Stratigraphic development and petroleum prospectivity of northern Zealandia

By

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Abstract

Northern Zealandia lies between Australia, New Zealandia, and New Caledonia. It has an area of 3,000,000 km² and is made up of bathymetric rises and troughs with typical water depths of 1000 to 4000 m. I use 39,309 line km of seismic-reflection profiles tied to recent International Ocean Discovery Program (IODP) drilling and three boreholes near the coast of New Zealand to investigate stratigraphic architecture and assess the petroleum prospectivity of northern Zealandia.

Sparse sampling requires that stratigraphic and petroleum prospectivity inferences are drawn from better-known basins in New Zealand, Australia, New Caledonia, Timor-Leste and Papua New Guinea. Five existing seismic-stratigraphic units are reviewed. Zealandia Seismic Unit U3 is sampled near New Zealand and may contain Jurassic Muhiriku Group coals. Elsewhere, Seismic Unit 3 may have oil-prone equivalents of the Jurassic Walloon Coal Measure in eastern Australia; or may contain Triassic-Jurassic marine source rocks, as found in offshore Bonaparte Basin, onshore Timor-Leste, and the Papuan Basin in Papua New Guinea. Seismic Unit U2b (Mid-Cretaceous) is syn-rift and may contain coal measures, as found in Taranaki-Aotea Basin and New Caledonia. Seismic Unit U2a (Late Cretaceous to Eocene) contains coaly source rocks in the southeastern part of the study area, and may also contain marine equivalent carbonaceous mudstone, as found at Site IODP U1509. Unit U2a is transgressive, with coaly source rocks and reservoir sandstones near its base, and clay, marl and chalk above that provides a regional seal. Seismic Unit U1b (Eocene-Oligocene) is mass-transport complexes and basin floor fans related to a brief phase of convergent deformation that created folds in the southern part of the study area and regionally uplifted ridges to create new sediment source areas. Basin floor fans may contain reservoir rock and Eocene folding created structural traps. Seismic Unit U1a is Oligocene and Neogene chalk, calcareous ooze, and marl that represents overburden. Mass accumulation rates (MAR) and climatic temperatures were high in the late Miocene and early Pliocene, resulting in peak thermal maturity and hydrocarbon expulsion at ~3 Ma.

Approximately one-fifth of the region has adequate source rock maturity for petroleum expulsion at the base of Seismic Unit U2: Fairway Basin (FWAY), southern New Caledonia Trough (NCTS) and Reinga Basin (REIN). Plays may exist in either Seismic Unit U3 or U2, with many plausible reservoir-seal combinations, and several possible trapping mechanisms: unconformities, normal faults, folds, or stratigraphic pinch-out. The rest of the region could be prospective, but requires a source rock to exist within Seismic Unit U3, which is mostly unsampled and remains poorly understood.

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1 Introduction

1.1 Thesis aim, objectives and structure

The aim of my study is to investigate the classification and mapping of the stratigraphic architecture of northern Zealandia, and hence to provide an updated assessment of hydrocarbon prospectivity. This is achieved by (1) reviewing existing data and interpretations, (2) by analysing newly-acquired well-based data from the International Ocean Discovery Program (IODP) Expedition 371 (Sutherland, 2019a, Sutherland, 2019b, Sutherland et al., 2020), and (3) analysing the new seismic data collected as part of the TECTA and TAN1409 seismic-reflection voyages (Collot et al., 2016, Sutherland et al., 2014, Sutherland et al., 2017).

The stratigraphic succession preserved on the submerged northern Zealandia continent (Fig. 1.1) records the geological evolution of the southwest Pacific and potentially contains hydrocarbon or/and other mineral resources. My investigation of this succession is restricted to data collected by drilling and seismic-reflection methods (Burns, 1973a, Burns and Andrews, 1973, Sutherland et al., 2012, Sutherland et al., 2017).

The region's stratigraphic succession records three tectonic phases: Mesozoic Gondwana subduction margin, Cretaceous rift-drift, and Cenozoic subduction initiation and final burial (Bache et al., 2014a, Mortimer, 2004). The Gondwana subduction margin produced the basement rock consisting of continental fragments. The Gondwana subduction phase resulted in quartzose metasedimentary rocks, granitoids of Palaeozoic and Mesozoic age and lithic-rich metasedimentary rocks formed in a trench-slope environment. Sedimentary rock that was deposited in the marginal seas of Gondwana is very poorly sampled and understood. The Cretaceous rift phase involved intracontinental rifting and extension followed by seafloor spreading and the opening of the Tasman Sea. This period of widespread rifting resulted in normal faulting across northern Zealandia (Uruski and Wood, 1991, Collot et al., 2009, Strogon et al., 2017). Lastly, Cenozoic subduction-related deformation and volcanism has resulted in Eocene-Oligocene unconformity development and deformation of sediment (Sutherland et al., 2017, King, 2000b, Sutherland, 1995, Sutherland et al., 2010, Collot et al., 2008, Stagpoole and Nicol, 2008, Herzer et al., 1997, Herzer, 1995, Schellart et al., 2006).

Petroleum source rocks may occur within the Mesozoic succession of the Gondwana margin (Bache et al., 2014a). The Mesozoic succession in northern Zealandia is understood to contain coal-bearing sediments such as those identified in the Muhiriku Supergroup, New Zealand (Bache et al., 2014a, Cook et al., 1999, Suggate, 1990) and may be equivalent to Mesozoic successions in Queensland Australia, Papua New Guinea (PNG) and Timor-Leste (Brown et al., 1979, Charlton, 2002, Ingram et al., 1996, O'Brien et al., 1994, Peters et al., 1999). The Murihiku Supergroup rocks comprise Triassic to Jurassic volcanoclastic sandstone, mudstone, and thin bituminous coals. Strata were mostly deposited in non-marine conditions but intercalated shell beds indicate episodic marine flooding (Suggate, 1990, Cook et al., 1999). Similarly, organic-rich rocks have been found in the Jurassic Walloon Coal Measures and the Koukandowie Formation of Queensland, Australia (Ingram et al., 1996). The Walloon Coal Measures were deposited in fluvial and lacustrine environments (Ingram et al., 1996). Clay rich marine source rocks have been observed in the Late Jurassic Imburu Formation of western PNG containing terrigenous organic matter (Waples and Wulff, 1996). Similar aged source rocks have been identified in Timor-Leste, where the primary potential source rocks have been found in the restricted marine mixed carbonate and clastic sequence of Late Triassic age (Charlton, 2002).

Cretaceous sedimentation in northern Zealandia occurred in a series of rift basins, which formed during the break-up of eastern Gondwana and subsequent Paleogene events, which may have affected the petroleum accumulation in this region. Cretaceous rift basins may contain coaly sediment facies (petroleum source rocks) overlain by transgressive marine sandstone and mudstone (petroleum reservoir and seal rocks) (Bache et al., 2014a, King and Thrasher, 1996). During Cretaceous time, the region experienced transgression that resulted in early terrestrial deposits succeeded by a thick interval of non-marine and marine graben-filling sediments, including coastal and shelf sands and bathyal muds (Stagpoole et al., 2009). The Paleogene was characterised by deposition of fine-grained sediments and represents the passive filling of the basin after rifting. Paleogene tilting altered the petroleum migration pathways and created traps. These Cretaceous-Paleogene transgressive sedimentary rocks form the basis of well-known petroleum systems in the Gippsland and Taranaki basins (King and Thrasher, 1996).

Subduction initiation changed the geography, crustal thickness, and crustal composition across northern Zealandia (Sutherland et al., 2020), and caused 1-3 km elevation changes in the region. These changes may relate to crust delamination and mantle flow that led to slab formation (Sutherland et al., 2020, Sutherland et al., 2010). Subduction rupture triggered lithospheric-scale faults across northern Zealandia and further tectonic forces occurred as subducted slabs grew in size and hence changed the plate-motion. Widespread uplift was followed by subsidence and crustal deformation in response to the subduction initiation at the plate boundary (Sutherland et al., 2010). The resulting Eocene-Oligocene deformation affected some strata in the region which experienced folding and reverse faulting.

Based on the geological history of the region, I identify three components of study. Firstly, I identify 'acoustic basement' in the study area that may have petroleum source rock potential. Secondly, I review the rift-drift to subduction-related stratigraphic succession, to assess petroleum prospectivity. Finally, I analyse the maturity, migration, and potential charge that has occurred in a stable Neogene tectonic environment. An understanding of the sedimentary and oceanic system since the Oligocene in the study area is critical for this last objective.

The structure of the thesis is based on work components to address each objective. (1) Identify the acoustic basement from seismic reflection data and try to interpret the 'basement' in term of possible Gondwana origin because it may be an indication of source rock. (2) Review and improve the mapping and understanding of Cretaceous-Paleogene stratigraphic architecture, which is essential for assessment of the basic components of any petroleum system (source rocks, reservoir rocks, seal rocks and trapping mechanism). (3) Identify Cenozoic burial and maturity history from detailed mapping of as many reflectors where age control at boreholes can be confidently tied to seismic reflectors. The distribution of Cenozoic sediments may further reveal clues to the oceanographic, thermal evolution, current-controlled deposition history and sedimentary location since the Oligocene. (4) Conduct a petroleum system analysis of northern Zealandia and evaluate petroleum prospectivity of the region.

Figure 1.1. Northern Zealandia bathymetric map showing the location and distribution of seismic data (black lines = existing surveys & red lines = TAN1409 & TECTA survey) showing relationship of study area to east Australia and New Caledonia. Boreholes represent yellow circles and stars. Yellow star = IODP borehole; yellow circle = DSDP borehole.

1.2 Seismic reflection data

Seismic reflection data of the study area consist of multi-channel 2D data (1879 lines) (Fig. 1.1). I made detailed interpretations during this study of 217 seismic lines (39,309 line km; Fig. 1.2 and Table 1.1) covering $> 1,000,000 \text{ km}^2$ from the Challenger Plateau in the south, to north of Lord Howe Rise, including Fairway Basin, New Caledonia Trough and Norfolk Ridge (Fig. 1.2).

Seismic reflection surveys record seismic pulses returning to the surface after reflection off concealed interfaces. An acoustic impedance is the product of velocity and density, and seismic reflections arise at boundaries across which acoustic impedance changes. Reflection will not occur if the impedance does not change, even if there is a lithology change. The reflection will be stronger (higher amplitude) where there is a larger difference in acoustic impedance across the layer. The reflection coefficient (RC) is the ratio of incident to reflected amplitude and can be expressed for normal incidence as:

$$RC = \left(\frac{I_2 - I_1}{I_2 + I_1} \right)$$

Where I_1 and I_2 are impedances of the top and bottom layers.

I particularly focus on twelve surveys (see Table 1.1): 114 (Australian Geological Survey Organization), S206 (Australia Geological Survey Organisation), ZoNeCo-5 (IFREMER), lhrnr-b-nz (New Zealand UNCLOS program), 232 (Geoscience Australia/Service des Mines et de l'Energie), ZoNeCo-11 and Noucaplac-2 (French UNCLOS program), 302 (Geoscience Australia survey), STRAT09 (CGG Veritas Marine), and REI09 (CGG). New seismic surveys include the TAN1409 and TECTA surveys (Loubrieu et al., 2004, Lafoy et al., 1998, Collot et al., 2016). These seismic lines zig-zag from southwest to northeast crossing the Lord Howe Rise (Lord Howe Rise South & Lord Howe Rise North), Fairway Basin, Reinga Basin and New Caledonia Trough. Table 1.1 gives details of each survey (Fig. 1.2).

The TAN1409 voyage objective was to understand the process of subduction initiation and Paleogene climate (Sutherland et al., 2014). It surveyed six sites for IODP

Expedition 371 drilling (sites 1506-1511, Fig.1.1). The purpose was to document a detailed grid of high-resolution data at each potential IODP site.

The TECTA seismic survey was designed to link the TECTA voyage with existing surveys (Fig. 1.1) (Collot et al., 2016). The TECTA voyage was placed to connect Fairway Basin, Lord Howe Rise and Norfolk Ridge data with northern New Caledonia Trough, and hence to IODP sites and DSDP Site 206 (See Fig. 1.2 & Table. 1.1).

Table 1.1. Seismic acquisition parameters of seismic data used in this study (Sutherland et al., 2012).

Survey	Year	Line (Km)	Streamer Length (km)	Number of channels	Receiver immersion (m)	Source volume (cu)	Source type	Shot interval (m)
114	1992	756.2	3	120	15	3000	Airgun	50
GA-206	1998	3409	3.3	264	10	3000	First peak	50
ZoNeCo-5	1995	8554	6	6	7	N/A	First peak	50
Lhmr-b-nz	2000		N/A	N/A	N/A	N/A	Airgun	50
232	2001	2410	3	24	8	90	Airgun	50
ZoNeCo-11	2004	2606	4.5	360	15	8000	Single Bubble	150
Noucaplac-2	2004	1945	4.5	360	15	8000	Single Bubble	75
GA-302	2006-2007	5815	8	636	10	4140	Airgun	37.5
STRAT09	2008	1464	7.9	636	7	4140	Airgun	37.5
CGG-REI09	2009	5216	7.9	636	7	5000	Single bubble-bolt/mini GI	25
TAN1409	2014	1361.2	5	48	5	45/105	A single GI gun	25
TECTA	2015	5049	4.5	720	7	2690	Airgun	50

The quality of seismic data is variable. Multiple energy is a problem on many surveys. Seismic surveys across Fairway Basin vary from poor-quality single-channel lines to high-resolution, low penetration (1.5 s twt) six-channel seismic data acquired during the ZoNeCo-5 voyages (Rouillard et al., 2017). Reinga Basin has high-quality survey data collected in 2009.

Interpretation of seismic reflection data was performed on a workstation using SeisWare Geophysics (version 10.0). No bulk shifts were applied, because objectives were regional in nature.

1.3 Borehole data

Seismic reflectors were tied to Deep Sea Drilling Program (DSDP) Legs 21 and 90 (Fig. 1.3 & 1.4) (Burns, 1973a, Burns and Andrews, 1973, Kennett and von der Borch, 1986), International Ocean Discovery Program (IODP) Expedition 371 (Burns and Andrews, 1973, Sutherland et al., 2018a, Sutherland et al., 2012), and dredge and core samples (Fig. 1.1, Fig. 1.5).

DSDP Leg 21 drilled sites 206, 207 and 208 in September - December 1971 (Fig. 1.3) (Burns, 1973a, Burns and Andrews, 1973). Site U206 was drilled just east of a small-elongated rise on the deepest part of the southern section of New Caledonia Trough (Fig. 1.1). The location was parallel to the trend of Lord Howe Rise to the west and Norfolk Ridge to the east. Sites U207 and U208 were drilled on Lord Howe Rise (Fig.1.1).

Figure 1.3. Stratigraphic columns of DSDP Leg 21 (boreholes U206, U207 & U208). Adapted from (Burns and Andrews, 1973, Burns et al., 1973a, Burns et al., 1973b).

Site U206 was cored to a depth of 734 (mbsf) with a water depth of 3196 m (Fig. 13) (Burns, 1973a, Burns and Andrews, 1973). There were 67 cores obtained at Site U206. The stratigraphic succession was divided into four units. Unit 1 (0 – 389 mbsfs) contained early Miocene to Pleistocene nannofossil ooze with variable quantities of foraminifera and minor volcanic ash. Unit 2 (389 – 614 mbsf) was middle Oligocene to early Miocene semi-lithified clayey nannofossil ooze. Unit 3 (614 - 677 mbsf) was middle to late Eocene semi-lithified, radiolarian-rich nannofossil ooze. Unit 4 (677 – 734 mbsf) was early Palaeocene to middle Eocene nannofossil chalk and clay with minor chert.

Site U207 penetrated to a depth of 513 mbsf with a water depth of 1389 m (Fig. 13) (Burns, 1973a, Burns and Andrews, 1973). Fifty-five cores were collected (5 in hole 207 and 50 in hole 207A). Unit 1 (0 - 142 mbsf) comprised middle Miocene to Pleistocene foraminiferal nannofossil ooze and nannofossil foraminiferal ooze. Unit 2 (142 – 309 mbsf) was Palaeocene to middle Miocene foraminiferal and nannofossil ooze to foraminiferal-bearing nannofossil ooze and clayey nannofossil ooze or chalk with subordinate siliceous fossil-bearing foraminiferal-nannofossil ooze. Unit 3 (309 to 357 mbsf) was Maastrichtian glauconitic silty claystone (sandstone at the very base). Unit 4 (357 to 433 mbsf) was Upper Cretaceous rhyolitic (pumiceous) lapilli tuffs, and vitrophyric rhyolite flows that were more fragmented in part. Unit 5 (433 to 513 m) was Upper Cretaceous or older and Vitrophyric rhyolite flows, fragmented in part.

Site U208 penetrated to a depth of 594 mbsf in water depth 1545 m (Fig. 13) (Burns, 1973a, Burns and Andrews, 1973) and collected 34 cores. Unit 1 (0 to 488 mbsf) was late Oligocene to late Pleistocene unconsolidated to semi-lithified, foraminiferal nannofossil ooze to foraminiferal-rich nannofossil ooze with subordinate nannofossil foraminiferal ooze and foraminiferal-bearing nannofossil ooze. Unit 2 (488 to 594 mbsf) was composed of Late Cretaceous to middle Eocene siliceous fossil-bearing nannofossil chalk to nannofossil-bearing radiolarite or diatomite and chalk.

DSDP Leg 90 was conducted during December 1982 to January 1983 and recovered more than 3700 m of sediment cores from eight sites (587 - 594) (Kennett and von der Borch, 1986, Kennett et al., 1985) (Fig.1.1). The primary objective of Leg 90 was to define paleoceanographic history including the surface and bottom-water circulation pattern, and the biogeographic development of planktonic and benthic species (Kennett

and von der Borch, 1986, Kennett et al., 1985). Site U592 was drilled with the objective of comparing the sedimentation rate of calcareous biogenic ooze with other Leg 21 and 90 sites and of providing another late Neogene sequence of shallow-water benthic foraminifers (Fig. 1.4).

Figure 1.4. Stratigraphic columns of DSDP Leg 90 (boreholes U588, U589, U590, U591 & U592). Adapted from (Kennett et al., 1986a, Kennett et al., 1986b, Kennett et al., 1986c, Kennett et al., 1986e, Kennett et al., 1986d)

Site U588 was located very near (1.3 km) to DSDP Site 208 but had greatly superior core recovery in 4 holes (Fig. 1.4) (Kennett et al., 1986c). Hole 588 cored from 0 to 236 m sub-bottom. Hole 588A continued core from 236 to 344.4 m. Hole 588B cored from 0 to 277.4 m and Hole 588C was core from 305.7 to 488.1 mbsf. Site U588 penetrated to a depth of 488.1 mbsf with a water depth of 1533 m. The section was divided into two sedimentary units, based on color and composition. Subunit 1A (0-6.6 or 6.8 mbsf) was Quaternary grayish orange to yellowish brown foraminifer-bearing nannofossil ooze. Subunit 1B (6.6-250 mbsf) contained Quaternary to middle Miocene white to light gray foraminifer-bearing nannofossil ooze to nannofossil ooze. Subunit 1C (226-469 mbsf)

was middle Miocene to late Oligocene white to light gray to light greenish gray, foraminifer-bearing nannofossil chalk to nannofossil chalk. Unit 2 (469-488.1 mbsf) was middle Eocene light greenish gray siliceous foraminifer-bearing nannofossil chalk and chert.

Site U589 penetrated a depth of 36.1 mbsf in water depth 1391 m (Fig. 1.4) (Kennett et al., 1986d). The stratigraphic section was divided into two subunits that were distinguished by color, grain size and compaction. Subunit 1A (0-0.4 mbsf) contained late Pleistocene foraminiferal-nannofossil ooze of greyish orange color and had a coarse grain size. Subunit 1B (0.4- 36.1 mbsf) was early Pleistocene foraminiferal-nannofossil ooze to nannofossil ooze with colors of light greenish gray and pale olive to white and very light gray.

Site U590 was drilled to a depth of 449.1 mbsf in a water depth of 1299 m (Fig. 1.4) (Kennett et al., 1986a). The section was predominantly calcareous biogenic sediments and could be divided into three subunits. Subunit 1A (0-0.4 mbsf) was late Quaternary yellowish orange foraminifer-nannofossil ooze. Subunit 1B (0.4-280.8 mbsf) contained late Miocene very light gray foraminifer-bearing nannofossil ooze to light olive gray foraminifer-nannofossil ooze. Subunit 1C (278.1-499.1) late Miocene to early Miocene light gray foraminifer-bearing nannofossil chalk to recrystallized nannofossil chalk.

Site U591 penetrated to a depth of 500.4 mbsf in water depth 2131 m (Fig. 1.4) (Kennett et al., 1986e). The stratigraphic sequence at Site 591 was divided into three subunits. Subunit 1A (0-6.2 mbsf) was late Quaternary yellowish gray to pale yellowish-brown foraminifer-bearing nannofossil ooze. Subunit 1B (6.2-289.8 mbsf) was composed of Quaternary to upper Miocene light gray foraminifer-bearing nannofossil ooze to a nannofossil ooze. Subunit 1C (289.8-500.4 mbsf) consisted of late Miocene to early Miocene very light gray to light greenish gray chalk and ranged from a foraminifer-bearing nannofossil chalk to a nannofossil chalk.

Site U592 penetrated to a depth of 388.5 mbsf and was drilled in a 1088 m water depth on the southern Lord Howe Rise (Fig. 1.4) (Kennett et al., 1986b). The section was divided into five subunits. Subunit 1A (0-0.3 mbsf) consisted late Quaternary very pale orange to pinkish gray foraminifer-bearing nannofossil ooze. Subunit 1B (0.3-273.3 mbsf) was late Quaternary to early Miocene white to light gray foraminifer-bearing

nannofossil ooze to nannofossil ooze. Subunit 1C (273.3-305.8 mbsf) contained early Miocene white to very light greenish gray foraminifer-bearing nannofossil chalk to nannofossil chalk. Subunit 1D (305.8-350.1 mbsf) was composed of early Oligocene to late Eocene white to very light gray nannofossil ooze. Subunit 1E (350.1-388.5 mbsf) was late Eocene white to very light gray nannofossil chalk.

The International Ocean Discovery Program (IODP) Expedition 371 of the R/V *JOIDES Resolution* drilled six sites (U1506-U1511) between 27 July and 26 September 2017 (Fig. 1.1 & 1.5) (Sutherland et al., 2018a). The primary objective of IODP 371 was to obtain information on Tonga-Kermadec subduction initiation through investigation of the Paleogene sediment record (Sutherland et al., 2018a). The secondary objective was to understand regional oceanography and climate since the Paleogene.

Figure 1.5. Stratigraphy columns showing main lithology at the IODP boreholes (Adapted from (Sutherland, 2019b))

Figure 1.6. Age-depth models for each IODP sites (Sutherland, 2019b).

Site U1506 penetrated to a depth 306.07 mbsf with a water depth of 1505 m (Fig. 1.5 & 1.6) (Sutherland, 2019b). Site U1506 was 265 m of Pleistocene-middle Eocene nannofossil ooze and chalk overlying 40 m of volcanic rock. The succession was divided into two units, and the upper sequence was further divided into three subunits. Subunit IA (0.00–258.23 mbsf) contained homogeneous Pleistocene to middle Miocene white nannofossil ooze and chalk with varying amounts of foraminifers. Subunit IB (258.23–264.29 mbsf) was late Oligocene pale yellow nannofossil chalk. Subunit IC (264.29–264.63 mbsf) was composed of middle Eocene light greenish gray nannofossil chalk. Unit

II (264.29–264.63 mbsf) consisted of a sequence of mafic crystalline volcanic rocks with a range of textures and mineralogy and varying amounts of carbonate as veins and void infills.

Site U1507 penetrated to a depth 855.64 mbsf with a water depth of 3568 m (Fig. 1.5 & 1.6) (Sutherland, 2019b). Site U1507 was made up of 685 m of Pleistocene to upper Eocene biogenic ooze and chalk interbedded with calcareous and volcanoclastic turbidites overlying 170 m of more homogeneous clayey nannofossil chalk. The section was divided into two units and the upper part further divided into three subunits. Subunit 1A (0.00–401.19 mbsf) was Pleistocene to lower Miocene nannofossil ooze and chalk with varying amounts of clay interbedded with foraminiferal ooze, chalk and limestone, nannofossil-rich clay with ash, and rare volcanoclastic layers. Subunit 1B (401.19–542.9 mbsf) was composed of lower Miocene to upper Oligocene clayey nannofossil chalk with varying amounts of foraminifers, volcanic ash, and clasts interbedded with foraminiferal limestone and tuffaceous conglomerate and sandstone. Subunit 1C (542.90–685.52 mbsf) contained lower Oligocene to upper Eocene volcanoclastic sandstone and conglomerate alternating with clayey calcareous chalk with ash and foraminiferal limestone. Unit II (685.52–855.64 mbsf) was upper to middle Eocene clayey nannofossil chalk and limestone interbedded with rare foraminiferal limestone.

