Seismic Attributes to Constrain the Distribution of Rakopi Formation Coals in the Southwest Offshore Taranaki Basin, New Zealand

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Abstract

The Rakopi Formation, in the Taranaki Basin of New Zealand, is a Late Cretaceous (Haumurian) sequence of coal measures interbedded with siltstone and sparse sandstone. It is the lowest widespread stratigraphic unit in the Taranaki Basin, and has a syn-rift deposition which is concentrated in isolated grabens and sub-basins. It was deposited during the extensional tectonic regime linked to the breakup of Gondwana.

The Rakopi is one of the major hydrocarbon source rocks in the Taranaki Basin; New Zealand's only currently-producing basin. However, there are very few well penetrations of the Cretaceous interval within the basin, and this fact – coupled with the non-continuous deposition – means that the Rakopi's distribution is poorly constrained further away from wells.

In petroleum systems models, the entire Rakopi Formation interval is commonly represented entirely as source rock facies. By observing the limited well penetrations available, it is known that this is not the case. As such, it is likely that the total hydrocarbons generated within the basin are overestimated when modelled. Improved constraint of the distribution of the coal within the Rakopi Formation will improve the accuracy of these models.

This study presents the results of the extraction and analysis of a suite of seismic attributes from 3D seismic reflection surveys in the southwest offshore Taranaki Basin, for the purpose of constraining the distribution of coal within the Rakopi Formation. The attribute outputs were temporally averaged, with the resulting frequency distributions analysed for significant patterns or variations between the coaly- versus non-coaly vertical intervals of the formation.

Within the Maari 3D seismic reflection volume, six attributes were identified which correlated with the presence of coals observed in the Maui-4 well. These attributes were temporally averaged within the Rakopi Formation interval in both the Maari 3D and Pipeline 3D volumes, with the areas of high average values identified as being more likely to contain coal.

Using this attribute analysis method, the distribution of coal within the Rakopi Formation has been better constrained. Attribute analysis is easily transferable, and has the potential to be utilised elsewhere for the identification of hydrocarbon source rocks.

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1 Introduction

In the Taranaki Basin, coaly rocks of Cretaceous age are of interest to the oil and gas industry, as they often contain the requisite organic carbon content to produce hydrocarbons, as well as being buried deeply enough to be thermally mature.

The Pakawau Group is a Late Cretaceous sedimentary sequence in the Taranaki Basin which contains coal measures (Browne et al. 2008). It consists of two formations: the upper, shallow marine North Cape Formation, and the lower, more coal-rich terrestrial Rakopi Formation (Wizevich et al. 1992; Wizevich 1994). The coaly facies of the Rakopi Formation are one of the major hydrocarbon source rocks in the Taranaki Basin, which is currently the only hydrocarbon-producing basin in New Zealand (King & Thrasher 1996).

The Rakopi Formation has been the subject of numerous previous studies (Armstrong et al. 1996; Browne et al. 2008; King et al. 1999; King & Thrasher 1996; Sherwood et al. 1992; Sykes et al. 2004; Sykes et al. 2014; Thrasher 1992; Uruski 2008, and Wizevich et al. 1992). These studies designate the Rakopi Formation as a predominantly terrestrial coal measure formation, with some marine influence in the upper strata. It is credited as being one of the predominant source rocks in the Taranaki Basin (Browne et al. 2008; Uruski 2008), with hydrocarbon generation beginning in the Paleocene-Eocene (Armstrong et al. 1996).

In petroleum systems models which aim to predict (both known, and as-yet-undiscovered) hydrocarbon accumulations, the Rakopi Formation is commonly represented as consisting entirely of source rock facies. However, the spatial variability of the source rock potential of the Rakopi Formation in the subsurface is not well understood (Kroeger et al., 2016). The lithological variation of the formation has been acknowledged from both well and outcrop studies (e.g. Browne et al., 2008), meaning that the total source rock contained within the Rakopi Formation, and therefore the Taranaki Basin as a whole, is currently overestimated. Improved mapping of the Rakopi Formation, especially the coal-rich portions of the formation, would provide more accurate assessments of the total volume of hydrocarbons generated within the basin.

1.1 Seismic Attributes

“Seismic Attributes are all the information obtained from seismic data, either by direct measurements or by logical or experience based reasoning.” – Taner 2003.

Seismic attributes are measures of seismic data which enable it to be visually enhanced, or enable features to be quantified for the purpose of interpretation. Desirable attributes are those which are

sensitive to a geologic feature or lithologic property, and enable definition of a structural or depositional environment (Chopra & Marfurt 2007).

This thesis ties together attributes from the selected 2D and 3D seismic reflection data with exploration wells – together with results from previous studies based on outcrop information – to investigate a new way to constrain the extent of coaly facies within the Cretaceous interval of the offshore southwest Taranaki Basin. By extracting selected attributes from the seismic data, this study seeks to determine whether the coaly facies of the Rakopi Formation can be identified and constrained away from well penetrations. The results generated here have the potential to be applied elsewhere,

so that further coaly facies can be identified in other areas and stratigraphic intervals in the basin, and potentially elsewhere in the world.

1.2 Study Area

The Taranaki Basin is a mostly offshore sedimentary basin, located off the west coast of the North Island of New Zealand (Figure 1.1). It covers an area of approximately 100,000 km², ranging from the top of the South Island in northwest Nelson, and extending approximately 200 km off the west coast from Taranaki (King & Thrasher 1996). This research project is focused on the southwest offshore region of the Taranaki Basin, in the Pakawau and Maari sub-basins (Figure 1.2), due to the availability of 3D seismic reflection data which can be tied to exploration wells.

The Cretaceous Rakopi and North Cape formations are present throughout this area, although their distributions are not continuous, and there are limited well penetrations (Figures 2.5 & 3.2).

1.3 Project Aims and Outline

This aim of this project is to determine whether seismic attributes can be used to identify and constrain the coaly rocks from within the Cretaceous interval of the Taranaki Basin – in particular the Rakopi Formation – in areas removed from well penetrations.

This is to be done with the following steps:

- Conducting well-ties to link the seismic reflection data to the lithology
- Interpretation of 2D and 3D seismic reflection data to identify the top of the Rakopi, North Cape, and Farewell formations, along with Top Basement, which defines the base of the Cretaceous succession, and the top of the Eocene Mangaheua Formation
- Interpretation of top, base, and intra-formational Cretaceous horizons
- Characterisation of seismic facies
- Identification of meaningful seismic attributes, and their extraction from the data
- Analysis of interpreted seismic intervals and extracted attributes, with correlation to well data
- Identification of an attribute or combination of attributes which predict the occurrence of coaly facies away from well locations
- Use of the identified attributes to constrain the likely distribution of coals within the study area

The study area contains limited well penetrations of the Cretaceous interval; however, the Rakopi Formation is penetrated by the Maui-4 well, which is located within the Maari 3D seismic volume (Figure 2.5). The Maui-4 and Pukeko-1 wells will be correlated between by using the selected 2D and 3D seismic reflection data to carry out a local interpretation of the relevant Cretaceous and Paleocene strata for this project.

2 Background Geology

2.1 Taranaki Basin Tectonic Setting

The Taranaki Basin sits atop the Australian Plate, approximately 300-450 km to the west of its convergent boundary with the Pacific Plate (Figure 2.1) (King & Thrasher 1996). The subduction zone to the east of the lower North Island is known as the Hikurangi Margin, and extends to the northeast into the Kermadec Trench (Holt & Stern 1994). The tectonic setting of New Zealand and the Taranaki Basin has altered significantly over the last 100 Ma, with separate phases of rifting, passive subsidence, and convergence (King 2000). As a result of this tectonic history, the basin is comprised of several superimposed sub-basins (Figure 2.5), with the different parts of the basin having undergone various types of deformation, resulting in complex faulting patterns, especially in the eastern basin (King & Thrasher 1996).

The basin is bounded to the east by the Taranaki Fault (Figure 2.1), and consists of 2 major components; the Eastern Mobile Belt and the Western Stable Platform (King & Thrasher 1996). The basin makes up part of the deformation zone associated with the contemporary Australian-Pacific plate boundary (Muir et al. 2000).

The Eastern Mobile Belt contains superimposed features of both tectonic compression (thrust faults and folding) and extension (normal faults and grabens), and is separated from the more tectonically-dormant Western Stable Platform by the Cape Egmont Fault – a Cretaceous normal fault which was reactivated as a reverse fault during the Miocene (Figures 1.2 & 2.1) (Nicol et al. 2005).

2.2 Tectonic and Sedimentary History

There are 3 main phases of activity which have been recognised in the overall tectonic regime of New Zealand (Gaina et al. 1998, King & Thrasher 1996, Stern & Davey 1990):

- Late Cretaceous and Palaeocene extension
- Late Eocene-Oligocene and younger contraction
- Plio-Pleistocene extension

The formation of the Taranaki Basin began with the breakup of Gondwanaland, which provided the oldest phase of extension in the Taranaki Basin, occurring during the late Cretaceous (Haumurian Stage; 83.5-65.5 Ma). The separation of Australia from Zealandia during this period caused the formation of the Tasman Sea (Gaina et al. 1998, Thrasher 1992). During this, the first phase of New Zealand's tectonic history, the sedimentary regime was that of a transgressive systems tract (TST), as

Figure 2.1 Taranaki Basin Tectonic Subdivision

Bounding faults/fault zones are indicated by the solid black lines, and the dashed lines represent the inferred boundaries between the Western Stable Platform and the Eastern Mobile Belt, and the eastern boundary of the basin respectively.

Adapted from King & Thrasher 1996. For map location see Figure 1.1.

part of the overall sedimentary “megasequence” described in detail in King (2000) and King et al. (1999). The general stratigraphic succession of the Taranaki Basin is given by Figure 2.2.

As the proto-New Zealand landmass broke away from Gondwana, it began to drift north, away from the spreading ridge (Gaina et al. 1998). The Late Cretaceous onlap surface represents the start of the deposition of the Pakawau Group in the Taranaki Basin, and corresponds with the beginning of the aforementioned Late Cretaceous TST (King 2000).

As this spreading took place, the subsidence of both the Eastern Mobile Belt and the Western Stable Platform began, with rifting continuing throughout the deposition of the Pakawau Group, which

Figure 2.2 Generalised Taranaki Basin Stratigraphic Column

From Bull et al. 2016.

opened up north-south and southwest-northeast striking half-grabens and sub-basins, creating the accommodation space into which these Cretaceous sediments were deposited (King & Thrasher 1996; King 2000; Thrasher 1992).

At the Cretaceous-Paleocene boundary (K-T boundary; 65.5 Ma), the New Zealand proto-continent was drifting away from the spreading rift to the southwest (Figure 2.3A) (Gaina et al. 1998, King & Thrasher 1996). At 65.5 Ma, relative sea level was at its lowest point, which meant that the largest New Zealand land area of any time was exposed, the erosion of which provided ample sediment to the surrounding basins (King & Thrasher 1996). The basin subsequently became a passive margin setting, with slow subsidence, and large-scale sediment accumulation during the late-rift and post-rift transgressive sequence of the Paleocene and Eocene respectively (King et al. 1999).

During the Oligocene Epoch, the basin transitioned to a foreland basin, due to the subduction of the Pacific Plate under the Australian Plate, which caused basin-wide compression and subsequent

thrusting along the Taranaki Fault (Palmer & Andrews 1993; King & Thrasher 1996; Stagpoole & Nicol 2008; Voggenreiter 1993). This began the overall sedimentary shift into a regressive systems tract (RST), with foredeep and distal sediment-starved shelf and slope sequences giving way to a regressive sequence in the Miocene (King & Thrasher 1996). The Hikurangi Margin accommodated the subduction, which caused widespread contraction along the eastern boundary of the basin (Reilly et al. 2015). This zone of contraction widened and migrated westward during the Miocene with the migration and enlargement of the subduction zone (King 2000; King & Thrasher 1996) (Figure 2.3A & 2.3B). Many of the Taranaki Basin's large extensional faults which were displaced during the Late Cretaceous extension were reactivated as thrust faults during this subsequent deformation to accommodate the contraction (Holt & Stern 1994; King & Thrasher 1996; Pilaar & Wakefield 1978).

In the Mid to Late Miocene, rifting began in the northern Taranaki Basin – attributed to slab rollback or slab steepening at the Hikurangi Margin – and migrated through the southern basin, giving way to the overall extensional tectonic regime at around 3-4 Ma (Reilly et al. 2015, from Ballance 1976), and with the sedimentary regime remaining in a regressive systems tract (King & Thrasher 1996).

Subsequently through the Plio-Pleistocene, some new fault traces were created by the extension, but other older faults such as the Cape Egmont Fault – which had undergone Cretaceous normal faulting and been re-activated as a Miocene reverse fault – was reacted once again, this time in a normal sense, to accommodate the ongoing extension (King & Thrasher 1996; Reilly et al. 2015).

