Sutherland et al., 2006).

U-SLN4-1, U-SLN4-2 and U-SLN4-3 strata are undeformed relative to underlying strata, indicating a tectonically quiescent earliest Pliocene-Recent sequence.

Fig. 6.15: Changing tectonic regime at Parara Anticline from Paleogene extension to late Neogene compression. Southward thickening of U-SLN3-1 and U-SLN3-2, deposited from ~11–5 Ma, indicate increasing accommodation space on the footwall of the Parara fault after late Miocene reactivation as a reverse fault. The inset shows internal reflection character of U-SLN3-1 and U-SLN3-2 strata, which provided constraints for reverse movement (U-SLN3-1) and passive infill (U-SLN3-2). The extent of this inset is shown in Fig 5.2

6.4 Tauru High: SLN-SLS Correlation

Tauru High is a barrier to sediment transport and hence stratal continuity, and is the reason for defining separate northern and southern stratigraphic units. Despite this, mapping of stratigraphic reflections has enabled a geologic evolution model for Tauru High (Fig. 6.16) to be made. In this section, I analyse the stratigraphy either side of Tauru High and make correlations between the north and south sub-basins. Refer to Fig. 6.17 (Panel A) for a view of the internal structure of Tauru High.

6.4.1 Before inversion

The Tauru Fault developed as a listric fault in an extensional setting during the Paleogene (see Sutherland and Melhuish, 2000). Evidence for its listric nature is U-SLN1-1 fanning growth strata adjacent to the fault (Fig. 6.16, Panel A). This occurs due to accommodation space creation, and block rotation of the hanging wall (van der Pluijm and Marshak, 2004).

Downlapping of U-SLN2-1 strata (deposited from ~ 23 – 15 Ma) onto U-SLN1-1 is observed; this and slight northward thickening indicates southward deposition (Fig. 6.16, Panel A). The lack of U-SLN1-1 or U-SLN2-1 strata on the footwall suggests either erosion of these units or minimal accommodation space created on the footwall, or both. The geometrical relationships suggest no Tauru Fault movement. Overlying U-SLN2-1, U-SLN2-2 was deposited from ~ 15 – 11 Ma, where the upper age of this unit (~ 11 Ma) is based on ties to Parara-1. These strata downlap U-SLN2-1 north of the Tauru Fault, with basement onlap observed south of the fault (Fig. 6.16, Panel A). During this passive phase, north to south deposition is implied due to southward thinning of U-SLN2-2. Its presence on the hangingwall implies there was accommodation space prior to thrusting.

In the southern sub-basin, U-SLS1-1 is the correlative of U-SLN2-2. As discussed in following subsections, as well as subsections 5.2.4 and 5.3.2 of Chapter 5, the upper reflection of these units marks a megasequence boundary at Parara-1 and Tauru High respectively, related to the onset of reverse reactivation of these structures. This places the upper age of U-SLS1-1 as ~ 11

Ma.

Fig. 6.16: Evolution of Tauru High from the Paleogene to the present day. Initial growth was as an extensional feature (Panel A), after which changing stress conditions led to compressional folding of the hanging wall. Oversteepening caused collapse of hanging wall strata as a soft sediment slump (Panel B). Stratal onlap Tauru High indicating that its growth precedes deposition of onlapping strata (Panel C). Stratal onlap and downlap are shown with black arrows. Internal deformation is shown by red curved arrows. Units defined in Chapter 5 are labelled

6.4.2 End inversion

Soon after deposition of U-SLN2-2/U-SLS1-1 (~ 11 Ma), inversion of the Tauru Fault began. This saw the advent of development of Tauru High as an anticlinal structure, with associated folding of strata within the hanging wall. As a result of folding, it is theorised that incipient collapse of hanging wall strata occurred (e.g. Bonini et al., 2000). Elevated hanging wall topography was conducive to progressive erosion of hanging wall strata, which were re-deposited as downlapping U-SLS2-1 strata on the footwall of the anticline (Fig. 6.16, Panel B).

Sustained compression saw increased folding and hence increased steepening of hanging wall strata. Deposition was preferential on the footwall due to accommodation space created, accounting for the depositional hiatus (equivalent of U-SLN3-1) on the hanging wall (Fig. 6.16, Panel B). Oversteepened strata became gravitationally unstable and slumped southwards onto the downlapping U-SLS2-1 strata, with internal deformation inferred. The fault plane, without brittle strata to propagate into, developed along the failure plane of the slumped material. Coincident with this collapse is mass wasting of sediment as U-SLS2-2 to the south (Fig. 6.16, Panel B). This is evidenced by the basal high amplitude, reverse polarity reflection (section 5.3.3). These mass wasting strata locally downlap this basal surface (see Fig. 6.17, CDP 8000–9000, Panel A). On line M18-17b, from CDP 3600–7000, ~ 5 s TWT, erosion of underlying U-SLS2-1 strata is noted, which may be the result of mass wasting (see Fig. 5.3, Chapter 5).

In Fig. 6.16, the age of this gravitational collapse is unclear, due to a lack of tie to Parara-1. Here, I propose that it occurs at ~ 9 Ma i.e. the age at the base of U-SLS2-2 is 9 Ma. In Chapter 5, a moderate to high amplitude, reverse polarity reflection defines the base of U-SLN3-2 (section 5.2.5) in the northern sub-basin. A similarly moderate to high amplitude, reverse polarity reflection marks the base on U-SLS2-4 (section 5.3.5) in the southern sub-basin. From this and the similar seismic character of U-SLN3-2 and U-SLS2-4 strata, the base of both units is interpreted as a correlative surface. A tie to Parara-1 provides an age of ~ 7 Ma for this basal reflection. Assuming an approximately linear sedimentation rate between this basal surface and the base of U-SLS2-1 (i.e. the beginning of tectonic deformation at ~ 11 Ma), this suggests an age of ~ 9 Ma for the base of U-SLS2-2.

6.4.3 Post-inversion

The main phase of compression on the Tauru Fault ended at ~ 9 Ma. In the northern sub-basin, this is evidenced by onlap of U-SLN3-2 strata onto underlying U-SLN3-1. Onlap of U-SLS2-2, U-SLS2-3 and U-SLS2-4 onto Tauru High occurs the southern sub-basin (Fig. 6.16, Panel C). Basin fill in both sub-basins was therefore deposited in a passive tectonic environment, with relatively little tilting or deformation.