Site U1508 penetrated to a depth 701.92 mbsf with a water depth of 1609 m (Fig. 1.5 & 1.6) (Sutherland, 2019b). Site U1508 was composed of 700 m of Pleistocene to lower Eocene foraminiferal ooze with varying amounts of nannofossil and coarse-grained bioclasts, and calcareous ooze and chalk with different amounts of clay. Unit 1 (0.00–90.08 mbsf) was Pleistocene to Pliocene foraminiferal ooze with varying amounts of nannofossils and coarse-grained bioclasts. Unit IIA (90.08–200.93 mbsf) contained Pliocene to upper Miocene clayey nannofossil ooze with varying amounts of foraminifers and sponge spicules and rare ash layers. Unit IIb (200.61–324.28 mbsf) was middle Miocene to upper Oligocene interbedded foraminiferal ooze and chalk with varying concentrations of clay, silicate minerals, and volcanic clasts. Unit IIIA (379.30–491.61 mbsf) was composed of upper Eocene to middle Eocene clayey nannofossil chalk with sporadic centimeter-scale siliceous intervals (cherty limestone). Unit IIIB (493.80–701.92 mbsf) was middle Eocene to lower Eocene nannofossil chalk and nannofossil limestone with foraminifers.

Site U1509 penetrated to a depth 701.92 mbsf with a water depth of 2911 m (Fig. 1.5 & 1.6) (Sutherland, 2019b). Site U1509 was comprised of 415 m of Pleistocene to upper Palaeocene calcareous ooze, chalk and limestone overlying 275 m of Palaeocene to Upper Cretaceous claystone. The section was divided into two units. Subunit IA (0–99.60 mbsf) was Pleistocene to upper Oligocene calcareous ooze and chalk with rare tuffaceous beds. Subunit IB (99.60–139.28 mbsf) was composed of upper to lower Oligocene slumped calcareous chalk. Subunit IC (139.28–414.57 mbsf) contained lower Oligocene to upper Paleocene calcareous chalk and limestone with biosilica and chert. Subunit IIA (414.57–614.20 mbsf) was Paleocene calcareous claystone. Subunit IIB (614.20–689.68 mbsf) contained Upper Cretaceous claystone.

Site U1510 penetrated to a depth 478.1 mbsf with a water depth of 1238 m (Fig. 1.5 & 1.6) (Sutherland, 2019b). Site U1510 contained 138 m of Pleistocene to middle Miocene calcareous ooze overlying 340 m of upper to lower Eocene calcareous ooze and chalk interbedded with cherty limestone and chert and rare volcanic layers. Subunit IA (0.0–60.0 mbsf) was Pleistocene to Pliocene Color-banded calcareous ooze alternating with discrete beds of foraminiferal ooze. Subunit IB (60.0–66.6 mbsf) was composed of Pliocene to lower Miocene homogeneous calcareous ooze alternating with discrete beds of foraminiferal ooze. The stratigraphic section was separated into two units. Subunit IIA (138.0–147.5 mbsf) contained upper Eocene calcareous ooze with bioclasts accompanied by extra clasts of chert, cherty limestone, and lithics. Subunit IIB (147.5–349.4 mbsf) was upper Eocene to middle Eocene clayey calcareous chalk with bioclasts punctuated by common cherty limestone and chert. Subunit IIC (349.4–478.1 mbsf) consisted of middle Eocene to lower Eocene homogeneous calcareous chalk with chert interbedded with sparse volcanoclastic deposits.

1.4 Seismic stratigraphy

Seismic horizons were identified based on principles of seismic stratigraphy (Fig 1.7 & 1.8). Seismic stratigraphy provides a framework for seismic mapping and interpretation of depositional setting, facies and geological history (Mitchum Jr et al., 1977a, Mitchum Jr et al., 1977b, Vail et al., 1977) (Fig. 1.7). Seismic facies are defined using characteristics of seismic reflection amplitude, configuration, continuity and polarity (Mitchum Jr et al., 1977b). (Fig. 1.7 & 1.8).

Each sequence bounding reflector was identified based on stratal terminations that occurred above and below that stratigraphic surface (Fig. 1.7) (Mitchum Jr et al., 1977a, Mitchum Jr et al., 1977b). Onlap and truncation are identified as up-dip terminations of strata against a basal or overlying surface, and truncations indicate either erosional hiatus or structural disruption (Vail et al., 1977) (Fig 1.7 & 1.8). Downlap is down-dip termination of strata against a basal surface at shallower dip (Fig. 1.7A & B). Onlap, downlap and toplap can be interpreted as non-depositional hiatuses. Seismic units were identified using stratal termination relationships and the geometry of intervening reflectors (stacking pattern), which indicate discreet units separated by structural disruption, sediment supply changes, or unconformities.

Figure 1.7. Stratigraphy relationships adapted from Catuneanu et al., (2009) and Mitchum et al (1977) used to map seismic stratigraphy in the study area. (A) Relationship to termination of overlying and underlying reflectors. (B) Reflector configuration seen on seismic reflection data in the study area. Horizons interpretation in the study area are represented by the blue surface based on its relationship where terminations occur above and below a stratigraphy surface. (C) Stratigraphy relationships used for seismic mapping.

Figure 1.8. Reflection configurations used for seismic facies interpretation in the study area (Mitchum Jr et al., 1977b, Mitchum Jr et al., 1977a) ; (A) Simple seismic reflector geometries; (B) Complex seismic reflector geometries; (C) Different types of progradational clinoforms; (D) Some external forms of troughs and their pattern of fills which are common in seismic facies analysis.

Seismic reflector mapping in northern Zealandia is a challenge as sedimentary and structural barriers affect the continuity of sequence and megasequence boundaries. In addition, the study area is a large region that covers the southern New Caledonia Trough (NCTS), northern New Caledonia Trough (NCTN), southern Lord Howe Rise (LHRS), northern Lord Howe Rise (LHRN), Fairway Basin (FWAY) and Reinga Basin (REIN) (Fig. 1.1). Names of each seismic-stratigraphic unit are defined in each region and locally near boreholes.

Each seismic reflector and unit are assigned a three-part code, for instance, U-NCTN-1a (Fig. 3.19) and UB-1510-6 (Fig. 4.11) or UB-NCTN-8 (Fig. 4.23). Part one identifies the bounding surface (UB) - with the prefix U referring to the underlying seismic unit; part two refers to the seismic reflector from north of New Caledonia Trough or IODP site U1510; and part three is used to identify the seismic unit (e.g., 1-9) and sub-unit (e.g., 1a-1d). Nomenclature for seismic stratigraphic units (U) and bounding surfaces (UB) is adapted from Bache et al. (2012a, b).

1.5 Depth from two-way-travel time

Two way travel time (TWT) to depth conversion is required to tie TWT seismic reflection interpretation to borehole data (e.g., lithology and biostratigraphy data). Boreholes in northern Zealandia generally do not have check shot data. Depth conversion is accomplished by using synthetic seismograms to model velocity and density variation and hence correlate between core data and reflection seismic data (Stratford et al., 2018, Sutherland, 2019a, Sutherland, 2019b, Sutherland et al., 2018a) (Fig. 1.9, 1.10 & 1.11).

Figure 1.9. Physical property data DSDP 208 (north of Lord Howe Rise) from Stratford et al. (2018) shows (A) raw and drilling core correction (red and black) used to measure velocity and density; (B) velocity and density interpolated from adjacent measurements then plotted as white circles; (C) impedance (ρV_p).

Figure 1.10. Seismic line Ga-302-09 at Site DSDP 208 showing borehole data tie to Site 208 from Stratford et al. (2018). The seafloor reflection indicates a strong positive polarity used to normalise amplitude for synthetic model. A zero point in TWT for data in circles 1-4 is defined by seafloor. There is change in reflectivity at c.220 ms TWT related to increase lithification at 300 ms TWT (chalk). High amplitude negative polarity reflection at 490 ms TWT is related to Eocene/Oligocene unconformity. Two high positive reflections in circle 4 (540 and 580 ms TWT) are chert and opal-A/CT transition. Normalised amplitude of real (red) and synthetic (black) seismic data and reflection coefficients are also shown.

Figure 1.11. Seismic line TAN1409-NCTN-11 at CDP 4020 recorded at Site U1507 shows borehole tie (Sutherland, 2019a, Sutherland, 2019b, Sutherland et al., 2018a). A-B are fit well by the synthetic seismogram. (A) Horizontal line = lithostratigraphic unit boundary, dashed horizontal line = sub-unit boundaries; (B) TWT was calculated from depths below seafloor and numerical solution for two-way time (twt) with depth (z) is given by $z=294.43*twt^2+ 822.34*twt$. Red circles are reflectors correlated in C and D and white open circles is not correlated, dashed lines appeared to fit between seismic survey data in D and synthetic trace in C. (C) red synthetic trace, (D) MCS trace data at Line TAN1409-NCTN-11 and A–H labels showing seismic reflectors and seafloor (SF).

The physical property measurements were mostly done on cores. The cores were divided into units based on lithology to do physical measurement (Fig. 1.9, 1.10 & 1.11) (Stratford et al., 2018, Sutherland, 2019a, Sutherland, 2019b, Sutherland et al., 2018a). *P*-wave velocity and density data obtained from cores used to calculate acoustic impedance, reflection co-efficients and synthetic seismograms (Sutherland, 2019c, Sutherland et al., 2018b, Sutherland, 2019a, Sutherland, 2019b, Stratford et al., 2018).

Two-way-time depth tie points were selected (Fig. 1.10 & 1.11) and hence two-way time (*tw**t*) was calculated from depth (*z*) below seafloor (Table 1.2). Acknowledgement is made to Wanda Stratford of GNS Science, who provided and facilitated access to the twt-depth relationships.

Table 1.2. The numerical solution from Stratford et al., (2018), Sutherland et al., (2018) and Sutherland et al., (219a, b, c) that use as a function of depth to derive single two-way-time versus depth relationship.

DSDP Boreholes	Numerical solution for TWT (t) with death (z)	IODP Boreholes	Numerical solution for TWT (t) with death (z)
208	$z = 486.55 \cdot \text{tw}t^2 + 779.09 \cdot \text{tw}t$	U1506	$z = 120.53 \cdot \text{tw}t^2 + 846.37 \cdot \text{tw}t$
207	$z = 664.28 \cdot \text{tw}t^2 + 682.42 \cdot \text{tw}t$	U1507	$z = 294.43 \cdot \text{tw}t^2 + 822.34 \cdot \text{tw}t$
206	$z = 388.97 \cdot \text{tw}t^2 + 779.23 \cdot \text{tw}t$	U1508	$z = 326.77 \cdot \text{tw}t^2 + 781.74 \cdot \text{tw}t$
592	$z = 418.42 \cdot \text{tw}t^2 + 801.55 \cdot \text{tw}t$	U1510	$z = 319.58 \cdot \text{tw}t^2 + 862.35 \cdot \text{tw}t$

2 Geographical and Geological Setting

Northern Zealandia is a very large area with a boundary frontier location containing possible potential for petroleum accumulation. Discoveries of economically viable oil and gas fields in the Gippsland and Taranaki basins have attracted interests in the region surrounding northern Zealandia (see discussion in chapter 3, section 8.1 & chapter 5). Northern Zealandia is contained within the Exclusive Economic Zone (EEZ) and Extended Continental Shelf regions of New Zealand, Australia and France (GNS, 2015, Willcox et al., 2001). The remote boundary location will play a key role in any future exploration and development of the region (chapter 5). Hence, I include here some description of northern Zealandia's geographical setting, and the ports, cities and islands that might provide essential infrastructure (Fig. 2.1).

The current oceanography of the region provides valuable insight for mapping and understanding of the Cenozoic sequence more generally (see result in Chapter 4). Variations of ocean currents strongly impact biogenic productivity and hence sediment distribution in the region (chapter 4) (Deacon, 1982, Smith et al., 2013). I provide here some background information on the oceanic system in the region to provide a basis for understanding the significant changes in sedimentation patterns during Neogene time.

The summaries in this section are focused on: human geography (population, cities and ports) in relation to chapter 5 (petroleum analysis and future prospectivity); physical geography (ocean-climate system) in relation to chapter 4 (Cenozoic sedimentation); and tectonic history in relation to chapters 3, 4 and 5, because it shaped northern Zealandia and affected all aspects of geological development.

2.1 Human geography

The study area is underlain by the hidden continent Zealandia, and it is 95% underwater with just a few islands (Mortimer et al., 2017). Hence, I discuss the geography of Australia, New Caledonia, New Zealandia and islands (Norfolk Island, the Lord Howe Island group, and Elizabeth and Middleton reefs), including their population, major cities, and ports. These countries and islands provide access or resources to support research studies or future petroleum exploration and development in the region.

The Australian continent includes the island of Tasmania and numerous smaller islands (Fig. 2.1). Some islands of Zealandia belong to the Australian territories and include the Lord Howe Rise Island Group, Norfolk Island, and Elizabeth and Middleton reefs (Coral Sea Island Territory). The major cities in Australia close to the study area are Brisbane, Sydney, Canberra and Melbourne (Fig. 2.1). Its closest neighbours to the north are New Caledonia, Fiji, Papua New Guinea, Timor-Leste and Indonesia (Fig. 2.1). The population of Australia is about 25 million (Australia Bureau of Statistics, 2019) and Australia has a land area of about 7.692 million km² (Fig. 2.1).

Lord Howe and Norfolk islands are isolated in the southwest Pacific. Lord Howe Island (31.5° lat) lies 1,200 km south of New Caledonia, ~1,600 km north of New Zealand and ~600 km east of Australia (Fig. 2.1). Lord Howe Island has an area of 15 km² and lies in the centre of a 20 km wide platform. According to the Australia Bureau of Statistics (2018), Lord Howe Island has a population of 400 and there are seven uninhabited islands to the north of the island. Norfolk Island (29°02'S, 167°57'E) covers about 35 km² and has two nearby smaller uninhabited islands Nepean (1 km²) and Phillip (5 km²) (Nash, 2013). It is located about 1700 km from Sydney and 1100 km from Auckland. Norfolk Island has a population of about 2,000 (Nash, 2013).

New Zealand is an island country in the southwest of Pacific and has two main landmasses, North Island and South Island. The capital city is Wellington and other cities near the study area are Auckland (North Island) and Nelson (South Island) (Fig. 2.1). The land area is 114,000 km². New Zealand is located about 2000 km east of Australia across the Tasman Sea and 1000 km south of the Pacific island of New Caledonia and Fiji (Fig.

2.1). The population of New Zealand is about 4.8 million based on United Nation data (2019).

New Caledonia (*Nouvelle-Calédonie*) is known as a special territory of France and the capital city is Noumea (Fig. 2.1). New Caledonia (20°S & 22°30S, 164°E & 167°E) (Fig. 2.1) covers about 16,900 km² and is nearly 500 km long and up to 50 km wide (Chevillon, 1996). The New Caledonian population is 271,407 according to 2019 census data (ISEE, n.d).

Ports discussed in this section are identified based on relevance for enabling support to any future offshore petroleum exploration across northern Zealandia (Fig. 2.1). Ports are also needed for the transportation of goods and people, and act as a gateway to the southwest Pacific region. There are eight ports in key locations for supply activities to the study area: in Papua New Guinea (PNG), Australia, and New Zealand (Fig. 2.1). The PNG port is close to the capital city of Port Moresby. Other ports are Botany (Sydney) and Brisbane ports located in eastern Australia (Fig. 2.1) and these ports are known as Australia's largest container ports, especially for trade and bulk liquid imports. There are alternative ports close to Port Botany in Sydney, Port Kembla and Newcastle. Lastly, four main ports in New Zealand include Nelson, Wellington, Taranaki, Auckland and Northland ports (Fig. 2.1). Most of the ports in New Zealand link domestic and international shipping services. These ports provide wide channels to supply vessels and landside infrastructure to provide water, fuel, drilling mud, deck equipment, and to support any research study or petroleum exploration in the region.

Figure 2.1. Bathymetry map showing the southwest Pacific region with major cities and ports. White circle = major cities; Yellow stars = major ports; LHRN = Northern Lord Howe Rise; LHRN = Southern Lord Howe Rise; FWAY = Fairway Basin; NCTN = Northern New Caledonia Trough; NCTS = Southern New Caledonia Trough and REIN= Reinga Basin.

The southwest Pacific region has relatively low population but Asian countries represent significant markets, and have existing economic and strategic interests in the region (Mediansky, 1987). Relationships and new economic and strategic interests have emerged in this region. Economic development in the Pacific region is relatively low but it is strategically essential for possible petroleum potential and very large area (Lum and Vaughn, 2007). New Zealand, Australia and Asia are known as the fastest growing economic region. The region depends on Australia and New Zealand to support and promote development (e.g. through natural resources and primary production), and to maintain political stability in the region. The local economies of the region rely on Australia and New Zealand, but China is now the largest trading partner with both countries and has been investing in the Pacific Island states.

2.2 Physical geography

The Tasman Sea sector of Zealandia in the southwest Pacific region is a region of about 3,000,000 km² (Sutherland et al., 2012, Mortimer et al., 2017) composed of bathymetric rises and troughs (Fig. 2.1 & 2.4). The region has water depths between 1000 and 4000 m. The New Caledonia Trough (NCT) is a northwest-oriented bathymetric feature, about 2000 km long and 250 km wide with a water depth of 2000-3500 m (Sutherland et al., 2010) (Fig. 2.1). The Lord Howe Rise (LHR) extends about 2800 km from the central Coral Sea in the tropical north to the Challenger Plateau in the southwest of New Zealand with water depths between 500-2000 m (Standard, 1961, van der Linden, 1970). Adjacent bathymetric features comprise Fairway Basin (FWAY), New Caledonia Trough (NCT), Norfolk Ridge (NR) and Reinga Basin (REIN) lying to the east of Lord Howe Rise. FWAY is 700 km long and 150 km wide with a water depth ranging from 500-3000 m (Rouillard et al., 2017). The NR runs between New Caledonia and New Zealandia with a water depths between 0-2000 m (Sutherland et al., 2010). The REIN extends ~500 km with a water depth ranging from ~1000-2000 m, and shallow water is less than 500 m (Stagpoole et al., 2009).

I introduce the ocean climate system of the southwest Pacific region in Figures 2.2, 2.3 and 2.4. The main components of the ocean climate system in the region: Australia, the inflow/outflow of ocean currents (South Equatorial Current, East Australia Current & Antarctic Circumpolar Current), the consequent existence of different water masses (Subtropical Water and Subantarctic Water), and winds. A schematic of the ocean circulation (Fig. 2.2) shows the relationships between water masses, fronts and their distribution. Ocean currents are created by surface winds, temperature and salinity gradients, and tides (Sudre et al., 2013, Durack and Wijffels, 2010, Hill et al., 2008). Ocean currents transport warm water and precipitation from the equator towards the poles and cold water from the poles back to the tropics. This circulation controls primary productivity, pelagic sedimentation and reworking of seafloor sediments by bottom currents. The ocean climate system behaviour responds to changes in Australian climate, the South Equatorial Current (SEC), East Australia Current (EAC), Antarctic Circumpolar Current (ACC), Subtropical Water (STW) and Subantarctic Water (SAW), the Subtropical Front (STF) and wind influences (Fig. 2.2 & 2.4).

Figure 2.2. Global setting illustrates the major ocean currents that occurred through northern Zealandia. Blue darck arrows = ocean circulation pattern; EIN = East India; SAT = Southern Atlantic; NPSG = North Pacific subtropical gyre; EEP = East Equatorial Pacific; TAS = Tasman Sea. Ocean currents are South Equatorial Current (SEC), East Australia Current (EAC), and Antarctic Circumpolar Current (ACC). Water masses are Subtropical Water (STW), Subantarctic Water (SAW), and Subtropical Front (STF). Modified from Sutherland et al in preparation.

Figure 2.3. Antarctic Circumpolar Current (ACC) fronts from south to north where blue line is Southern ACC Front (SACCF), magenta line is Polar Front (PF) and black line is Subantarctic Front (SAF, black). The background is bathymetry (Sokolov and Rintoul, 2009).

The Australian climate is controlled by a complex network of currents in the surrounding ocean. Australia is located at the crossroads of oceans and currents (Fig. 2.2). The primary exchange between ocean basins has a significant influence on global ocean circulation and climate, for example, the Indonesian through flow and the Antarctic Circumpolar Current (ACC) (Hu et al., 2015). The combined strength of the ocean circulation affects the area around Indonesia and the north and east of Australia.

The southwest Pacific climate is partly controlled by the broad westward flow of the South Equatorial Current (SEC) that is part of the South Pacific subtropical gyre (SPSG) (Webb, 2000) (Fig. 2.2). The South Pacific subtropical gyre moves water into the Coral Sea (Fig. 2.1) as part of the broad westwards flow of the SEC which meets islands and creates boundary currents that separate into westward jets at their northern and southern tips (Ganachaud et al., 2014). Acceleration of the current occurs southward along the coastal boundary (east Australia) and there separates into north-eastward (Subtropical Counter-Current), eastward (Tasman Front) and southward (Tasman Outflow) components (Fig. 2.4) (Ganachaud et al., 2014, Ganachaud et al., 2007b).

The eastward flow of the East Australian Current (EAC) corresponds with the Tasman Front that divides subtropical and sub-Antarctic surface water masses (Fig. 2.2 & 2.4) (Mulhearn, 1987). The wind driven EAC is the main western boundary current of the South Pacific Ocean (Ganachaud et al., 2014, Oke and Middleton, 2001). The EAC seems to begin on the west edge of the South Pacific gyre, where it collects nutrient-poor water. Currents flow along the east coast of Australia carrying a large amount of warm tropical water from the equator southward, entraining nutrients along its path. The EAC appears to provide nutrients through the Tasman Front towards New Zealand (Oke and Middleton, 2001). The Tasman Front moves across the Tasman Sea where it interacts with the various ridge systems with part of the flow continuing into the Pacific. The Tasman Front flow has high temporal and spatial variability and influences nutrients around seamounts, reefs, and islands (Przeslawski et al., 2011). Currents bring different types of nutrients to the oceanic waters over the submerged parts of northern Zealandia and affect the productivity and pelagic sedimentation in the region (Kennett et al., 1975).

The Antarctic Circumpolar Current (ACC) creates three fronts; the Sub-Antarctic Front (SAF), the Polar Front (PF) and the Southern ACC Front (SACCF) (Chiswell et al., 2015) (Fig. 2.3). The SAF affects mostly the New Zealand region and it flows through the Macquarie Ridge and pushes south by the Campbell Plateau (Fig. 2.4) (Sokolov et al., 2006). The SAF moves from the Campbell Plateau to the east into the Pacific Ocean (Morris et al., 2001). The PF appears to be more stable in time than the SAF (Budillon and Rintoul, 2003), but in contrast the SACCF is significantly more stable compared to the PF and SAF (Chiswell et al., 2015).

The Subtropical Front (STF) separates waters in the subtropical gyres from Sub-Antarctic waters (Orsi et al., 1995) (Fig. 2.2 & 2.4). The STF region experiences mixing between Subtropical Water (STW) and Sub-Antarctic Water (SAW). This is enclosed by the North STF and South STF (Belkin and Gordon, 1996, Hamilton, 2006, Stanton and Ridgway, 1988, Sutton, 2001, Belkin, 1988). The southern STF is strongly meandering in the Tasman Sea and this may be associated with high mesoscale activity generated from the EAC (Fig. 2.2 & 2.4) (Hamilton, 2006, Stramma et al., 1995). The STF flows around the Tasman Sea and the southern tip of the South Island of New Zealand before turning north along the Campbell Plateau (Fig. 2.4). The STF in the Tasman Sea moves to a gap in the Macquarie Ridge (49 °S) and flows with eddy and meander-like features (50°S) then continues north across Campbell Plateau (Fig. 2.2 & 2.4) (Smith et al., 2013).

Figure 2.4. Bathymetry of southwest Pacific showing depth shallower than 6000 m and the main currents. The arrows represent circulation of surface currents around northern Zealandia (principally the East Australia Current). They are driven by west winds in east Australia. Yellow circles = DSDP boreholes; Yellow stars = IODP boreholes. Modified from Sutherland et al., in preparation.