Figure 2.4 Rakopi Formation Outcrop in Northwest Nelson

A) Rakopi outcrop. B) Sampled sequence of 10 coal seams in the upper reaches of the Paturau River, overlain by thick, channel sandstones. The lowest seam is out of view to left. The inset shows (b) a closer up view of the middle 8 seams, highlighting sharp contacts with the intervening carbonaceous (coaly) mudstone-siltstone beds, and mudstone laminae within seam 6. Numbers refer to seam and sample numbers (Table 1). Scale bar in both images is ca. 1 m long (taken from Sykes et al. 2004).

2.3 Petroleum System

The Taranaki Basin is New Zealand's largest hydrocarbon-producing basin, and (as at the close of 2011) had produced some 418 million barrels of oil and 6190 billion cubic feet of gas, with commercial-scale petroleum having been found at every level between Pliocene-Paleocene (New Zealand Petroleum and Minerals 2016). It produces from around 20 fields, the largest of which is the Maui gas-condensate field, the original gas reserves of which were calculated at 3.4 trillion cubic feet (New Zealand Petroleum and Minerals 2016).

Samples of Cretaceous age coals within the basin have shown that they are thermally mature source rocks (Thompson 1982). The rapid deposition of the Pakawau Group, coupled with the high heat flow resulting from rifting, led to early localised hydrocarbon generation during the Cretaceous (King 2000; Wood et al. 1998).

2.4 Pakawau Group

The Pakawau Group includes all of the Late Cretaceous sedimentary deposits in the Taranaki Basin, and is comprised of 2 formations: the lower, coal-bearing Rakopi Formation, and the upper siltstones, sandstones, and conglomerates of the North Cape Formation (Wizevich et al. 1992; Thrasher 1992).

The Pakawau Group is Haumurian in age (~83.5-65.5 Ma), and is largely thought of as a coal measure sequence. The division of the Pakawau Group into the Rakopi and North Cape formations is defined from lithofacies character in exploration wells, outcrop in northwest Nelson, and seismic reflection mapping offshore (Browne et al. 2008). The boundary between the Rakopi and North Cape formations represents the onset of the oldest regionally defined marine transgression in the Taranaki Basin (King & Thrasher 1996).

The Pakawau Group is between 500-4200m thick, and was deposited during the rift phase of Tasman seafloor spreading, and is found in interconnected depocentres as well as in isolated sub-basins (Wizevich 1994). The top of the group's seismic reflector generally ties closely in exploration wells with the paleontologically-dated Cretaceous-Tertiary boundary, although in the Pakawau sub-basin the K-T boundary is marked by an unconformity within Paleocene strata (King & Thrasher 1996).

2.4.1 Rakopi Formation

The Rakopi Formation is largely sub-surface, with limited outcrop to the northwest of Nelson (Figure 2.4). As such, the available geological data is largely confined to drill cores, wireline logs, and cuttings. Given the wide variability the formation displays in exploration wells, and the sparse occurrence of Cretaceous well penetrations, it can be difficult to correlate the formation using the connecting seismic data.

The Rakopi Formation is the earliest-deposited Cretaceous-Cenozoic unit with a widespread distribution in the Taranaki Basin (Uruski 2008), although is not continuous due to its syn-rift deposition (Figure 2.5). It is named after a coal exploration hole drilled in 1915 at Rakopi on Whananui Inlet, and the type section is that of the Cape Farewell-1 exploration well from 1160-2690m (Figure 3.2) (King & Thrasher 1996).

The formation's age has been dated based on palynological data from outcrop (Browne et al. 2008; Raine 2004). The upper age of the Rakopi has been constrained by dinoflagellate cyst assemblages which have been identified as having similar composition to those from the base of the overlying North Cape Formation, and thus an early Late Maastrichtian (early Late Haumurian) age has been inferred (Browne et al. 2008).

The Rakopi Formation is penetrated by only 7 exploration wells within the Taranaki Basin (Cape Farewell-1, Cook-1, Fresne-1, Maui-4, Tahi-1, Takapou-1, and Tane-1) (Figure 3.2), as well as outcropping in northwest Nelson amongst forestry blocks (Figures 2.4 & 2.5) (Browne 2008). In most areas it is generally less than 1000m thick, and thins towards the south onto basement, as well as thickening into then-active Late Cretaceous extensional faults, reaching local thicknesses of up to 2500m next to the Taranaki, Rua, and Wakamarama faults (Figure 2.2), as well as reaching a maximum recorded thickness of 3000m (King & Thrasher 1996).

The formation contains a series of repeated metre- to tens-of-metres-thick fining-upwards cycles, observed in both outcrop and subsurface records. The general pattern of these cycles consists of a planar base, which is succeeded by pebbly sandstone, followed by interbedded sandstone and siltstone, then carbonaceous mudstone, and finally coal at the top of the succession (Browne et al. 2008). The majority of Rakopi Formation coal seams in outcrop and intersected by drill holes are less than 50cm thick, which is well below minimum seismic resolution (Wizevich 1994).

The paraffinic oil potential of the formation is controlled primarily by leaf-derived liptinites, with the preservation of leaf biomass by deposition in thin, planar coal seams producing waxy crude oils (Sykes et al. 2004).

Rakopi Formation Depositional Environment

The Rakopi Formation was deposited largely as a channel-dominated fluvial coastal plain succession (King & Thrasher 1996). However, the presence of a marine influence is inferred from the presence of dinoflagellate cysts and glauconite grains in the upper Rakopi Formation (Wizevich 1994). Further palynological sampling of outcrop rocks has confirmed this periodic marine influence (Browne et al. 2008). In addition to outcrop sampling, coal sulphur data acquired in offshore wells provides evidence for more widespread marine influence throughout the formation (Sykes et al. 2004).

The fine-grained sequence of fining-upward channel sandstones, including numerous coal seams, indicates that the Rakopi Formation was deposited in a low-gradient fluvial system. This is inferred as either a meandering (Wizevich 1994), or braided (Browne et al. 2008) stream depositional environment.

The marine influence at the top of the formation is inferred to represent the shift towards a deltaic plain or lagoonal swamp setting during the deposition of the upper coal measures, which is consistent with the overall sedimentary regime shift as part of the transgressive systems tract. Given that marine coaly facies contain greater amounts of organic carbon, this has implications for the source rock potential of the upper Rakopi Formation, which could have greater potential than if it were comprised of purely terrestrial sediments (Browne et al. 2008). A study of coaly Eocene

source rocks in the Taranaki Basin found that while a greater marine influence only had a very minor effect on the abundance of organic carbon in coaly source rocks, it did increase the Hydrogen Index (HI), and thus the potential for paraffinic oil charge (Sykes et al. 2014).

The intervals of seismic data which correspond to the Rakopi Formation in well-bores display a high amplitude, hummocky, and laterally-discontinuous seismic character (e.g. Figure 4.3). The disconformable contact between the Rakopi Formation and the overlying North Cape Formation is largely uniform in the seismic data throughout the Taranaki Basin (Thrasher 1992).

2.4.2 North Cape Formation

The North Cape Formation is the name of the upper unit of the Pakawau Group, and is distinguished from the underlying Rakopi Formation by a more bland seismic reflection character, as well as the greater marine influence on its deposition (King & Thrasher 1996).

The formation has a maximum thickness of approximately 1800m, but is generally less than 1000m thick in most areas, with an average thickness of approximately 300-400m (Wizevich et al. 1992). It consists of a sequence of siltstones, sandstones, and conglomerates, with minor coal seams. The Puponga and Wainui Members are localised units of coal measures within the North Cape Formation, which are found in the Pakawau sub-basin and the northwest part of the Taranaki Basin respectively (King & Thrasher 1996).

North Cape Formation Depositional Environment

The North Cape Formation was deposited in terrestrial, marginal marine, and marine environments, and represents a transgressive sequence of marine, paralic, and coastal plain sediments, which were deposited as a result of regional flooding of the Taranaki Rift in the Late Cretaceous (Thrasher 1992).

2.4.3 Coaly Facies

Coals are largely made up of organic matter and carbonaceous sediment, as well as containing various impurities, which are mainly comprised of siliclastic materials such as ash (Boggs 1995)

Coal definition (Boggs, quoting Schopf 1956):

“Coal is a readily combustible rock containing more than 50% by weight and more than 70% by volume of carbonaceous material, formed from compaction or induration of variously altered plant remains similar to those of peaty deposits. Differences in the kinds of plant materials (type), in degree of metamorphism (rank), and range of impurities (grade), are characteristic of the varieties of coal.”

Coaly facies is the name which has been chosen to represent strata which contain significant coal seams. The depositional environment of coaly facies varies from terrestrial (fluvial/lacustrine) to

marginal marine, although the development of coals requires organic carbon to decay in place, which is less likely to occur with more marine influence, due to sediments being disturbed by tides and currents (Boggs 1995).

Coaly facies which are buried deeply enough to be thermally mature are a common hydrocarbon source rock worldwide, and make up some of the major source rocks in the Taranaki Basin (Uruski 2008).

2.4.4 Cretaceous Coals in New Zealand

The Cretaceous coals in New Zealand present a record of the tectonic change which took place during the time period. The relationships between lithofacies, as well as the properties of the coals, represent the many-faceted interplay between modern tectonic influence and paleoenvironmental factors (Sherwood et al. 1992).

The earliest-deposited (Mid-) Cretaceous coal measures in New Zealand are predominantly made up of breccia and conglomerate, as well as containing thin, discontinuous coal seams which are not significant economically. The Latest Cretaceous coal measures (including the Rakopi Formation and its stratigraphic equivalents) were largely deposited in fluvial/lacustrine environments, and are dominated by sandstone, siltstone, and mudstone, as well as discontinuous but thick coal seams. Atop these terrestrial coal measures there exist near-shore, fine-grained coal measures with a marine depositional influence, which reflects the overall marine transgression occurring at the time (Sherwood et al. 1992).

2.5 Summary

The Taranaki Basin is New Zealand's only hydrocarbon-producing sedimentary basin, and has a complex tectonic history. The Rakopi Formation was deposited in a fluvial flood plain as a series of coal measures, in mostly isolated sub-basins, during the Late Cretaceous rifting of the Taranaki Basin. The coaly facies within the formation comprise one of the major hydrocarbon source rocks of the basin, the true extent of which is largely unknown due to its discontinuous deposition and lack of well penetrations.

3 Data

3.1 Introduction

New Zealand Petroleum and Minerals archives and distributes all well and seismic data acquired under the Crown Minerals Act (1991). This project has used a subset of these data, in order to identify and characterise the coaly facies of the Rakopi Formation, by tying the seismic facies to the physical geology recorded in exploration wells.

This project utilises two 3D seismic reflection volumes, namely the Maari and Pipeline volumes, located in the southwest offshore Taranaki Basin (Figure 3.1). In addition, a number of 2D seismic lines have been used to correlate between the 3D volumes and outlying wells where possible. Well data has been utilised to tie the seismic data to the physical geology of the basin (Figure 3.2).

3.2 Seismic Reflection Data

The seismic data which has been used for this project is a series of post-stack multi-channel seismic reflection data gathered under various exploration licenses within the Taranaki Basin (Figure 3.1). It consists of a total length of approximately 704 km of 2D seismic lines, in addition to the Maari and Pipeline 3D seismic volumes which cover an area of approximately 935 km² (Table 3.1).

	Maari 3D	Pipeline 3D
Area Covered	~500km ²	435km ²
Survey Dates	12th March 1999 - 14 April 1999	19th Feb 2013 - 4th April 2013
Source	2 x 2368in ³ . Bolt Guns	2 x 3080 in ³ . Bolt Guns
Shot Interval	18.75m	18.75m
Fold	40	80
Inline Separation	25m (stack), 12.5m (migration)	12.5m
Crossline Separation	12.5m (stack and migration)	12.5m
Water Depth	~100m	100-150m
Inline Orientation	Approx N/S	002/182
Streamer Length	3000m	6000m

Table 3.1 Selected 3D Seismic Reflection Volumes' Acquisition Parameters

3.3 Well Data

The wells which have been predominantly utilised for this study have been the Maui-4 and Pukeko-1 wells, due to their location within the Maari and Pipeline 3D seismic volumes respectively. A summary of Cretaceous well-penetrations is shown in Table 3.2.

Well Name	Cape Farewell-1	Cook-1	Fresne-1	Maui-4	North Tasman-1	Pukeko-1	Tahi-1
Spud Date	29-Nov-85	10-Aug-70	14-Jan-76	11-May-70	26-Oct-78	28-Apr-04	1-Feb-84
Depth	2817m	2689m	2503m	3919.4m	2727m	4190m	1776m
Objective	Lower Late Cretaceous SST	Kahurangi Prospects hydrocarbon potential	Pakawau Coal Measures	Lower Tertiary Sands	Pakawau & Kapuni SST reservoirs	Test Kapuni Sands	Late Cretaceous Pakawau equivalent
Thickness of Cretaceous	2641m	1504m	1580m	1042m	606m	160m	609m
Hydrocarbon Shows	Oil and gas	None	Minor gas	Oil	None	Oil and gas	None
Petroleum Report	1234	513	674	543	736	2928	1030
Latitude	40° 30' 10 " S	40° 26' 29" S	40° 21' 3.6" S	40° 02' 24" S	40° 12' 0" S	39° 33' 8" S	40° 5' 6" S
Longitude	172° 41' 55" E	172° 16' 51" E	173° 04' 46" E	173° 14' 27" E	173° 16' 19" E	172° 33' 41" E	174° 9' 51" E
Status	Plugged and abandoned	Plugged and abandoned	Plugged and abandoned	Plugged and abandoned	Plugged and abandoned	Abandoned	Plugged and abandoned
Formation TD'd	Rakopi Formation	Rakopi Formation	Rakopi Formation	Basement	Basement	Basement	Rakopi Formation

Table 3.2 Cretaceous-Penetrating Wells in Study Area
See Figure 3.1 for well locations.