U-SLS2-3 was probably deposited just before ~ 7 Ma. The base of U-SLN3-2 and U-SLS2-4 is a correlative surface, thus these units are correlatives of each other. The base of U-SLN4-1 in the northern sub-basin is a low to moderate amplitude, reverse polarity reflection, which has been tied to Parara-1 and is a megasequence boundary related to onset of reverse reactivation and channelisation at Solander Anticline (subsection 5.2.6). The base of U-SLS3-1 is a low amplitude, reverse polarity reflection. Similarities in thickness and the basal surface of these strata suggests that they are correlative packages. Tying this basal reflection to Parara-1 yields an age of ~ 5 Ma.

Lastly, U-SLN4-2 and U-SLN4-3 are interpreted as the correlative units of U-SLS3-2. Both northern units and U-SLS3-2 overlie a low amplitude, reverse polarity reflection, with high continuity reflections. The basal surface of these strata is mapped at Parara-1, where an age of ~ 3 Ma is determined.

6.4.4 Age correlation model

Analysis of the evolution of Tauru High has provided age correlation from the northern sub-basin to the southern sub-basin. This allows for ages determination of strata as far south as $\sim 49.5^\circ\text{S}$, which is the southern-most age correlation using seismic data ever made in this region. Fig. 6.16 (Panel B) illustrates these age correlations, relative to the seismic units identified in Chapter 5.

Fig. 6.17: Modern day setting of Tauru High (Panel A). Labelled are stratal relationships to the north and south, the slump failure plane and associated basal erosion surface, slumped material, growth strata and mass wasting strata. Panel B summarises age correlations of strata tied to Parara-1 in the northern sub-basin (SLN) to strata south of Tauru High in the southern sub-basin (SLS)

6.5 Basin Analysis

The following section summarises the regional basin evolution of Solander Trough, using a synthesis of previous chapters. Paleogeographic reconstructions for certain time periods are shown in Fig. 6.18.

6.5.1 pre-40 Ma

During the early Cretaceous, rifting related to (but pre-dating) rifting of Zealandia from Gondwana saw development of half-grabens. After cessation of Tasman seafloor spreading (Gaina et al., 1998; Laird and Bradshaw, 2004), further rifting in the Eocene and Oligocene due to southward migration of the Euclidean pole (Turnbull et al., 1993; Sutherland, 1995) saw further development of extensional basins around New Zealand and changes in Eocene plate boundary configuration.

Cretaceous sediment is present in onshore Fiordland in fault-bound grabens (Norris and Turnbull, 1993). Paleocene strata are not present in the onshore region, probably due to non-deposition/peneplanation related to Tasman Sea rifting (Turnbull et al., 1993; Uruski and Turnbull, 1990). Paleocene strata are interpreted in the Parara-1 well "...from association with regional geology, samples and electric log characteristics" (Hunt International Petroleum Company, 1976, pg. 14), though this is contradicted by biostratigraphy results within the same report, which indicates a late Eocene age for the oldest strata.

During the Eocene, fluvial and lacustrine deposition dominated the onshore region, with some shallow marine strata deposited in Te Anau Basin (Turnbull et al., 1993, Fig. 6.18, Panel D). In the offshore realm, Eocene strata were encountered at Parara-1 (Hunt International Petroleum Company, 1976, see also Fig. 2.2), comprising kaolinitic sandstones with coal measures, suggesting non-marine deposition. Non-marine Eocene deposition was also interpreted from onshore seismic data (Turnbull et al., 1993). The Eocene is partly represented by U-SLN1-1 (see Chapter 5). Growth strata against the Parara Fault (Fig. 6.15) and the Tauru Fault (Fig. 6.16) (e.g. Sutherland et al., 2006) indicate deposition contemporaneous with normal faulting. Though the

Solander Fault was active as a normal fault, the adjacent Solander High was an elevated area of non-deposition (Fig. 6.18). The Eocene section of U-SLN1-1 is interpreted as low amplitude, more discordant reflections that suggest a higher energy, non-marine depositional setting (Sangree and Widmier, 1979). Eocene normal faulting is recognised onshore, with some inferred reactivation of Cretaceous normal faults (Uruski and Turnbull, 1990).

Regional subsidence was concurrent with normal faulting, and Oligocene deepening of basins saw a shift from terrestrial to marine deposition (Norris and Turnbull, 1993; Turnbull et al., 1993). During the Oligocene, transgression flooded the Fiordland region. Onshore geology in the Te Anau and Waiau sub-basins record sea level rise, shown as an upward fining sequence of turbiditic sands to bioclastic limestone toward the late Oligocene, indicating maximum transgression around this time (Norris and Turnbull, 1993), and a marine connection of the Te Anau and Waiau basins (Uruski and Turnbull, 1990). In the offshore area, this sequence of upward fining clastic to carbonate facies is observed in Balleny Basin (Norris and Turnbull, 1993) and Solander-1 (Engmann and Fenton, 1986) (see also Fig. 2.4). Though carbonate facies are not observed before the Otaian at Parara-1 (Fig. 2.2), general upward fining of U-SLN1-1 from coarser turbidite facies is interpreted from well logs. At Solander-1, the Oligocene is interpreted as a terrestrial sequence, which indicates that the Solander High was emergent during Oligocene transgression (Norris and Turnbull, 1993, see Fig. 6.18). The Oligocene section of U-SLN1-1 comprises higher amplitude, concordant reflections, which indicates a comparatively lower energy depositional environment.

U-SLN1-1 strata have no age correlative mapped south of Tauru High (see Chapter 5). In Fig. 6.18, the ACC, which developed around the Eocene/Oligocene boundary (Barker et al., 2007; Katz et al., 2011) is interpreted to have scoured/re-transported sediment derived from the north and any biogenic sediment. Schuur et al. (1998) observed similar erosion of sediment down to basement at $\sim 53.5^{\circ}\text{S}$ due to a gap in the Macquarie Ridge Complex, enabling erosion by strong ACC waters. Additionally, a lack of Cretaceous/Eocene rift basins in this southern area implies a lack of accommodation space for sediments (Fig. 6.18).