The southwest Pacific circulation is associated with south-easterly trade winds in the northern part of my study area (Ganachaud et al., 2013, Ganachaud et al., 2014). The wind direction and strength in the southern extra-tropical storm belt comprises southerly winds in the colder and wetter season and strong north-easterly winds and hurricanes during the summer. Hurricanes occur less frequently in a subtropical region, but tropical cyclones can reach as far south as the North Island of New Zealand (Shaw, 1983).

The Tasman Sea is influenced by prevailing westerly winds (Chiswell et al., 2015, Hamilton, 2006). Westerly winds have marked variation in strength with latitude in response to the annual cycle of mean atmospheric pressure across the Tasman Sea throughout the year. The zonal westerly wind increases relate to sea temperature gradients (Mickelson et al., 1991). The zonal westerly wind can deflect the EAC to the east, hence decrease the temperature gradient in the Bass Strait. The EAC determines the strength and direction of wind (Fig. 2.4). Westerly winds carry wet weather to mountain chains, warm weather along the east coasts, and extend for thousands of kilometres upstream of New Zealand.

2.3 Tectonic history

2.3.1 Introduction

Geophysical studies done during the 1960s and the 1970s revealed that the Lord Howe Rise may have an underlying continental crustal structure, and marginal basins east of Norfolk Ridge were associated with Cenozoic evolution of Tonga Kermadec subduction (Sutherland et al., 2017, Shor Jr et al., 1971, Karig, 1971). The stratigraphic framework, tectonic structure and history of the region were mapped and confirmed during legs 21, 30 and 90 of the Deep Sea Drilling Project (Burns, 1973a, Burns and Andrews, 1973, Kennett and von der Borch, 1986, Kennett et al., 1985). These previous works, combined with detailed offshore studies and analysis of land area (Bache et al., 2012a, King, 2000a, King and Thrasher, 1996, Bache et al., 2014a, Sutherland et al., 2017), suggest that northern Zealandia experienced four phases: the Gondwana subduction margin (>350 - 100 Ma), rifting (100-80 Ma), passive margin (80-50 Ma), and Cenozoic initiation of Tonga-Kermadec subduction (50-0 Ma) (see Fig. 2.5).

Figure 2.5. Four phases of tectonic evolution of the southwest Pacific (Bache et al., 2014a). The first phase is Triassic to early Cretaceous (>100 Ma) Gondwana margin subduction, the second phase (100-80 Ma) is widespread rifting and extension, the third phase relates to opening of the Tasman Sea, isolating Zealandia, and the last phase is associated with Cenozoic initiation and evolution of Tonga-Kermadec subduction.

2.3.2 Basement rock of Zealandia

The basement rock in northern Zealandia is composed of Palaeozoic to Mesozoic volcanic and sedimentary terranes associated with subduction along the Gondwana margin (Bache et al., 2014b, King, 2000a, King and Thrasher, 1996, Mortimer, 2004). This period of convergence (southwest dipping subduction of the Pacific-Phoenix Plate) led to terrane accretion, uplift and erosion (Laird and Bradshaw, 2004). The basement rock types have been inferred from dredge samples (Tulloch et al., 1991), seismic velocities (Klingelhofer et al., 2007), gravity and magnetic anomalies (Sutherland, 1999, Wood and Woodward, 2002), and the geology of Australia, New Zealand, New Caledonia, PNG and Timor-Leste.

The Lord Howe Rise may contain rocks referred to as Western Province terranes in New Zealand (Mortimer et al., 1998, Sutherland, 1999, Ballance and Campbell, 1993) or the New England or and Lachlan Fold Belt orogen in Australia (Flood and Aitchison, 1992, Norvick et al., 2001). These rocks are quartzose metasedimentary and granitoids of Paleozoic age and they are known as the eastern edge of Gondwana.

Permian-Mesozoic rocks found in the north of New Zealand are composed of four metasedimentary terranes (Isaac, 1996, Stagpoole et al., 2009, Adams et al., 2002). The Murihiku Terrane is late Permian to late Jurassic volcanoclastic marine sandstone and mudstone (Ballance and Campbell, 1993, Mortimer, 2004). The Dun Mountain-Maitai Terrane comprises a narrow belt of serpentinised ultramafic rocks associated with a linear magnetic anomaly (Junction Magnetic Anomaly) (Sutherland, 1999, Hunt, 1978). The Caples Terrane consists of a metamorphosed sequence of marine volcanoclastic Permian-Triassic greywacke and argillite (Mortimer, 2004). The Bay of Islands Terrane is made up of Permian, Triassic and early Jurassic basalt, chert, and limestone which are tectonically intercalated or reworked into Triassic to Jurassic trench and trench-slope sandstones and mudstones (Moore and Smith, 1995).

In Papua New Guinea, Mesozoic sediments were deposited on Palaeozoic continental rocks (Ahmed et al., 2012). The Mesozoic rift succession in the Papuan Basin is similar to hydrocarbon-bearing basins on the northern and western Australian continental margin (Struckmeyer et al., 1990). The Papuan Basin was formed during Triassic-Jurassic (back-arc) rifting of the northern margin of Australia (Ahmed et al., 2012). Jurassic strata are

composed of fine marine shelf clastic sediments deposited during inundation of the margin (Brown et al., 1979). This marine transgression continued into the Early Cretaceous, with deposition of fine clastic sediment followed by shallow-water marine clastic sediment in the Late Cretaceous.

Paleozoic-Mesozoic rocks in Timor-Leste and the Bonaparte Basin in the north of Australia were deposited on north-eastern Gondwana prior to breakup in the Late Jurassic. The Bonaparte Basin was formed by: Palaeozoic extension, Middle to Late Triassic compression, and Jurassic extension that stopped after breakup of Gondwana in the Middle Jurassic (Mory, 1991). The Middle to Late Triassic sequence (Anisian- Norian) found in the Petrel-1 well consists of sandstones and minor amounts of siltstones and shales (Mory, 1991). Northeast–southwest rifting resulted in widespread erosion and a transition from marine to terrestrial deposition. Thermal subsidence occurred in the Early Cretaceous and formed a thick prograding wedge of siliciclastic and carbonate sediment. The east Gondwana megasequence in Timor-Leste ranges from the Permian to Middle Jurassic (Haig and McCartain, 2007, Haig et al., 2019), and was deposited prior to final break-up of north-eastern Gondwana at 155 Ma. Timor Island contains Gondwana Jurassic carbonate-platform facies and shelf facies overlain by Cretaceous deep-water pelagic deposits (Haig et al., 2019).

Mesozoic sediments are found on the Norfolk Ridge. Magnetic anomalies and one dredge sample from the West Norfolk Ridge suggest a magmatic arc of late Palaeozoic and Mesozoic age underlies the southern New Caledonia Trough (Mortimer et al. 1998; Sutherland, 1999). They formed along the active margin of Gondwana. The Norfolk Ridge System is identified as having Mesozoic forearc accretionary rocks that formed at the convergent margin of Gondwana (Adams, Cluzel, & Griffin, 2009; Cluzel et al., 2012; N Mortimer, 2004).

Figure 2.6. Tectonic reconstruction of the southwest Pacific region showing the configuration of rifting during the Late Cretaceous (chron 33; 74 Ma). The Zealandia continental fragment was rifted from the Gondwana supercontinent during this time following by a long period of subduction (Sutherland, 1999).

Figure 2.7. Mesozoic – Cenozoic break-up of the eastern Gondwana margin from (Higgins et al., 2014); (a) pre-Cretaceous subduction margin; (b) early rifting or syn-rift 1; (c) late rifting or syn-rift 2; (d) post-rift sag and drape.

2.3.3 Cretaceous rifting

During the Cretaceous, Zealandia separated from eastern Australia and Antarctica (Exon et al., 2007, Gaina et al., 1998). Subduction terminated during the Late Cretaceous (~105-100 Ma) followed by widespread rifting and extension (Matthews et al., 2012, Davy et al., 2008). This was preceded by widespread magmatic activity with variable calc-alkaline and adakitic rock chemistry (Tulloch et al., 2009, Mortimer et al., 1999, Cluzel et al., 2010, Higgins et al., 2011). Marginal breakup moved eastward from 130-95 Ma in eastern Australia (Fig. 2.7) to about 105-80 Ma in New Zealand (Cluzel et al., 2010, Davy et al., 2008).

Widespread rifting across northern Zealandia resulted in formation of grabens and half-grabens during the Late Cretaceous (Fig. 2.6) (Uruski and Wood, 1991, Collot et al., 2009, Strogen et al., 2017, King and Thrasher, 1996). These extensional basins are recognised in seismic reflection data at the base of the southern New Caledonia Trough (Collot et al., 2009, Strogen et al., 2017, Uruski and Wood, 1991), the Reinga Basin (Bache et al., 2012a) and the Lord Howe Rise (Higgins et al., 2015). They are inferred to have a coal-rich succession overlain by transgressive marine sandstone and mudstone, similar to that observed in the Taranaki Basin (King and Thrasher, 1996). This stratigraphic motif underpins the petroleum system in New Zealand and eastern Australia (Gippsland and the Taranaki regions) (King and Thrasher, 1996). Widespread rifting stopped at ~83 Ma, in northern Zealandia (Mortimer et al., 2014, Strogen et al., 2017) which led to the subsequent transition to passive margin conditions which were synchronous with the onset of seafloor spreading in the Tasman Sea.

2.3.4 Cretaceous and Paleogene passive margin

The opening of the Tasman Sea and the end of rifting led to development of passive margins surrounding eastern Australia, New Caledonia and New Zealand (Ballance, 1993, Cluzel et al., 2010). Magnetic anomalies show that seafloor spreading occurred from the Late Cretaceous to early Cenozoic (Hayes and Ringis, 1973, Weissel and Hayes, 1977). The earliest seafloor spreading may have occurred before 83 Ma east of Tasmania (Hayes and Ringis, 1973) while marginal seafloor spreading occurred at 83-79 Ma along the western edge of Lord Howe Rise (Gaina et al., 1998, Sutherland, 1999).

Northern Zealandia experienced passive tectonic subsidence after Cretaceous extension terminated, resulting in marine transgression and widespread deposition of terrestrial to shallow marine sands and coal (Baur et al., 2014, King and Thrasher, 1996, King, 2000a, Laird and Bradshaw, 2004, Herzer et al., 1997, Uruski and Warburton, 2010, Bache et al., 2012a). Marine sediments sampled at DSDP sites 206, 207 and 208 indicate flooding of lower-lying ridges surrounding New Caledonia Trough during Cretaceous time (Burns and Andrews, 1973, Burns et al., 1973a, Burns et al., 1973b).

The history of seafloor spreading in the Tasman Sea is inferred from magnetic anomalies (Hayes and Ringis, 1973, Weissel and Hayes, 1977). Royer and Rollet (1997) suggest that seafloor spreading may have occurred at ~83 Ma east of Tasmania, but Gaina et al. (1998) and Sutherland (1999) suggest that marginal seafloor along the western edge of the Lord Howe Rise may have formed during ~83-79 Ma.

The end of Tasman seafloor spreading was at about 53-52 Ma (Gaina et al., 1998). Passive subsidence of Lord Howe Rise resulted in a progression from coastal-marine and estuarine settings to shelf and bathyal settings, as indicated by benthic foraminifera found in DSDP 208 and 207 boreholes (Burns and Andrews, 1973, Burns et al., 1973a, Burns et al., 1973b). Based on fossils in dredged mudstone, it appears that Reinga Basin experienced deep-water bathyal conditions during the Palaeocene time, and dredged Palaeocene mudstone sampled from eastern Lord Howe Rise shows that a low-energy marine bathyal environment occurred in late Palaeocene (59-56 Ma) (Browne et al., 2016). Transgression occurred from north and west to south and east along areas of Taranaki and the southern New Caledonia Trough experiencing a bathyal environment at 56 Ma (King and Thrasher, 1996, Strogon et al., 2017).

2.3.5 Eocene Tonga-Kermadec subduction

Wide tectonic changes throughout the Pacific and Indian Ocean occurred during the Eocene (53-43 Ma) (Sutherland et al., 2017). Pacific plate motion dramatically changed as new subduction zones formed in the western Pacific, resulting in the Emperor-Hawaii seamount chain bend (Steinberger et al., 2004). During Middle and Late Eocene times, New Caledonia experienced deformation, exhumation, and emplacement of ultra-mafic, mafic, and sedimentary allochthons (Cluzel et al., 2001, Baldwin et al., 2007, Aitchison

et al., 1995). In New Zealand, regional deformation and emplacement of allochthons was later than in New Caledonia and the Norfolk Ridge System, and occurred during the Late Oligocene and Early Miocene (30-20 Ma) (Bache et al., 2012a, Herzer et al., 1997, Stagpoole and Nicol, 2008).

Seismic-reflection interpretation and rock sample studies (Sutherland et al., 2017) reveal that Eocene Tonga-Kermadec subduction initiation was associated with compressional plate failure after 53-48 Ma and until 37-34 Ma in northern Zealandia and eastern Australia. Folding, uplift and reverse faulting was observed in the Lord Howe Rise and Reinga Basin (Orr et al., 2020, Sutherland et al., 2020, Bache et al., 2012a, Sutherland, 2019c, Sutherland, 2019b). The northern Lord Howe Rise at IODP Site 1506 shows uplift to sea level at 50 Ma, and at Site 1510 an uplift between 41 and 32 Ma in the south was confirmed (Sutherland, 2019b, Sutherland et al., 2020). Orr et al. (2020) identified that the Reinga Basin experienced compression and reverse faulting at 39-43 Ma resulting in Eocene and older strata along the northeastern basin margin and in western New Zealand. Reverse faulting termination was determined from undeformed bioclastic limestone (subided >1 km since 36-30 Ma), and syn-tectonic deposits dated at 56-43 Ma (Orr et al., 2020, Sutherland et al., 2017).

From the Oligocene to present day, subduction zone roll-back has formed back-arc basins (Loyalty, Norfolk, Fiji, Havre and Lau) and arc ridges (Loyalty, Three Kings, Lau-Colville, Tonga-Kermadec and Vanuatu) (Herzer et al., 2009, Herzer and Mascle, 1996, Schellart et al., 2006, Mortimer et al., 2007). There are active arcs east of the Norfolk Ridge system that may include older Cenozoic arc rocks. The back-arc region has isolated the submerged continental part of the Tasman Frontier from Cenozoic subduction-related deformation and volcanism, but sediment supply in southern New Caledonia Trough is sourced from the active plate boundary through New Zealand.

3 Synthesis of Regional Seismic Stratigraphy

3.1 Introduction

This chapter reviews, reanalyses and updates the regional Cretaceous-Cenozoic stratigraphy of northern Zealandia. I have reanalysed the seismic data, approximately 70% of lines, and identified horizons (Fig. 3.1). Seismic reflection, borehole data, and published works underpin my analysis (Auzende et al., 2000b, Bache et al., 2014a, Bache et al., 2012a, Burns, 1973a, Burns and Andrews, 1973, Collot et al., 2009, Exon et al., 2007, Exon et al., 2004, Hashimoto et al., 2009, Hashimoto et al., 2008, Kennett and von der Borch, 1986, Lafoy et al., 2005, Rouillard et al., 2014, Sutherland, 2019b, Sutherland, 2019c, Sutherland et al., 2017, Sutherland et al., 2010, Sutherland et al., 2018a, Rouillard et al., 2015, Etienne et al., 2018). I mapped the stratigraphy locally in each sub-region (Fig. 1.2), and then made regional correlations (discussion provided in each section of this chapter and chapter 5).

Bache et al. (2014) defined the seismic-stratigraphic architecture of northern Zealandia into three megasequences U3, U2, and U1 (Fig. 3.2). U3 is the deepest section. It is associated with the long-lived eastern Gondwana active margin before the Late Cretaceous (King and Thrasher, 1996, Mortimer, 2004, Mortimer et al., 2017). U2 is an extensional syn-rift to post-rift margin that ranges from Late Cretaceous to Eocene, involving detritus (syn-rift, subunit U2b) that originated from subaerial erosion of East Gondwana. U2a lies on top of U2b and is composed of transgressive marine sediments that were deposited during post-rift thermal subsidence. Finally, U1 deposition was influenced by compressive or passive regimes since Eocene inception and development of Tonga-Kermadec subduction. This stratigraphic framework is reviewed for data from northern Lord Howe Rise (LHRN), southern Lord Howe Rise (LHRS), northern New Caledonia Trough (NCTN), southern New Caledonia Trough (NCTS), Fairway (FWAY) and Reinga (REIN) basins (Fig. 1.1 & 1.2).

Bache et al. (2014) identified two unconformities (RU2 and RU1) that separated the three megasequences (Fig. 3.2). RU2 is the boundary between U3 and U2 with truncation of U3 strata, and U2 onlaps U3. RU1 is the boundary between U2 and U1 and corresponds

to a regional Paleogene hiatus on ridges, and high local rates of deposition in New Caledonia Trough and Reinga Basin (Bache et al., 2014a, Bache et al., 2012a).

Figure 3.1 Seabed ribbon of the region showing where key horizons were identified.

Stratigraphy	Seismic Units	Unconformities	Seismic Patterns	Tectonic Phases
Oligocene-Miocene to Recent	U1a		Basal onlaps (e.g., Lord Howe Rise, Reinga Basin and north of New Caledonia); Flat-lying reflectors (e.g., south of Lord Howe Rise)	Subduction roll-back back-arc basin opening
Eocene	U1b	Ru1	Basal downlaps and onlaps (Lord Howe Rise, Reinga Basin and north of New Caledonia); Wedging geometries, discontinuous to chaotic	Contraction
50 Ma			Truncation /disconformities in basins	Tonga-Kermadec subduction
Late Cretaceous -Paleocene	U2a		Basal onlaps Comfortable reflectors	POST-RIFT Tasman Sea Opening
80 Ma			Erosional truncations	Continental break-up
Cretaceous	U2b	Ru2	Basal downlaps Basal onlaps Fanning reflectors	SYN-RIFT Eastern Gondwana Extension
100 Ma			Erosional truncations	Rift Onset
Mesozoic - older	U3		Toplaps and normal faults truncated by a highly reflective Upper boundary Acoustic basement chaotic	Eastern Gondwana Subduction

Figure 3.2 Stratigraphic framework adapted from (Bache et al., 2014a, Bache et al., 2012a, Etienne et al., 2018, Rouillard et al., 2017): U3 (eastern Gondwana active margin), U2b (Late Cretaceous syn-rift); U2a (Late Cretaceous to Palaeocene post-rift); U1b (Eocene compression); U1a (subduction inception and Oligocene to Neogene roll-back).

3.2 Southern Lord Howe Rise (LHRS)

Previous interpretations (Bache et al., 2014a, Sutherland et al., 2017) of the seismic stratigraphy of southern Lord Howe Rise (LHRS) identified a series of seismic-stratigraphic units (Table 3.1 & Fig. 3.3) related to tectonically-driven basin filling phases (Fig. 3.3). I mapped seismic stratigraphic units of LHRS based on broad correlation to horizons of Bache et al. (2012) and adoption and modification of their nomenclature (see Table. 3.1). LHRS seismic stratigraphy is divided into three units: U-LHRS-1 (U1a & U1b), U-LHRS-2 (U2a & U2b) and U-LHRS-3 (Table 3.1 & Fig. 3.3).

Table 3.1. LHRS Seismic unit characteristics.

Seismic Units	Seismic pattern & key features	Previously named	References
U-LHRS-1a	- Continuous moderate-amplitude reflectors with some complex internal bedforms - Flay in some place - Continuous reflectors with polygonal faults, channels at base of U1a - Onlap	Zealandia U1a; Unit 1a (Sutherland et al., 2017); Zealandia-1a (Bache et al., 2014a)	(Sutherland et al., 2017, Bache et al., 2014a, Sutherland, 2019b, Sutherland et al., 2018a)
U-LHRS-1b	- Flat erosion surface incised by channels - Continuous reflectors with erosional channels and fanning or onlap next to fault or folds - Fanning growth strata - Volcano sits on unconformity - Syn-tectonic	Zealandia U1b (Bache et al., 2014); Unit 2b (Sutherland et al., 2017); Zealandia-1b (Bache et al., 2014a)	
U-LHRS-2a	- Reverse faulting - deformation - Locally folded	Zealandia U2a; Unit 2a (Sutherland et al., 2017); Zealandia U2a (Bache et al., 2014a)	
U-LHRS-2b	- Parallel, fanning reflectors - Truncation - Unconformity unit & normal faulting	Zealandia U2b; Unit 2b (Sutherland et al., 2017); Zealandia-2b (Bache et al., 2014a)	
U-LHRS-3	- Moderate to low amplitude discontinuous to chaotic reflectors a - folded - Truncation	Zealandia U3; Unit 2b (Sutherland et al., 2017); Zealandia-2b (Bache et al., 2014a)	

Figure 3.3. Seismic stratigraphy cartoon for southern Lord Howe Rise (LHRS). This seismic stratigraphy cartoon is based on TAN1409-LHRS-16 and 114-06.

3.2.1 U-LHRS-3

U-LHRS-3 contains moderate to low amplitude discontinuous reflectors that are folded and truncated by a prominent unconformity (RU2) southwest of Site U592 (Fig. 3.3 & 3.4) (Sutherland et al., 2010). RU2 is concordant with U-LHRS-2a reflectors above (Fig. 3.4, Table 3.1) but is itself folded (Bache et al., 2014b, Sutherland et al., 2010). A similar architecture is observed in Northland and Reinga (Bache et al., 2014a, Bache et al., 2012a).

Figure 3.4. TAN1409-LHRS-16 seismic reflection image (above) and sketch interpretation of Seismic Units U-LHRS-1a, U-LHRS-1b, U-LHRS-2a and U-LHRS-3 (below). Folded reflectors truncated of U-LHRS-3, folded U-LHRS-2a, and continuous reflectors with channels U-LHRS-U1b.

3.2.2 U-LHRS-2b

U-LHRS-2b has variable amplitude and continuity of reflectors (Fig. 3.3, 3.5, Table 3.1). U-LHRS-2b is characterised by moderate to high-amplitude with moderate to continuous reflectors. U-LHRS-2b has a highly-variable thickness and fanning reflectors are observed close to normal faults, e.g. near Site U207 (Fig. 3.5). The thickness the U-LHRS-2b is locally (seismic line 114-06) about 0.1 to 0.6 s TWT (Fig. 3.5 & 3.6A). The upper boundary of U-LHRS-2b locally truncates reflectors and is interpreted as an unconformity (Fig. 3.3) (Sutherland et al., 2010), but is a conformity or disconformity over most of the region. U-LHRS-2b is highly localised in small faulted depressions, and therefore it is difficult to define its thickness.

3.2.3 U-LHRS-2a

U-LHRS-2a is mapped as moderate to high-amplitude continuous reflectors, which are locally folded and reverse faulted (Fig. 3.3, 3.4, 3.5 & Table 3.1). U-LHRS-2a is thinner (< 0.5 s TWT) near Site U207 than at Site U1510 (Fig. 3.6B). The thickness of U-LHRS-2a is 0.2 to 0.9 s TWT (Fig. 3.6B). The channel and growth strata of U-LHRS-1b lie on top of folded and reverse faulted U-LHRS-2a. U-LHRS-2a near Site U592 is folded with parallel to subparallel reflectors (Fig 3.3, 3.4 & 3.5). U-LHRS-2a near Site U207 is mapped as low to moderate amplitude continuous reflectors in its upper part, and the lower part has high amplitude continuous reflectors that contain a broken or blocky appearance in some places (Fig 3.4 & 4.16).

Figure 3.5. 114-06 seismic reflection image (above) and sketch interpretation of Seismic Units U-LHRS-1a, U-LHRS-2a and U-LHRS-2b (below). Seismic Units U1a, U2a and U2b near Site U207, where an Eocene-Miocene erosion surface (disconformity) separates U-LHRS-2a and U-LHRS-1a.

Figure 3.6. Unit thicknesses in second two-way time (TWT): (A) U-LHRS-2b near Site U207, and (B) U-LHRS-2a.

3.2.4 U-LHRS-1b

U-LHRS-1b is characterised by high-amplitude continuous reflectors, lateral continuity, and with prominent channel forms (Fig. 3.3 3.4. & Table 3.1). U-LHRS-1b buries a narrow highly reflective mound and a similar feature is found near Site U592 (Fig. 3.4 & 4.17). Near Site U592, U-LHRS-1b basal high amplitude channel reflectors onlap folded U-LHRS-2a (Fig. 3.4). Near Site U1510, U-LHRS-1b contains a channel that cuts into its top surface and has fanning low to moderate amplitude continuous undulating reflectors (Fig. 4.11 & 4.12). The thickness of U-LHRS-1b is variable and depends on folds and reverse faults beneath U-LHRS-1b. U-LHRS-1b is missing at Site U207 (Fig. 3.5). The thickness of U-LHRS-1b ranges from 0.04 – 0.5 s (Fig. 3.7A & B).