Of the many exploration wells that are located within the study area, there are only 7 which penetrate Cretaceous rocks, with 5 of these intersecting the Rakopi Formation (Table 3.2). Additionally, the isolated deposition of the Rakopi Formation and its equivalents means that in general, only wells in close proximity with the 3D seismic volumes can tie the Cretaceous interval directly with the 3D data without significant inference being required. The Maui-4 and Pukeko-1 wells are the wells utilised for this project, due to their location within the Maari and Pipeline 3D seismic volumes respectively.

Figure 3.3 Pipeline 3D Seismic Volume Representative 2D Line #2169

Shown is the Pukeko-1 well, and the interpreted presence of the Rakopi Formation on either side of the basement high into which the well is drilled, on crossline 2169 running west-to-east through the Pipeline 3D seismic volume. For seismic survey location see Figure 3.1.

3.3.1 Maui-4

The Maui-4 well is located in the south western quadrant of the Maari 3D seismic volume (Figure 3.1). It was drilled to a depth of 3919.4m, where it terminates in basement rock. Directly above this, the penetration of the Rakopi Formation includes a significant thickness of coaly facies, and has been subdivided in this project into a further 3 seismic facies packages (see Chapter 5 - Methods), based on seismic character and lithology, for the purpose of attribute extraction and analysis. The Maui-4 well contains the best record of Cretaceous coaly facies which occurs within a 3D seismic volume, and has been used to typecast these facies for attribute extraction.

3.3.2 Pukeko-1

The Pukeko-1 well is located in the northwest quadrant of the Pipeline 3D seismic volume (Figure 3.1), and was drilled to a total depth of 4190m, targeting a localised basement high. While it penetrates the Cretaceous interval, Pukeko-1 does not intersect the Rakopi Formation. However, upon analysis of the character of the surrounding strata using the seismic data, it appears that the Rakopi Formation is present in the immediate vicinity, but pinches out onto the Pukeko-1 basement high (Figure 3.3). This assessment is based on comparisons of the seismic character of the Rakopi Formation in the adjacent Maari 3D seismic volume, and on correlations between the 2 3D surveys carried out using the linking 2D seismic data.

4 Seismic Interpretation

4.1 Introduction

Seismic reflection profiling is a method of imaging the structure of the subsurface, by means of recording the travel times of reflected seismic energy pulses from beneath the earth's surface. This produces a representative picture of the stratigraphy, measured in time rather than depth (Kearey & Brooks 2002). From this, laterally-continuous seismic reflections can be interpreted to represent surfaces of synchronous deposition or unconformities, and correlate to particular chronostratigraphic units (Allaby 2013).

In this chapter, the relevant Cretaceous and Paleogene horizons have been interpreted within the 3D and 2D seismic reflection data, in order to prepare it for the extraction of seismic attributes.

4.2 Software and Hardware Setup

The technical work involved in this project has been conducted in SeiswareTM, which is a piece of software designed for interpretation of 2D and 3D seismic data, allowing the identification of many tectonic and sedimentary features. Additionally, and critically for this project, it includes the ability to extract seismic attributes from the data, and to display averaged values of these attributes in both representative 2D lines and in pan view on the basemap. The interpretation of the relevant Cretaceous and Paleogene horizons, and extraction of seismic attributes, was carried out with SeiswareTM version 8.0, on a Dell PC running an Intel 3.4 GHz processor, with 24 Gb RAM, provided by Victoria University of Wellington.

4.2.1 SeiswareTM Setup

The following steps were taken to set up the project before any work commenced.

- A project was created in SeiswareTM called HarryGreenfield
- The New Zealand coastline “culture data” was loaded
- Keyword files were obtained to enable 2D and 3D project data to be loaded respectively. The keyword files contained the following information:
 - o CDP (2D data)
 - o Shot sequence number (2D data)
 - o Line sequence number (3D data)
 - o Trace sequence number (3D data)
 - o X, Y coordinates (both 2D and 3D data)
- The 2D and 3D seismic data was then loaded into the project
- The well data was loaded, including:
 - o X, Y coordinates
 - o Wireline log data
 - o Imported stratigraphic formation tops

Figure 4.1 2D Seismic Line through Maui-4 Well with Interpreted Horizons

Representative 2D seismic line – Mohoa_dsir_matched. Shows the relevant sedimentary horizons interpreted and utilised in this project, in relation to the Maui-4 well, which has been used as the focal point of seismic attribute extraction in later chapters. Inset is a map of the study area, showing the location of the Mohoa line in green, as well as the nearby 3D seismic reflection volumes; Maari and Pipeline. For map location see Figure 1.1.

4.3 Methods

The following steps were taken to prepare the data for interpretation, and to carry out the interpretation itself:

- To ensure no time mismatch between any of the seismic surveys, interpretation of the seabed was carried out. The seabed was picked on a high amplitude peak, indicating normal polarity data. This interpretation was used to calibrate the differing 2D lines and 3D surveys. Bulk shifts were conducted of up to approximately 10ms where required, to align the data together.
- Following this, the Maui-4 and Pukeko-1 wells were tied to the Maari and Pipeline 3D seismic volumes respectively by generating a velocity curve using the sonic log (from the imported wireline data). The Maui-4 well produced a good tie to the seismic data with prominent reflections corresponding to formation tops in the well
- For the Pukeko-1 well, the velocity curve generated from the sonic log failed to produce a good correlation with the seismic data. To improve the correlation, the Top Basement horizon in the well was matched to the clear (high amplitude, low frequency) basement reflector in the seismic data (confidently interpreted to represent the top of basement rocks), and the well was scaled to fit. Following this, well formation tops for other pertinent horizons (Rakopi, North Cape, Farewell formations) were able to be correlated with prominent reflections which matched those confidently tied to the Maui-4 well. The correlation thus achieved was deemed adequate to proceed with seismic interpretation.
- Within the Maari 3D volume, 4 seismic horizons were interpreted (Top Basement, Top Rakopi, Top North Cape, and Top Farewell formations), and extrapolated outwards from the Maui-4 well to the east of the Maari Fault (Figure 4.1). In addition, 2 intra-formational horizons within the Rakopi Formation were interpreted in an area of approximately 32km² directly surrounding the Maui-4 well (Figures 4.5 and 6.16; see Section 5.4 for more detailed explanation).
- Within the Pipeline 3D volume, the Top Basement, Top Rakopi, Top North Cape, and Top Farewell horizons were interpreted; however, given that the Pukeko-1 well does not penetrate the Rakopi Formation or its equivalent, and there is no 2D line which directly connects the Top Rakopi Formation between Maari and Pipeline, inferences were made in order to interpret the Rakopi Formation within Pipeline, based on the seismic character of the Rakopi Formation (Figure 4.4) (Section 4.5).
- In addition to these Cretaceous-Paleocene horizons, the top of the Mangahewa Formation was also picked in the Maari 3D volume, as it contains coaly facies in similar quantities to those of the Rakopi Formation, as displayed in the Maui-4 well (Figure 3.2). This was done in order to carry out direct comparisons of seismic attributes extracted from the Cretaceous coaly facies (Section 6.3.2).

- Major basement-cutting faults were interpreted within both the Maari and Pipeline 3D volumes, and were triangulated using SeiswareTM, in order to be represented on the basemap (e.g. Figure 5.1).
- Seismic loop ties were attempted by using a combination of 2D seismic lines to connect the 3D data with itself, especially where interpretation was required to cross major faults, which affected the continuity of reflectors (for example, across the Maari Fault; Figure 4.1).
- Isochron maps were generated for each of the interpreted intervals to evaluate thickness (in TWTT) within the 3D volumes (Figure 4.2).

4.4 Maari 3D Seismic Reflection Volume

The Maari 3D volume is tied to the Maui-4 well and images part of the Maui sub-basin, within which the Rakopi Formation is thought to be extensively deposited (King & Thrasher 1996). As such, the Maari 3D has been used as the focus of this project, as the Maui-4 well records the most abundant Cretaceous coaly facies of all of the nearby wells (Figure 3.2). The Rakopi Formation interval within the Maari 3D, defined by the Top Basement-Top Rakopi seismic horizons, has been used as the focus point for the extraction of seismic attributes which best represent the coaly facies encountered in the well. However, all attributes have also been extracted from the Pipeline 3D volume as well, for the purpose of comparison and potential identification of coaly source rocks away from the Rakopi Formation well penetrations.

4.4.1 Gridding Horizons in SeiswareTM

Due to the impracticality of interpreting every line of the 3D data sets, the interpretation was carried out on a grid (one line every 10-30 inlines and crosslines, depending on proximity to the Maui-4 well) within the Maari 3D volume, which was then interpolated through the rest of the volume. This was carried out using the triangulation algorithm in SeiswareTM, which automatically creates direct lines between the points of a horizon which has been manually picked. The reason this method was chosen instead of one which would apply a “smoothing” effect to the horizons is that the smoothing can result in deviation from the values picked, and horizons extending beyond their boundaries. After some experimentation with different gridding methods, triangulation was deemed the best method, as it simply extrapolates between picked points, giving a more true fit to the interpreted horizons.

4.5 Interpreted Horizons

The following horizons have been interpreted within the Maari and Pipeline 3D volumes, as well as on the selected connecting 2D lines (Figure 4.1). Where seismic character is referred to, it is in reference to the characterisations made by Mitchum et al. 1977 (Figure 4.2).

Reflection configurations	Geological interpretation	Clinoforms	Geological interpretation
Parallel - even	Stratified sedimentary rock deposited at uniform rates in a uniformly subsiding area	Sigmoid clinoforms	Relatively low sediment supply, relatively low basin subsidence and / or relative sea level rise to allow preservation of topsets.
Parallel - wavy		Oblique – tangential clinoforms	Relatively high sediment supply, slow-no basin subsidence and / or relative sea level standstill to allow basin-ward progradation and bypass or scour of the upper surface
Sub-parallel		Oblique – parallel clinoforms
Divergent	Thickening beds caused by lateral variations in rates of deposition or syn-sedimentary tilting	Complex sigmoid-oblique clinoforms	Alternations of sigmoid and oblique characteristics and depositional influences
Contorted	Discordant reflector packages with non-systematic terminations. Strata deposited in a variable, high-energy environment or affected by soft-sediment deformation.	Shingled clinoforms	Thin discontinuous clinoform exhibiting both toplap and downlap. Commonly progrades into shallow water.
Lenticular		External form	
Hummocky		Sheet	Lense
Chaotic		Wedge	Mound
Reflection free	Homogeneous, non-stratified lithologies or highly steeply dipping strata	Ramp	Fill
Disrupted	Parallel strata disrupted or offset by subsequent factors such as faulting or gas chimneys		

Figure 4.3 Typical Seismic Reflection Pattern Configurations and Interpretations
Modified from Mitchum et al. 1977.

4.5.1 Top Basement

The top of basement is defined as “acoustic basement”, in that it is defined by its seismic character alone. It is interpreted as the deepest relatively-continuous seismic reflector that can be identified, and is variable in character across the study area. The Top Basement reflector separates reflections above – that are deemed to represent layers of sedimentary stratigraphy – from the discontinuous, chaotic facies below. Top Basement is represented in most areas by a semi-continuous, high amplitude peak. In many areas, the basement is cut by faults of varying size, which introduce further discontinuity and make the reflector difficult to correlate in places.

4.5.2 Top Rakopi Formation

The Top Rakopi Formation is represented in the seismic section by a hummocky trough amidst several other medium-amplitude peaks and troughs. It is highly laterally-variable, and coupled with poor data quality in some areas, can be difficult to constrain accurately in these places.

Within the Rakopi Formation, the seismic data displays some distinct characteristics. Namely, the division into different seismic facies. In the Maari 3D volume, examining the seismic data around the Maui-4 well shows that the more high-amplitude parts of the data correspond with the coaly facies (Figure 4.2). Thus, it is possible to infer the presence of these coaly facies in other parts of the 2D and 3D seismic data.

An example of this occurs, in the 2D seismic line mohoa_dsir_matched, wherein there is displayed a clear division in the Cretaceous package in the west part of the line, between relatively bland seismic character and stratified, more laminar, high amplitude packages, which are interpreted as being representative of coaly facies, (Figures 4.1 & 4.4).

Figure 4.5 Rakopi Subdivision Map, Representative 2D Seismic Line, and Well Lithology

Rakopi Subdivision (the name given to this part of the Rakopi Formation which has been divided into 3 distinct seismic (and lithologic) packages – the Upper Coals, Mid Silts, and Lower Coals. Detailed in Chapter 5.3). For map location see Figure 1.1.