Fig. 6.18: (Caption on next page)

Fig. 6.18: Paleogeographic reconstructions for the offshore and southernmost onshore Fiordland region. Time intervals represented are: 5 Ma (Panel A); 11 Ma (Panel B); 15 Ma (Panel C); 40 Ma (Panel D). Onshore reconstructions are based on Turnbull et al. (1993), and plate boundary reconstructions are from Lebrun et al. (2003) and Sutherland et al. (2006). Bold abbreviations are location names: CT=Caples Terrane; FM=Fiordland Margin; HR=Hump Ridge; PR=Puysegur Ridge; TM=Takitimu Mountains; TB=Te Anau Basin; WB=Waiau Basin. Italicised abbreviations are faults: AF=Alpine Fault; MFS=Moonlight Fault System; PaF=Parara Fault; PuF=Puysegur Fault; PTh=Puysegur Thrust; SF=Solander Fault; TF=Tauru Fault

6.5.2 23–11 Ma

The early Miocene saw a major change in plate motions to strike-slip (Cande and Stock, 2004), and propagation of the Alpine Fault through New Zealand (Kamp, 1986; Sutherland et al., 2000). Transtensional faulting closer to the coast, related to increased convergence of the Pacific and Australian Plates (Walcott, 1978; Sutherland, 1995; Cande and Stock, 2004), resulted in uplift of southwestern Fiordland (e.g. Sutherland et al., 2009, see Fig. 6.18, Panel C). This provided a sediment source for the Te Anau and Waiau Basins, which were continually subsiding and subject to marine deposition (Uruski and Turnbull, 1990).

During the early Miocene, Oligocene carbonate sequences were overlain by clastic sediment. Major sediment sources in the onshore region included the Fiordland margin and the Caples Terrane in the northeast (see Fig. 1.2; Fig. 6.18), which provided significant clastic material that was deposited as bathyal turbidites in the Te Anau and Waiau basins (Turnbull et al., 1993). Early Miocene deep marine mudstones (Hunt International Petroleum Company, 1976; Turnbull et al., 1993) deposited as turbidite sequences at Parara-1 and Solander-1 (Norris and Turnbull, 1993) overlie Oligocene strata, which indicates rapid subsidence of these offshore basins despite the beginning of uplift in the onshore region (Sutherland et al., 2009). This subsidence is significant as the Solander High was emergent in the Oligocene (Turnbull et al., 1993). These turbidite sequences are interpreted to be sourced from the Fiordland margin and potentially the Caples Terrane in the north.

The mid Miocene saw significantly increased terrigenous input from uplifted sources such as the Caples Terrane, resulting in marine regression. For example, in northern Te Anau Basin, fluvial conglomerates overly shelfal early-mid Miocene deposits (Norris and Turnbull, 1993).

Though still in a marine setting, stratigraphy at Parara-1 shows upward coarsening from clays and muds to more common sands and shales (Hunt International Petroleum Company, 1976). Solander-1 exhibits upward coarsening from silty muds to interbedded conglomerate and sands (Engmann and Fenton, 1986). This coarser material is inferred to be sourced from uplifted onshore areas.

In the northern sub-basin, the interval ~ 23 – 11 Ma comprises U-SLN2-1 and U-SLS2-2 (see also Fig. 6.17, Panel B). U-SLN2-1, deposited from ~ 23 – 15 Ma, is solely present at Parara Anticline and Tauru High. This implies that deposition was localised in depressions. Non-deposition of U-SLN2-1 strata south of Tauru High implies a lack of depocentre, potentially from lack of accommodation space on the footwalls of Parara Anticline or Tauru High. Additionally, during this time, the ACC was unimpeded by topography in the southern sub-basin during deposition of U-SLN2-1, causing re-transportation of strata of this age (Fig. 6.18, Panel B). If Puysegur Ridge acts as a barrier to ACC flow, similar to the Macquarie Ridge Complex to the south (e.g. Schuur et al., 1998), it implies that Puysegur Ridge was not developed at ~ 15 Ma.

U-SLN2-2, on the other hand, is a noticeably thicker sedimentary unit at Parara Anticline and north of Tauru High (Fig. 5.1). It was deposited from ~ 15 Ma to ~ 11 Ma; its deposition indicates a significant increase in sedimentation rates after deposition of U-SLN2-1 (i.e. after ~ 15 Ma). Its correlative unit south of Tauru High, U-SLS1-1, is much thinner and is locally folded. U-SLS1-1 strata are mappable to Puysegur Ridge (Figs. 5.6 and 5.7), which implies that Puysegur Ridge has begun to develop after ~ 15 Ma. Contrasting with U-SLN2-1, the presence of U-SLS1-1 strata south of Tauru High indicates that growth of Puysegur Ridge provided sufficient impedance of the ACC, which in turn allowed for deposition and preservation of U-SLS1-1 strata.

6.5.3 11–5 Ma

During the late Miocene and early Pliocene, sediments became folded and thrust up above sea level (e.g. Sutherland et al., 2009). Offshore basins were still subsiding irrespective of onshore uplift in locations like the Fiordland Margin (Sutherland et al., 2009): this is due to compressive development of the Pacific-Australian plate boundary further to the west of Fiordland (Sutherland et al., 2006), as well as accommodation of plate motions by the Moonlight and Hollyford

Fault Systems to the north (see Fig. 1.2, Turnbull et al., 1993). The late Miocene saw reactivation of normal faults as compressional features (see sections 6.3 and 6.4, and Fig. 6.18, Panel B).

Late Miocene onshore sediments are characterised by terrestrial deposition, typically in lacustrine and swampy settings (Norris and Turnbull, 1993; Turnbull et al., 1993). Major onshore sediment sources in the north imply north to south sediment flow to offshore basins. Maximum uplift of Hump Ridge north of Stewart Island occurred (Fig. 6.18, Panel B), and continued growth of the Parara and Solander Anticlines saw mass flow deposits sourced from these structures (Turnbull et al., 1993). At Parara-1, U-SLN3-1 channelisation southwest of the anticline is observed, a result of the topographic low created from uplift (see section 6.3; Fig. 6.15). At Parara-1 and Solander-1, shelfal muds dominate the late Miocene-earliest Pliocene sequence (Hunt International Petroleum Company, 1976; Engmann and Fenton, 1986), which may be attributed to continued subsidence of offshore basins.