Figure 3.7. Unit thicknesses in second two-way time (TWT): (A) U-LHRS-1b near Site U1510, and (B) U-LHRS-1b near Site U592.

3.2.5 U-LHRS-1a

U-LHRS-1a is mapped as variable amplitude continuous reflectors (Fig. 3.3, 3.4, 3.5 & Table 3.1). Flat-lying continuous reflectors are observed near Site U592. U-LHRS-1a contains some complex bedforms with moderate-amplitude continuous reflectors observed at Site U1510 (Fig. 4.11), and reflectors show local onlapping relationships (Fig. 3.4, 4.11 & 4.12). U-LHRS-1a has thickness near Site U1510 of 0.3 to 0.6 s TWT, and near Sites U207 and U592 of about 0.3 s TWT.

3.3 Northern Lord Howe Rise (LHRN)

Numerous studies are published (Hashimoto et al., 2010, Willcox et al., 2001, Staggs et al., 2002, Willcox and Sayers, 2002) on stratigraphy and structural analysis of the region. Previous work defined Mesozoic (inferred) stratigraphy of the region as Syn-rift (1 and 2) and Sag 1 (Table 3.2) (Higgins et al., 2015, Norvick et al., 2008a, Willcox and Sayers, 2001, Willcox et al., 2001), and Late Cretaceous-Paleocene post-rift is Sag 1 and Cenozoic is Sag 2 (Table 3.2). I based my mapping on previous work of Colwell et al. (2010), Higgins et al. (2015), and Sutherland et al. (2010); with nomenclature after Bache et al. (2014) (Table 3.2 & 3.8). I mapped pre-rift 'basement' as Seismic Unit U-LHRN-3; Syn-rift and Sag 1 as U-LHRN-2b1 (Syn-rift 2) and U-LHRN-2b2 (Syn-rift 1) (Fig. 3.8 & 3.9). Post-rift and Sag 1 are U-LHRN-2a and Sag 2 is Seismic Unit U-LHRN-1 (Table 3.2 & Fig. 3.8) (Bache et al., 2014a, Colwell et al., 2010a, Higgins et al., 2015, Sutherland et al., 2010).

Table 3.2. LHRN Seismic units characteristics.

Seismic Units	Seismic pattern & key features	Previously named	References
U-LHRN-1a	• Unconformity prominent in someplace with flat-lying to internal complex geometry with a little volcanic on the top • Continuous unit with polygonal faults • Onlaps • Drape material • Filling V-shape channel	Sag 2 (Sutherland et al., 2010); Post-rift Drape sediment (Colwell et al., 2010a, Higgins et al., 2015)	(Colwell et al., 2010b, Higgins et al., 2015, Hashimoto et al., 2009, Sutherland et al., 2010)
U-LHRN-1b	• Discontinuous reflectors • Thin section • hiatus	Sag 2 (Sutherland et al., 2010);	
U-LHRN-2a	• Erosional truncations • unconformity • Parallel, clinoformal • Variable frequency and amplitude reflectors	Sag 1 (Sutherland et al., 2010); Upper and Lower Sag sediment, Post-rift Sag (Colwell et al., 2010a, Higgins et al., 2015)	
U-LHRN-2b	• Parallel, moderate to high amplitude reflectors • Normal faulting • Multiples phases of syn-rift Unconformity unit	Sag 1 (Sutherland et al., 2010); Syn-rift 2 & Syn-rift-1 (Colwell et al., 2010a, Higgins et al., 2015)	
U-LHRN-3	Variable chaotic to locally continuous, stratified within tilted blocks	Pre-rift & basement (Colwell et al., 2010a, Higgins et al., 2015)	

Figure 3.8. Seismic stratigraphy cartoon for northern Lord Howe Rise (LHRN).

3.3.1 U-LHRN-3

U-LHRN-3 is characterised by variable amplitude chaotic to locally continuous reflectors (Fig. 3.8, 3.9, 3.10 & Table 3.2). U-LHRN-3 contains layered facies featuring subparallel to parallel reflectors that are truncated by faults, and at unconformity RU2 at its top (Fig. 3.10). The thickness is unknown because the base of the unit is not imaged.

3.3.2 U-LHRN-2b

U-LHRN-2b is found in NNW-trending grabens that are offset by NE-trending accommodation zones (Willcox et al., 2001). U-LHRN-2b (Fig. 3.8, 3.9 & Table 3.2) can be divided into sub-units U-LHRN-2b₁ and U-LHRN-2b₂ (Fig. 3.9). U-LHRN-2b₁ has parallel, divergent reflectors with high amplitude, and moderate continuity that are inferred to be growth strata adjacent to bounding faults (Fig. 3.8 & 3.9) (Colwell et al., 2010b, Higgins et al., 2015). There are some blocky high-amplitude and discontinuous reflectors that may indicate the presence of coal and lacustrine deposition accompanying

faulting during initial rifting (Hashimoto et al., 2012). U-LHRN-2b₁ has thickness up to ~2.6 km (~0.9 to 1.5 s TWT) (Higgins et al., 2015). U-LHRN-2b₂ has a typical thickness of about 1.1 km where it can be identified (Higgins et al., 2015) and contains parallel reflectors with moderate to high-amplitude. U-LHRN-2b₂ has maximum mapped thickness of ~2.8 km 1.5 s TWT in northern Western Flank (Higgins et al., 2015).

3.3.3 U-LHRN-2a

U-LHRN-2a is characterised by parallel, high-amplitude reflectors with high continuity (Table 3.2, Fig. 3.9 & 3.10) (Colwell et al., 2010b, Higgins et al., 2015). Faults that bound or offset the U-LHRN-2b sequence show little or no offset of U-LHRN-2a (Fig. 3.8 & 3.9) (Higgins et al., 2015). U-LHRN-2a is locally truncated overlying by U-LHRN-U1a and underlying by U-LHRN-3 (Fig. 3.8, 3.9 & 3.10). The thickness of U-LHRN-2a is mostly ~0.5 s TWT.

Figure 3.9. 302-009 seismic reflection image (above) and sketch interpretation of Seismic Units U-LHRN-1a, U-LHRN-1b, U-LHRN-2a, U-LHRN-2b₁, U-LHRN-2b₂ and U-LHRN-3 (below).

3.3.4 U-LHRN-1b

U-LHRN-1b is characterised by a thin parallel layer with high to moderate amplitude reflectors (Fig. 3.8, 3.9, 3.10 & Table 3.2). U-LHRN-1b is mostly not present and instead represented by an erosional hiatus. Volcanic edifices are associated with the unconformity that lies in place of U-LHRN-1b (Higgins et al., 2015, Rollet et al., 2012).

Figure 3.10. 302-001 seismic reflection image (above) and sketch interpretation of Seismic Units U-LHRN-1a, U-LHRN-1b, U-LHRN-2a, U-LHRN-2b and U-LHRN-3. U-LHRN-3 is overlapped by U-LHRN-2a. Black arrows = truncation.

3.3.5 U-LHRN-1a

U-LHRN-1a is mapped as parallel low-amplitude reflectors (Fig. 3.8, 3.9, 3.10 & Table 3.2). A high-amplitude continuous reflector observed at the base of U-LHRN-1a is shown at Site U208 to be an Eocene-Oligocene unconformity. This distinctive reverse polarity reflection separates chalk of U-LHRN-1a from siliceous ooze of U-LHRN-2a (Fig. 3.9 & 3.10). U-LHRN-1a is up to 800 m (1.5 s TWT) thick and dominated by calcareous foraminiferal and nannofossil chalk and ooze (Burns and Andrews, 1973) (Higgins et al., 2015, Colwell et al., 2010b, Burns and Andrews, 1973) to the south of Site U208. U-LHRN-1a has complex bedding over a volcanic complexes (Rollet et al., 2012).

3.4 Fairway Basin (FWAY)

The stratigraphy of Fairway Basin (FWAY) was described in detail by Rouillard et al. (2014), Rouillard et al. (2015), Collot et al. (2009), and Bache et al. (2014a); and hence this section only presents seismic figures from the recent TECTA survey (Fig. 1.2, Fig. 3.13 & Fig. 3.14). I used new seismic data, the TECTA survey (Collot et al., 2016), to correlate and connect FWAY, LHRN and Norfolk Ridge with NCTN (Fig. 1.1 & 3.24). I mapped FWAY into three units: U-FWAY-1 (U1a & U1b), U-FWAY-2 (U2a & U2b) and U-FWAY-3. The seismic pattern and key features are presented in Table 3.3 and Figure 3.11 and recent TECTA seismic data as presented in Figure 3.13 & 3.14.

Table 3.3. FWAY Seismic units characteristics.

Seismic Units	Seismic pattern & key features	Previously named	References
U-FWAY-1a	• Conformable • Erosive complex in the central basin • Continuous unit with polygonal faults • Onlaps	Zealandia U1a (Bache et al., 2014a); Fw1a (Rouillard et al., 2015)	(Auzende et al., 2000b, Auzende et al., 2000a, Collot et al., 2009, Hashimoto et al., 2010, Rouillard et al., 2015)
U-FWAY-1b	• Downlap • Onlap • Prograding series	Zealandia U1b (Bache et al., 2014a); Fw1b (Rouillard et al., 2015)	
U-FWAY-2a	• Slightly folded • Diapirs • Shelf type of feature, prograding wedges along the LHR in the NW • Fanning reflectors	Zealandia U2a (Bache et al., 2014a); Fw2a (Rouillard et al., 2015)	
U-FWAY-2b	• Normal faulting • Half-graben in the south	Zealandia U2b (Bache et al., 2014a); Fw2b (Rouillard et al., 2015)	
U-FWAY-3	• continuous and stratified reflections • chaotic packages • horst, tilting blocks, normal faults • Toplaps	Zealandia U3 (Bache et al., 2014a); Fw3 (Rouillard et al., 2015)	

Figure 3.11. Seismic stratigraphy cartoon is modified from Rouillard et al. (2015) illustrating seismic units of Fairway Basin (FWAY).

3.4.1 U-FWAY-3

U-FWAY-3 corresponds to acoustic basement and is characterised by chaotic high amplitude to locally continuous and stratified reflections within horsts and tilted blocks (Fig. 3.11 & Table 3.3) (Bache et al., 2014b, Exon et al., 2007, Rouillard et al., 2015). The top of U-FWAY-3 is a high-amplitude reflector with variable continuity. U-FWAY-3 is folded and faulted (Collot et al., 2009, Exon et al., 2007, Lafoy et al., 2005, Rouillard et al., 2015), and the thickness is unknown because it is only locally reflective and no clear base to the unit is visible.

3.4.2 U-FWAY-2b

U-FWAY-2b is characterised by moderate to high-amplitude continuous reflectors (Table 3.3 & Fig. 3.12). U-FWAY-2b has clinoform overlapping mounded features in the north and fanning geometries filling half-grabens in the south of the Basin (Auzende et al., 2000b, Rouillard et al., 2015, Exon et al., 2007). U-FWAY-2b has variable-amplitude clinoform reflectors that onlap onto horsts of Lord Howe Rise and Fairway Ridge (Exon et al., 2007, Bache et al., 2014a, Rouillard et al., 2015, Rouillard et al., 2017). The upper boundary of the U-FWAY-2b is a continuous high-amplitude reflector (Collot et al., 2009, Rouillard et al., 2015). U-FWAY-2b has restricted distribution but locally has a thickness of up to 1.1 s TWT (Rouillard et al., 2015).

Figure 3.12. LHRNR-BA seismic reflection image (above) and sketch interpretation of Seismic Units 2b, 2a, 1b and 1a (U2b, U2a, U1b and U1a) in FWAY and NCTN (below).

Figure 3.13. TEC14 seismic reflection image (above) and sketch interpretation of Seismic Units U-FWAY-1a and U-FWAY-2a (below). Seismic Unit U-FWAY-2a with mounded features interpretation as diapirs (Auzende et al., 2000b). Black arrows=fluid scapes and red arrows=onlaps.

3.4.3 U-FWAY-2a

U-FWAY-2a has medium to high amplitude reflectors with slight folding, and onlap into U-FWAY-2b (Table 3.3, Fig. 3.11, 3.12 & 3.13) (Collot et al., 2009, Lafoy et al., 2005, Rouillard et al., 2015). U-FWAY-2a is affected by diapirism and fluid expulsion above diapirs (Fig. 3.11 & 3.13) (Auzende et al., 2000b). There are thin sigmoid seismic facies on the eastern flank of Lord Howe Rise (Rouillard et al., 2017). The top of U-FWAY-2a is associated with erosion and truncation adjacent to Lord Howe Rise and Fairway Ridge. U-FWAY-2a is deformed near Site U206 (Fig. 3.13). U-FWAY-2a has variable thickness from 0.6 to 1.1 s TWT (Fig. 3.15B) (Rouillard et al., 2015).

3.4.4 U-FWAY-1b

U-FWAY-1b as a stacked prograding series of high to medium amplitude continuous reflectors (Rouillard et al., 2015). Prograding series have variable directions (west to east or east to west), as indicated by downlaps and onlaps onto U-FWAY-2a (Fig. 3.11, 3.12, 3.12 & Table 3.14). U-FWAY-1b has high amplitude reflectors isolated within V-shape depressions. These facies are interpreted as channels, with high amplitude reflectors interpreted as coarse-grained channel infill (Damuth et al., 1988). South of Fairway Basin, near Site U206, the borehole U206 crosses small faults related to local deformation where the unit is unsampled (Fig. 3.15). Turbidite systems with channel-levee features indicate there was sediment supply from surrounding ridges. The thickness of U-FWAY-1b is < 0.7 s TWT (Fig. 3.15C) (Rouillard et al., 2015).

The upper part of U-FWAY-1b contains a bottom-simulating reflector (BSR) that was identified by Auzende et al., (2000) and Nouzé et al., (2009). This BSR is observed throughout Fairway Basin, and Nouzé et al. (2009) conclude it is related to silica diagenesis.

Figure 3.14. Tec 20 near Site U206, seismic reflection image (above) and sketch interpretation of Seismic Units U-206-1a, U-206-1b and U-206-2a (below). Black arrows = onlaps and red arrows = downlaps relationship.

3.4.5 U-FWAY-1a

U-FWAY-1a is the shallowest seismic unit and mapped as variable amplitude continuous reflectors with basal onlaps. U-FWAY-1a has low amplitude reflectors with low continuity, suggesting erosive complexes in the central basin (Table 3.3, Fig. 3.11, 3.12 & 3.13) (Ravenne et al., 1977, Rouillard et al., 2015, Rouillard et al., 2017). U-FWAY-1a contains polygonal faulting. U-FWAY-1a is interpreted as aggrading basal deposits or pelagic draping interrupted by episodic turbidites and mass transport deposits (Rouillard et al., 2015, Rouillard et al., 2017). The thickness of U-FWAY-1a is about 0.8 s TWT (Rouillard et al., 2015).

Figure 3.15. Unit thickness in second two-way time (TWT) in FWAY basin, (A) U-FWAY-U2b (B) U-FWAY-U2a and, (C) U-FWAY-U1b.

3.5 Southern New Caledonia Trough (NCTS)

Previous work has been done on the seismic stratigraphy of southern New Caledonia Trough (NCTS) (Bache et al., 2014a, Collot et al., 2009, Etienne et al., 2018, Rouillard et al., 2015). I mapped seismic units of NCTS based on broad correlation to horizons of Bache et al. (2014), Collot et al. (2009) and Etienne et al. (2018), and adapted their nomenclature (Table 3.4 & Fig. 3.16). I mapped three seismic units: Seismic Unit U-NCTS-1 (U1a & U1b), U-NCTS-2 (U2a & U2b) and U-NCTS-3 (Table 3.4 & Fig. 3.16). The cartoon in Figure 3.16 is based on sequence-stratigraphic relevance to basin-filling phases and is adapted from previous published work (Bache et al., 2014a, Collot et al., 2009, Etienne et al., 2018, Rouillard et al., 2015).

Table 3.4. NCTS Seismic units characteristics.

Seismic Units	Seismic pattern & key features	Previously named	References
U-NCTS-1a	- Horizontal-parallel continuous reflectors - Onlaps	Zealandia U1a (Bache et al., 2014a)	(Sutherland et al., 2010, King and Thrasher, 1996, Baur et al., 2014, Bache et al., 2014a, Collot et al., 2009, Etienne et al., 2018)
U-NCTS-1b	- Syn-tectonic deformation with folding on the ridge - Downlaps and wedge geometry - Onlap termination - Locally shows slumping	Zealandia U1b (Bache et al., 2014a)	
U-NCTS-2a	- Continuous reflectors - Weakly deformed - Slightly tilted and folded - Reverse faulted	Zealandia U2a (Bache et al., 2014a)	
U-NCTS-2b	- a basal sequence of variable thickness - asymmetric half graben geometries to be normal faulted in many places - Locally reverse faulting, deformation?	Zealandia U2b (Bache et al., 2014a)	
U-NCTS-3	- Moderate to high-amplitude reflectors - Folded & faulted	Zealandia U3 (Bache et al., 2014a)	

Figure 3.16. Seismic stratigraphy cartoon for southern New Caledonia Trough (NCTS).

3.5.1 U-NCTS-3

U-NCTS-3 has chaotic discontinuous reflectors or transparent seismic facies, but dipping reflectors with moderate continuity are locally present (Table 3.4) (Bache et al., 2014a, Etienne et al., 2018, Sutherland et al., 2010, Collot et al., 2009). U-NCTS-3 is faulted and folded and truncated at its top (RU2 regional unconformity) (Bache et al., 2014a, Etienne et al., 2018).

3.5.2 U-NCTS 2b

U-NCTS-2b is characterised by high to moderate amplitude continuous reflectors. U-NCTS-2b has basal onlap termination of continuous or semi-continuous subparallel reflectors and is faulted at its base (Table 3.4 & Fig. 3.16) (Bache et al., 2014a, Sutherland et al., 2010, Etienne et al., 2018). U-NCTS-2b onlaps basement and is in turn onlapped by U-NCTS-2a (Fig. 3.16). U-NCTS-2b has a thin section < 0.5 s TWT.

3.5.3 U-NCTS 2a

U-NCTS-2a has moderate to high amplitude continuous subparallel reflectors (Table 3.4) (Bache et al., 2014a, Etienne et al., 2018, Sutherland et al., 2010). U-NCTS-2a onlaps underlying strata U-NCTS-2b and basement (RU2 regional unconformity) (Fig. 3.2, 3.16 & 3.26). U-NCTS-2a is locally deformed by reverse faulting (Fig. 3.16) (Bache et al., 2014a, Collot et al., 2009, Etienne et al., 2018). U-NCTS-2a has a few narrow diffractive intrusions along TL-1 line. Thickness is about 1 to 1.3 s TWT at Site U1509 and farther north near Site U206 (Fig. 3.17A), and the thickness of U-NCTS-2a is up to 2.5 s TWT at the edge of Deepwater Taranaki Basin (Collot et al., 2016).

3.5.4 U-NCTS-1b

U-NCTS-1b has moderate to high amplitude continuous seismic reflectors that either onlap or downlap onto U-NCTS-2a. (Table 3.4 & Fig. 3.16) (Sutherland et al., 2010, Etienne et al., 2018). U-NCTS-1b onlaps its basal surface (RU1) at the basin flank. U-NCTS-1b is divided into two sub-units (U1b₁ and U1b₂) based on stratal stacking pattern. U-NCTS-1b₁ has basal downlap interpreted as prograding sediment that resulted from erosion or transgressive wave ravinement of West Norfolk Ridge (Fig. 3.25), which is cut by a flat planation surface (Sutherland et al., 2010, Orr et al., 2020). U-NCTS-1b₂ is growth strata and onlaps folds and faults and interpreted as syn-tectonic (Etienne et al., 2018). U-NCTS-1b has a thickness of 0.1 to 1 s TWT (Fig. 3.17B).

Figure 3.17. Unit thicknesses in second two-way time (TWT) in NCTS and REIN, (A) U-NCTS-U2 (B) U-NCTS-1b.

3.5.5 U-NCTS-1a

U-NCTS-1a has moderate amplitude horizontal continuous reflectors that onlap U-NCTS-2a and U-NCTS-1b that are interpreted as turbidites filling the axis of the trough (Table 3.4 & Fig. 3.16) (Sutherland et al., 2010). U-NCTS-1a has a blanket of semi-continuous low-amplitude reflectors on the flank of the trough interpreted as pelagic drape. The thickness of U-NCTS-1a is up to 1.3 s TWT, and is thinner (0-0.4 s TWT) on the Lord Howe Rise slope (Fig. 3.25) (Etienne et al., 2018).

3.6 Northern New Caledonia Trough (NCTN)

The interpretation of stratigraphy of northern New Caledonia Trough (NCTN) is described and interpreted based on seismic reflection data tied to IODP borehole U1507 (Sutherland, 2019b) (Table 3.5, Fig. 3.19, Fig. 20 & Fig. 4.23). I created a seismic stratigraphy cartoon (Fig. 3.18) based on seismic reflection interpretation that is presented in Figures 3.19, 3.20 and 4.23. The seismic stratigraphy of NCTN is connected with other regions (e.g., FWAY, LHRN and down to U206) using the TECTA seismic survey (Figs. 1.1 & 3.19). I used Zealandia-wide megasequence nomenclature of Bache et al. (2014) to define three seismic units in NCTN: U-NCTN-1a, U-NCTN-U1b, and U-NCTN-2a (Table 3.5 & Fig. 3.18).

Table 3.5. NCTN Seismic units characteristics.

Seismic Units	Seismic pattern & key features	Previously named	References
U-NCTN-1a	• Low to moderate amplitude continuous reflectors • Sub-horizontal continuous reflector, • Onlap	Zealandia U1a (Bache et al., 2014a)	(Bache et al., 2014b, Sutherland, 2019b, Sutherland et al., 2020)
U-NCTN-1b	• High to low amplitude continuous reflectors • Downlap • Onlaps • Syn-folded	Zealandia U1b (Bache et al., 2014a)	
U-NCTN-2a	• Continuous reflectors • Small Faulting • Slightly/locally folded	Zealandia U2a (Bache et al., 2014a)	

Figure 3.18. Seismic stratigraphy cartoon for northern New Caledonia Trough (NCTN).

3.6.1 Basement

U-NCTN-3 contains isolated discontinuous high amplitude reflectors that could be volcanic intrusions or faults, but no coherent reflection packages of possible sedimentary origin were identified (Fig. 3.18 & 3.19).

3.6.2 U-NCTN-2a

U-NCTN-2a has continuous high amplitude reflectors (Table 3.5 & Fig. 3.12, 3.18, 3.19 & 3.20) (Sutherland, 2019b). U-NCTN-2a is cut by small faults and apparent volcanic intrusions (Fig. 3.19). U-NCTN-2a is thin (<0.4 s TWT, Fig. 3.20A) near Site U1507, and is underlain by and onlaps flat basement (Fig. 3.12, 3.18, 3.19 & 3.20). U-NCTN-2a becomes thick (>0.5 s TWT) further west through Fairway Basin (Fig. 3.15B & 3.21A) and south near Site U206 (Fig. 3.14). U-NCTN-2a is weakly deformed by minor normal faulting near Site U1507 (Fig. 3.18 & 3.19), causing local tilting of reflectors (Fig. 3.19). U-NCTN-2a is overlain by U-NCTN-1b which are sourced from lateral sediment supply coming from adjacent ridges (Fig. 3.18). U-NCTN-2a continuity is interrupted by Fairway (FWAY) Ridge, which is a basement high structure that can be traced from a seabed ridge into a basement high that is onlapped by subsurface strata.

Figure 3.19. Intersection seismic reflection line TEC 11 and TEC 08 across NCTN (above) and sketch of stratigraphy (below). Note that the thickness of Seismic Unit 1b (U1b) throughout NCTN is relatively large, and Seismic Unit 2a (U2a) is relatively thinner than in FWAY Basin.

3.6.3 U- NCTN-1b

U-NCTN-1b is characterised by onlap and downlap termination with continuous to semi-continuous moderate amplitude reflectors (Table 3.5, Fig. 3.18, 3.19 & 3.20) (Sutherland, 2019b). U-NCTN-1b has two sub-units U1b₁ and U1b₂, based on their seismic character (Fig. 3.19). These two sub-units are interpreted as having been deposited during times of active uplift and erosion, which is similar to inferences concerning U1b in the NCTS and REIN regions. U-NCTN-1b₁ shows onlap and downlap onto U-NCTN-1b₂, which in turn onlaps U-NCTN-2a (Fig. 3.18, 3.19 & 3.20). U-NCTN-1b₁ contains volcanoclastic deposits at Site U1507 with a variety of sedimentary facies indicative of various gravity-flow processes (Sutherland, 2019b). The thickness of U-NCTN-1b ranges from 0.7 to 1.2 s TWT (Fig. 3.21B).