A: Crossline 1020 within the Maari 3D volume. Maui-4 well shown by vertical black line.

B: Map showing location of Maari 3D volume, and the area of Rakopi Formation distribution within the volume, as well as the area within which the Rakopi Subdivision is interpreted.

C: Close up view of the Rakopi Subdivision in the 2D seismic (Maui-4 well as black vertical line), and the correlation to the lithology observed in the Maui-4 well (bottom right).

4.5.3 Rakopi Subdivision

In general, the Rakopi Formation has a high degree of lateral variation. It has a contorted and sometimes chaotic seismic character, as a result of soft-sediment deformation rather than a high energy depositional environment (Browne et al. 2008). Much of the Rakopi Formation is med-high amplitude, with a lack of lateral continuity leading to horizons which are difficult to constrain (Figure 4.5A).

Within the Maari 3D volume, in the immediate vicinity of the Maui-4 well, the Rakopi Formation has been subdivided into 3 distinct seismic facies packages linked directly to the lithology as observed at the Maui-4 well (Figure 4.5). 2 intra-formational horizons were interpreted in order to subdivide the packages, which have been labelled the Lower Coals, the Mid Silts, and the Upper Coals. The splitting of the Rakopi Formation into these distinct seismic facies packages over approximately 32km² (Figure 4.5B) directly around the Maui-4 well is henceforth referred to as the Rakopi Subdivision. It should be noted that the Rakopi Subdivision has only been observed in a limited area of approximately 32km² (Figures 4.5B & 6.2) directly around the Maui-4 well, and that farther afield the seismic facies character becomes too indistinct to interpret with confidence.

4.5.3.1 Lower Coals

The Lower Coals interval contains the highest percentage thickness of coal seams (which make up 43% net thickness of the interval as measured at the Maui-4 well; Figure 4.5C) of all of the Rakopi Subdivision. As such, it is the best representation of Cretaceous coaly facies in the study area. The remaining lithology is almost all siltstone, with a small amount of isolated sandstone. The seismic character of this facies package is high amplitude, low frequency, and semi-continuous within the small area it is contained.

4.5.3.2 Mid Silts

The Mid Silts contains very little coal, with approximately 12 very thin coal seams being present in the well lithology (Figure 4.5 stratigraphic column). It is comprised mostly of siltstone, with thin sandstone beds sparse throughout. The seismic character of this package is relatively bland when compared to the Lower Coals and Upper Coals, is low to medium amplitude, and highly laterally discontinuous.

4.5.3.3 Upper Coals

The Upper Coals contain far less of a thickness of coal seams than the Lower Coals (10.6% net thickness as measured at the Maui-4 well; Figure 4.5C), but is still considered to be coal-rich when compared to the Mid Silts. The lithology (apart from the coals) is largely claystone, with sparse interbedded siltstone and sandstone. The seismic character is comprised of 3-4 medium to high amplitude, semi-continuous, sub-parallel reflectors, with medium to low frequency.

4.5.3.4 Top North Cape Formation

Compared to the Rakopi Formation, the North Cape Formation is much more laminar, with a largely sub-parallel and hummocky reflection configuration, and an overall moderately-bland seismic character, which onlaps in places onto the unconformable surface of the Top Rakopi Formation (Figure 4.1).

The top of the North Cape Formation has a much lower amplitude and indistinct seismic character than the Rakopi Formation. It is characterised by a low-amplitude trough amidst medium-amplitude troughs and peaks. Due to the limited well-ties, and its bland seismic character, it can be difficult to identify with confidence in areas away from exploration wells.

4.5.4 Top Farewell Formation

The Farewell Formation is comprised of sub-parallel, hummocky reflectors which are semi-continuous, and slightly higher in amplitude than the underlying North Cape Formation (Figure 4.1).

The top of the Farewell Formation, as seen at the Maui-4 well, is best characterised by the group of 3-4 high amplitude peaks and troughs directly above it, with the formation itself making up the lowest of the series of troughs, above a relatively bland, low amplitude vertical interval of seismic data.

4.5.5 Top Mangaheva Formation

The Mangaheva Formation is an Eocene-age formation which is also recognised as being rich in coals, and provides a further source rock interval within the Taranaki Basin (King & Thrasher 1996).

While the Mangaheva Formation is not the focus of this project, it contains a prolific coaly interval that is present throughout the study area and is intersected by the Maui-4 well (Figure 6.17).

Therefore it has been identified as a comparable unit to the Rakopi Formation, on which to test the results of seismic attribute analysis (see Chapter 6). A Top Mangaheva Formation horizon has been interpreted in selected seismic lines, and parts of the 3D volumes.

The Mangaheva Formation itself consists of a semi-continuous, parallel series of 5-6 high-amplitude reflectors (Figure 4.1). The top of the formation is characterised by a semi-continuous low frequency, med-high amplitude trough with similar peaks either side of it, lying above a series of high amplitude peaks and troughs.

5 Seismic Attribute Extraction

5.1 Seismic Attributes

Seismic attributes allow information to be extracted from the data which is not apparent from viewing a conventional seismic reflection image. This is possible due to the adjustment and simplification of the data which occurs in compiling it for easier stratigraphic interpretation. Any measure of seismic data which visually enhances or quantifies a feature of interpretational interest is a seismic attribute (Chopra & Marfurt 2007).

Conventional seismic reflection images display the waveforms of each seismic trace as a positive half-cycle in black. This is done to merge the shaded areas between traces into continuous black lines, to allow correlation of features across a section for the purpose of structural interpretation (Kearey et al. 2002).

One negative effect of this process is that the waveform's exact amplitude and shape is lost. Given that the amplitude of a reflected wave corresponds directly to the reflection coefficient at the reflective interface, any variation in amplitude along a reflective surface should correlate with variation in the properties of the respective formations (Kearey et al. 2002). As such, this process results in available information about the properties of the strata above and below a reflective surface being unrepresented in the seismic image. Additional information can be revealed by the extraction of seismic attributes (Chopra & Marfurt 2007).

There are many seismic attributes, which are not all independent of each other, but are all derivatives of the basic seismic measurements of time, amplitude, frequency, and attenuation (Brown 2004).

5.1.1 Seismic Amplitude

Seismic amplitude is just one simple example of an attribute of the seismic wave which can be examined for what it represents in terms of variations in physical geology. These variations can be viewed by imaging the seismic section with the amplitude displayed as a colour scale, to reveal changes in amplitude along a continuous reflector (Kearey et al. 2002).

Amplitude changes along a reflective surface can correlate to changes in rock pore fluid (among other things), and as such can be direct hydrocarbon indicators (DHIs) under ideal circumstances (Brown 2004).

5.1.1.1 Amplitude Attributes

In order to identify a potential attribute or combination which would identify coaly facies, seismic attributes were extracted from the interpreted intervals within both the Maari and Pipeline 3D seismic volumes. Initially, a number of calculations were carried out using SeiswareTM, based on variations in

amplitude, which were then displayed in plan view as amplitude maps (Figure 5.1 and Appendix A). The purpose of this was firstly to compare them with the isochron map of the Rakopi Formation (Figure 5.1D), to see if there was any indication that an attribute was not merely a representation of a variation in thickness. Additionally, amplitude maps allow analysis of the areal distribution of amplitudes, to any potential depositional or lithologic variation.

The operations which were undertaken to facilitate extraction and display of the initial amplitude attributes are as follows:

- An “Elevated Basement” horizon was generated 20ms above the triangulated basement horizon within both of the 3D volumes, to ensure that the high amplitude Basement reflector was excluded as much as possible from any attributes extracted
- A total of 19 amplitude-based calculations (the full list of which is displayed in Appendix A) were made within the Maari and Pipeline 3D volumes, on the interval between the Elevated Basement and Top Rakopi Formation
- 3 sets of calculations were made: on the interval as a whole; on the bottom 100ms, and on the bottom 50ms. The results were very similar between the 3 datasets, and as such the bottom 50ms was selected as representative, due to the occurrence of lower-formation coaly facies within the Rakopi Formation being present at the Maui-4 well (Figures 3.2 & 4.5). While the lower coal succession in the Rakopi Formation is around 100ms thick in most areas, the bottom 50ms was selected to ensure that none of the overlying formation was included in the attribute analysis.
- The results of the extraction of these attributes from the bottom 50ms of the Rakopi Formation were exported as horizons for display as amplitude maps (Appendix A).

The initial amplitude attribute calculations were carried out as a first look at the expression of the coals, as coals commonly show a strong amplitude response relative to background rocks (Sahoo et al. 2014). Calculating these initial attributes was less computationally intensive than the more sophisticated Rock Solid Attributes (Section 5.2), so they were extracted as a first look at the Rakopi.

Since the resultant amplitude maps have not been used for this project, they have been confined to Appendix A, other than a representative image (Figure 5.1). Upon visual analysis of the spatial distributions of the 19 different amplitude attribute maps, three different types have been identified:

Figure 5.1 Representative Amplitude Attribute Types and Rakopi Formation Isochron Map

Each attribute type discussed in 5.1.2-5.1.4 is represented in A-C respectively, with each section showing the distribution of values within the Rakopi Formation interval of the Pipeline (left) and Maari (right) 3D seismic volumes, with major basement-cutting faults shown by the coloured lines. The Rakopi Isochron Map is included (D) to show any potential relationship between value distributions and formation thickness. The 3 representative attributes are: PC – Peak Count; ABS – Average Absolute; SA – Sum of Amplitudes. More information on these attributes is listed in Appendix A.

5.1.2 Type 1: Thickness Dependent Amplitude Maps

The values displayed in these appear to be governed by the thickness of the formation, and as such bear a close resemblance to the Rakopi isochron map (Figure 5.1A & 5.1D). As such, they are likely responding to the thickness of the formation, rather than any of its lithologic properties, and are not significant to any attribute analysis.

5.1.3 Type 2: Isochron Dependent Amplitude Maps

The values displayed in these maps are partially reminiscent of the isochron map, but with differences, and less of a strong correlation (Figure 5.1B). As such, they may be partially influenced by formation thickness, and partially be responding to variations in lithology.

5.1.4 Type 3: Other Amplitude Maps

These maps are completely non-conformable with the isochron map (Figure 5.1C). As such, they are likely representing something other than a reflection of the formation thickness. There are only 2 of these amplitude maps of the 19 total amplitude attributes (Sum of Amplitudes (SA), and Zero Crossing Frequency (ZCF); Figures 9.18 & 9.19 in Appendix A).

5.2 Rock Solid Attributes

SeiswareTM uses a proprietary set of attributes called Rock Solid Attributes (RSAs), produced by and purchased from a company called Rock Solid Images (RSI). A total of 34 different RSAs were extracted from the Maari and Pipeline 3D volumes for this project (Table 5.1).

The steps which were taken to extract and analyse the selected RSAs from the seismic data are as follows:

- Within the Maari 3D volume, attributes were extracted from within the 3 intra-formational packages of the Rakopi Subdivision (Lower Coals, Mid Silts, and Upper Coals).
- The 34 RSAs were averaged through the Rakopi Formation interval as a whole (Figure 5.1), as well as the Lower Coals, Mid Silts, and Upper Coals separately.
- RSAs extracted from the Farewell and Mangahewa formations, and the interval between the Mangahewa Formation and a purpose-generated horizon (Manganui Horizon – this was not interpreted) 150ms above it. This was carried out in the 32km² area around the Maui-4 well over which the Rakopi Subdivision extends (see Rakopi Subdivision Polygon; Figure 6.17), for the purpose of comparison of attribute averages of the coaly and non-coaly intervals.
- The resultant attribute averages were output as surfaces on amplitude maps, and the attribute-averaged surfaces were exported from SeiswareTM, and processed in the software package MatLab for statistical analysis of the results (Chapter 6.2).

A final selection of the RSA amplitude maps are analysed in Chapter 7. The entire suite of RSA amplitude maps are displayed in Appendix B.

Of the 34 total RSAs extracted, 15 were deemed to be significant, and/or display enough variance between the coaly and non-coaly facies to warrant the results being included in this thesis (based on analysis of outputs detailed in Chapter 6.2) (Figures 6.1-6.15).