In the northern sub-basin, this time interval is composed of U-SLN3-1 and U-SLN3-2 strata. U-SLN3-1 was deposited from ~ 11 Ma to ~ 7 Ma, and U-SLN3-2 from ~ 7 Ma to ~ 5 Ma. At Tauru High, U-SLN3-1 strata are of note as the equivalent units south of Tauru High, U-SLS2-1, U-SLS2-2 and U-SLS2-3, encompass the same time interval as U-SLN3-1. As per section 6.4, this represents a significant increase in accommodation space south of Tauru High, indicating that there were several kilometres of accommodation space creation to the south during deposition of these three units. The presence of U-SLS2-1, U-SLS2-2 and U-SLS2-3 at Puysegur Ridge, suggests deposition during Puysegur Ridge growth. This means that Puysegur Ridge was continually developing from ~ 11 Ma to ~ 3 Ma.

6.5.4 5 Ma–present

During the Pliocene to Pleistocene, uplift in the modern onshore setting shaped modern topography (Sutherland et al., 2009; Turnbull et al., 1993, see also Fig. 6.18, Panel A). Along with Solander Island and Little Solander Island (Reay and Parkinson, 1997), other subduction-related volcanism included submarine Pliocene volcanics imaged on seismic data west of the offshore Moonlight Fault System (Sutherland et al., 2006). Further to the south, the Snares Zone

marks a change from strike-slip faulting on the Puysegur Fault, south of 47°S, to subduction at the Puysegur Trench (Lamarche and Lebrun, 2000). Uplift is ongoing to the present day (e.g. Kim and Sutherland, 2004).

Terrestrial to shallow marine Pliocene claystones and sandstones in the onshore region are restricted to Te Anau and Waiau Basins. These deposits unconformably underlie Pleistocene glacial sediment, though raised beach deposits in the southern Waiau Basin overlie these Pliocene strata (Turnbull et al., 1993). Glacial scouring shaped onshore ranges like Fiordland and Caples Terrane (Norris and Turnbull, 1993, see also Fig. 1.2). Pliocene to Pleistocene sediments at Parara-1 comprise deepwater claystones and siltstones (Hunt International Petroleum Company, 1976). Interestingly, a Pliocene-Recent sequence was not encountered at Solander-1 which has been attributed to "...uplift and erosion" by Engmann and Fenton (1986).

In the northern sub-basin, this time period comprises U-SLN4-1, U-SLN4-2 and U-SLN4-3. These units were deposited from ~ 5 Ma to ~ 3 Ma, ~ 3 Ma to 2 Ma and ~ 2 Ma to the present, respectively. The onset of reverse reactivation of the Solander Fault occurs at ~ 5 Ma, which is evidenced by channelisation of U-SLN4-1 strata, likely within a topographic low created by uplift (similar to U-SLN3-1 strata). SLN4 strata are rich in foraminifera at Parara-1 (Hunt International Petroleum Company, 1976); reflections within these units are also low amplitude and continuous. These observations indicate hemipelagic sedimentation (Sangree and Widmier, 1977). U-SLN4-3, shaped by modern-day processes, shows evidence of fluid escape structures (Fig. 6.14) and active channelisation (Fig. 6.5). Also, on the modern-day continental shelf (Fig. 6.12 and Fig. 6.13), stacked clinoforms indicate shelf progradation during deposition of this unit. Correlatives of these strata south of Tauru High are U-SLS3-1 and U-SLS3-2, deposited from ~ 5 Ma to ~ 3 Ma and ~ 3 Ma to ~ 2 Ma, respectively. Active channelisation, sedimentation and erosion of these strata is discussed in section 6.2.2. In Appendix 4, Fig. 4A-2 also shows active sedimentation and erosion. U-SLS3-1 onlaps strata uplifted on Puysegur Ridge (Fig. 5.7), suggesting that a new phase of significant folding and uplift of Puysegur Ridge occurred at ~ 5 Ma. U-SLS3-2 onlaps U-SLS3-1 on this line; this suggests that by ~ 3 Ma, the eastern margin of Puysegur Ridge was significantly uplifted and deposition is now preferentially on the basin floor, due to the previously mentioned increased impedance of the ACC by Puysegur Ridge.

Chapter 7

Conclusions

This study has provided new geologic insights into the evolution of Solander Trough. The thesis objectives outlined in section 1.7 have all been addressed.

7.1 Thesis Objectives

1. Reprocessing of Line P1

In Chapter 3, 2D seismic reflection data acquired during voyage EW9601a in 1996 were reprocessed prior to and during MGL1803. The processing sequence has resulted in a seismic section of superior quality to the original results of Melhuish et al. (1999).

2. Acquisition and processing of 2D seismic reflection data

Chapter 4 covered the acquisition and processing of 2D seismic reflection acquired during voyage MGL1803 in 2018. These data provided the first seismic data tie from northern pre-existing petroleum industry seismic and well data to Solander Trough, south of $\sim 46.5^{\circ}\text{S}$.

3. Seismic stratigraphy of Solander Trough

The first seismic stratigraphic analysis of Solander Trough was achieved by combining MGL1803 2D seismic reflection, petroleum industry seismic reflection and petroleum well data (Chapter 5). A northern sub-basin and southern sub-basin stratigraphy is defined. Four megasequence boundaries and eight sequences are defined in the northern sub-

basin; in the southern sub-basin, three megasequences boundaries and seven sequences are mapped.

4. Depositional model and basin history for Solander Trough

Discussion of Parara Anticline evolution provided depositional ages of seismic units. Analysis of Tauru High growth enabled age correlations of seismic units in the northern sub-basin to seismic units in the southern sub-basin.

Modern and past depositional processes were elucidated using seismic and high resolution swath bathymetry data. Combining these datasets with age-determined seismic stratigraphy provided a regional basin synthesis for Solander Trough. It was found that Solander Trough is a geologically young ($< \sim 15$ Ma) sedimentary depocentre. Depositional sequences in the southern sub-basin have been influenced by interactions of terrestrial and biogenic sediment supply with current action and tectonics, namely the interaction between the ACC and Puysegur Ridge.

7.2 Recommendations for Future Work

The results presented lay a foundation for exciting future work in Solander Trough. Some potential future avenues include natural resource extraction (petroleum, manganese mining etc.), subduction initiation mechanisms (in the process of currently unpublished work by Gurnis et al.) and Integrated Ocean Discovery Program (IODP) drilling. IODP drilling remains a hopeful prospect for future work, especially for sampling the shallow sedimentary sequence present on Puysegur Ridge. Providing further age control to data acquired during MGL1803 would be a valuable venture and would help further understanding of Solander Trough evolution.