3.6.4 U- NCTN-1a

U-NCTN-1a has continuous to semi-continuous moderate amplitude reflectors and chaotic layers up to 20 km across that are interpreted as debris flows (Table 3.5, Fig. 3.20 & Fig. 4.23) (Sutherland, 2019b). U-NCTN-1a onlaps U-NCTN-1b₁ (Fig. 3.18, 3.19 & 3.20). U-NCTN-1a contains scar failures on the basin margins that indicate mass failures and collapse into the trough. U-NCTN-1a has a thickness of <0.9 s TWT.

Figure 3.20. TEC06 seismic reflection image (above) and sketch interpretation of Seismic Units U-NCTN-1a, U-NCTN-1b and U-NCTN-2a (below). U1b is characterised by downlap and onlap termination.

Figure 3.21. Unit thickness in second two-way time (TWT) in NCTN, (A) U-NCTN-2a, (B) U-NCTN-1b.

3.7 Reinga Basin (REIN)

Previous workers defined seismic stratigraphic units (Bache et al., 2012a, Bache et al., 2012b, Herzer et al., 1997, Orr et al., 2020, Bache et al., 2014a) (Table 3.6). Broad correlation to horizons indicated in Bache et al. (2012 a, b) led to modification of their nomenclature and hence I define seismic units: U-REIN-1 (U1a & U1b), U-REIN-2 (U2a & U2b) and U-REIN-3 (Table 3.6 & Fig. 3.22). The cartoon in Figure 3.22 shows the general stacking pattern and Table 3.6 compares the seismic stratigraphic framework with previous work (Bache et al., 2012a, Bache et al., 2012b, Herzer et al., 1997, Orr et al., 2020, Bache et al., 2014a).

Table 3.6. REIN seismic unit characteristics.

Seismic Units	Seismic pattern & key features	Previously named	References
U-REIN-1a	• Sub-horizontal surface associated with polygonal faults in some places • Onlaps	Neo-4, Neo-2,3 & Neo-1, (Herzer et al., 1997); Seismic Unit U5, U6, U7 & U8 (Bache et al., 2012a); Zealandia U1a (Bache et al., 2014a); U9 (Orr et al., 2020)	(Bache et al., 2014a, Bache et al., 2012a, Baur et al., 2014, King and Thrasher, 1996, Orr et al., 2020)
U-REIN-1b	• Onlaps • Downlaps • Strongly deformed	Pal-1 & P1 (Herzer et al., 1997); Seismic Unit U4-U5 (Bache et al., 2012a); Zealandia U1b (Bache et al., 2014a, Orr et al., 2020)	
U-REIN-2a	• Strongly deformed, folded • Erosional truncations, unconformity unit • Onlaps	Cre-1 & Pal-2 (Herzer et al., 1997); Seismic Unit U2-U4 (Bache et al., 2012a); Zealandia U2a (Bache et al., 2014a)	
U-REIN-2b	• High amplitude, subparallel reflectors • Onlap termination • Folded then truncation by a planation surface in some places • Inversion • Normal faults, fanning growth strata	Cre-1 (Herzer et al., 1997); Seismic Unit U1 (Bache et al., 2012a); Zealandia U2b (Bache et al., 2014a)	
U-REIN-3	• Divergent seismic reflectors • Normal faults	Zealandia U3 (Bache et al., 2014a)	

3.7.1 U-REIN-3

U-REIN-3 has variable amplitude continuous reflectors that are parallel and with high to moderate continuity, stratified and folded (Table 3.6 & 3.23). U-REIN-3 is characterised by erosional truncations at its top and onlapping reflectors above (Table 3.6, Fig. 3.22) (Bache et al., 2014a, Bache et al., 2012a, Herzer et al., 1997). This unconformity (RU2) is overlain by younger successions with less deformed seismic reflectors (U-REIN-2a and U-REIN-2b) (Fig. 3.22) (Bache et al., 2012b).

3.7.2 U-REIN-2b

U-REIN-2b corresponds to syn-rift half-grabens fill, as interpreted by Bache et al. (2012a), Bache et al. (2012b), and Herzer et al. (1997) (Fig.3.22 & 3.23). U-REIN-2b corresponds to Seismic Unit U1 of Bache et al. (2012b). U-REIN-2b has basal onlap terminations with continuous or semi-continuous reflectors, fanning reflectors, and is typically faulted at its base (Fig. 3.23). U-REIN-2b has thickness <0.7 s TWT near Site U1508.

Figure 3.23. REIN09-012 seismic reflection image (above) and sketch interpretation of Seismic Units U-REIN-1a, U-REIN-1b, U-REIN-2a, U-REIN-2b and U-REIN-3 (below). Black arrows are onlaps (adapted from Bache et al., 2014; Orr et al., 2020).

3.7.3 U-REIN-2a

U-REIN-2a is locally affected by later folding or reverse faulting (Bache et al., 2014a, Bache et al., 2012a). Deposition resulted in onlap against basement highs created by earlier extensional faulting (Table 3.6, Fig. 3.22 & 3.23) (Bache et al., 2012a, Bache et al., 2012b, Herzer et al., 1997).

Bache et al. (2012) nomenclature of this unit is Seismic Unit U2 to U4. Seismic Unit U2 is characterised by sub-parallel reflectors with onlaps. Seismic Unit U3 has parallel continuous reflectors that are strongly folded in the NW, and the thickness is about 1.0 to 1.2 s TWT the Northland Basin to the SE. Seismic Unit U4 has folded parallel reflectors in eastern Reinga Basin and is strongly folded in the NW and less folding in south Northland Basin (Bache et al., 2012a). Seismic Unit U4 has a thickness of about at 0.2 to 0.4 s TWT (Bache et al., 2012a).

U-REIN-2a has parallel folded reflectors, onlaps topographic highs, is truncated by RU1, and overlain by U-REIN-1a (Fig. 3.22 & 3.23). Near Site U1508, discontinuous reflectors of U-REIN-2a are eroded near volcanic and structural highs, and at basin margins (Fig. 3.22 & 4.29A) (Orr et al., 2020, Bache et al., 2012a). U-REIN-2a ranges in thickness up to 2.1 s TWT (Figure 3.24A).

Figure 3.24. Unit thicknesses in second two-way time (TWT) in REIN basin near Site U1508, (A) U-REIN-2a, and (B) U-REIN-1b.

3.7.4 U-REIN-1b

U-REIN-1b has high-amplitude continuous reflectors, fanning, downlap and onlap (Table 3.6, Fig. 3.22 & 3.23) (Bache et al., 2014a, Bache et al., 2012a, Sutherland, 2019c, Orr et al., 2020). U-REIN-1b is divided into two sub-units U-REIN-1b₁ and U-REIN-1b₂, based on seismic character. U-REIN-1b₁ is characterised by downlap, and U-REIN-1b₂ onlaps folded U-REIN-2a reflectors (Fig. 3.22 & 3.23). U-REIN-1b₁ contains volcanic detritus that relates to initial arc volcanism near North Island. U-REIN-1b corresponds to Seismic Unit U4-U5 of Bache et al. (2012b) (Fig. 4.28 & 4.29). Seismic Unit U5 is characterised by high-amplitude continuous reflectors with distinctive basal onlap surface, slightly deformed to undeformed. Seismic Unit U5 separates less deformed subhorizontal reflectors from underlying folded U4 (Orr et al., 2020, Bache et al., 2012a). Seismic Unit U5 has a thickness of <0.2 s TWT (Orr et al., 2020). The thickness of U-REIN-1b ranges from 0.1 to 0.7 s TWT (Fig. 3.24B).

3.7.5 U-REIN-1a

U-REIN-1a has continuous variable-amplitude reflectors (Table 3.6, Fig. 3.22 & 3.23). U-REIN-1a has complex internal bedforms and is associated with small-offset polygonal faults (Fig. 3.23, 4.28 & 4.29). U-REIN-1a contains four Seismic Units (U6, U7, U8, and U9 of Bache et al. (2012) and Orr et al. (2020)) (Table 3.6). Herzer et al. (1997) defined four-units, namely Neo-4, Neo-2, 3, and Neo-1 (Table 3.6). U-REIN-1a is variable in thickness: thin near Site U1508 and thick further from the basin margin (Fig. 4.28). The thickness ranges from < 0.2 to 0.6 s TWT (Orr et al., 2020).

3.8 Interpretation and discussion

Folded, faulted, and truncated Seismic Unit U3 is overlain by less deformed seismic reflectors with onlap relationship (Seismic Units U2a and U2b). Onlap and downlap of Seismic Unit U1b onto unconformity RU1 at the top of U2 occurred in many places across northern Zealandia. However, seismic stratigraphy observed in northern Zealandia has little borehole control. DSDP boreholes (U206, U207 and U208) have penetrated Late Cretaceous to Eocene strata (Burns et al., 1973a, Burns et al., 1973b). IODP drilling data (U1509) in NCTS penetrated to Cretaceous, and to Eocene in LHRN (U1506), NCTN (U1507), REIN (U1508) and LHRS (U1510). Hence, dredged rock samples, DSDP and IODP sites can be tied to seismic data to map and interpret seismic-stratigraphic relationships across northern Zealandia.

3.8.1 Geology relationship across northern Zealandia

Basement in New Zealand contains a series of linear terranes that are approximately parallel with the ancient Gondwana margin (Mortimer, 2004, King, 2000b, King and Thrasher, 1996, Uruski et al., 2003). The basement comprises metamorphosed igneous and volcanoclastic sediments of Paleozoic and Mesozoic ages, and a relic arc called the Median Batholith or Median Tectonic Zone (Mortimer et al., 1997). Petroleum wells near the coast of New Zealand also place some control on the distribution of basement terranes, e.g. the Wainui-1 well penetrated Paleozoic Takaka Terrane (metamorphosed siliceous sandstone) (SBPT, 1982).

The Murihiku Supergroup is inferred in the REIN-Northland Basin based on well and dredge sampling (Mortimer et al., 2009), and in southeast Zealandia in the Great South Basin based on seismic reflectors (Cook et al., 1999b). The Seismic Unit U3 is characterised by folded strata, and erosional truncations that I interpret as Murihiku Supergroup, similar to exposed geology on the margins of Northland and Great South Basin. These interpretations are supported by the Waka Nui-1 well, which penetrated late Jurassic-early Cretaceous Murihiku Supergroup volcanoclastic coal measures (Mortimer et al., 2009). In New Caledonia, the Teremba Terrane contains Late Permian to Mid Jurassic calc-alkaline volcanic rocks and volcanoclastic rocks with similarities in age and lithology to the Murihiku Supergroup (Cluzel et al., 2012, Campbell et al., 1985). 120 km

NW of Waka Nui-1, Early Cretaceous dinoflagellates sampled at onshore Waimamaku-2 are interpreted as Murihiku Supergroup (Hornibrook et al., 1976). In NCTS, Seismic Unit U3 is unsampled but may contain equivalents of Murihiku Supergroup (Bache et al., 2014a; Bache et al., 2012a). The Murihiku Supergroup onshore in New Zealand contains Early Triassic to Late Jurassic marine and non-marine sandstone and mudstone, including basal Late Permian sandstone (Campbell et al., 2003).

Norvick et al. (2008) suggest that a Lower-Middle Jurassic pre-rift sequence might exist on Lord Howe Rise that is an equivalent of the Late Jurassic Walloon Coal Measures and Koukandowie Formation of Queensland. The Walloon Coal Measures were deposited in fluvial and lacustrine or swampy environments in the Clarence-Moreton and Surat basins (Ingram et al., 1996). Hydrogen-rich coals of the Walloon Coal Measures were also deposited in Surat Basin. In northern Queensland in the Laura and Carpentaria basins, the latest Jurassic-Neocomia Gilbert Formation contains lagoonal to marginal marine strata (Turner et al., 2009).

In south-eastern Australia, the Late Jurassic and Early Cretaceous rift-related volcanoclastic Strzelecki Group of the Gippsland Basin is also a possible correlation of U3. Gippsland Basin contains coal measures and lacustrine facies of the Jurassic Beds that deposited during the early stages of the Otway Rift Phase (Norvick et al., 2001). This rift occurred through the Early Cretaceous, synchronous with deposition of the Strzelecki Group. A Campanian (100-90 Ma) unconformity in Gippsland is overlain by Emperor and Golden Bay subgroups deposited in the Late Cretaceous (Norvick et al., 2001, Uruski et al., 2003). Non-marine units are found in eastern Australia basins, and marine strata are unknown.

North of Australia, Marine Triassic-Jurassic strata are found in the onshore Timor-Leste and offshore Bonaparte Basin (Charlton, 2002, Audley-Charles, 1968). Triassic radiolarian wackestone interbedded with shale of the Aitutu Formation was deposited in marine conditions (Audley-Charles, 1968). The Gondwana Jurassic in onshore Timor contains carbonate-platform facies and shelf facies overlain by Cretaceous deep-water pelagic deposits (Haig et al., 2019). The Early to Middle Jurassic Plover Formation of Bonaparte Basin consists of sandstones and shale (Mory, 1991, Jules et al., 2015). Early to Middle Jurassic sandstones and shale (Plover Formation) are non-marine to marginal

marine and overlies Middle Jurassic shallow marine sandstone (Robinson, 2012, Jules et al., 2015, Mory, 1991).

Further northeast of Australia, marine clastic sediments are known in Papua New Guinea (Brown et al., 1979). The Papuan Basin in PNG contains Mesozoic sediments deposited on Palaeozoic continental basement rocks (Waples and Wulff, 1996, Ahmed A. S. et al., 1988). The Jurassic marine shelf clastic sediments (Imburu Formation of the Papuan Basin) was deposited during inundation of the margin (Ahmed A. S. et al., 1988). Middle to Upper Jurassic clay-rich marine source rocks contain terrigenous higher plant organic matter deposited under oxic condition (Ahmed et al., 2012, Waples and Wulff, 1996).

Marine Mesozoic strata are extensively developed in the offshore Bonaparte Basin and onshore Timor-Leste (Charlton, 2002; Mory, 1991; Robinson, 2012), and marine clastic sediments are known in Papua New Guinea (Brown et al., 1979). It is plausible that similar marine source rocks are imaged as Seismic Unit U3 in northern Zealandia.

Eastern Australia and Zealandia experienced widespread Mesozoic contractional uplift and subaerial erosion followed by rifting, subsidence, and relative sea-level rise during the Late Cretaceous to Eocene (Bache et al., 2014a, Sutherland et al., 2010). The result of this erosion is the RU2 unconformity (Bache et al., 2014a). Regionally, the products of this erosion and transgression caused deposition of a coal measure–sandstone–mudstone sequence, overlain by fluvial, coastal, and shallow-marine sandstones (Bache et al., 2014a, King, 2000b, King and Thrasher, 1996). Lithostratigraphic correlation is possible between southeastern Australia (Golden Beach and Latrobe groups of Gippsland Basin), New Zealand (Pakawau and Kapuni groups of Taranaki Basin), and New Caledonia (“Formation à charbon” and “phtanites”) (Norvick et al., 2001, King and Thrasher, 1996, Baur et al., 2014, Cluzel et al., 2010).

The lithostratigraphy of Seismic Unit U2b across northern Zealandia is inferred from geology relationships in the region. Seismic Unit U2b has never been sampled in the remote Zealandia offshore region, and comparison to New Zealand, New Caledonia and eastern Australia suggests the likely occurrence of fluvial sandstone, mudstone and coal, grading upwards to claystone associated with marine transgression (King and Thrasher, 1996, Collot et al., 2009, Cluzel et al., 2012, Campbell et al., 1985, Norvick et al., 2001).

Cretaceous volcanic rocks, including pyroclastic deposits, flows and sills are observed onshore in New Caledonia (Maurizot and Vendé-Leclerc, 2009) and could be interbedded with U-FWAY-2b. A shallow-water fragment was associated with the 74 ± 0.7 Ma latite dredge sample from Fairway Ridge (Higgins et al., 2011, Colwell et al., 2006). In NCTS, Seismic Unit U2b can be correlated with mid Cretaceous strata in Taranaki-Aotea Basin, where coal measures, alluvial plain, and marginal marine facies are sampled in wells (Uruski and Baillie, 2004, Collot et al., 2009, Strogon et al., 2017, King and Thrasher, 1996).

Based on comparison to eastern Australia, New Caledonia and New Zealand, Seismic Unit U2a in LHRN is probably dominated by Late Maastrichtian and Palaeocene claystone and chalk with chert (Site U208) (Fig. 5.5) (Burns and Andrews, 1973, Hashimoto et al., 2012). Cretaceous coaly sandstone rocks were dredged from the western flank of West Norfolk Ridge (Herzer et al., 1999), but it is not clear from which seismic unit. In NCTS (Seismic Unit U2a), Late Cretaceous marine claystone was sampled at Site U1509 (Fig. 5.7), and closer to Taranaki, (Sutherland et al., 2010, Collot et al., 2009) seismic interpretations tied to boreholes were used to map Late Cretaceous coal measures of Rakopi Formation (Baur et al., 2014).

Figure 3.25. Cartoon diagram showing stratigraphy of seismic Units across northern Zealandia, based on this study and previous works (Auzende et al., 2000b, Bache et al., 2014a, Bache et al., 2012a, Collot et al., 2008, Collot et al., 2009, Exon et al., 2007, Lafoy et al., 1994, Rouillard et al., 2015, Sutherland et al., 2017, Sutherland et al., 2010).

3.8.2 Seismic Unit U3-U2b stratigraphic relationships

The LHRN region is made up of a series of NNW trending horsts and grabens offset by NE trending accommodation (Willcox et al., 2001). LHRN is composed of pre-rift and basement which is speculated to contain several discrete terranes (Palaeozoic orogeny, pre-rift sedimentary and rift-precursor igneous rocks) and two Early Cretaceous syn-rift phases divided by Cenomanian uplift or inversion (rifting during eastern Gondwana breakup) (Higgins et al., 2015, Norvick et al., 2008a, Willcox and Sayers, 2001, Willcox et al., 2001).

Based on the seismic facies, Seismic Unit U3 recorded in LHRN (Table 3.2) is probably sedimentary strata (Fig. 3.9, 3.10 & 3.25). U-LHRN-3 may contain more than one unit (rift 1, pre-rift and basement). U-LHRN-3 (pre-rift) contains parallel to subparallel with high-moderate-amplitude continuous reflectors, stratified, uniformly tilted, and these characters indicate that U-LHRN-3 is sedimentary in origin.

U-LHRN-3 has been speculated to be Cretaceous in age (Hashimoto et al., 2010, Higgins et al., 2015), but U-LHRN-3 could be older than Cretaceous. U-LHRN-3 could be early Cretaceous or Jurassic or even could be Triassic-Permian in age. The seismic interpretation shows a significant break-in time, separating the rifting event (unconformity between U-LHRN-2b₂ and U-LHRN-2b₁) and hence U-LHRN-U2b₂ may also be classified as U-LHRN-U3 rather U-LHRN-2b (Fig. 3.8 & 3.9). Further northeast of LHRN (near Site U1507), there is no convincing evidence that the older unit beneath U-NCTN-2a contains sedimentary strata (Fig. 3.19, 3.20 & 3.25). The oldest sequence does not have continuous reflectors. Reflectors could be faults or volcanic intrusions. Further south in REIN (near Site U1508), U-REIN-3 is interpreted to contain the Murihiku Supergroup, which is supported by the Waka Nui-1 well.

3.8.3 Seismic Unit U2a-U1b stratigraphic relationships

The stratigraphic relationship between Seismic Unit U2a and Seismic Unit U1b is defined based on seismic interpretation data, drilling and dredge samples. By comparing the sedimentary thickness of Seismic Unit U2a with the other five regions (Fig. 3.25), it is noteworthy that Seismic Unit U2a is a thin unit in NCTN and becomes thicker in FWAY, NCTS, and REIN. Seismic Unit U1b in NCTN is thicker (Fig. 3.19, 3.20 & 3.21B) than other regions (Fig. 3.12, 3.19 & 3.21B). The thickness of sediment is a signal of lateral sediment supply coming from the LHRN and Norfolk Ridges. These observations appear to be consistent through the south and southeast region, where the LHRN experienced subaerial erosion between 45 and 34 or 29 Ma, REIN 34 and 24 Ma and New Caledonia was after circa 34 Ma (Sutherland et al., 2020, Collot et al., 2008, Sutherland et al., 2017).

Seismic Unit U1b shows evidence of hiatus (on ridges) across the Eocene-Oligocene boundary, but this hiatus is not observed in NCTN. Site U1507 records no missing time across the Eocene-Oligocene boundary, but an unconformity exists in the adjacent LHRN region, where subaerial erosion occurred at about 50 Ma at Site U1506. The reason a hiatus is not observed in NCTN is because Seismic Unit U1b in NCTN was located at a low point, where there was rapid sedimentation in the depocenter. LHRN was swept by current across a top that was shallow, and hence materials are deposited into the trough.

NCTS and REIN basins contain deformed Cenozoic strata and flat unconformities. In NCTS, Seismic Unit U2a is overlain by a mass-transport complex deposit due to slope oversteepening resulting in Seismic Unit U1b (Fig. 3.25) (Etienne et al., 2018, Poestma et al., 2009). Seismic reflectors at Site U1509 show that Seismic Unit U1b thins onto the western slope of the basin, where there is exposure of Seismic Unit U2a deformed strata (Fig. 3.25). Due to tectonic subsidence along the New Caledonia Trough axis, uplift and erosion occurred on the LHRN slope and West Norfolk Ridge, and formed subtle tilting, reverse faulting (Fig. 3.25, 4.11 & 4.12), and minor folding of Seismic Unit U2a strata (Sutherland, 2019b, Sutherland et al., 2010). In REIN basin, Eocene contraction occurred leading to deformation of U-REIN-2a (Bache et al., 2012a, Sutherland, 2019c). Folding and uplift occurred at 56-43 Ma along West Norfolk Ridge to create wave ravinement surfaces (Orr et al., 2020), and compression and reverse faulting in the east occurred at 39 to 34 Ma (Sutherland et al., 2017).

3.9 Chapter summary

I have reviewed and mapped the Bache et al. (2014) seismic-stratigraphic architecture framework of northern Zealandia, based on seismic analysis for multiple locations (LHRN, LHRs, FWAY, NCTS, NCTN and REIN). Seismic Unit U3 contains faulted, folded, and truncated reflectors overlain by Seismic Unit U2b (onlap relationship, fanning reflectors adjacent to normal faults) and Seismic Unit U2a (minor amount of deformation with onlap relationship). Seismic Unit U1b comprises fanning reflectors (near folds or sediment sources) that onlap and downlap, recording uplift, subsidence, erosion, and volcanic input to the basin. Lastly, Seismic Unit U1a is drape sequence onto older units, and gravity flows within the axes of troughs.

Seismic Unit U3 is only sampled in the Waka Nui-1 well in northern Zealandia. Elsewhere, Seismic Unit U3 may be similar to the Murihiku Supergroup (Bache et al., 2014a; Bache et al., 2012a), or Triassic–Jurassic coal measures of the Clarence–Moreton Basin of Queensland (O'Brien et al., 1994, Ingram et al., 1996), or Late Jurassic and Early Cretaceous rift-related volcanoclastic Strzelecki Group of the Gippsland Basin (Norvick et al., 2001). Hence, Seismic Unit U3 may contain sandstone, mudstone, and organic-rich shale or coal, folded volcanoclastic sediment and magmatic rock formed on a low-lying broad continental margin that was episodically flooded by the ocean near a Mesozoic subduction margin (Bache et al., 2014a, Bache et al., 2012a, Mortimer, 2004). Seismic Unit U3 is mostly unsampled and it is plausible that organic-rich marine source rocks equivalent to those found in Timor-Leste and Papua New Guinea may also be present.

Seismic Unit U2b is interpreted as syn-rift (Bache et al., 2014a, Bache et al., 2012a, Herzer et al., 1999). Seismic Unit U2b is unsampled in the study area and restricted in extent. Comparison to New Zealand, New Caledonia and SE Australia suggest that Seismic Unit U2b may contain fluvial sandstone, mudstone and coal, grading upwards to shallow marine transgressive deposits (Campbell et al., 1985, Cluzel et al., 2012, Collot et al., 2009, King and Thrasher, 1996, Norvick et al., 2001). In the southern part of the region in Taranaki-Aotea Basin (NCTS, REIN), Seismic Unit U2b may correlate with mid Cretaceous coal measures, alluvial plain, and marginal marine facies (Uruski and Baillie, 2004, Collot et al., 2009, Strogon et al., 2017, King and Thrasher, 1996). Seismic

Unit U2b may contain coaly source rocks as observed onshore New Caledonia (“Formation à charbons”) and further south in NCTS (Herzer et al., 1999, Collot et al., 2009). Seismic Unit U2b in FWAY is interpreted as stacked delta fans from erosion of FWAY Ridge and LHR (Collot et al., 2009, Rouillard et al., 2015, Rouillard et al., 2017). Terrestrial and shallow marine sandstone in Seismic Unit U2b is possible reservoir rock.