Attribute Name	Rock Solid Attribute Brief Description
Real Part of Complex Trace	Recorded part of seismic trace (amplitude)
Imaginary Part of Complex Trace	Real part, phase shifted by 90 degrees
Trace Envelope	Total instantaneous energy of the complex trace
Time Derivative of Envelope	Rate of change of wavelet envelope over time
Instantaneous Phase (Degrees)	Phase of the trace at any given instant
Instantaneous Frequency (Hz)	Frequency at any given instant - rate of change of phase over time
Dominant Frequency (Hz)	RMS frequency of amplitude spectrum
Band Width (Hz)	Difference between upper and lower frequencies in a continuous set
Instantaneous Q Factor	Seismic attenuation at any given instant
Normalised Amplitude	Cosine of instantaneous phase
Relative Acoustic Impedance	Pressure from vibration of seismic layer at a given frequency
Wavelet Envelope	Instantaneous attributes at maximum point of envelope
Time Derivative of Wavelet Envelope	Rate of change of envelope over time
Wavelet dominant Frequency (Hz)	Frequency for wavelet biased towards the dominant frequency
Wavelet Q Factor	Rate of decay of wavelet envelope
Dip Similarity	Dip determined from the similarity
Dip Variance	Difference between smoothed dip of maximum similarity and local value of dip of maximum similarity
Similarity	Similarity of trace compared to neighbours computed over a moving weighted window
Similarity Variance	Difference between smoothed similarity and local value
Smoothed Dip Similarity	Maximum similarity's calculated dip smoothed with a low pass filter for long windows
Dip Azimuth	Azimuth of crossline axis is added to azimuth of maximum instantaneous dip
Mean Curvature	Mean curvature of each trace and surrounding 8 traces
Max Curvature	Largest curve at any point
Min Curvature	Smallest curve at any point
Most Negative Curvature	Largest negative curve at any point
Most Positive Curvature	Largest positive curve at any point
Spectral Balance Traces	Spectral balancing of the input using the wavelet transform calculated sub bands
Band Limited Relative Acoustic Impedance	A simple band limited inversion using integration and 90 degree phase shift
Mean Frequency of Spectra	Mean frequency of the spectra calculated from the wavelet transform sub bands
Band Width of Spectra	Bandwidth of the Spectra calculated from the wavelet transform sub bands
Max Subband of Envelope	Amplitude envelope of the peak frequency of the spectrum as calculated from the wavelet transform sub bands
Frequency of Max Subband Envelope	Peak frequency of the spectrum as calculated from the wavelet transform sub band
Q by Frequency Shift	Absorption Q estimate using a frequency shift method (see other documentation)
Q by Spectral Ratio	Absorption Q estimate using a spectral ratio method (see other documentation)
Semblance	Measures the coherency of adjacent traces

Table 5.1 List of Seisware™ Rock Solid Attributes used in this Project

Taken from Seisware™. For more information on Rock Solid Attributes, see Taner (2003) and/or the Rock Solid Images website: <http://www.rocksolidimages.com>

Figure 5.2 Example of Rock Solid Attribute Averaging within the Rakopi Formation

Shown is the Pipeline (left) and Maari (right) 3D seismic reflection volumes. The representative 2D seismic lines at the bottom of the figure show the Trace Envelope (the attribute which has been chosen as an example) through each 3D volume, and intersect the Pukeko-1 and Maui-4 wells respectively. Major basement-cutting faults are represented by the coloured lines through the 3D volumes.

To produce the attribute amplitude maps displayed, the Trace Envelope values have been temporally averaged (i.e. all of the values in a vertical interval have been averaged to give a single point) within the Rakopi Formation interval (shaded areas on 2D lines), with the resultant horizons shown on the basemaps above, with a red/white/blue, which has been set for each 3D survey separately (as per the numbers on either side of the inset colour scale), to best portray the range of attribute values in each case.

This process has been used to output all subsequent attribute maps in this thesis. For map location see Figure 1.1

6 Analysis of Seismic Attributes

6.1 Introduction

The aim of this project was to identify an attribute or combination of attributes which would enable the identification of Cretaceous coaly facies in areas removed from well penetrations. In order to do this, a quantitative method was needed to test whether what was being observed was actually representative of coaly facies.

In this chapter, RSAs extracted from the Rakopi Subdivision and other vertical seismic intervals at the Maui-4 well are analysed in order to identify attributes which are responding to the presence of coal.

6.2 Methods

6.2.1 Rakopi Subdivision Rock Solid Attributes

In Chapter 4.4, the Rakopi Formation was divided into the Rakopi Subdivision, with extracted RSAs being averaged within each of the resultant temporal intervals. This provided a visual representation of the attribute values as they are distributed throughout the Maari and Pipeline 3D seismic volumes (see Appendix B).

6.2.2 RSA Value Distributions in Rakopi Subdivision

In addition to visual analysis of the basemap representations of the extracted RSAs' average values, a method of statistical analysis was used to quantify and summarise their results. The averaged attribute values for each Rakopi Subdivision interval were exported as horizons (X, Y, and attribute value) into the software package Matlab, where frequency plots were analysed to observe any pattern in their distributions (Figures 6.1-6.15). These frequency distributions were also compared to ideal distributions for comparison (e.g. normal distribution, bimodal distribution, etc). The display of attribute outputs both as temporally-averaged amplitude maps, and frequency distributions based on the values observed in the amplitude maps, enabled any patterns or differences in distributions between the different sets of data to be analysed visually. The differences which were being looked for were those which placed the distributions of values from the coal-rich intervals markedly different from those from the non-coaly intervals.

Note that multi-trace attributes such as Semblance, Similarity, Variance, etc, are already a derivative of their surrounding traces (Table 5.1). These attributes are based on statistical comparisons of a given trace to its adjacent traces (Chopra & Marfurt 2007) and as such any further averaging or analysis of the distribution of attribute values over a larger area will be subject to a “double smoothing” effect, which needs to be considered when viewing their results.

Of the 34 RSAs extracted, 15 showed significant variation between the coaly versus non-coaly seismic packages. These 15 can be grouped into 4 general attribute categories which are discussed below, with reference to Figures 6.1-6.15. All of the remaining (discarded) RSA frequency distribution graphs are included in Appendix C. The division into these categories was done by visual analysis of the difference between the frequency distributions of RSA values of the coaly- versus non-coaly intervals.

6.2.2.1 Category 1: Coal Percentage Order

These attributes have frequency distributions which appear to be influenced by the increased presence of coals within each interval. The value distributions for each interval are separated, and are in order of most- to least-coaly. These attributes are likely to be scaling with the percentage of coal by volume present, rather than responding to the absolute presence or absence of a certain percentage of coal (see Category 2).

The Coal Percentage Order category includes: Trace Envelope, Wavelet Envelope, Time Derivative of Wavelet Envelope, and Q by Frequency Shift (Figures 6.1-6.4).

6.2.2.2 Category 2: Coal Separate

These attributes display the 2 least-coaly intervals (Upper Coals and Mid Silts) with very similar frequency distributions to each other, and the (most-coaly) Lower Coals interval having a different distribution. Given that the Lower Coals contain significantly greater total percentage of coals than the Upper Coals (Figure 4.3), this indicates that these attributes are likely to be responding to a threshold percentage thickness of coals, below which they are not recognised, in comparison to responding linearly to the percentage of coals as in Category 1.

Note that the Category 2 attribute values which relate to coals are the lowest values, whereas the coal-indicating attribute values for Category 1 are the highest values.

The Coal Separate category includes: Relative Acoustic Impedance, Band Limited Impedance, Imaginary Part of Complex Trace, Spectral Bandwidth, Spectral Balance, and Time Derivative of Envelope (Figures 6.5-6.10).

6.2.2.3 Category 3: Burial Depth Order

These attributes show a range of values which varies between each sampled seismic interval; however, the order of values correspond to the order of burial depths of the respective formations (i.e. the most shallow interval plots at one end of the frequency distribution, and the least shallow interval plots at the opposite end). Given this fact, it is possible that these attributes are responding to increased compaction or a further effect of burial depth, rather than the presence of coals or another lithological factor.

If these RSA attributes are indeed responding to burial depth, they could be a useful porosity indicator, due to the fact that in general, porosity is inversely correlated with burial depth due to compaction (Allen & Allen 2013).

The Burial Depth category includes: Wavelet Dominant Frequency, Q by Spectral Ratio, Maximum Subband Envelope Frequency, and Mean Frequency of Spectra (Figures 6.11-6.14).

6.2.2.4 Category 4: Not Meaningful

These attributes either show no variation in the frequency distributions between the seismic packages, or show variations, but in a way which runs counter to that which is expected.

Semblance (Figure 6.12) belongs in this category. There were other RSA attribute outputs which displayed strange or noteworthy distributions, but they were deemed not to be significant, due to no observable and significant variation between the coaly and non-coaly intervals sampled (see Appendix C).

Figure 6.1 Category 1 Rock Solid Attribute Temporal Averages and Frequency Distributions – Trace Envelope

Figure 6.2 Category 1 Rock Solid Attribute Temporal Averages and Frequency Distributions – Wavelet Envelope

Shown to the left are the temporally-averaged values of this attribute within the 3 vertical intervals of the Rakopi Subdivision (Fig 6.16) displayed as amplitude maps (see Section 4.5.3 and Figure 4.5). The graphs show the distributions of these values (left graph), and their fit to model distributions (right graph) (Lower Coals: red = actual values; orange = model distribution. Mid Silts: darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution). See Figure 6.16 for Maui-4 well location.

Figure 6.3 Category 1 Rock Solid Attribute Temporal Averages and Frequency Distributions – Time Derivative of Wavelet Envelope

Figure 6.4 Category 1 Rock Solid Attribute Temporal Averages and Frequency Distributions – Q by Frequency Shift

Shown to the left are the temporally-averaged values of this attribute within the 3 vertical intervals of the Rakopi Subdivision (Fig 6.16) displayed as amplitude maps (see Section 4.5.3 and Figure 4.5). The graphs show the distributions of these values (left graph), and their fit to model distributions (right graph) (Lower Coals: red = actual values; orange = model distribution. Mid Silts: darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution). See Figure 6.16 for Maui-4 well location.

Figure 6.5 Category 2 Rock Solid Attribute Temporal Averages and Frequency Distributions – Relative Acoustic Impedance

Figure 6.6 Category 2 Rock Solid Attribute Temporal Averages and Frequency Distributions – Imaginary Part of Complex Trace

Shown to the left are the temporally-averaged values of this attribute within the 3 vertical intervals of the Rakopi Subdivision (Fig 6.16) displayed as amplitude maps (see Section 4.5.3 and Figure 4.5). The graphs show the distributions of these values (left graph), and their fit to model distributions (right graph) (Lower Coals: red = actual values; orange = model distribution. Mid Silts: darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution). See Figure 6.16 for Maui-4 well location.

Figure 6.7 Category 2 Rock Solid Attribute Temporal Averages and Frequency Distributions - Band Limited Relative Acoustic Impedance

Figure 6.8 Category 2 Rock Solid Attribute Temporal Averages and Frequency Distributions – Spectral Balance

Shown to the left are the temporally-averaged values of this attribute within the 3 vertical intervals of the Rakopi Subdivision (Fig 6.16) displayed as amplitude maps (see Section 4.5.3 and Figure 4.5). The graphs show the distributions of these values (left graph), and their fit to model distributions (right graph) (Lower Coals: red = actual values; orange = model distribution. Mid Silts: darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution). See Figure 6.16 for Maui-4 well location.

Figure 6.9 Category 2 Rock Solid Attribute Temporal Averages and Frequency Distributions – Spectral Bandwidth

Figure 6.10 Category 2 Rock Solid Attribute Temporal Averages and Frequency Distributions – Time Derivative of Envelope

Shown to the left are the temporally-averaged values of this attribute within the 3 vertical intervals of the Rakopi Subdivision (Fig 6.16) displayed as amplitude maps (see Section 4.5.3 and Figure 4.5). The graphs show the distributions of these values (left graph), and their fit to model distributions (right graph) (Lower Coals: red = actual values; orange = model distribution. Mid Silts: darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution). See Figure 6.16 for Maui-4 well location.

Figure 6.11 Category 3 Rock Solid Attribute Temporal Averages and Frequency Distributions – Wavelet Dominant Frequency

Figure 6.12 Category 3 Rock Solid Attribute Temporal Averages and Frequency Distributions – Maximum Subband Envelope Frequency

Shown to the left are the temporally-averaged values of this attribute within the 3 vertical intervals of the Rakopi Subdivision (Fig 6.16) displayed as amplitude maps (see Section 4.5.3 and Figure 4.5). The graphs show the distributions of these values (left graph), and their fit to model distributions (right graph) (Lower Coals: red = actual values; orange = model distribution. Mid Silts: darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution). See Figure 6.16 for Maui-4 well location.

Figure 6.13 Category 3 Rock Solid Attribute Temporal Averages and Frequency Distributions – Q by Spectral Ratio

Figure 6.14 Category 3 Rock Solid Attribute Temporal Averages and Frequency Distributions – Mean Frequency of Spectra

Shown to the left are the temporally-averaged values of this attribute within the 3 vertical intervals of the Rakopi Subdivision (Fig 6.16) displayed as amplitude maps (see Section 4.5.3 and Figure 4.5). The graphs show the distributions of these values (left graph), and their fit to model distributions (right graph) (Lower Coals: red = actual values; orange = model distribution. Mid Silts: darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution). See Figure 6.16 for Maui-4 well location.

6.3 Control Tests

To increase confidence in the likelihood that the 15 chosen RSAs are responding to the presence of coal, as opposed to other factors, 2 types of control tests were carried out based on

- a) Scalability of results; and
- b) Repeatability of results in another coal-rich interval from the seismic data.

These tests were carried out for the entire suite of RSAs rather than just the selected 15, for reasons of due diligence, in case there were significant differences between the coaly and non-coaly intervals which were not apparent in the analysis thus far.