Appendices

1 Appendix: Introduction

Fig. 1A-1: New Zealand geological stages, for the Jurassic to present. Adapted from Institute of Geological and Nuclear Sciences (2015)

Acquisition	Hunt PR556	NZPET70	Mobil72	Hunt A	Hunt B	Hunt D
Vessel	M/V Teledex	?	?	Aquatic Explorer	Aquatic Explorer	Aquatic Explorer
Year	1969	1970	1972	1970 - 1971	1972	1972 - 1973
Source	Hunt PR556	NZPET70	Mobil72	Hunt A	Hunt B	Hunt D
Source type	sparker	airgun array	airgun array	Aquapulse	Aquapulse	Aquapulse
Source volume (in ³)	N/A (120 kJ)	40 - 160	?	N/A	N/A	N/A
Source depth (m)	?	?	10.6	8	8	8
Shotpoint interval (m)	?	?	12 s	22	23	22
Recording	Hunt PR556	NZPET70	Mobil72	Hunt A	Hunt B	Hunt D
Record length (s)	4	5*	6	6	6	6
Sample Interval (ms)	?	2 - 4	?	4	4	4
Fold	?	1 - 6	3	12	12	12
Cable	Hunt PR556	NZPET70**	Mobil72	Hunt A	Hunt B	Hunt D
# Groups	100	1 ?	?	24	24	24
Group Spacing (m)	?	N/A 70.1	100	22	22	22
Near Offset (m)	?	? ?	301.8	297	297	297
Far offset (m)	?	? ?	804.7	1830	1907	1830
Tow Depth (m)	?	? ?	?	16	12	16
Streamer Length (m)	?	? ?	?	1600	1600	1600
Publications	PR556	PR538	PR738	PR558, PR934	PR620	PR620, PR934

Table 1A-1: Summary acquisition parameters for the "vintage surveys". Publications where further information can be found is provided. *Record length here is that shown in seismic data. **Some lines shot as single channel. ?'s refer to unknown data

Acquisition	S82	S84	Solander-85	S86	LM06
Vessel	M/V Geco Kappa	Western Odyssey	M/V Yardie Creek	M/V Grant Mariner	M/V Pacific Titan
Year	1982	1984	1984	1986	2006
Source	S82	S84	Solander-85	S86	LM06
Source type	Airgun array	Airgun array	sparker	Airgun array	Airgun array
Source energy (in ³)	2520 (20 guns)	1530 (20 guns, 4 sub-arrays)	27 kJ	3000 (18 guns, 3 sub-arrays)	3040 (26 guns)
Source depth (m)	6.5	6	3	7	4
Shotpoint interval (m)	25	26.67	7.62	25	25
Recording	S82	S84	Solander-85	S86	LM06
Record length (s)	5	6	2	6	8
Sample Interval (ms)	2	2	1	2	2
Fold	48	60	24	60	40
Cable	S82	S84	Solander-85	S86	LM06
# Groups	96	240	24	120	324 480
Group Spacing (m)	25	26.67	15.24	25	12.5
Near Offset (m)	270	197	50	150	130
Far offset (m)	2651	3370.33	400.52	3125	4350 6000
Tow Depth (m)	13	12 $\pm$ 2	4.5	6 - 9.1	7
Streamer Length (m)	2400	3200 m	365.76	3000	4050 6000
Publications	PR912	PR1027	PR1121	PR1165	PR3397

Table 1A-2: Summarised acquisition parameters for the S82, S84, Solander-85, S86 and LM06 surveys

2 Appendix: Voyage EW9601a

2.1 Line P1 processing, employed by Melhuish et al. (1999)

Process description
1. Resample to 4 ms
2. Edit bad/dead traces
3. Static shift to correct for gun-receiver depth
4. Fill in missing traces to ensure standard geometry before CDP sort
5. Receiver array simulation - 1:3:1 mix of adjacent receivers
6. Gain recovery using spherical divergence correction
7. Wide bandpass filter (1-4-80-90 Hz) before deconvolution
8. Wiener deconvolution, gap 128 ms, operator length 500 ms
9. Wiener deconvolution, gap 28 ms, operator length 200 ms
10. Frequency filter (5-8-25-30 Hz)
11. Sort to CMP domain
12. NMO velocities from semblance plots (every 1.25 km)
13. Whole trace balance before stack
14. Surgical front mute for shallow seafloor areas
15. Polygonal inner trace mute for multiple attenuation
16. Stack (40 fold)
17. Wiener deconvolution (100 ms gap, 500 ms operator)
18. Wiener deconvolution (200 ms gap, 800 ms operator)
19. Frequency filter (5-10-25-35 Hz)
20. 5 trace weighted running mix as coherency filter
21. Resample to 8 ms and 2:1 trace sum prior to migration
22. Finite difference migration
23. 2 s AGC
24. Display

Table 2A-1: Processing sequence for Line P1 employed by Melhuish et al. (1999)

2.2 Processing sequence employed in this thesis

EW9601_prevoyage.job			
01 SEISJOB		02 READSEGY	
Parameter name	Value ascribed	Parameter name	Value ascribed
Linenum	pateljite1	Segyfile	[segd name].sgy
ProcID	pateljite1	PKeyname	ShotID
JCS_Tail	_<SEQnum>	SKeyname	Channel
SEP_Logs	Yes	RecType	None
		Int_Format	IBM
		Flt_Format	IBM
		TrLength	16382
		SampRate	2
03 TREMOVE		04 TREMOVE	
Parameter name	Value ascribed	Parameter name	Value ascribed
Keyname	FTrace	Keyname	TrType
Keylist	2-160	Keylist	2 3 4 5 6 7 8
Action	Keep	Action	Remove
05 SETLASTTR		06 XVIEW	
Parameter name	Value ascribed	Parameter name	Value ascribed
PKey	ShotID	FoldMode	Single
		N_ENS	160
07 WRITESEGY		DispType	Beside
Parameter name	Value ascribed	PseudoTrace	No
Filename	[segd name]_converted.sgy	Mix_Seismic	No
Revision_1	No	HScale	4
Format	IBM	VScale	2.5
Endian	Big	Mode	VAWG
RecType	None	HDR_Labels	ShotID Channel
AmpScale	1	HDR_Freqs	1 10
RCommand	stdinsegy	Colours	0.0 0.0 17 32