Seismic Unit U2a is interpreted as transgressive marine sediments deposited during Zealandia thermal subsidence (Bache et al., 2014a). Seismic Unit U2a is Late Cretaceous to Eocene in age. Cretaceous carbonaceous mudstone (marine equivalent coaly mudstone) is known at Site U1509 (Sutherland, 2019b, Sutherland et al., 2018a) suggesting the base of the Seismic Unit U2a has potential for marine petroleum source rock in addition to the proven coaly source rocks of this age in Taranaki Basin (King and Thrasher, 1996). Transgressive sandstones within Seismic Unit U2a may contain reservoir rock similar to petroleum producing reservoirs of this age in Taranaki Basin.

Seismic Unit U1b resulted from regional uplift involving erosion that supplied clastic sediment into Seismic Unit U1b (Orr et al., 2020, Bache et al., 2014a). Based on seismic character, spatial distribution and information from available boreholes, Seismic Unit U1b contains mass-transport complexes and basin floor fans (Sutherland, 2019b). Basin floor fans could be reservoir rock. Eocene folding associated with Seismic Unit U1b generated structural traps in the southern part of the region.

Seismic Unit U1a is a drape sequence onto older units and contains gravity flows within the axes of troughs. Oligocene and Neogene chalk, calcareous ooze and marl represent overburden (Burns and Andrews, 1973, King and Thrasher, 1996, Sutherland, 2019b, Sutherland et al., 2018a, Bache et al., 2014a).

4 Cenozoic Sedimentation Rate

4.1 Introduction

Maturation of Mesozoic source rocks was associated with Cenozoic burial. Migration and trapping of any petroleum might have been affected by tectonic tilting and faulting associated with initiation of the Tonga-Kermadec subduction system (see discussion in Chapter 2) (Bache et al., 2014b, Hashimoto et al., 2012, Rouillard et al., 2015, Sutherland et al., 2017). Accordingly, detailed estimates of Cenozoic sedimentation rates are crucial in reconstructing the burial histories of northern Zealandia and hence the timing and migration of petroleum migration in the context of trap development.

Northern Zealandia experienced significant tectonic modification during the Cenozoic that may have been associated with delamination of lithosphere and initiation of subduction followed by rapid foundering and rollback of the slab (Sutherland et al., 2010). New Caledonia Trough subsided, and Lord Howe Rise and Norfolk Ridge System experienced transient uplift (Sutherland et al., 2020). Late Cretaceous and Paleogene strata are affected by subtle tilting and local reverse faulting and folding. Thermal and dynamic processes accompanying lithosphere delamination appear to have generated broad >700 km transient uplift with an amplitude of 1-2 km (Sutherland et al., 2010, Sutherland et al., 2020).

Climate played a key role in development of Cenozoic stratigraphic sequences over northern Zealandia, because most of the sediment is biogenic (Kennett, 1977, Kennett et al., 1975). The separation of Antarctica from Australia and the opening of the Tasmania Gateway caused regional changes in oceanic circulation during the Eocene to Oligocene (Kennett 1977). The Eocene-Oligocene boundary at ~34 Ma signified the onset of significant Antarctica glaciation that reduced the temperature by ~5°C and led to the formation of the Antarctic ice sheet (Kennett, 1977). The Antarctica Circumpolar Current (ACC) was initiated when the Tasmanian gateway opened in the early Oligocene (Carter et al., 2004, Kennett et al., 1975). A warmer sup-tropical gyre separated from the cold southern gyre affected distribution and migration of planktonic species (Kennett, 1980). Erosion in the deep ocean basins was due to an increase in bottom current activity.

Environmental changes affected biogenic primary productivity and hence sedimentation rate.

The objective of this chapter is to describe the Cenozoic sedimentation rates succession deposited over northern Zealandia. This is achieved using boreholes to provide age and lithological calibration for seismic interpretations, and I restrict my analysis to regions near borehole control (Fig 1.2, 1.3, 1.4, 1.5 & 1.6). Detailed age-models are tied to seismic reflection data (Sutherland et al., 2018a). I map and calculate Cenozoic depositional rates across northern Zealandia. Results are of interest for understanding past environmental variability and are needed to assess the timing of any potential hydrocarbon generation and expulsion (Henriksen et al., 2011, Sutherland et al., 2017, Sutherland et al., 2010).

Stratigraphic names used in this chapter are local to the immediate region being analysed, and most represent subdivisions of Zealandia Seismic Unit U1. I use local name definitions that are consistent with the approach of Bache et al. (2012) but note that these names are not consistent with Zealandia-wide megasequence nomenclature (Bache et al. 2014). The naming creates any inconvenience or confusion but following a previously used scheme seemed the most pragmatic way to proceed. It would be sensible in future to redefine all names to a uniform Zealandia-wide set of conventions.

4.2 Mass accumulation rate (MAR)

Mass accumulation rate (MAR) calculation is based on microfossil datums that define the age-depth relationship (Fig. 4.1) and hence the linear sedimentation rate at each site is converted to MAR using measurements of density and porosity (Sutherland, 2019a, Sutherland, 2019b, Sutherland et al., 2018a). Age models are available from recent paleontological reanalysis (Sutherland, per. comm. 2019) for each site (U1506-U1510 and U208, U207 and U592).

Figure 4.1 Depth age relationships at IODP boreholes and DSDP Sites (Burns, 1973a, Burns and Andrews, 1973; Sutherland, pers. comm. 2019; Sutherland, 2019c; Sutherland et al., 2018b).

The linear sedimentation rate (LSR) is simply the observed thickness of a sediment layer divided by period of time it took to deposit. MAR is calculated using depth-density and depth-porosity relationships. The relation between depth of burial and the density and porosity for different types of sediment can be expressed by exponential equations (Athys, 1930).

$$\phi(z) = \phi_o e^{-\frac{z}{L}}$$

$$\rho_{sed} = \rho_{fluid}\phi + \rho_{grain}(1 - \phi)$$

$$Grain\ mass = (1 - \phi)\rho$$

Where z is depth below the surface, L represents compaction length; ρ is grain density and ϕ is porosity.

MAR is calculated for each borehole, and for layers defined by seismic horizons that could be tied to boreholes. Rupert Sutherland wrote computer code that made these calculations. We use surface porosity and compaction length parameters from recent measurements and compilations (Stratford et al., 2018, Sutherland R. et al., 2019) (Fig. 4.2).

Figure 4.2. IODP Expedition 371 porosity measurements of bathyal pelagic sediment (Sutherland, 2019a, Sutherland, 2019b, Sutherland et al., 2018a). The porosity-depth profiles have near surface porosity of 60 to 70 % and a decrease to about 25 to 30% by 700 m depth below seabed.

4.3 Northern Lord Howe Rise (LHRN)

As many reflectors as possible above the Eocene-Oligocene unconformity were locally mapped between boreholes DSDP 208 and IODP U1506 (Fig. 1.2 & 2.4). The Oligocene-Eocene unconformity creates a distinctive negative-polarity seismic reflector that is underlain by several high amplitude continuous reflectors (Stratford et al., 2018). Five seismic units (U5-U9) and thirteen sub-units were identified (Fig. 4.3, 4.4, 4.5 & 4.6). These are all subunits of the regional Zealandia U1 megasequence.

Some reflectors can be mapped regionally between boreholes, whereas others can only be confidently identified close to one of the boreholes (Fig. 4.6 & 4.7). The extent to which a unit can be mapped is identified in its name: LHRN- for regional extent within the 302 survey, and U208- or U1506- for local extent.

4.3.1 Results of seismic stratigraphy interpretation

The following section describes the seismic stratigraphy at Site U208 and U1506 using seismic surveys 302 and TAN1409-LHRN. Site U208 has four bounding surfaces (UB-LHRN-5 to UB-LHRN-8) defining four seismic units that are further subdivided into ten sub-units (Fig. 4.3 & 4.4).

Figure 4.3. Seismic stratigraphy of northern of Lord Howe Rise near Site U208.

Figure 4.4. Seismic stratigraphy of northern Lord Howe Rise near Site U1506.

Figure 4.5. Seismic line 302-009 on the northern Lord Howe Rise at Site U208, (A) seismic reflection showing seismic time horizons interpretation in colour (B) polygonal faulting in Neogene sediments.

Figure 4.6. Seismic reflection line TAN1409-LHRN-06 through borehole U1506, (A) seismic reflection image, and (B) sketch of scour and onlapping reflector geometries. Miocene/Eocene unconformity appears as a continuous reverse polarity reflection nearby, but is a positive reflection at Site U1506.

Seismic Unit 6 (U-LHRN-6) represents a transparent seismic facies with low to moderate-amplitude semi-continuous reflectors of Late Oligocene age. There is an unconformity/hiatus documented at Site U208 between U-LHRN-6 and ULHRN-5 (Fig. 4.5). This unit is composed of foraminiferal nannofossil chalk with clay (Fig. 4.7). U-LHRN-6 strata onlap volcanic edifices associated with the Eocene-Oligocene unconformity elsewhere in the region (Higgins et al., 2015, Sutherland et al., 2017).

Figure 4.7. Borehole DSDP 208 age-depth relationship. The TWT seismic reflectors were converted to depth using velocity model (Sutherland et al., pers. comm. 2019). Late Oligocene/Middle Eocene unconformity UB-LHRN-5 occurs at depth 492.4 m.

Onlaps and scour development near Site U1506 suggest strong bottom-current activity (Fig. 2.4) that likely caused erosion of U-LHRN-6 at Site U1506. The channelling and erosion surfaces indicate periods of strong bottom currents.

The Miocene to Pliocene succession correlates with Seismic Units 7, 8 and 9 (U-LHRN-7, U-LHRN-8 and U-LHRN-9). Based on foraminiferal data and age model, these units were deposited between 22.5 and 5.6 Ma and are composed of calcareous ooze and chalk (Fig. 4.7 & 4.8). There are small faults in the chalk and ooze layers that are interpreted as polygonal faults (Fig. 4.5). Polygonal faults are observed most places near Site U208 (Fig. 4.5) but are not so common at Site U1506 (Fig. 4.6). At Site U1506, all units are affected by polygonal faulting but at Site U208, polygonal faults die out towards the seabed, and they only develop as part of the response to compaction and ooze-chalk transition. Polygonal faulting reflects dewatering of sediment during compaction. U-LHRN-7 and U-LHRN-8 are characterised by wide V shape channels with bidirectional onlap (Fig. 4.6) near Site U1506, where V-shape erosional features may be indicative of channelized bottom currents.

UB-LHRN-5 represents a hiatus from middle Eocene to Oligocene (25.5 Ma to 43.7 Ma) (Fig. 4.3 & 4.4). At Site 208, there is an unconformity between Seismic Units 5 and 6. A major reorganisation of ocean currents is inferred from changes in foraminifera assemblages in the Oligocene (foraminiferal and nannofossil chalk) and middle Eocene (siliceous microfossil-bearing chalk, radiolarite, and diatomite) (Burns and Andrews, 1973, Kennett et al., 1975). This unconformity is also documented at borehole IODP U1506 between U-LHRN-7 and U-LHRN-5 (Fig. 4.4). Burrow fill sampled in subunit 1c of Sutherland et al. (2018) is late Oligocene in age and indicates erosion or nondeposition of middle Eocene to upper Oligocene sediment (Fig 4.3, 4.4 & 4.6). This unconformity could have a primary tectonic origin but be enhanced in place by non-deposition due to current action.

Figure 4.8. Borehole IODP U1506 age-depth relationship. The TWT seismic reflectors were converted to depth using velocity model (Sutherland et al., pers. comm. 2019).

4.3.2 Burial analysis

The mass accumulation rate (MAR) was calculated using seismic reflectors and well data (microfossil datums). A solid red line represents the average MAR (Fig. 4.9). Figure 4.9 includes values for the rates of mass accumulation for sediment that was based on microfossil datums from boreholes (U1506, U208, U588, U589, U590 and U591) and extrapolated and averaged away from the borehole using seismic mapping (U1506 and U208). The early Eocene (~ 50 Ma) has MAR about 8 kg ky⁻¹ m⁻² and increased to 27 kg ky⁻¹ m⁻² in middle Eocene (~ 45 Ma). The middle Eocene (~ 43 Ma) to early Oligocene (~ 30 Ma) have constant MAR of about 1 to 2 kg ky⁻¹ m⁻². The MAR value slightly increased from 5 to 15 kg ky⁻¹ m⁻² in the Late Oligocene (~ 25 Ma), which began to fluctuate about 23 to 11 Ma ago (early to late Miocene). During the late Miocene to early Pliocene ~8-3 Ma, there were high accumulation rates that reached a peak of about 50 to 59 kg ky⁻¹ m⁻². The accumulation rates during the late Pliocene to Pleistocene fell from 59 to 10 kg ky⁻¹ m⁻². There is consistently higher accumulation rate through late Miocene to early Pliocene time.

Changes in MAR may reflect actual changes in calcareous biogenic productivity related to global climate events (Kennett and von der Borch, 1986). The regional climate may cause changes in ocean circulation (Fig. 2.2). The region LHRN is located in the central zone of the Tasman Front, which is the oceanic current that flows past northern New Zealand (Fig. 2.2 & 2.4). The highest MAR during latest Miocene may reflect increased biogenic productivity due to nutrient-enriched water near divergences in ocean current.

The lower MAR value during the latest Pliocene and Quaternary are probably related to increased winnowing by bottom currents varying the amount of foraminifera in this interval at Sites U1506 and U590 may indicate that sediments experienced a period of fluctuating bottom current activity (Kennett and von der Borch, 1986). Foraminifera documented at Site U208 have faunal changes in the Pleistocene.

Figure 4.9. Line graph shows mass accumulation rate over time for the boreholes and seismic reflectors on northern Lord Howe Rise. Grey crosses are mass accumulation rate from seismic units (horizontal = age range of the unit for the top and the bottom & vertical = standard deviation of the mass accumulation rate actual lateral variability). The solid black line is the mean value of seismic reflector data. The solid red line is the average of seismic and well data.

4.4 Southern Lord Howe Rise (LHRS)

The southern Lord Howe Rise (LHRS) region was interpreted over about 10,000 km² with age and sediment calibration provided by three Sites U1510, U207 and U592 (Fig. 1.1 & Fig. 1.2). These three sites are located near the southern end of the LHRS.

Seismic mapping was tied to Sites U1510, U207 and U592. Each bounding reflector was picked based on its relationship to termination of overlying and underlying reflectors (Mitchum Jr et al., 1977a, Mitchum Jr et al., 1977b, Vail et al., 1977). Several key stratigraphic surfaces (seismic unconformity), seismic units and sub-units were defined (Fig. 4.10 & 4.11).

It is hard to determine the stratigraphic relationship between these three boreholes due to a lack of continuity of the succession across the LHRS region. This is partly related to local tectonism and associated volcanism that resulted in development of unconformities (Sutherland et al., 2017, Sutherland et al., 2010). There is clear evidence of this in seismic lines TAN1409-LHRS-02 (Fig. 4.11 & 4.12) and TAN1409-LHRS-01 (Fig. 4.17).

4.4.1 Seismic interpretation for borehole IODP U1510

Two unconformities (UB-U1510-8 and UB-U1510-6) were identified at Site U1510 bounding four seismic sub-units (Fig. 4.11). Four seismic sub-units are part of the Zealandia-U1 megasequence.

Figure 4.10. Seismic stratigraphy for Lord Howe Rise near Site U1510.

Figure 4.11. Seismic reflection line TAN1409-LHRS-02 at Site U1510, (A) seismic reflection image, and (B) sketch of onlapping sediments, which extended to the NW and sediments appear to compress in the SE.

Seismic Unit 6 (U-1510-6) spans the Eocene 46 to 36.3 Ma (Fig. 4.10). U-1510-6 comprises clayey calcareous chalk with bioclasts punctuated by cherty limestone and chert (Fig. 4.13). Folds within U-1510-6 are associated with reverse faults that lie beneath sub-unit U6a (Fig. 11). This reverse faulting and associated uplift during the Eocene is referred to as the Tectonic Event of the Cenozoic in the Tasman Area (TECTA) (Sutherland et al., 2017). U-1510-6 strata may record two types of deformation including a folded and faulted succession pre-dating deformation overlain by an onlapping syn-tectonic sequence. U-1510-6 contains onlapping (UB-1510-6a) and growth strata reflectors that indicate progressive deformation (Fig. 4.11).

Figure 4.12. Seismic reflection line TAN1409-LHRS-02 through borehole U1510, (A) seismic reflection image, and (B) illustrates Eocene reverse faulting, deformation, volcanism and erosional unconformity.

The Miocene to Pleistocene 17.8 to 3.6 Ma succession correlates with Seismic Units 7, 8 and 9 (U-1510-7, U-1510-8 and U-1510-9) (Fig. 4.10 & 4.11). U-1510-7 is composed of homogeneous calcareous ooze alternating with discrete beds of foraminiferal ooze (Fig. 4.13). U-1510-7 contain unconformities interpreted as current scours and channel complexes, and strata onlap small folds and volcanic edifices in the southeast of LHRS

(Fig. 4.12). U-1510-8 and U-1510-9 are made up of calcareous ooze alternating with foraminiferal ooze (Fig. 4.13).

A late Eocene-early Miocene unconformity (UB6), represented by a high amplitude continuous reflector and onlapped by U7 strata (Fig. 4.11 & 4.12), exists between U6 and U7 with missing time spanning 36.3 to 17.8 Ma. A late Miocene-early Pliocene unconformity (UB8) exists between U8 and U9 (3.6 Ma) (Fig. 4.10).

Figure 4.13. IODP U1510 age-depth relationship. Stratigraphy column shows lithology and is correlated biostratigraphic data and TWT seismic reflectors. (Sutherland, 2019a, Sutherland, 2019b). TWT seismic reflectors were converted to depth using velocity model (Sutherland et al., pers. Comm. 2019).

4.4.2 Seismic interpretation for boreholes DSDP 207 and 592

Sites U207 and U592 have two unconformities (UB-207-4 and UB-592-5) and six seismic units that are subdivided into ten seismic sub-units (Fig. 4.14, 4.15 & 4.16).

Figure 4.14. Seismic stratigraphy for Lord Howe Rise near Site U207.

Figure 4.15. Seismic stratigraphy for Lord Howe Rise near Site U592.

Figure 4.16. Seismic reflection line 114_07 at Site U592 and U207. (A) seismic reflection image, and (B) two sites show a lack of continuity of strata beneath an unconformity.

Seismic Units 4 and 5 (U-207-4 & U-5925) are locally folded and have fanning reflectors. U-207-4 at Site U207 has age 48 to 40.6 Ma (Fig 4.14 & 4.15). U-207-4 comprises calcareous fossil ooze with clay (Fig. 4.18). U-592-5 at Site U592 has age 34.3 to 32.5 and is made up of calcareous fossil ooze (Fig. 4.19). The channeling and erosion within U-207-4 and U-592-5 suggest significant downslope movement (Fig. 4.16). The volcanic activity was characterised by small cones associated with U-592-5.

The Miocene to Pleistocene succession correlates with Seismic Units 6, 7, 8 and 9 (U-LHRS-6, U-LHRS-7, U-LHRS-8 and U-LHRS-9) that have age range from 18 to 0 Ma (Fig. 4.14 & 4.15). These units are calcareous fossil ooze (Fig. 4.18 & 4.19) that was deposited in a bathyal environment (Kennett and von der Borch, 1986). Polygonal faulting affects these units. Flat unconformity formed between UB-207-4 and UB-592-5, with a possible relationship to past sea level (Sutherland et al., 2010).

Figure 4.17. Seismic line TAN1409-LHRS_01 on the southern Lord Howe Rise at Site U592, (A) seismic reflection image, and (B) sketch of onlapping section just above Miocene unconformity (black yellow dash line).

Figure 4.18. Borehole IODP DSDP 207 age-depth relationship. TWT seismic reflectors were converted to depth using velocity model (Sutherland et al., press. comm. 2019).

Figure 4.19. Borehole DSDP 592 age-depth relationship. TWT seismic reflectors were converted to depth using velocity model (Sutherland et al., press. comm. 2019).

4.4.3 Burial analysis

Sites U1510, 592 and U207 had variable mass accumulation rates (MAR) over time (Fig. 4.20). The MAR started to fluctuate about 50 to 42 Ma (early to middle Eocene) and reached a peak of up to $43 \text{ kg ky}^{-1} \text{ m}^{-2}$. Between middle to late Eocene (~ 38 to 35 Ma), rates of accumulation dropped significantly from about 43 to $3 \text{ kg ky}^{-1} \text{ m}^{-2}$ and it appeared to increase slightly up to about $15 \text{ kg ky}^{-1} \text{ m}^{-2}$ in the early Oligocene (~ 32 Ma) then fell to $2 \text{ kg ky}^{-1} \text{ m}^{-2}$. Between early Oligocene and early Miocene near constant MAR was 2 to $4 \text{ kg ky}^{-1} \text{ m}^{-2}$. During Miocene time (~ 18 to 5 Ma), MAR fluctuated considerably reaching a peak of up to $30 \text{ kg ky}^{-1} \text{ m}^{-2}$ and dropped to about $19 \text{ kg ky}^{-1} \text{ m}^{-2}$ in late Pliocene and Pleistocene time. Each of the sites is marked by lower accumulation rates of nearly 4 to $7 \text{ kg ky}^{-1} \text{ m}^{-2}$ since 3 to 4 Ma.

LHRN and LHRS have late Miocene peaks in MAR. LHRS has higher MAR in Eocene time compared to LHRN and this is presumably due to its oceanographic setting (mainly biogeneic sediment). This may relate to bottom current intensit in the region, creating a major hiatus where there was a break of sediment accumulation between late Eocene, early Oligocene and lower Miocene.

Figure 4.20. The Line graph illustrates a mass accumulation rate over time for the boreholes and seismic reflectors on the southern Lord Howe Rise. Grey crosses are mass accumulation rate from seismic units (horizontal = age range of the unit for the top and the bottom & vertical = standard deviation of the mass accumulation rate actual lateral variability). The solid black line is the mean value of seismic reflector data and the solid red line is the average of seismic and well data.

4.5 Northern New Caledonia Trough (NCTN)

The northern New Caledonia Trough was mapped over about 1500 km² with age and sediment calibration provided by Site U1507. Examination of 2D seismic reflectors allowed description of four bounding surfaces (UB-NCTN-5 to UB-NCTN-8) and five seismic units. These five seismic units contain nine sub-units or facies (Fig. 4.21). These are all subunits of the regional Zealandia U1 megasequence.

Figure 4.21. Seismic stratigraphy for northern New Caledonia Trough near Site U1507.

4.5.1 Result of seismic stratigraphy interpretation

Eocene and Oligocene chalk and limestone correlates with Seismic Units 5 (U-NCTN-5) and 6 (U-NCTN-6). The age of U-NCTN-5 is 43 to 37 Ma (Fig. 4. 24), and U-NCTN-6 is at 37 to 23.6 Ma. Eocene-Miocene (36-20 Ma) strata at borehole U1507 contained clayey chalk and volcanic turbidites (Fig. 4.23 & 4.25) (Sutherland et al., 2018a) derived from large sub-merged volcanoes west of the crest of Norfolk Ridge. Seabed dredging from the southern end of this volcanic chain yielded a volcanic age of 26 Ma (Mortimer et al., 2014).

The Miocene succession correlates with Seismic Units 7 (U-NCTN-7) and 8 (U-NCTN-8). U-NCTN-7 and U-NCTN-8 are conformable units that have an age of 23.5 to 5 Ma and comprise clayey calcareous ooze/chalk (Fig. 4.24). U-NCTN-8 and U-NCTN-7 contain reworked pelagic sediment. U-NCTN-8 is delimited at its top by a surface of truncation indicated by reflector toplap at the seabed (Fig. 4.24). Sub-units 7a (U-NCTN-7a) and 7b (U-NCTN-7b) are truncated by UB-NCTN-7, which marks the top of discontinuous moderate to high-amplitude reflectors (Fig. 4.23). There is probably erosion by flows at the base of U-NCTN-8. U-NCTN-7 and U-NCTN-8 are affected by small polygonal faults (Fig. 4.23).