6.3.1 Scale Tests

To test whether the results were consistent at different spatial scales – which would give indications as to the lateral continuity of the formations in question – the RSA extraction and analysis process was repeated in 2 concentrically smaller areas around Maui-4 (Figure 6.16). These covered approximately the following total areas:

- Scale Test 1 – 2 km²
- Scale Test 2 – 13.5 km²

For comparison, the Rakopi Subdivision was mapped over an area of approximately 32km², and the total area which the Rakopi Formation is interpreted to extend within the Maari 3D survey is approximately 320km².

The result of the scale tests was that most of the chosen 15 RSAs were scalable, i.e. the results were the same when the analysis was repeated over areas of differing size (see Section 6.3.3), with a few exceptions. The results of these scale tests increase the confidence in the results of the attribute analysis carried out thus far, due to the fact that the only place where the lithology is known with certainty is at the Maui-4 well. The further from this the interpreted Rakopi Subdivision goes, the less confidence there can be in the subdivision's lateral continuity. As such, Scale Test 2 is the most valuable set of data, as it was conducted in the smallest area around Maui-4 (Figure 6.2) and therefore provides the closest example of the attributes' response to the known lithology.

6.3.2 Mangaheva Control Group

The second control test was conducted to explore the ability of the chosen RSAs to identify coaly facies in other coal-rich intervals. This was done by following the process of extracting the same attributes from another known coaly interval penetrated by the Maui-4 well – the Eocene Mangaheva Formation (see Section 4.5.5). Given that this formation is coal-rich, and is overlain by siltstone

(Figure 6.17), the comparison between the coals and these silts has been contrasted by extracting the full suite of 34 RSAs from these seismic intervals.

To do this, all of the RSAs, within a selected polygon with an area of approximately 135km² within the Maari 3D (Figure 6.1), were averaged in 2 time intervals (Figure 6.3), as follows:

- i) Between the top of the Farewell Formation and the top of the Mangahewa Formation
- ii) Between the top of the Mangahewa Formation and a horizon generated 150ms above it (the Manganui Horizon. See Section 5.2 & Figure 6.17C).

The averaged RSA values were then exported as horizons and entered into Matlab for statistical analysis, with the results being plotted next to the existing averaged attribute distributions in the Rakopi Subdivision for comparison (Figures 6.18.6.32).

Figure 6.17 Mangahewa Control Test Map, Representative Seismic Line, and Well Lithology

Shown is the link between the lithology at the Maui-4 well and the seismic character of the Mangahewa Formation and a section of the overlying Manganui Formation. The resultant seismic facies packages were used as a control test, described in Chapter 6.3, to test the repeatability of the Rock Solid Attribute results from the Rakopi Subdivision intra-formational packages (Figures 6.1-6.15

A: Crossline 1020 within the Maari 3D volume. Maui-4 well shown by vertical black line.

B: Map showing location of Maari 3D volume.

C: Close up view of the Mangahewa Formation and the overlying silts in the 2D seismic (Maui-4 well as black vertical line), and the correlation to the lithology observed in the Maui-4 well (bottom right).

6.3.3 Control Test Results

Six of the RSAs extracted from the Mangahewa interval and the Rakopi Subdivision have been identified which could be predicting coaly facies, based on both scalability and repeatability of the results in the control tests.

The following details which of the RSAs remained consistent in the Control Tests, from each of the 4 categories identified earlier in this chapter.

6.3.3.1 Category 1: Coal Percentage Order

Of the 15 RSA attributes which show variation, the 4 attributes in Type 1 (Trace Envelope, Wavelet Envelope, Time Derivative of Wavelet Envelope, and Q by Frequency Shift) all remained consistent over both different scales, as well as the Mangahewa Control Group. They appear to be responding to the presence of coals, with higher values corresponding to greater inferred coal content in all intervals tested (Figures 6.18-6.21)

6.3.3.2 Category 2: Coal Separate

Of the 6 RSAs in Category 2 (Relative Acoustic Impedance, Band Limited Impedance, Time Derivative of Envelope, Imaginary Part of Complex Trace, Spectral Bandwidth, and Spectral Balance), Spectral Bandwidth and Spectral Balance were inconsistent after the control tests. Both RSAs showed difference in the Scale Tests (Figures 6.25 & 6.26), showing distributions which put them in Category 3 – Burial Depth Order. Additionally, Spectral Balance is inconsistent where applied to the Mangahewa Control Group, showing no significant difference between the coaly and non-coaly intervals. As such, these 2 RSAs have been removed from the potential coal-predicting attributes.

Of the remaining 4 RSAs in Category 2, Relative Acoustic Impedance and Imaginary Part of Complex Trace showed significant variation between the coaly and non-coaly intervals of the Mangahewa Control Group, as well as remaining consistent with scale (Figures 6.22 & 6.23), and thus are likely the more consistent coal predictors. Time Derivative of Envelope and Band Limited Impedance, while consistent over the Scale Tests, did not show variation between the coaly and non-coaly intervals of the Mangahewa Control Group (Figures 6.24 & 6.27), and were therefore discarded from the suite of applicable RSA attributes.

6.3.3.3 Category 3: Burial Depth Order

All 4 RSAs identified in Category 3 (Maximum Subband Envelope Frequency, Wavelet Dominant Frequency, Q by Spectral Ratio, Mean Frequency of Spectra) produced frequency relative frequency distributions between the coaly and non-coaly seismic intervals which remained reasonably consistent with scale (Figures 6.28-6.31). However, since the

variations in distributions are likely explained by the difference in burial depth, they have been omitted from the list of coal-predicting attributes.

6.3.3.4 Category 4 – Not Meaningful

Semblance is the sole Category 4 attribute worth noting, and only so because it displays the opposite of what reasonable intuition may suggest, in that coaly facies are generally not highly laterally continuous, due to their depositional environments (Sherwood et al. 1992). Given that Semblance is a measure of similarity of adjacent traces, it could be expected that the Semblance values would be higher for non-coaly intervals, but in fact the opposite is displayed in the Rakopi Subdivision and in Scale Tests 1 and 2 (Figure 6.32A-6.32C). However, the Mangahewa Control Group produced Semblance values which were significantly higher for the coaly interval than for the non-coaly, which is what is expected in this case (Figure 6.32D).

In addition to these inconsistencies, the Upper Coals display higher overall values of Semblance than the Lower Coals, despite containing less than 50% of the thickness of coal by volume at the Maui-4 well. As such, in this case, Semblance cannot be used as a predictor of coaly facies. However, it is possible that these results are due to the small sample size.

The final suite of RSAs which are potential coal-predictors is as follows: Trace Envelope; Wavelet Envelope; Time Derivative of Wavelet Envelope; Q by Frequency Shift; Relative Acoustic Impedance, and Imaginary Part of Complex Trace.

Trace Envelope - Log Normal Distribution

Figure 6.18 Category 1 RSA Frequency Distributions and Model Distribution Fits – Trace Envelope

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Wavelet Envelope - Log Normal Distribution

Figure 6.19 Category 1 RSA Frequency Distributions and Model Distribution Fits – Wavelet Envelope

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Time Derivative of Wavelet Envelope - Log Normal Distribution

Figure 6.20 Category 1 RSA Frequency Distributions and Model Distribution Fits – Time Derivative of Wavelet Envelope

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Q by Frequency Shift - Bi-Exponential Distribution

Figure 6.21 Category 1 RSA Frequency Distributions and Model Distribution Fits – Q by Frequency Shift

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Relative Acoustic Impedance - Bi-Exponential Distribution

Figure 6.22 Category 2 RSA Frequency Distributions and Model Distribution Fits – Relative Acoustic Impedance

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Imaginary Part of Complex Trace - Bi-Exponential Distribution

Figure 6.23 Category 2 RSA Frequency Distributions and Model Distribution Fits – Imaginary Part of Complex Trace

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Band Limited Impedance - Bi-Exponential Distribution

Figure 6.24 Category 2 RSA Frequency Distributions and Model Distribution Fits – Band Limited Relative Acoustic Impedance

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Spectral Bandwidth - Bi-Exponential Distribution

Figure 6.25 Category 2 RSA Frequency Distributions and Model Distribution Fits – Spectral Bandwidth

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Spectral Balance - Bi-Exponential Distribution

Figure 6.26 Category 2 RSA Frequency Distributions and Model Distribution Fits – Spectral Balance

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Time Derivative of Envelope - Bi-Exponential Distribution

Figure 6.27 Category 2 RSA Frequency Distributions and Model Distribution Fits – Time Derivative of Envelope

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Wavelet Dominant Frequency - Log Normal Distribution

Figure 6.28 Category 3 RSA Frequency Distributions and Model Distribution Fits – Wavelet Dominant Frequency

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Frequency of Maximum Subband Envelope - Log Normal Distribution

Figure 6.29 Category 3 RSA Frequency Distributions and Model Distribution Fits – Frequency of Maximum Subband Envelope

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Q by Spectral Ratio - Bi-Exponential Distribution

Figure 6.30 Category 3 RSA Frequency Distributions and Model Distribution Fits – Q by Spectral Ratio

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Mean Frequency of Spectra - Log Normal Distribution

Figure 6.31 Category 3 RSA Frequency Distributions and Model Distribution Fits – Mean Frequency of Spectra

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

Semblance - Beta Distribution

Figure 6.32 Category 4 RSA Frequency Distributions and Model Distribution Fits – Semblance

Shown in each section A-D are the frequency counts of the attribute values in each respective seismic interval (left graph), and the fit to a model distribution (right graph). Data Set A – Total Rakopi Subdivision (see Section 4.5.3 and Figures 4.4 and 6.16); Data Set B – Scale Test 1; Data Set C – Scale Test 2 (see Section 6.3.1 and Figure 6.16), and Data Set D – Mangahewa Control Group (see Section 6.3.2 and Figure 6.16). (Lower Coals (A-C)/Mangahewa Coals (D): red = actual values; orange = model distribution. Mid Silts (A-C)/Manganui Silts (D): darker green = actual values, lighter green = model distribution. Upper Coals: dark blue = actual values, light blue = model distribution).

6.4 Final RSA Suite Descriptions

Time Derivative of Wavelet Envelope displays frequency distributions almost identical to that of Trace Envelope (Figures 6.21 & 6.17) respectively). As compared to both Time Derivative of Wavelet Envelope and Trace Envelope, Wavelet Envelope also displays very similar frequency distributions of values. The one obvious difference is that in the case of Wavelet Envelope (Figure 6.18), the frequency distributions of the Upper Coals are closer to those of the Mid Silts, whereas for the other 2 attributes (Trace Envelope and Time Derivative of Wavelet Envelope), the Upper Coals frequency distributions are very close to those of the Lower Coals. This could indicate that Wavelet Envelope is more sensitive to specific coal content than the other Category 1 RSAs.\

6.4.1 Trace Envelope

Trace Envelope, otherwise known as total instantaneous energy of the complex trace, or instantaneous amplitude, is a physical attribute, and can be used as an indicator of numerous changes in lithological characteristics. It represents mostly the acoustic impedance contrast – and thus reflectivity – and can display lithologic (and hence depositional) changes, faulting, unconformities, thin bed tuning effects, and more (Taner 2003).

6.4.2 Wavelet Envelope

Rock Solid Images (2016), who created the RSAs for use by SeiswareTM, defines this attribute as: “Instantaneous attributes at the maximum point of the envelope”. There is no further specific information provided about this attribute. However, given the description of Trace Envelope above, it is inferred that Wavelet Envelope is referring to the instantaneous amplitude at the peak of the wavelet envelope.

6.4.3 Q by Frequency Shift

Q, or Quality Factor, is the inverse of the seismic attenuation. It is calculated by the ratio of the peak energy in a waveform to the energy it loses by dissipation over distance travelled (Allaby 2013). High Q therefore implies low absorption rates of the surrounding rocks.

Seismic attenuation increases with frequency for most natural materials, with the seismic signal's high-frequency components being attenuated more rapidly than low-frequency. Therefore, the signal spectrum centroid downshifts during seismic wave propagation, and this can be observed to reconstruct the attenuation distribution (Quan & Harris 1997).

6.4.4 Time Derivative of Wavelet Envelope

This attribute is given by the rate of change of the wavelet envelope over time (Rock Solid Images 2016). It represents the steepness of the seismic wavelet.

6.4.5 Imaginary Part of Complex Trace

This trace has an identical amplitude spectrum to the real part of the complex trace. Rock Solid Images (2016) defines this as: “The real part of the complex trace (amplitude) phase shifted by 90 degrees”.

6.4.6 Relative Acoustic Impedance

This attribute is a physical attribute, which reflects a contrast between the physical properties of rocks, which can be correlated to a change in compaction and porosity (Rock Solid Images 2016).

7 Discussion and Conclusions

7.1 Introduction

The previous chapters have outlined the process involved in identifying the chosen RSAs, which are displaying significant variations in their value distributions between coaly versus non-coaly intervals. The selected RSAs outlined in chapters 5 and 6 (4 from Category 1, and 2 from Category 2) appear to be correlating to the presence of coaly facies in the study area (Chapter 6.3.3). However, a method does not yet exist for application of this correlation to other seismic reflection data for the purpose of coal prediction.