Table 2A-2: Explanation of parameters used in EW9601_prevoyage.job modules. Summarised steps are shown in Table 3.2

EW9601_shot_writesegy.job	
01 SEISJOB	
Parameter name	Value ascribed
Linenum	pateljitel
ProcID	_ <SEQnum>
JCS_Tail	Yes
SEP_Logs	
02 READSEGY	
Parameter name	Value ascribed
listfile	Line_P1.sfl
PKeyname	ShotID
SKeyname	Channel
RecType	None
Int_Format	IBM
Flt_Format	IBM
TrLength	16382
SampRate	2
03 WRITESEGY	
Parameter name	Value ascribed
Filename	Line_P1.sgy
Revision_1	No
Format	IBM
Endian	Big
RecType	None
AmpScale	1
RCommand	stdinseg

Table 2A-3: Explanation of parameters used in EW9601_shot_writesegy.job modules. Summarised steps are shown in Table 3.3

Job: ew9601_geometry.dat		
Module	Parameter	Value
MKDATA	Sample rate	4 ms
	Record ength	6 s
	Data start time	0 s
MARINE	Channels per shot	161
	Near channel #	161
	Near trace offset	25.9 m
	Receiver spacing	25 m
	Shot interval	50 m
	Starting shot #	51900

Table 2A-4: Explanation of parameters used in ew9601_geometry.dat modules. Summarised steps are shown in Table 3.4

Job: GIN		
Module	Parameter	Value
GIN	Sample rate	2 ms
	Traces per ensemble	161
	Sort Key	SHOT
	Data read direction	INCR*
	Tape Format	SEGY
	Header entry name	SHOT
	Byte location	17
	Byte length	4
	Header format	INT**
DSOUT	Output fine name	ew9601-plc_shots.sgy

Table 2A-5: List of modules and parameters in the "GIN" job. Summarised steps are shown in Table 3.5. *=incrementing; **=integer

Job: ew9601_p1c_edit_decon_sort.dat		
Module	Parameter	Value
DSIN	Input file	ew9601-p1c_shots.sgy
	Shot list	52123 - 58230
GEOMLD	RadN	99999
	RadP	N/A
	Keyname	shot
	StaType	Normal
EDIT*	Shot	
	Channel	
	Channel	*range*
	CDP	
FILTER	Butterworth	5 2 85 2
RESAMP	Sample rate	4 ms
	Record length	16 s
REGLO	XGate	200 cdps
	MaxDip	700 us
	Fmax	80 Hz
	SKeyMin	-4026
	SKeyInc	25
	NSKey	161
GAIN	Velocity function	stacking_stef
	SphDiv	t ^{1.5}
HEADPUT	Defines seafloor start time for decon	
HDRMATH	Applies header info and math operations	
STATIC	Offtime (remove)	-500 ms
MCDECON	Gap Length	75 ms
	Op. length	450 ms
	Design window	3500 ms
	App. window	0–16 s
	Gap Length	24 ms
	Op. Length	450 ms
	Design Window	3500 ms
	Application Window	0–16 s
SORT	Max # Traces/ensemble	200
	Sort Key	CDP
DSOUT	Output file name	ew9601-p1c_decon_cdps.sgy

Table 2A-6: Explanation of parameters in "ew9601_p1c_edit_decon_sort.dat" job modules. Summarised steps are shown in Table 3.6. * see <https://bit.ly/2ZF4SP0> for a full list of removed traces

Job: ew9601-p_velocity.dat		
Module	Parameter	Value
DSIN	Input file	ew9601-p1c_steffen_decon_cdps.sgy
	CDP list	795–24805
	CDPs per group	15
	CDP increment	200
FILTER	Filter type	Butterworth
	Phase	Zero
	frequencies	0 5 35 3
AGC	1000 ms sliding window AGC	
VELDEF	Output file name	stacking_stef

Table 2A-7: Explanation of parameters used in "ew9601-p_velocity.dat". Summarised steps are shown in Table 3.7

Job: ew9601-radonstack.dat		
Module	Parameter	Value
DSIN	Input file	ew9601-p1c_steffen_decon_cdps.sgy
	CDP list	705 - 25001
NMO	Velocity function	stacking_stef
NMO OVCAPP	Sample trace time to apply overcorrection	500 1500 2500 4500 7000 (ms)
	Offset at which to apply overcorrection	4200 4200 4200 4200 4200 (ms)
	Amount of overcorrection to apply	1500 1000 300 200 100 (ms)
HDRMATH	Header info and math operations	
RADNPAR	Forward	Transforms data to the tau-p domain
	Max. offset	4026 m
	# parabolas for use in the transform	300
	Min. moveout at max. offset	100 ms
	Max.moveout at max. offset	1000 ms
	Start-end times for operation	0–16000 ms
	Inverse	Re-transforms data to x-t domain, with a 50 ms ramp length
DSOUT	Output file name	EW9601_p1_radon_cdps
GOUT	Output file name	EW9601_p1.radon.cdps.segy

Table 2A-8: Explanation of parameters used in "ew9601-radonstack.dat" modules. Summarised steps are shown in Table 3.8

Job: ew9601-steffen_radonstack.dat		
Module	Parameter	Value
DSIN	Input file CDP list	ew9601-p1c_steffen_radon_cdps.sgy 705 – 25001
GAIN (removal)	Velocity model applied pre-gain	stacking_stef
	removes velocity cmpt of sph. div. correction	-2
	removes time cmpt of sph. div. correction	-1
GAIN (application)	Applies a scalar multiplier for traces	$t^{1.5}$
NMO	Applies NMO	stacking_stef
MUTE	Applies an NMO stretch mute (stored in trace header)	ssmute
MUTE	Applies an inner trace mute	INSIDE_MUTE
STACK	Stacks traces in CDPs	N/A
HDRMATH	Applies header info and math operations	
MUTE	Restores NMO stretch mute (from trace headers)	
MUTE	Restores inner trace mute (from trace headers)	

Table 2A-9: Explanation of parameters used in "ew9601-steffen_radonstack.dat" job (DSIN-MUTE). Summarised steps are shown in Table 3.9