The Pliocene to Recent correlates with Seismic Unit 9 (U-NCTN-9) and has an age ranged from 5 to 2 Ma containing calcareous ooze/chalk with clay and slumps (Fig. 4.24) affected by debris flow activity. Seismic sub-units 9c (U-NCTN-9c) and 9b (U-NCTN-9b) within U-NCTN-9 (at 5.0 to 4.8 s twt) are onlapped by a major infilling unit with horizontal, laterally continuous moderate-amplitude reflectors and intercalated bodies with transparent to chaotic facies (Fig. 4.23 & 4.24). This unit drapes the underlying onlapping Seismic Unit 8 (U-NCTN-8) at CDP 2490 to 3015 (Fig. 4.24). Transparent-chaotic facies within Seismic Unit 9 (U-NCTN-9) are interpreted as large-scale mass transport deposits.

The occurrence of common reworked sediment has been discussed in the report by Expedition 371 Scientists (Sutherland et al., 2018a). I reinterpret the top two first occurrence datums as reworked older sediment from the basin flank (Sutherland et al., 2018; Table 3, Pg. 15) and hence obtain a revised age model with more uniform

sedimentation rate, shown by the straight red line between ages 3.8 and 1.6 Ma (Fig. 4.25).

Gravity flows have produced localised erosion within U-NCTN-9 where axial channels or lateral lobes rework and entrain older sediment. The former abruptly pinch out laterally. Axial turbidite deposits of U-NCTN-9 pinchout laterally onto the slope with onlap configuration. Slope failure scars on the seabed are consistent with active downslope flow processes on the slope (Fig. 4.22).

Figure 4.22. Bathymetry showing failure scars and small canyons at the lower part of Norfolk Ridge (Sutherland et al., 2018a)

Basin floor fans are derived from incised canyons on the lower part of Norfolk Ridge. Downslope of the arcuate escarpments seen on the bathymetry, erosional canyon scars are consistent with active downslope flow processes on the slope (Fig. 4.22).

Figure 4.23. Seismic line line TAN1409-NCTN-11 at Site U1507, (A) seismic reflection image with horizons picked in colour, and (B) sketch of onlapping and downlapping strata near Site U1507. Stratigraphic onlaps are shown with small black arrow facing northeast and small two arrows with purple and blue colour are toplapping reflectors. Black line is polygonal faulting.

Figure 4.24. Seismic line TAN1409-011 shows deposition of reworking sediment at the basin; (A) seismic reflection image, and (B) interpreted illustrating the relative position of slope failure scars at seabed and pinchout or onlap mass transport deposits at the edge of the basin, and buried escarpments on the slope.

Figure 4.25. Borehole IODP U1507 showing depth-age relationship. Stratigraphy column shows lithology and biostratigraphic data and TWT (Sutherland et al., pers. comm. 2019; Sutherland, 2019b; Sutherland et al., 2018). Horizontal dash lines = seismic reflection/time horizons picked for units boundaries, red solid line=age model correlation for microfossil datum accounting for reworking (correction from U-NCTN-B9a to U-NCTN-B9c) and blue solid line= published age model from borehole data/sediment sampled at borehole U1507 (Sutherland, 2019b, Sutherland et al., 2018a).

4.5.2 Burial analysis

The mass accumulation rate (MAR) was calculated between seismic reflectors and borehole data (revised age model from microfossil datums). Figure 4.26 illustrates the result of the mass accumulation rates for Site U1507. In the early Eocene to late Oligocene, rapidly fluctuating MAR reached a peak of $79 \text{ kg ky}^{-1} \text{ m}^{-2}$. The higher MAR during Eocene-Oligocene may relate to active uplift, erosion and volcanism activity near Norfolk Ridge. Then, it decreases and becomes constant between 23 and 11 Ma with an accumulation rate of 14 to $20 \text{ kg ky}^{-1} \text{ m}^{-2}$. The late Miocene-Pliocene biogenic bloom signal is observed reaching a peak MAR of $50 \text{ kg ky}^{-1} \text{ m}^{-2}$ at 5-7 Ma, and the Pleistocene rate has dropped to about $40 \text{ kg ky}^{-1} \text{ m}^{-2}$ but is uncertain due to reworking of fossils and hence poor resolution of the age model.

Figure 4.26. Line graph shows mass accumulation rate over time for the boreholes and seismic reflectors in northern New Caledonia Trough. Grey crosses are mass accumulation rate from seismic units (horizontal = age range of the unit for the top and the bottom & vertical = standard deviation of the mass accumulation rate actual lateral variability). The solid black line is the mean value of seismic reflector data and the solid red line is the average of seismic and well data.

4.6 Reinga Basin (REIN)

Reinga Basin covers about 90,000 km² but only about 30,000 km² was mapped that can be tied to borehole U1508. Seismic reflector units U5-U9 are part of the Zealandia-U1 megasequence, but for this local analysis I adopt the nomenclature of Bache et al., (2012).

Five seismic unconformities (UB-REIN-4 to UB-REIN-8) were identified encompassing six seismic units (U-REIN-4 to U-REIN-9) and seven sub-units (Fig. 4.27 & 4.28).

4.6.1 Result of seismic stratigraphy interpretation

The Eocene succession correlates with Seismic Units 4 (U-REIN-4) and 5 (U-REIN-5) (Fig. 4.27 & 4.28). Seismic Unit 4 (U-REIN-4) is correlated with early to middle Eocene pelagic carbonate deposition (Sutherland, 2019c, Sutherland, 2019b). U-REIN-4 is 43.4-36.2 Ma and contained clayey nannofossil ooze/chalk and limestone (Fig. 4.30). U-REIN-5 has an age of 36.2-33.4 Ma and is composed of nannofossil chalk. U-REIN-5 onlaps folded U-REIN-4 near Site U1508. Faults and folds observed within U-REIN-4 and U-REIN-5 created accommodation space that filled by downslope sediment transport from newly-formed sediment sources (reworking), resulting in deposition of U-REIN-5. Compression appears to be accommodated by fault propagation folds in the NE that located under South Maria Ridge (Fig. 1.1, 4.28 & 4.29).

Figure 4.27. Seismic stratigraphy for Reinga Basin near Site U1508 (after Orr et al. 2020). The units adopt the nomenclature of Bache et al (2012a, b).

Figure 4.28. Seismic reflection line REIN09-012, (A) seismic reflection image, and (B) sketch of onlapping and channelling fill geometries.

The Oligocene sequence correlates with Seismic Unit 6 (U-REIN-6) (Fig. 4.27 & 4.28). U-REIN-6 is defined to have age range from 33-23 Ma. Dredge sediment samples contain foraminiferal ooze and chalk with clay and volcanic clast with age 28-23 Ma (Sutherland, 2019c). Reworked microfossils observed at Site U1508 provide evidence for nearby shallow-water, consistent with evidence for nearby wave ravinement of South Maria Ridge (Fig 1.1 & 4.28). Overlying younger strata than U-REIN-5 onlap features interpreted as volcanoes (Orr et al., 2020) (Fig. 4.29) indicating volcanism began during the hiatus at Site U1508 at 34-28 Ma.

Figure 4.29. Seismic reflection line REIN09-011 illustrates horizons picked and seismic units across the site U1508 in the Reinga Basin; (A) seismic reflection image and, (B) interpreted seismic reflection presenting key seismic stratigraphic relationship along the strike. UB-REIN-5 appeared to correspond with the base strata, UB-REIN-6 and UB-REIN-7 onlap the volcano in the SE where seabed seems scouring against the volcano.

The Miocene to Recent sequence correlates with Seismic Units 7 (U-REIN-7), 8 (U-REIN-8) and 9 (U-REIN-9). U-REIN-7 and U-REIN-8 tie to borehole U1508 where they are 17.3-6.1 Ma containing foraminiferal ooze/chalk with clay interbedded thin foraminiferal ooze/chalk with sand (Fig. 4.30). Downlapping reflectors within U-REIN-7 are consistent with evidence for volcanic input at borehole U1508 (Fig. 4.28 & 4.29). U-REIN-8 is variable across Reinga Basin. It is conformable in most places and drapes older units, but is locally truncated by UB-REIN-8 (Fig. 4.27 & 4.28). U-REIN-9

comprises countourites and a channel complex (Fig. 4.29). U-REIN-8 and U-REIN-9 contain undulating reflectors that drape older sediment. U-REIN-8 and U-REIN-9 are composed of pelagic ooze and bioclastic ooze (Fig. 4.30).

Figure 4.30. Borehole IODP U1508 age-depth relationship. TWT seismic reflectors were converted to depth using velocity model (Sutherland et al., press. comm. 2019).

Examination of seismic stratigraphy allowed division of seismic units into three categories. Faulted and folded strata are older than the tectonic event (Orr et al., 2020). Syn-tectonic growth strata record deformation and younger strata are undeformed (Fig. 4.28). U4 to U5 are composed of folded, faulted, and onlapping reflectors that record progressive deformation (Fig. 4.29). U6 to U7 are fanning reflectors, that onlap and downlap, and have volcanic and clastic input (Sutherland, 2019c). Finally, U8 to U9 are drape strata with an architecture related to variable bottom current strength and changes in sea level and sediment supply.

4.6.2 Burial Analysis

Sedimentation rate calculation at Site U1508 reveals a significant result: seismic reflectors mapping gives an opposite result to that obtained from borehole data (Fig. 4.31). In the late Eocene (~33 Ma), mass accumulation rate (MAR) fluctuated up to about $62 \text{ kg kyr}^{-1} \text{ m}^{-2}$ and was similar in the late Oligocene (~ 26 Ma). In contrast, Miocene values vary considerably, depending on whether they are calculated from seismic or borehole data (Fig. 4.31). The mean value shows that MAR is $180 \text{ kg kyr}^{-1} \text{ m}^{-2}$ in late Miocene to early Pliocene.

Hence, the observations show that when a hiatus is present on the flank of South Maria Ridge (Site U1508), a thick unit accumulates in the deepest part of the basin. Very low sedimentation rates on the ridge correspond to high sedimentation rates in the basin (Fig. 4.28 & 4.31). It implies some role of the variable Tasman Front (Fig. 2.4), which is scouring and reworking sediment from the ridges into the basin.

Figure 4.31. Line graph shows mass accumulation rate over time for the boreholes and seismic reflectors data in the northern New Caledonia Trough. Grey crosses are mass accumulation rate from seismic units (horizontal = age range of the unit for the top and the bottom & vertical = standard deviation of the massive accumulation rate actual lateral variability); blue line is Site U1508 The solid black line is the mean value of seismic reflector data and the solid red line is the average of seismic and well data.

4.7 Interpretation and conclusion

Global climatic events played a key role in shaping stratigraphic sequences of the northern Zealandia region. Kennett (1977) summarised instances of climatic change through the Oligocene to Eocene when the tectonic separation of Antarctica and Australia caused regional changes in oceanic circulation patterns. During this time there was a rapid transition from Eocene siliceous bathyal sediments to Oligocene marine carbonate-rich rocks (Kennett, 1980).

Figure 4.32. Summary of MAR data in northern Zealandia; (A) Global isotopes curve (Zachos et al., 2008a) shows carbon isotope ($\delta^{13}\text{C}$) which is yellow curves and oxygen isotope ($\delta^{18}\text{O}$) in blue and (B) Mass accumulation rates for the LHRN (solid black line), LHRS (solid red line), NCTN (solid purple line) and REIN (solid dash line). LHRN, LHRS and NCTN are defined using seismic and boreholes data but Reinga Basin is only seismic data and represents MAR in the basin depocentre only.

Significant change in the ocean and sediment patterns occurred in the Neogene. Warmer conditions were temporarily developed during the mid-Miocene (~17-15 Ma) followed by a long-term global climate deterioration (Fig. 4.32) (Zachos et al., 2008b).

Sedimentation rates in the study area are consistent across the region and correlate with periods of global climate change. LHRN, LHRS, NCTN and REIN have MAR peaks during the earliest Pliocene to the latest Miocene (Fig. 4.32). Highest values in LHRN and REIN correspond to regions of high Tasman Front flow (Fig. 2.2 & 2.4).

The South Pacific Gyre is the large-scale circulation of tropical water that accumulates in the western Pacific and then flows southward to include the East Australia Current and Tasman Front on its way to mixing with the Antarctic Circumpolar Current (Fig. 2.2 & 2.4) (Rintoul et al., 2001, Ganachaud et al., 2014, Ganachaud et al., 2007a, Mulhearn, 1987). Strong currents result in biological productivity where upwelling of deep nutrient-rich water mixes with shallow subtropical water at local divergent zones (controlled by seabed topography and fluid mechanics).

The MAR results calculated here show that biogenic input (carbonate and biosilica) increased substantially between 9 and 3 Ma, consistent with observations at Site U590 that suggest increased upwelling within the Tasman Front at that site at that time (Grant and Dickens, 2002). This phenomenon of Latest Miocene to Early Pliocene increased productivity is observed throughout the global tropical and subtropical ocean and has been termed the 'Late Miocene Biogenic Bloom' (Dickens and Owen, 1999, Peterson et al., 1992, Farrell et al., 1995, Van Andel et al., 1975, Rea and Snoeckx, 1995, Dickens and Owen, 1996, Grant and Dickens, 2002).

How and why the climate system was working at that time is not entirely clear, and this issue is outside the scope of my thesis. However, it is interesting to note that MAR observations are consistent with those elsewhere and indicate a signal of global climate change. It is significant for petroleum prospectivity because sedimentation rate was high and water temperatures were likely to have been relatively warm in the early Pliocene. This means that peak thermal maturity of petroleum source rocks was likely achieved at 4-2 Ma across much of this region.

5 Petroleum System Analysis

5.1 Introduction

The objective of this chapter is to present stratigraphic correlation (locally and regionally) and petroleum system analysis of northern Zealandia and hence conclude how prospective for petroleum are different parts of the region, and what play types might exist.

Northern Zealandia may have a working petroleum system, and it has petroleum production in northern New Zealand (Collot et al., 2009, Rouillard et al., 2014, Rouillard et al., 2015). Hence, the petroleum industry has been interested in the region since the 1970s; however, it has left the area largely unexplored. Northern Zealandia comprises sedimentary basins that may share a common geological origin with the Taranaki Basin in New Zealand and Gippsland Basin in southern Australia. Petroleum systems have been proved by discoveries since 1969 (McBeath, 1977, Mehin and Bock, 1998, Skinner, 2008). The Taranaki Basin is the only hydrocarbon-producing basin in New Zealand and the Maui field was discovered in 1969 (Skinner, 2008, McBeath, 1977). The total production in the Maui field was about 4 TCF (trillion cubic feet) of gas and 300 Mbbbl of light oil. The production in Gippsland Basin was approximately 3,450 MMBO (million barrels of oil) and 4.8 TCF of gas, with remaining reserves totalling 629.9 MMBO and 4.8 TCF (Mehin and Bock, 1998).

Further northwest, numerous oil and gas fields have been discovered in the Timor Sea (Bonaparte Basin) and Papua New Guinea (PNG) (Papuan Basin). In Bonaparte Basin, the Bayu-Undan field was discovered in 1995, and the field reserves are 350-400 million barrels of hydrocarbon liquids and 3.4 TCF of gas (Brooks et al., 1996, Ledlow et al., 2008). Production started in 2004 with total production of 115,000 barrels per day of condensates and LPG. In Papua New Guinea, the first commercial oil discovery was at the Kutubu field in the Southern Highlands Province in the late 1980s, and production commenced in 1991 with about 200 million barrels produced in total (Rickwood, 1990, Owen and Lattimore, 1998).

Northern Zealandia has had no petroleum exploration borehole drilled, but in the southern part it has Romney-1 (deepwater Taranaki Basin) and Waka Nui-1 well (offshore Northland Basin). Until the REIN09, TAN1409, TECTA survey, and IODP drilling, there was no way to tie seismic surveys together or tie with biostratigraphic or lithology data. However, in New Zealand, particularly in Taranaki Basin, numerous exploration and production wells have been drilled, and the basins are well understood (King and Thrasher, 1996). Consequently, our understanding of potential petroleum system elements in northern Zealandia is informed by onshore geology, and especially that of Taranaki Basin.

Geochemically, oil from Taranaki Basin is typed to Late Cretaceous-Paleogene coaly source rocks (Sykes, 2001, Sykes and Snowdon, 2002). The source rock intervals in Taranaki include Seismic Unit U2a: the Late Cretaceous Rakopi Formation, Late Cretaceous North Cape Formation, Palaeocene Farewell Formation; and Seismic Unit U1b (Mangahewa Formation), Early Eocene Kaimiro Formation and Middle to Late Eocene Mangahewa Formation (Cook, 1987; S. Killops et al., 1998). The source rocks have type III kerogen coals with interbedded carbonaceous shales, which are also known to have high liptinite and a minor contribution of marginal marine material or bacterial modification (Killops et al., 1994; Sykes et al., 2004).

Reservoirs found in the Maui, Kapuni, Kupe, Pohokura, Mangahewa, and Tui fields are composed of Paleocene shoreline and Eocene coastal plain sandstones of the Farewell, Kaimiro, Mangahewa and McKee formations (King and Thrasher, 1996, GNS, 2015). Neogene Mount Messenger and Moki Formations are submarine fan sandstones but contain only small petroleum accumulations (King and Thrasher, 1996).

Seals formed during Cretaceous and Paleocene flooding when mudstones of the Turi Formation and micritic carbonate-rich rocks of the Tikorangi Formation were deposited (King and Thrasher, 1996).

Structural traps within Taranaki Basin include four-way dip, three-way dip and fault closures, drape folds, thrust controlled anticlines, and overthrusts (Nicol et al., 2004). These structural traps resulted from Neogene tectonic deformation. Older trapping structures may correspond to Cretaceous normal faulting, but Neogene reverse faulting

and fault reactivation makes it difficult to divide the two stages of structural development (King and Thrasher, 1996).

5.2 Source rocks

Petroleum source rocks likely to be present within northern Zealandia are likely to be similar to those in adjacent better-known basins such as Taranaki Basin in New Zealand and Gippsland Basin in eastern Australia and it is plausible that there are similarities with Timor-Leste and PNG. Based on evidence from Australia, New Zealand, Timor-Leste, PNG, dredge samples, drilling in Taranaki Basin, seismic anomalies, and previous seismic interpretation (Burns and Andrews, 1973, Burns, 1973a, Burns, 1973b, Ingram et al., 1996, King, 2000b, King and Thrasher, 1996, Rouillard et al., 2015, Sutherland, 2019b, Sutherland et al., 2018b, King, 2000a), there are three general groups of sedimentary formations in northern Zealandia that represent potential petroleum source rocks. They are defined from oldest to youngest: Mesozoic Gondwana margin-marine, terrestrial, lacustrine, or marine sediments; Late Cretaceous Gondwana break-up coal measures and possibly any associated lacustrine or marine facies; and post-break-up Zealandia subsidence coal measures or marine rocks.

The oldest rocks with source potential in New Zealand occur within the Mesozoic Murihiku Supergroup. The Murihiku Group has traditionally been defined as economic basement in New Zealand, but is known to contain coaly source rocks (Mortimer, 2004, Mortimer et al., 2009, Cook et al., 1999). The proposed depositional environment was a large fore-arc basin near the Gondwana margin that extended from south of New Zealand to at least as far north as New Caledonia (Ballance, 1993). Waka Nui-1 in Northland Basin intersected Jurassic grey-red, veined, and mottled mudstone interbedded sandstone, siltstone, and coal (Milne and Quick, 1999, Mortimer et al., 2009). Vitrinite reflectance (VR) analysis of Jurassic coal was 0.7% (West, 1999), indicating it is immature and close to the top of the oil window at ~3602 m bsf (Hegarty, 1999, Uruski et al., 2004). Middle Jurassic coals discovered in Waka Nui-1 are immature, and outcrop of Late Jurassic coals onshore indicate that the Jurassic succession (Murihiku Supergroup) may contain petroleum source potential (Campbell et al., 2003). Head-space gas and pore water chemistry results from U1508 suggest active petroleum migration at that site that is likely sourced from Murihiku coaly source rocks (Sutherland, 2019c).

Australia Gondwana source rocks may extend throughout the region. It is plausible that a wide range of terrestrial, coastal and marine facies exist across northern Zealandia. Australia Gondwana source rocks are Jurassic Walloon Coal Measures and Koukandowie Formation of Clarence-Moreton Basin, “Jurassic Beds” of the Gippsland Basin (Holdgate and McNicol, 1992). Marine mixed carbonate and clastic sequences in Timor-Leste and Jurassic clay-rich marine source rocks of Imburu Formation in PNG may also have correlative in northern Zealandia (Cameron, 1907, Ingram et al., 1996, Whitehouse, 1955, Charlton, 2002, Ahmed A. S. et al., 1988, Brown et al., 1979, Volk et al., 2005).

Jurassic sediments with source potential are present in several basins around the Tasman Sea: in the Gippsland Basin (Holdgate and McNicol, 1992), the Clarence-Moreton and Surat in Queensland (O'Brien et al., 1994, Ingram et al., 1996, Shaw et al., 2001, Wells and O'Brien, 1994). The Walloon Coal Measures and Koukandowie Formation contain interbedded sandstone, siltstone, claystone and coal (Ingram et al., 1996, Khorasani, 1987). In Surat Basin, oil generation is from hydrogen-rich coals such as those of the Walloon Coal Measures, which hydrocarbons are expected to generate from subereous components and terpene resinates in low rank lignites and sub-bituminous coals (Khorasani, 1987). Further south in Australia, the oldest sediments in Gippsland Basin are the Late Jurassic and Early Cretaceous rift-related volcanoclastic Strzelecki Group underlain by the “Jurassic Beds” (Holdgate and McNicol, 1992, Norvick et al., 2001). The “Jurassic Beds” contains coal measures and lacustrine facies deposited during the early stages of the Early Otway Rift Phase (Norvick et al., 2001).

Timor-Leste and PNG contain Mesozoic marine source rocks. The main source rocks in Timor-Leste is likely Upper Triassic to Lower Jurassic restricted marine source rocks (Charlton, 2002, da Costa Monteiro, 2003). In onshore Timor-Leste, Mesozoic samples from the Triassic Niof Formation and Late Triassic Aitutu Formation comprise type II and type III kerogens that deposited in suboxic to anoxic clay-rich environment with some terrigenous input (da Costa Monteiro, 2003, Peters et al., 1999). Geochemically, source rocks in PNG have a mixture of marine and terrestrial organic matter deposited under mildly oxygenated conditions in an open marine to deltaic environment (Ahmed A. S. et al., 1988, Ahmed et al., 2012). The Papuan Basin contains mainly clay-rich, terrestrial-influenced Jurassic marine source rocks deposited under oxic conditions (Ahmed et al.,

2012), and are comparable in organic facies and share many similarities with Upper Jurassic source rocks present on the North West Shelf of Australia (Volk et al., 2005).

Gondwana break-up started in the mid-Cretaceous (~110-100 Ma) and persisted until full Zealandia separation was achieved by 85-80 Ma (Cluzel et al., 2010, Davy et al., 2008, Matthews et al., 2012, Uruski, 2008, Norvick et al., 2001). The mid-Cretaceous phase deposition of the Taniwha Formation (100–90 Ma) and the Golden Beach Group (98-80 Ma) (Norvick et al., 2001, King and Thrasher, 1996, Lowry and Longley, 1991, Uruski et al., 2003, King, 2000a). The middle Cretaceous Taniwha Formation contains possible coaly source rock in Taranaki Basin (Killops et al., 1994). The Taniwha Formation comprises siltstone, sandstone, coal, and carbonaceous shale and represents deposition in marginal marine to terrestrial environments (King & Thrasher 1996). During the Late Cretaceous, fluvial-deltaic sediments are found in the region. The Golden Beach is a subdivision of the lower part of Gippsland Basin's Latrobe Group and is interpreted as an unconformity-bounded depositional system. It recorded the transition from rift system to continental margin deposition (Bernecker and Partridge, 2001). The Golden Beach represents marine and marginal marine environments in Santonian and Campanian times (Duff et al., 1991, Bernecker and Partridge, 2001). The Golden Beach rapidly subsiding rift (Bishop, 2000) was filled by deepwater lakes following break-up of the southern Australia margin and was then flooded by marine water (Duff and others, 1991; Partridge, 1996). The Golden Beach is divided into marine shale and minor sandstones of the Anemone Formation and fluvial-deltaic and paralic Chimaera Formation (Bernecker and Partridge, 2001).