7.2 Summary of Results

Chapter 5 presented the results of extracting a wide range of amplitude-based attributes from the Rakopi Formation interval of both the Maari and Pipeline 3D volumes. The resultant amplitude maps (represented by Figure 5.1) did not show enough to be useful in identification of coals, and as such were largely confined to Appendix A. Additionally, Chapter 5 detailed the extraction of the suite of RSAs in SeiswareTM, the results of which were refined in Chapter 6, by spatially averaging the RSA values within the Rakopi Formation interval for display in pan view, and plotting the frequency distributions of these results for visual analysis. Also undertaken were several control tests based on both scalability, and repeatability of results in the coaly facies of the Mangahewa Formation. From these results, a series of attributes were identified which correlate to the increased presence of coaly facies within the selected intervals.

7.2.1 Coal Predicting Rock Solid Attributes

There are 6 attributes which appear to predict the increased presence of coals, as follows:

- Trace Envelope
- Wavelet Envelope
- Q by Frequency Shift
- Time Derivative of Wavelet Envelope
- Imaginary Part of Complex Trace
- Relative Acoustic Impedance

7.3 Discussion

The 6 selected RSAs all appear to be responding to variations in amplitude. High amplitude parts of seismic reflection data often represent hydrocarbon accumulations (Hart 1999). Given that the seismic velocity and density of coal is typically much less than that of sandstones and siltstones (e.g.

Hughes & Kennett 1983; Jackson et al. 2010), it is to be expected that the presence of coal seams in the seismic data would lead to amplitude anomalies. Additionally, the presence of stacked coal seams produces high-amplitude anomalies, due to the short-period multiples caused by many thin beds broadening the below-coal wavelet (Coulombe & Bird 1996).

7.3.1 Trace Envelope, Wavelet Envelope, Time Derivative of Wavelet Envelope

Trace Envelope is a measure of instantaneous amplitude, and it follows that it is correlated with the presence of coals within the Rakopi Formation. Coaly facies are associated with an increase in seismic amplitude (Hughes & Kennett 1983), and as such, it is to be expected that any attribute which measures an increase in seismic amplitude will predict coaly facies to some degree.

Wavelet Envelope describes another measure of seismic amplitude, and displays similar frequency distributions and corresponding spatial distributions to that of Trace Envelope (Figure 6.19). Time Derivative of Wavelet Envelope represents the rate of change of the wavelet envelope over time, it follows that it should display results similar to that of Wavelet Envelope (Figure 6.20).

7.3.2 Q by Frequency Shift

Of the 6 coal-predicting RSAs, perhaps the most significant is Q by Frequency Shift, in that it displays value distributions which appear to scale directly in accordance with the percentage thickness of coals (Figure 6.21), and does so on a more predictable scale than the other Category 1 attributes (Figures 6.18-6.20).

Q is a measurement of seismic attenuation (Section 6.4.3), which is a loss of seismic amplitude over distance travelled. As such, it is also a measure of amplitude.

7.3.3 Relative Acoustic Impedance & Imaginary Part of Complex Trace

Relative Acoustic Impedance is a measure of the change of seismic amplitude between layers, due to a difference between their relative densities, which causes changes in the level of impedance, and therefore affects the amplitude and frequency of seismic wave propagation.

Imaginary Part of Complex Trace is also an attribute which is dependent on seismic amplitude, in that it is a derivative of the real part of the complex trace, which is measured in amplitude (Section 6.4.5).

7.4 Inferred Coal Distributions by RSA Amplitude Map Analysis

In order to complete the objective set out by this project, the distribution of the coals within the Rakopi Formation of the study area must be constrained. In order to accomplish this, the averaged attribute maps for each of the 6 selected RSAs have been analysed, with the areas highlighted which are displaying attribute values that have correlated with coaly facies at the Maui-4 well through all control tests (Figures 7.1-7.6).

Figure 7.1 Rakopi Formation Inferred Coal Distributions - Trace Envelope

Shown are the temporally-averaged RSA attribute values for the entire Rakopi Formation interval in the Pipeline (left) and Maari (right) 3D seismic reflection volumes. The colour scales are individual for each survey, and are denoted by the attribute values on either side of the inset scale. The black shaded areas superimposed represent the likely areas of coals. Beneath each survey is a representative 2D line, displaying the attribute values amongst the interpreted Cretaceous horizons (crossline 2169 in Pipeline, and crossline 1020 in Maari; see Figures 3.3 and 4.1), the location of which within the surveys is given by the horizontal yellow lines.

Figure 7.2 Rakopi Formation Inferred Coal Distributions - Wavelet Envelope

Shown are the temporally-averaged RSA attribute values for the entire Rakopi Formation interval in the Pipeline (left) and Maari (right) 3D seismic reflection volumes. The colour scales are individual for each survey, and are denoted by the attribute values on either side of the inset scale. The black shaded areas superimposed represent the likely areas of coals. Beneath each survey is a representative 2D line, displaying the attribute values amongst the interpreted Cretaceous horizons (crossline 2169 in Pipeline, and crossline 1020 in Maari; see Figures 3.3 and 4.1), the location of which within the surveys is given by the horizontal yellow lines.

Figure 7.3 Rakopi Formation Inferred Coal Distributions - Time Derivative of Wavelet Envelope

Shown are the temporally-averaged RSA attribute values for the entire Rakopi Formation interval in the Pipeline (left) and Maari (right) 3D seismic reflection volumes. The colour scales are individual for each survey, and are denoted by the attribute values on either side of the inset scale. The black shaded areas superimposed represent the likely areas of coals. Beneath each survey is a representative 2D line, displaying the attribute values amongst the interpreted Cretaceous horizons (crossline 2169 in Pipeline, and crossline 1020 in Maari; see Figures 3.3 and 4.1), the location of which within the surveys is given by the horizontal yellow lines.

Figure 7.4 Rakopi Formation Inferred Coal Distributions - Q by Frequency Shift

Shown are the temporally-averaged RSA attribute values for the entire Rakopi Formation interval in the Pipeline (left) and Maari (right) 3D seismic reflection volumes. The colour scales are individual for each survey, and are denoted by the attribute values on either side of the inset scale. The black shaded areas superimposed represent the likely areas of coals. Beneath each survey is a representative 2D line, displaying the attribute values amongst the interpreted Cretaceous horizons (crossline 2169 in Pipeline, and crossline 1020 in Maari; see Figures 3.3 and 4.1), the location of which within the surveys is given by the horizontal yellow lines.

Figure 7.5 Rakopi Formation Inferred Coal Distributions - Relative Acoustic Impedance
 Shown are the temporally-averaged RSA attribute values for the entire Rakopi Formation interval in the Pipeline (left) and Maari (right) 3D seismic reflection volumes. The colour scales are individual for each survey, and are denoted by the attribute values on either side of the inset scale. The black shaded areas superimposed represent the likely areas of coals. Beneath each survey is a representative 2D line, displaying the attribute values amongst the interpreted Cretaceous horizons (crossline 2169 in Pipeline, and crossline 1020 in Maari; see Figures 3.3 and 4.1), the location of which within the surveys is given by the horizontal yellow lines.

Figure 7.6 Rakopi Formation Inferred Coal Distributions - Imaginary Part of Complex Trace

Shown are the temporally-averaged RSA attribute values for the entire Rakopi Formation interval in the Pipeline (left) and Maari (right) 3D seismic reflection volumes. The colour scales are individual for each survey, and are denoted by the attribute values on either side of the inset scale. The black shaded areas superimposed represent the likely areas of coals. Beneath each survey is a representative 2D line, displaying the attribute values amongst the interpreted Cretaceous horizons (crossline 2169 in Pipeline, and crossline 1020 in Maari; see Figures 3.3 and 4.1), the location of which within the surveys is given by the horizontal yellow lines.

These figures display the inferred distributions for coals within this interval for each of the 6 RSAs separately. This analysis was done visually, by noting areas where the spatial distribution of higher (or lower, which correlated to coals for Category 2 RSAs) temporally-averaged RSA values is concentrated within the 3D volumes.

Note that thresholding to produce the polygons in Figures 7.1-7.6 has been subjectively assigned. The colour distributions used for this thresholding were individually set for each RSA, in order to best display the distribution of values by utilising as broad a colour spectrum as possible in each case. As such, the threshold for coals for each RSA is somewhat arbitrary, but still serves as an adequate starting point for the prediction of coals based on temporally-averaged RSA values.

Extrapolating from this, the coal distributions predicted by each RSA individually have been superimposed upon one another to produce a further set of figures, with any areas which are not predicted by the chosen RSAs being trimmed off, to create a “Venn Diagram” of the respective coal distributions, based on cumulative prediction by successive RSAs. Given that the 2 categories of coal-predicting RSAs appear to be responding to the coals in a different way (section 6.2.2), this was done separately for each category (Figures 7.7-7.8), before being done for all 6 chosen RSAs together (Figure 7.9).

The results of the coal constraint inferences are displayed in Table 7.1 below.

RSA Category	Rock Solid Attribute (RSA) Name	Individual RSAs	Cumulative by Category	Cumulative All RSAs
1	Trace Envelope	58.6%	49.0%	13.9%
	Wavelet Envelope	61.3%		
	Time Derivative of Wavelet Envelope	57.9%		
	Q by Frequency Shift	65.8%		
2	Relative Acoustic Impedance	44.3%	28.8%	
	Imaginary Part of Complex Trace	50.0%		

Table 7.1 Rakopi Formation Inferred Coal Distribution Percentages.

Refer to Figures 7.1-7.9. For RSA category descriptions see Section 6.2.2.

Figure 7.7 Inferred Coal Distributions – All Category 1 RSAs

Shown is the Rakopi Formation isochron map for the Pipeline (left) and Maari (right) 3D seismic reflection volumes, with the thickness in ms TWTT given by the inset colour scale. Superimposed atop in pink is the inferred distribution of Rakopi Formation coals (49%), based on the overlap of areas predicted by all Category 1 RSAs (Figures 7.1-7.4).

KEY:
Rakopi Fm. Inferred Coal Distribution

Figure 7.9 Inferred Coal Distribution - Combined Category 1 & 2 RSAs

Shown is the Rakopi Formation isochron map for the Pipeline (left) and Maari (right) 3D seismic reflection volumes, with the thickness in ms TWTT given by the inset colour scale. Superimposed atop in pink is the inferred distribution of Rakopi Formation coals (13.9%), based on the overlap of areas predicted by all Category 1 and 2 RSAs (Figures 7.1-7.6).

7.5 Applications

7.5.1 Limitations and Uncertainty

All of the attribute analysis work so far has been conducted by comparing a coal-rich interval to a sandy/silty-dominated interval, and observing the differences in averages and distributions of attribute outputs. However, the efficacy of this sort of technique relies upon the presence of a significant sandy/silty layer in the vicinity of the coaly facies for comparison.

Since the acquisition parameters (and thus absolute values for amplitude and other variables) differ across each seismic survey, it is difficult to come up with a method of attribute analysis which deals with absolute values; rather, any coal-predicting attribute formula will need to be based on the ratio of values between coaly and non-coaly intervals. While this uncertainty may be able to be ameliorated by an amplitude/phase normalisation process between datasets, it still poses challenges for the application of this kind of method, which by definition will be used in areas removed from well penetrations, and as such the lithologies of seismic units in these areas are less likely to be known with any certainty.

Additionally, it is acknowledged that the process of averaging outputted attribute values within a stratigraphic interval may cause some simplification of the data, which could lead to a loss of information, especially in cases where the formation being averaged is very thick. In any future application of this method to thick intervals, it may be prudent to iso-slice the interval into several vertical sections, each to be analysed separately.

7.5.2 Applications to Other Data

In order to apply the results of this project to further 3D seismic volumes for the identification of coaly facies, the following steps could be followed:

- Interpretation of the relevant sedimentary horizons, to define the potentially coal-rich interval
- Gridding of these horizons throughout the seismic volume or the area of interest to produce continuous surfaces
- Extraction of selected attributes from the seismic volume
- Averaging of the attribute values within each vertical interval of interest, constrained by the interpreted horizons
- Display of these attribute averages in pan view on the basemap

By visually scanning the basemap averages of attribute outputs extracted, it may be possible to narrow down the areas in which coals are more likely to be present, by noting areas of anomalously high values (as carried out in section 7.5, and shown by Figures 7.1-7.9). These areas could then be used as a starting point for more localised attribute extraction on a finer scale.

If the surrounding lithology is known with some certainty, the stratigraphic sections of the seismic data which contain the highest averaged values of the coal-predicting attributes can be compared to the strata which are known to be silty/sandy, with the results analysed to determine the likelihood of the presence of coals.

However, this would still only give the average values for each given interval, and thus would be a low-resolution method, only giving the likelihood of coals being found within the whole vertical section. In order to gain a higher resolution method of coal identification, the data would need to be split into many subdivisions, with attributes averaged for each, and analysed separately. While this seems to be prohibitively laborious, it is likely that a simple routine could be established that would allow the procedure to be automated once the initial parameters have been determined.