Job: ew9601-steffen_radonstack.dat (continued)		
Module	Parameter	Value
FILTER*	static time = 100 ms	
	0 – 1000 ms application	5 - 95 Hz filter - 12 db/octave taper
	3000 – 5000 ms application	5 - 65 Hz filter - 12 db/octave taper
	8000 – 14000 ms application	5 - 40 Hz filter - 12 db/octave taper
	static time = 3000 ms	
	0 – 3500 ms application	5 - 95 Hz filter - 12 db/octave taper
	4500 – 5500 ms application	5 - 65 Hz filter - 12 db/octave taper
	8000 – 14000 ms application	5 - 40 Hz filter - 12 db/octave taper
	static time = 5000 ms	
	6000 – xxx ms application	5 - 95 Hz filter - 12 db/octave taper
	7000 – 7500 ms application	5 - 60 Hz filter - 12 db/octave taper
	9000 – 14000 ms application	5 - 40 Hz filter - 12 db/octave taper
MUTE	Restores NMO stretch mute (from trace headers)	
HDRMATH	Applies header info and math operations	
DSOUT	Output file name	EW9601-p1c.decon.radon.velstack
GOUT	Output file name	EW9601-p1c.decon.radon.velstack.segy

Table 2A-9: Explanation of parameters used in "ew9601-steffen_radonstack.dat" modules (FILTER-GOUT). Summarised steps are shown in Table 3.9

Job: ew9601-steffen_radonstack.dat (continued)		
Module	Parameter	Value
MIGDMO	USERVEL – Time Velocity pairs	0 1500, 100 1500, 1000 1500, 2000 1500, 5000 1500 8000 1500, 10000 1500, 12000 1500, 14000 1500
MUTE	Restores inner trace mute (from trace headers)	
DSOUT	Output file name	EW9601-p1c.decon.radon.velstack.fkmig
GOUT	Output file name	EW9601-p1c.decon.radon.fkmig.segy
AGC	1000 ms sliding window AGC	
GOUT	Output file name	EW9601-p1c.decon.radon.fkmig.agc.segy

Table 2A-9: Explanation of parameters used in "ew9601-steffen_radonstack.dat" modules (FILTER-GOUT). Summarised steps are shown in Table 3.9

3 Appendix: Voyage MGL1803

The user is referred to Echos by Paradigm internal help for detail explanation and requirements for each module hitherto described.

Job: MCSXXX_SEGD ¹		
Module	Parameter	Value
SEGD	Sample rate	2 ms
	Record length	14 - 16 s ¹
	# Channels	324 - 1008 ¹
	Data format (8058)	Demultiplexed 64-bit IEEE format
RESAMP	Sample rate	4 ms
	Record length	14 - 16 s ¹
DSOUT	Output file name	MCSxxx.shots ²
GOUT	Output file name	MCSxxx.segy ²

Table 3A-1: Explanation of parameters used in MCSxxx_SEGD¹ modules. Summarised steps are shown in Table 4.2. ¹ xxx refers to line number; ² see Table 4.1 for acquisition parameters

Job: MCSxxx_geometry.dat ¹		
Module	Parameter	Value
MKDATA	# shots	xxx ²
	# channels ³	324 - 1008
	Group interval	12.5 m
	Shot spacing	50 m
	First Shot #	xxx ²
VFNDEF	Stores time/velocity pairs into the vertical function repository	0 1500, 1000 1500, 2000 1500, 3000 1500, 5000 1500, 10000 1500, 15000 1500
VFNDEF	Stores time/velocity pairs for certain CDPs, into the vertical function repository.	Model name: brutestack_vels_seafloor
VFNDEF	Direct wave mute file name	DWAVE_MUTE
VFNDEF	Brute mute file name	BRUTE_MUTE
VFNDEF	Inside mute file name	INSIDE_MUTE

Table 3A-2: Explanation of parameters used in MCSxxx_geometry.dat¹ modules. Summarised steps are shown in Table 4.3.¹ xxx refers to line number; ² shot range varies by line; ³ see Table 4.1 for acquisition parameters

Job: MCSxxx_brute_stack.dat ¹		
Module	Parameter	Value
DSIN	Input file name	MCSxxx.shots ¹
	Shot list	x-x ²
	Supergath. Channels	1-200
EDIT	Shot range	1-99999
	Removed channels	1, 13, 21, 45, 93, 109, 117
HDRMATH	Header info and math operations	
FILTER	Butterworth	5-85 Hz, 12 db/octave taper
GEOMLD	Radius for trace spacing	6.25 m
	Radius for CDP designation	8000 m
SORT	Trace per CDP	400
	Offset order	600000
NMO	Velocity model	brutestack_vels_seafloor
MUTE	Brute mute name	BRUTEMUTE
STACK	Stacks data in CDPs	
DSOUT	Output file name	MCSxxx.brutestack ¹

Table 3A-3: Explanation of parameters used in MCSxxx_brute_stack.dat modules. Summarised steps are shown in Table 4.4. ¹ xxx refers to line number, ² shot range varies by line

Job: MCSxxx_cdpsort.dat ¹		
Module	Parameter	Value
DSIN	Input file name	MCSxxx.shots ¹
	Shot list	x – x ²
GEOMLD	Radius for trace spacing	6.25 m
	Radius for CDP designation	8000 m
EDIT	Shot range	1 – 99999
	Removed channels	1, 13, 21, 45, 93, 109, 117
HDRMATH	Header info and math operations	
FILTER	Butterworth	7–85 Hz 12 db/octave taper
DEBIAS	Removes DC bias from data	
	Equals the fold and regularises traces	
REGLO	Size of spatial gate for coherency analysis	100
	Maximum dip of traces	1000 us/trace
	Length of coherency smoothing wavelet	120 ms
GEOMLD	Radius for trace spacing	6.25 m
	Radius for CDP designation	8000 m
HEADPUT	Applies header info	
GAIN	Applies a spherical divergence correction	t ^{1.5}
HDRMATH	Header info and math operations	
STATIC	Applies a static shift to seismic data	-500 ms
MCDECON	Gap Length	75 ms
	Op. Length	450 ms
	Design Window	3500 ms
	Application Window	0–14/16 s ³
	Gap Length	24 ms
	Op. Length	450 ms
	Design Window	3500 ms
	Application Window	0–14/16 s ³
STATIC	Removes static shift from seismic data	-500 ms
SORT	Trace per CDP	400
	Offset order	600000
DSOUT	Output filename	MCSxxx.decon.cdps ¹
GOUT	Output filename	MCSxxx.decon.cdps.segy ¹