Northern Zealandia and Gippsland Basin experienced thermal subsidence after rifting, resulting in transgression and deposition of Late Cretaceous and Paleogene petroleum source rocks (85-55 Ma) (Laird and Bradshaw, 2004, Cook et al., 1999, King and Thrasher, 1996). Cretaceous coal measures are found within the Pakawau Group in Taranaki Basin and Latrobe Group of Gippsland Basin. The Pakawau Group contains Late Cretaceous Rakopi Formation coal measures and North Cape Formation shallow marine lithofacies (Killops et al., 1994, King and Thrasher, 1996). Uruski & Baillie (2004) interpreted that Rakopi Formation ended when rapid marine transgression inundated. Pakawau Group coals (Uruski et al., 2008) are thought to be a predominant source rock in Taranaki Basin (Killops et al., 1994). The Latrobe Group consists of Maastrichtian and Palaeogene sandstone, siltstone, mudstone, coal and volcanic rocks

(Fielding, 1992). Deposition of sandstones, shales and coal were in the alluvial plain, coastal plain, shoreface and shelf depositional environments along wave-dominated shorelines (Bernecker et al., 2003, Rahmanian et al., 1990, Fielding, 1992).

Romney-1 was drilled in the deepwater part of Taranaki and reached total depth in Late Cretaceous Taranaki aged sediment (91-87 Ma) (Rad, 2015). It intersected >33 m of brownish-black carbonaceous siltstone and claystone (Rad, 2015). Total thickness of this carbonaceous unit was not determined because the well stopped before reaching its base. Romney-1 penetrated 657 m of Late Cretaceous (Haumurian) coal measures assigned to the Rakopi Formation (Rad, 2015). Uruski and Warburton (2010) speculated from seismic facies mapping that the region around Romney-1 and Tane-1 contains coaly source rocks of the Rakopi Formation.

Cretaceous coaly rocks have been dredged in northern Zealandia. Herzer et al. (1999) report coaly sediments with age 95 to 87 Ma (late Cenomanian to late Coniacian) dredged from a seabed outcrop on the flank of West Norfolk Ridge. Another sample of mixed marine and terrestrial organic material dredged from Reinga Ridge had an age of 85 to 75 Ma (Santonian to Campanian) (Herzer et al., 1999). They both have low TOC and maturity, but such samples indicate potential coaly source rocks are present in the south of the region (Uruski et al., 2008, Herzer et al., 1999, Browne et al., 2016).

Taranaki and Gippsland Basins were separated by Tasman Sea opening and both basins had similar environmental controls on the deposition of coaly source rocks (Uruski et al., 2003). Taranaki and Gippsland contain coal measures of Cretaceous and Paleogene ages. Taranaki has minor volumes generated from Palaeocene black marine shale. Similarly, Gippsland contains predominantly terrestrial coaly source rocks, but a marine signature is detected in oil from the southeastern part of the basin (Gorter, 2001).

Seismic mapping in the study area identified bright discontinuous reflectors within Seismic Unit U3 sections that may be coal measures (Fig. 3.9). Comparison to eastern Australia and New Zealand (e.g., near Waka Nui-1) suggests these may be older source rocks of the Queensland Jurassic potential source rock type I or Murihiku potential source rock type III. Type II marine source rocks of PNG and Timor-Leste may have correlatives in northern Zealandia, but there is no way to verify this with seismic interpretation.

Based on similarities to Taranaki and Gippsland basins, it is likely many regions in northern Zealandia have potential coaly source rocks within Seismic Unit U2b (syn break-up), and at the base of Seismic Unit U2a (post break-up). Type II Late Cretaceous carbonaceous marine mudstone occurs in NCTS, based on samples and headspace gases collected at Site U1509 (Fig. 1.5) (Sutherland, 2019b).

5.3 Reservoir rocks

Reservoir rocks in Gippsland are Paleogene in age, but accumulations have also occurred in Late Cretaceous sediments (Uruski et al., 2003, Bishop, 2000). Reservoir rock in Taranaki is mainly Paleocene of the Kapuni Group, and there are also significant discoveries in fractured Oligocene limestone and Neogene turbidite fans (Uruski et al., 2003, King and Thrasher, 1996).

The primary reservoir of Gippsland Basin is Latrobe Group sandstones (McKerron et al., 1998, Thornton et al., 1980, Bishop, 2000). Reservoir distribution in the intra-Latrobe sequence involves deltaic sandstones and fluvial and submarine channels. Porosity in the reservoir is reported to be 12 to 30%, and permeability is locally above 1 Darcy (Kanen, 1993). Bishop (2000) reported that porosity decreased below 4 km depth.

The Rakopi Formation of Taranaki Basin comprises fluvial, marginal or shallow marine sandstones. Romney-1 penetrated (~236 m) shallow marine facies, and (~421 m) terrestrial facies of the Rakopi Formation (Rad, 2015, Schiøler et al., 2014). Petrological analysis (cores) showed that fluvial sandstones of Rakopi Formation had porosity up to 21.9% and permeability up to 64.3 mD (milli Darcy). In Tane -1, the Rakopi Formation is 475 m of terrestrial facies, with about 60% sandstone (Uruski and Warburton, 2010), based on geophysical wireline logs and cutting descriptions.

The North Cape Formation of Taranaki Basin contains a Late Cretaceous transgressive succession that is intersected in Romney-1, Tane-1, and Wainui-1. In Romney-1, North Cape Formation is dominated by shelfal, well-sorted fine sandstone (Rad, 2015). Fine sandstone beds have porosity up to 24 % and permeability up to 18 mD. Wainui-1 contains 113 m of North Cape Formation (SBPT, 1982); a lower sequence of 55 m of coastal plain coal measures, and an upper sequence of 58 m of shelfal marine

facies. In Tane-1, the North Cape Formation contains terrestrial coal measures (a lower sequence at depth 3307 m below seafloor) and transgressive shoreface to shallow marine sandstone (an upper sequence at depth 2448-3009 m below seafloor) (SBPT, 1977, Collot et al., 2009). Transgressive marginal marine deposits have porosities of up to 25% and permeabilities up to 1000 mD (SBPT, 1977).

Northland and Taranaki Basins experienced passive subsidence that led to burial of extensional horsts by Seismic Unit U2a (Bache et al., 2014a, Bache et al., 2012a). In Taranaki Basin, this is the transgressive terrestrial and marginal marine Kapuni Group, and the marine lateral equivalent is the Moa Group (King and Thrasher, 1996, Baur et al., 2014).

Seismic Units U2 and U1 contain potential reservoir rocks. Transgressive sandstones, as intersected in Tane-1 well, are present in Seismic Unit U2. Seismic Unit U2 is transgressive and onlaps basement highs across most of the Tasman Frontier region. Evidence for transgression is also found locally as clinoform sequences inferred to be of self-edge origin, e.g., U-FWAY-2b (Fig. 3.10) (Rouillard et al., 2015) or Aotea sequence (Baur et al., 2014). Some coastal sandstone facies have excellent reservoir properties (porosity >20%, permeability >200 mD, eg., Maui and Pohukura producing fields in Taranaki, New Zealand) (GNS, 2015).

Seismic Unit U1 was primarily deposited in bathyal conditions, as confirmed by drilling, and contains deepwater fans and channel systems, and pelagic drape deposits that are variably affected by bottom-currents. Late Eocene contraction locally folded Seismic Unit U2 and regional uplift involved erosion of topographic highs, with deposition of the products of this erosion into Seismic Unit U1b. High amplitude seismic facies within U1b may represent reservoir sandstones (Bache et al., 2012a, Bache et al., 2012b).

Deepwater channel and turbidite fans have been documented throughout the Neogene succession near New Zealand (Seismic Unit U1) (Baur et al., 2014, King and Thrasher, 1996, Strogon et al., 2014, Uruski and Wood, 1991), and may exist across all of northern Zealandia (Herzer et al., 1997, Etienne et al., 2018, Sutherland, 2019b). Neogene channels and fans may contain sandstone with high porosity and permeability due to their shallow burial (Uruski and Warburton, 2010). However, by analogy with reservoirs in Taranaki,

it is likely that reservoir rocks associated with Seismic Unit U1 are more restricted in extent and have poorer reservoir properties than those in Seismic Unit U2.

5.4 Seals

Cretaceous and Paleogene thermal subsidence resulted in deposition of the terrestrial and marginal marine Pakawau Group, Kapuni Group and the marine lateral equivalent called the Moa Group (King and Thrasher, 1996). The North Cape Formation of the Pakawau Group represents a Late Cretaceous transgressive sequence of dominantly marine sandstones. The Moa Group is dominated by fine-grained marine mudstone of the Turi Formation, including upper Eocene minor turbidite sandstone (Seismic Unit U1b) (King and Thrasher, 1996). The Turi Formation is a regional seal in Taranaki Basin. In Reinga and Northland Basins, Seismic Units U2 and U1b contain marine claystone, marl and limestones in the Waka Nui-1 well, and these units are correlated with the Turi Formation (Stagpoole et al., 2009). The Eocene succession contains bathyal claystone and siltstone and is calcareous (limestone in places) and found to be an effective seal, as identified in Romney-1 well (Rad, 2015). Formation pressure measurements in Romney-1 revealed that sandstones in the North Cape Formation have pore pressure up to 280 psi above hydrostatic pressure (at depth 3478.63 m).

Regional correlation combined with site data offer compelling evidence for the presence of a seal. Seismic Unit U2 has fine-grained shelf and bathyal mud, which formed during marine transgression (Rollet et al., 2012, Bache et al., 2014a, King and Thrasher, 1996). The seal in the study area is fine-grained mudstone and micritic limestone.

For a fine-grained sediment to be an effective petroleum seal, it must have low porosity, and this depends upon its maximum depth of burial. Porosity data collected during IODP Expedition 371 showed that porosity decreased from ~65% to ~25% during the first 800 m of burial (Fig. 4.2) (Sutherland, 2019b). At Site U1509, surface porosity is 63% and $c = 1952 \pm 140$ m (Sutherland, 2019b) and is similar to Taranaki mudstone ($\phi = 54\%$ and $c = 2000$ m) (Funnell et al., 1996). This indicates that Cretaceous claystone in Seismic Unit U2a is not an effective petroleum seal until it is buried by at least 1 km of overburden.

5.5 Traps and migration

Effective traps have been identified across southeast Australia and New Zealand (Auzende et al., 2000b, Bache et al., 2012a, Bache et al., 2013, Bache et al., 2012b, Bishop, 2000, Ingram et al., 1996).

Gippsland Basin experienced Eocene to Early Miocene compression resulting in anticlines and fault traps (Mebbersen, 1989, Moore et al., 1992, Ozimic et al., 1987). Petroleum mostly accumulated below the Top Latrobe unconformity in anticlines eroded and then sealed by the overlying regional Seaspray Group (micritic limestone, similar to Seismic Unit 1 in the Tasman region), e.g. the Kingfish and Barracouta fields (Mebbersen, 1989). Intra-Latrobe Group stratigraphic traps in the Barracouta Field formed at about 34 Ma (Early Oligocene) (Mebbersen, 1989). Fault traps within the Golden Beach Group (Late Cretaceous) are formed by lacustrine sandstones juxtaposed against thick lacustrine shale sections by Paleogene faulting (Bishop, 2000).

In Gippsland Basin, generation and expulsion of oil and gas started in Late Cretaceous and Early Palaeocene time, due to higher heat-flow and subsidence of this area before the formation of trapping structures in Late Eocene to Early Miocene time (Moore and others, 1992; Keall and Smith, 1996). Petroleum generation that filled many fields is inferred to be sourced from younger (Late Cretaceous) Latrobe source intervals (Moore et al., 1992).

Mapping of Seismic Units U3 and U2b reveals unconformities, truncation, onlap relationship, and faults and subsequent compaction-drape that provide a range of trapping mechanisms (Fig. 3.9, 3.11, 3.12, 3.15, 3.22 & 3.24). Eocene contraction created structural traps within Seismic Unit U2, particularly in the southern part of the region (Sutherland et al., 2017).

Multiple rifting phases created fault-related trapping styles, such as tilted fault blocks and drape over horsts within Seismic Unit U3 and the base of Seismic Unit U2b (Colwell et al., 2010b). Cenozoic tectonism may create a breach risk for trapped hydrocarbons within Seismic Units U2 and U3 (Rollet et al., 2012, Colwell et al., 2010b).

Some Cretaceous horst blocks were eroded, forming stratigraphic and compactional anticline traps above them (Seismic Unit U2). Transgressive deposition provides the opportunity for stratigraphic trapping of hydrocarbons, and naturally places clay-rich seal rock over coastal and shelf reservoir sandstones. Anticline traps are mapped in Reinga Basin, where Seismic Unit U2a is deformed (Bache et al., 2012a), and isolated anticlines are observed across the southern Tasman Frontier from Gippsland to Reinga Basin (Sutherland et al., 2017).

In the north part of the study area, seismic mapping shows that Seismic Unit U2 is affected by diapiric deformation (Fig 3.10) (Auzende et al., 2000b, Bache et al., 2014b, Exxon et al., 2007, Rouillard et al., 2015). The diapirs are abundant and form structural dips and faults that might focus petroleum migration and develop structural traps. The diapirs were probably triggered by Eocene compressional deformation (Auzende et al., 2000b), but require some (currently unknown) driving mechanism that may be provided by low-density salt or over-pressured claystone.

5.6 Overburden deposition and source rock maturity

Thermal maturity modelling (deepwater Taranaki Basin) (Fig. 5.1) (Uruski et al., 2003) predicts 3,200 m bsf for type III non-marine source rocks (Uruski et al., 2003, Sykes, 2001). The present-day gas window is estimated below 5,000 m bsf for type III source rocks (Uruski et al., 2003).

Source rock modelling predicted oil generation to start at ~95°C corresponding to a burial of about 3,200 m below seafloor, based on thermal gradient of 3°C/100 m (Sykes, 2001, Stagpoole et al., 2007). Romney-1 wireline logging measurement and bottom hole temperature of 116°C gives an observed thermal gradient of 3.5°C/100 (Rad, 2015), and modifies the local predicted top of the oil window to ~2,700 m bsf. Vitrinite reflectance (VR) analysis yields %Ro=0.8 at 2,950 m bsf, which confirms it is in the oil generation window (Rad, 2015).

Figure 5.1 Cretaceous and Tertiary stratigraphy of deepwater Taranaki Basin and Present day maturity model (Pepper and Corvi, 1995, Uruski et al., 2003).

Wells in NCTS reveal a rapid increase in sedimentation rate during the Neogene (Sutherland, 2019b). The influx of sediments is prograding northwest with detritus from the Southern Alps and North Island shelf (King and Thrasher, 1996). This influx of sediment is overburden to bury Rakopi Formation to ~2700 m below seafloor. Rapid sedimentation occurred in NCTS during the Neogene time due to the development of the plate boundary in New Zealand that resulted in rapid uplift and erosion. Neogene sedimentation rates reach about 1 km per million years and the overburden thickness is > 2 km over a large part of Taranaki Basin since 3 Ma.

On ridges (LHRN, LHRS) and away from Taranaki (REIN, NCTN), pelagic deposition since 4-2 Ma was characterised by lower mass accumulation rates values and colder ocean temperatures, suggesting thermal maturity at depth increased only slightly since then (Fig. 4.32). In the late Miocene and early Pliocene, burial by pelagic sediment rapidly occurred. During that time, the surface temperature was warmer, and hence the top boundary was affected by this temperature. Consequently, peak maturity of petroleum source rocks at greater depth probably developed in most places at the end of the Miocene to early Pliocene.

5.7 Distribution of petroleum system components

The assessment of petroleum system components in northern Zealandia is reviewed and evaluated from existing and new seismic (TECTA and TAN1409 surveys) reflection interpretation tied to scientific boreholes and a small number of petroleum exploration boreholes near the coast of New Zealand (Bache et al., 2014a, Bache et al., 2012a, Bache et al., 2013, Burns, 1973a, Burns, 1973b, Burns and Andrews, 1973, Burns et al., 1973a, Burns et al., 1973b, King, 2000b, King and Thrasher, 1996, Norvick et al., 2001, Rouillard et al., 2014, Rouillard et al., 2015, Stagpoole et al., 2009, Stagpoole et al., 2007, Uruski and Baillie, 2002, Uruski et al., 2003, Uruski et al., 2008, Uruski et al., 2004, Uruski and Warburton, 2010, SBPT, 1981, SBPT, 1977, SBPT, 1982, SBPT, 1984, SBPT, 1986). Basins around New Zealand (King and Thrasher, 1996), Papua New Guinea (Brown et al., 1979) and Australia (Bishop, 2000, Ingram et al., 1996, O'Brien et al., 1994) with proven petroleum systems provide analogues across the region that may be applicable within the Tasman Frontier.

Based on regional and local stratigraphic correlation and seismic interpretation results, I infer that source rock, reservoir rock, seal rock, and suitable petroleum traps are present (Magoon and Dow, 1994, Allen and Allen, 2013) in northern Zealandia (Fig. 5.2) Romney-1 drilling in southern New Caledonia Trough (NCTS) (Collot et al., 2009) confirmed that all elements of a petroleum system and shows of petroleum were present (Fig. 5.2), but no significant petroleum accumulation was discovered at that location.

Figure 5.2 Petroleum system diagram for northern Zealandia showing the relative timing for key petroleum system elements. The grey colour represents the time at which elements occurred (Bache et al., 2014a, King and Thrasher, 1996, Sutherland, 2019b, Sutherland, 2019c).

There is considerable uncertainty introduced in the inference of source-reservoir-seal possibilities due to very limited sampling of Mesozoic rocks. Mesozoic coals of eastern Australia and New Zealand may extend throughout the region (Norvick et al., 2008b). Some of this coal is speculated to be oil-prone equivalent of the Jurassic Walloon Coal Measure of the Clarence-Mareton Basin (Powell et al., 1993, O'Brien et al., 1994). The Papuan Basin (PNG) is mainly clay-rich, terrestrial-influenced Jurassic marine source rocks. Further to the south-east, Triassic-Jurassic source rocks having both oil-prone and gas-prone observed in the onshore Timor-Leste (Robinson, 2012, Charlton, 2002), and Jurassic marine claystone (Elang and Plover Formations) and Lower Cretaceous (Darwin Formation) of Bonaparte Basin are oil-prone restricted. The distribution and nature of Seismic Unit U3 remains poorly known and all these correlatives are plausible.

Cretaceous carbonaceous mudstones and coals exist as the primary source rock in Gippsland (Alexander et al. 1987; Moore et al. 1992; Stainforth 1984) and Taranaki basins (King & Thrasher 1996; Sykes et al. 2000). Late Cretaceous carbonaceous mudstone (oil-prone) in NCTS may be a marine equivalent in the southern New Caledonia Trough at Site U1509 (Sutherland, 2019b, Sutherland et al., 2018a).

Reservoir rocks may occur within pre-Cretaceous to Late Oligocene strata (Fig. 5.2). Jurassic and Late Cretaceous fluvial sandstone (Seismic Unit U3 and Seismic Unit U2), Late Cretaceous to Eocene transgressive (marginal or shallow marine) sandstones (Seismic Unit U2a) and Eocene to Late Oligocene slope/basin floor fans (Seismic Unit

U1b) (Fig. 5.2) are all likely to be present. Transgressive sands are inferred in Seismic Unit U2 in FWAY and NCTS and equivalent facies have good reservoir properties in Taranaki and Gippsland basins (Rouillard et al., 2015, Baur et al., 2014, GNS, 2015). Deepwater basin-floor systems are not usually as good as coastal sands, but likely exist in Seismic Unit U1b.

Seal rocks are inferred to be Cretaceous claystone, or clayey micritic limestone associated with Seismic Unit U2a (Fig. 5.2). Chalk and marl within U1a are unlikely to be compacted enough to be an effective petroleum seal (Yang and Aplin, 2010). There is required a porosity <30% to be a good seal, but porosity (Cretaceous claystone) observed at Site U1509 is about 50% at a depth of ~700 m bsf (Fig. 4.2) (Sutherland, 2019b). There is required a minimum of 1-2 km of burial of Seismic Unit U2 clay/chalk before an effective petroleum seal is produced.

Structural traps include Late Cretaceous rifting of Seismic Unit U2b, Late Cretaceous to Paleocene stratigraphic traps and compactional drape, and Eocene folding (Seismic Unit U2a and Seismic Unit U1b) (Fig. 5.2). Eocene folding occurred in the Early to Late Eocene about ~50-35 Ma (Bache et al., 2014a, King and Thrasher, 1996, Sutherland, 2019b, Sutherland, 2019c, Orr et al., 2020).

Mass accumulation rates (MAR) in the late Miocene and early Pliocene were high, as were climatic temperatures and hence peak thermal maturity, and hydrocarbon expulsion were likely at ~3 Ma (Fig. 4.32 & 5.2) across much of the region (everywhere except NCTS). In the late Miocene and early Pliocene, the surface temperature was warmer, and the top boundary was influenced by this temperature resulting in peak maturity of petroleum source rocks (at greater depth) at the end of Miocene to early Pliocene. The base of Seismic Unit U2 remains immature for petroleum generation over most of the region (Fig. 5.3).

5.8 Prospectivity

The foundation of a petroleum system is to have a mature hydrocarbon-expelling source rock (Allen and Allen, 2013, Magoon and Dow, 1994). The maturity for oil or gas expulsion can be modelled in the Tasman Frontier, based on burial depth and assumptions of basal heat flow and surface temperature (e.g. Uruski et al., 2003). The isopach map for combined units U1-U2 shows that potential source rock maturity at the base of Seismic Unit U2 is limited to approximately one-fifth of the region. The base of Seismic Unit U2 at the present day is potentially generating petroleum in Fairway Basin (FWAY), southern New Caledonia Trough (NCTS), Reinga Basin (REIN) and adjacent to New Caledonia (NCTN) (Fig. 5.3). Hydrocarbon expulsion and maturity started in Neogene time (Fig. 5.3). In these regions, petroleum source rocks within the lower parts of Seismic Unit 2 may be viable components of a working petroleum system. Source rocks within Seismic Unit U3 may be mature in any region (base unconstrained), but the composition and distribution of Seismic Unit U3 remains very poorly known.

Figure 5.3 Map showing hydrocarbon generation window across northern Zealandia; top oil window is about 3500 m bsf and gas expulsion at about 5 km (Uruski et al., 2003).

The coaly source rock of Rakopi Formation (Seismic Unit U2a) is confirmed to be within the oil-generation window at the Romney-1 well (Rad, 2015). Additionally, ethane and methane in head-space gases collected at Site U1509 (Sutherland, 2019b) provides evidence for thermogenic hydrocarbon generation near the axis of southern New Caledonia Trough (NCTS). Head-space gas and pore water chemistry results from Site U1508 (Sutherland, 2019c) indicate active petroleum migration in Reinga Basin (REIN), where this petroleum source may be Murihiku coaly rocks, as identified at Waka Nui-1 (Stagpoole et al., 2009), or Late Cretaceous coal/carbonaceous mudstone near the base of Seismic Unit U2.

In Summary, there are many play types that might exist. Sandstone-claystone in either Seismic Unit U3 or U2 provide plausible reservoir-seal combinations and there are many plausible trapping mechanisms related to either the RU1 or RU2 unconformities, normal faults, or folds, or stratigraphic pinch-out. Perhaps the key factors limiting future prospectivity are the unknown nature and thickness of Seismic Unit U3, and the limited maturity (burial) of Seismic Unit U2 (Fig. 5.2 & 5.3).

5.9 Future exploration prognosis

Petroleum system elements and sediment thickness in the region allow general regions of prospectivity to be identified, with approximately one-fifth of the region predicted to have mature petroleum source rocks within the lower part of seismic Unit U2 (Late Cretaceous): FWAY, NCTS and REIN (Fig. 5.3) and adjacent to New Caledonia (NCTN). The rest of the region may still be prospective, but requires that the source rock be within Seismic Unit U3, which is mostly unsampled.

The southwest Pacific has attracted interest as a frontier location with possible significant petroleum potential and very large area (the study area of this thesis is the size of India). New Zealand and Australia are a favourable investment destination with market-based economy and secure regulatory settings and a stable political environment, but New Zealand has recently banned new petroleum exploration. About 25% of the study area is within the New Zealand EEZ.

I conclude that the region has considerable potential for further discoveries, and that the large size of the region makes it globally significant. Northern Zealandia needs more industry-standard seismic data to better understand the sedimentary strata, and there are no samples from deep strata in most of the region. Hence, it is plausible that a wide range of terrestrial, coastal and marine facies exist as found around New Zealand, Australia, PNG and Timor-Leste. Further data are needed to identify the distribution of source rocks, the quality of reservoir and seals, and assess heat flow variations across the region.

Future exploration in the large deepwater frontier between Australia, New Caledonia and New Zealand might best be focused in FWAY, NCTS and REIN. The target might be in Seismic Unit U2b (Fig. 5.2 & 5.3). Seismic Unit U3 may be overmature locally but remains a high-risk but plausible target over much of the frontier area.

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Appendix A: New Zealand geological timescale

Figure A1. New Zealand geological timescale (Raine et al., 2012).