Table 3A-4: Explanation of parameters used in MCSxxx_brute_stack.dat modules. Summarised steps are shown in Table 4.5. ¹ xxx refers to line number; ² shot list varies by line; ³ see Table 4.1 for acquisition parameters

Job: MCSxxx_veldef.dat ¹		
Module	Parameter	Value
DSIN	Input file	MCSxxx.decon.cdps ¹
	CDP Range	x - x ²
	Supergather	8 CDPs
	CDP increment	1000/500/250
MUTE	Direct wave mute application	DWAVE_MUTE
Butterworth filter application		
FILTER	0–2 s	8–50 Hz
	4–14/16 s ³	8–35 Hz
AGC	300 ms sliding window	AGC
VELDEF	Output file name	MCSxxx_stackvels ¹

Table 3A-5: Explanation of parameters used in MCSxxx_veldef.dat modules. Summarised steps are shown in Table 4.6. ¹ xxx refers to line number; ² CDP range varies for velocity model picks; ³ see Table 4.1 for acquisition parameters

Job: MCSxxx_radon.dat ¹		
Module	Parameter	Value
DSIN	Input file name	MCSxxx.decon.cdps.sgy ¹
HDRMATH	Header info and math operations	
HDRMATH	Header info and math operations	
MUTE	Applies a direct wave mute	DWAVE_MUTE
NMO	Velocity file	MCSxxx_stackvels ¹
MUTE	Applies NMO stretch mute	MCSxxx_stackmute ¹
NMO OVCAPP	Applies an NMO overcorrection	
RADONPAR	Forward	Transforms data to tau-p domain
	Maximum offset within data	4026/12800 m ²
	# ensembles within a supergather for forward transform	1
	Reference offset for moveout computations	4026/12800 m ²
	# parabolas for use in the transform	300
	Min. moveout at max. offset	200 ms
	Max. moveout at max. offset	2500 ms
	Start – end times for operation	0 – 14/16 s ²
	Inverse	Re-transforms data to x-t domain, with a 50 ms ramp length
FKFILT	Dip filter taper %	25 %
	Low frequency protection	5 Hz
	Lower dip range for rejection	0.572 ms/trace
	Upper dip range for rejection	0.888 ms/trace
NMO	Removes NMO overcorrection	
NMO	Removes NMO corrections, prior to migration	MCSxxx_stackvels ¹
DSOUT	Output file name	MCSxxx.decon.radon.cdps ¹
GOUT	Output file name	MCSxxx.decon.radon.cdps.sgy ¹

Table 3A-6: Explanation of parameters used in MCSxxx_radon.dat modules. Summarised steps are shown in Table 4.7. ¹ xxx refers to line number; ² see Table 4.1 for acquisition parameters

Job: MCSxxx_Radon_stack ¹		
Module	Parameter	Value
DSIN	Input file	MCSxxx.decon.radon.cdps.sgy ¹
VFNDEF	Removes inside mute	INSIDE_MUTE
NMO	Applies NMO	MCSxxx_stackvels ¹
MUTE	NMO stretch mute	MCSxxx_stackmute ¹
MUTE	Removes inside mute	INSIDE_MUTE
STACK	Stacks traces in CDPs	N/A
HEADPUT	Applies header info	
MUTE	Restores inner mute	INSIDE_MUTE

Table 3A-7: Explanation of parameters used in MCSxxx_Radon_stack.dat" modules (DSIN-MUTE). Summarised steps are shown in Table 4.8. ¹ xxx refers to line number

Job: MCSxxx_Radon_stack ¹ (continued)		
Module	Parameter	Value
FILTER	static time = 100 ms	
	0–1000 ms application	5–95 Hz filter, 12 db/octave taper
	3000–5000 ms application	5–65 Hz filter, 12 db/octave taper
	8000–14000/16000 ms application ²	5–40 Hz filter, 12 db/octave taper
	static time=3000 ms	
	0–3500 ms application	5 – 95 Hz filter, 12 db/octave taper
	4500–5500 ms application	5 – 65 Hz filter, 12 db/octave taper
	8000–14000/16000 ms application ²	5- 40 Hz filter, 12 db/octave taper
	static time=6000 ms	
	0–6000 ms application	5–95 Hz filter, 12 db/octave taper
	7000–7500 ms application	5–60 Hz filter, 12 db/octave taper
	9000–14000/16000 ms application ²	5–40 Hz filter, 12 db/octave taper
MUTE	Restores mute	
HDRMATH	Applies header info and math operations	
MUTE	Restores mute	
MUTE	Restores mute	
HDRMATH	Applies header info and math operations	
DSOUT	Output file name	MCSxxx.decon.radon.velstack ¹
GOUT	Output file name	MCSxxx.decon.radon.velstack.segy ¹

Table 3A-8: Explanation of parameters used in MCSxxx_Radon_stack.dat" modules (FILTER-GOUT). Summarised steps are shown in Table 4.8. ¹ xxx refers to line number. ² see Table 4.1 for acquisition parameters

Job: MCSxxx_Radon_stack ¹ (continued)		
MIGDMO	Min. # CDPs in the data	50000
	# of traces used each common offset, controls migration swings	50000
	Distance between traces	12.5 m
	USERVEL – Time Velocity pairs	0 1480, 100 1480, 1000 1480, 2000 1480, 5000 1480, 8000 1480, 10000 1480, 12000 1480
MUTE	Restore mute	
DSOUT	Output file name	MCSxxx.decon.radon.velstack.fkmig ¹
GOUT	Output file name	MCSxxx.decon.radon.velstack.fkmig.segy ¹
AGC	1000 ms sliding window AGC	
GOUT	Output file name	MCSxxx.decon.radon.fkmig.agc.segy ¹

Table 3A-9: Explanation of parameters used in MCSxxx_Radon_stack.dat modules (MIGDMO-GOUT). Summarised steps are shown in Table 4.8. ¹ xxx refers to line number

4 Appendix: Discussion

Fig. 4A-1: Locations of swath images discussed in section 6.2. Triangles=Tasman Sea; stars/squares/inverted triangles=Solander Trough; circles=modern shelf and slope; diamonds=features observed only in swath (see Fig. 4A-2. Faults are displayed as thin black lines)

Fig. 4A-2: Erosion on the Campbell Plateau (Panel A) and a topographic high (Panel B). Explanation for Panel A is as for Fig. 6.3. The topographic high in Panel B is a potential source of sediment (shown by the dashed white arrow, see Fig. 6.18)

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