7.5.3 Ratios of RSA Values between Coaly and Non-Coaly Intervals

Given that the absolute values of amplitude will vary between seismic surveys, it is the ratios of temporally-averaged RSA values between the coaly and non-coaly intervals which could be used to predict coal percentages in further seismic data unpenetrated by exploration wells (Coaly/Non Ratios).

In order to predict coal volumes accurately, a method of converting these Coaly/Non Ratios into a range of possible coal percentages needs to be established. To do this, more data must be obtained, to narrow the range of the mathematical relationship between the Coaly/Non Ratios and coal percentage volume. Once such an algorithm for each attribute (an Attribute/Coal Relationship) has been deduced more comprehensively by the inclusion of further data, it could potentially then be applied to unexplored seismic data to estimate coal volumes.

Table 7.2 shows the ratios between the temporally-averaged RSA values for coaly and non-coaly facies respectively. This illustrates the wide variation between the ratios for each attribute. Scale Test 2 was conducted in the smallest area directly surrounding the Maui-4 well (Figure 6.2), and as such it should be returning the most accurate values corresponding to the presence of coals, given that the lithology is most certain where it is observed at the well penetration.

Based on the observed coal content of the Lower Coals (43%), Mangahewa Formation (21.3%), and Upper Coals (10.6%), it is expected that the Coaly/Non Ratios would reflect this, and would scale from the Lower Coals to the Upper Coals, correlating to relative coal volume. Comparing the ratios in Table 7.2 between Scale Test 2 and the Mangahewa Formation, it is only the Imaginary Part of Complex Trace attribute that returns a value that is predicted by the above.

It could be the case that there is some sort of threshold of coal volume, over which the attribute outputs change to represent this. It appears to be this way for the RSAs for which the Lower Coals are separate, and the Upper Coals and Mid Silts are basically identical distributions (e.g. Relative

Acoustic Impedance, Time Derivative of Wavelet Envelope), although for these attributes it is likely that the Attribute/Coal Relationship is non-linear.

	Total Rakopi Subdivision		Scale Test 1		Scale Test 2		Mangahewa Control Group	
Q by Frequency Shift	Lower:Mid	-0.83567	Lower:Mid	-7.37638	Lower:Mid	-1.55605	Coaly: Non-Coaly	-2.16782
	Upper:Mid	0.42013	Upper:Mid	-2.31645	Upper:Mid	-0.29286		
Relative Acoustic Impedance	Lower:Mid	-18.7518	Lower:Mid	-14.8522	Lower:Mid	-8.57443	Coaly: Non-Coaly	-1.14624
	Upper:Mid	0.411361	Upper:Mid	0.448339	Upper:Mid	-1.04646		
Imaginary Part of Complex Trace	Lower:Mid	778.2249	Lower:Mid	-29.0209	Lower:Mid	-7.07957	Coaly: Non-Coaly	-1.37786
	Upper:Mid	4.136103	Upper:Mid	0.394629	Upper:Mid	-1.49366		
Time Derivative of Wavelet Envelope	Lower:Mid	1.293331	Lower:Mid	1.517239	Lower:Mid	1.413624	Coaly: Non-Coaly	2.244853
	Upper:Mid	1.327224	Upper:Mid	1.430995	Upper:Mid	1.38161		
Trace Envelope	Lower:Mid	1.404939	Lower:Mid	1.637642	Lower:Mid	1.579719	Coaly: Non-Coaly	2.706131
	Upper:Mid	1.43148	Upper:Mid	1.616692	Upper:Mid	1.461435		
Wavelet Envelope	Lower:Mid	1.470466	Lower:Mid	1.78872	Lower:Mid	1.797877	Coaly: Non-Coaly	2.508478
	Upper:Mid	1.348148	Upper:Mid	1.461949	Upper:Mid	1.361227		

Table 7.2 Ratios of RSA Values in Coaly/Non-Coaly Intervals
Calculated from the average values for each RSA outputted from each interval sampled.

7.6 Outlook

The method of seismic attribute extraction and analysis heretofore described could potentially be applied to other 3D seismic reflection data, for the purpose of identifying and constraining coaly hydrocarbon source rocks in areas that are not penetrated by wells.

It would be useful to find a seismic section which contains a very high percentage of known coal seams (i.e. 70-80% intersected by a well), with a silty/sandy stratum in the same vertical section. By extracting the attributes from these, and comparing the Coaly/Non Ratios, this would produce results which would give a clearer picture of how the chosen attributes respond to very high levels of coals, as opposed to the levels of coals seen in the Lower Coals and Upper Coals respectively.

If more data is obtained, to display the full range of likely-occurring coal percentages by volume, a more quantitative sense will be gained of how the attributes respond to the increased volume of coals. If a rate of change can be observed between the coal percentage and the relative attribute outputs, then this will be able to be applied to other 3D datasets, to more accurately predict source rock volumes.

The actions which could be taken to assess the robustness of these attributes as coal predictors is as follows:

- Find additional 3D seismic volumes with well penetrations and known coaly facies
- Iso-slice the vertical section surrounding the well into 100ms slices (or sufficient resolution)
- Measure or estimate the coal percentage volume for each of the horizontal iso-slices
- Extract the chosen attributes from a small section of the data surrounding the well
- Average attributes for each iso-slice

From this, each interval's attribute averages can be assessed, and then the Coaly/Non Ratios can be recorded, and correlated to the coal percentage of each respective vertical interval to further constrain the Attribute/Coal Relationship.

After a few such tests as this, it should be apparent whether this method can be developed into a robust coal predictor.

7.7 Implications for Petroleum Systems Models

If the selected attributes are found to be a robust predictor of coaly facies, and a method can be developed to utilise them to locate coals in areas removed from well penetrations, this will have practical applications. Namely, it will assist in any volumetric calculations of hydrocarbon charge undertaken as part of drilling risk assessment, increasing accuracy, lowering risk, and ultimately reducing costs.

There have been a suite of 6 RSA attributes which have been identified as responding to the presence of coal rich intervals, either responding to the percentage of coal by volume (Category 1) or the absolute presence of a higher percentage of coal (Category 2). These RSAs produce repeatable results based on trials at different scales and in different intervals. Based on the occurrence of extreme values of these RSAs when viewed as average values within the Rakopi Formation as a whole, the likely areas of high coal concentration have been mapped within the Maari and Pipeline 3D seismic volumes.

This method of attribute extraction and analysis has potential to be applied to other seismic, and with further work could potentially be used to conduct volumetric calculations of coal volumes within a formation.

7.8 Conclusions

7.8.1 Summary

This project has shown that the coals in the southwest offshore Taranaki Basin are overestimated within the Cretaceous Rakopi Formation, and has succeeded in constraining them further based on temporally-averaged attribute value frequency distributions in coaly and non-coaly intervals, which were subject to numerous control tests.

7.8.2 Project Achievements

This project investigated the utility of extracted seismic attributes for the purpose of identifying Cretaceous age coaly hydrocarbon source rocks within the southern Taranaki Basin, New Zealand. This was undertaken through interpretation of the relevant strata in the 3D seismic data present in the study area, and subsequent extraction and analysis of seismic attributes from selected intervals.

In particular, this project has:

- Interpreted the Cretaceous and selected Paleogene strata within the Maari and Pipeline 3D volumes
- Constrained the distribution of the Rakopi Formation in the study area by seismic interpretation of the Basement and Top Rakopi Formation
- Identified a suite of 6 seismic attributes (SeiswareTM RSAs) which correlate strongly to the increased presence of coaly facies
- Estimated the coal distribution within the Rakopi Formation in the Pipeline and Maari 3D seismic volumes from the amplitude maps of the 6 selected RSAs

As such, this project has achieved its aim, and has been a valuable first step in the direction of being able to apply a volumetric calculation to seismic data to constrain the total percentage of coaly facies for the purpose of increased accuracy of the risk assessment of petroleum systems models.

7.8.3 Recommendation

As shown in Section 7.5, the distribution of coals within the Rakopi Formation can be constrained to a distribution throughout a maximum of 65.8% (as predicted by Q by Frequency Shift, see Figure 7.4 and Section 7.3.4), and as little as 13.9% of the total area of the formation (as predicted by the overlap of all 6 selected RSAs, see Figure 7.9). As such, the total hydrocarbons generated by the basin have been overestimated in petroleum systems models thus far. It is recommended that the models be adjusted to account for this lessened coal percentage by volume, instead of the entire Rakopi Formation being modelled as source rock. Ideally, the same method of attribute extraction and analysis would be conducted in other 3D surveys in the Taranaki Basin which contain the Cretaceous

interval, in order to collect more data. From this, a more accurate estimate of the coal percentage of the Cretaceous can be made, for the purpose of increased accuracy of hydrocarbon charge models in the basin.

7.8.4 Applications

The development and application of a method of seismic attribute analysis to predict coaly hydrocarbon source rocks in other areas is beyond the scope of this project. However, given further work, it may be possible to come up with a method, using a process similar to that outlined in Section 7.3.

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9 Appendix A

9.1 Amplitude Attributes

The following appendix displays the amplitude maps which were generated by the 19 calculations in Seisware™ based on amplitude, as described in Chapter 5. Each attribute image has its abbreviated name in the lower right. The full names and descriptions of each amplitude attribute calculation are listed below each figure. The results of the extraction of these amplitude-based attributes (which were calculated in the bottom 50ms of the Rakopi Formation interval in the Maari and Pipeline 3D seismic volumes, as outlined in Section 5.1.2) can be divided into 3 basic subcategories, based on the distribution of high and low values within the seismic volume (see Sections 5.1.2-5.1.4).

Each of the figures in this appendix displays the same layout. The Pipeline 3D volume on the left, and the Maari 3D volume on the right. Within these, the calculated amplitude values are displayed as a surface, with the values represented by different colours on an inset scale bar. Note that the values in each respective 3D volume are not on the same scale, and the values for each are shown to either side of the inset colour bar.

Figure 9.1 Type 1 Amplitude Attribute Maps - Peak Count

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from Seisware™).

Peak Count (PC):

This will compute the number of above-zero peaks in the sample set.

Please note that zero-crossing horizons work best with this attribute when using a one or two horizon window.

Figure 9.2 Type 1 Amplitude Attribute Maps – Average Thickness of Peak

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from SeiswareTM).

Amplitude Thickness of Peak (ATP):

This attribute will compute the number of milliseconds over which the peak lies. A "peak" is any value that is larger than the threshold value specified. Given a threshold of zero, the image to the left shows the samples that would be counted. Interpolated values are used for accuracy.

In this sample, the result will be Thickness A + Thickness B + Thickness C.

Figure 9.3 Type 1 Amplitude Attribute Maps - Amplitude Thickness of Trough

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from SeiswareTM).

Amplitude Thickness of Trough (ATT):

This attribute will compute the number of milliseconds over which the trough lies. A "trough" is any value that is smaller than the threshold value specified. Given a threshold of zero, the image to the left shows the samples that would be counted. Interpolated values are used for accuracy.

In this sample, the result will be Thickness A + Thickness B

Figure 9.4 Type 1 Amplitude Attribute Maps - Area Under Peak

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from SeiswareTM).

Area Under Peak (AUP):

This attribute will compute the area under the peak. Again, a "peak" is any value that is larger than the threshold value specified. Area is defined as the sample value multiplied by the sample rate and is summed for all samples that are a "peak". Given a threshold of zero, the image to the left shows the areas that would be summed up. Interpolated values are used for accuracy.

Figure 9.5 Type 1 Amplitude Attribute Maps - Area Under Trough

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from SeiswareTM).

Area Under Trough (AUT):

This attribute will compute the area under the trough. Again, a "trough" is any value that is smaller than the threshold value specified. Area is defined as the sample value multiplied by the sample rate and is summed for all samples that are a "trough". Given a threshold of zero, the image to the left shows the area that would be summed up. Interpolated values are used for accuracy.

Figure 9.6 Type 1 Amplitude Attribute Maps - Average Value

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from SeiswareTM).

Average Value (AVG):

This attribute will sum all the sample values within the window and divide by the number of samples. The threshold is ignored.

Figure 9.7 Type 1 Amplitude Attribute Maps - Peak Count

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from SeiswareTM).

Peak Count (PC):

This will compute the number of above-zero peaks in the sample set.

Please note that zero-crossing horizons work best with this attribute when using a one or two horizon window.

Figure 9.8 Type 1 Amplitude Attribute Maps - Sum of Absolute Amplitudes

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from SeiswareTM).

Sum of Absolute Amplitudes:

Computes the sum of the absolute value of all amplitudes within the window.

$$x_{saa} = |x_1| + |x_2| + |x_3| + \dots + |x_n|$$

Figure 9.9 Type 1 Amplitude Attribute Maps - Trough Count

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from SeiswareTM).

Trough Count (PC):

This will compute the number of below-zero troughs in the sample set.

Please note that zero-crossing horizons work best with this attribute when using a one or two horizon window.

Figure 9.10 Type 1 Amplitude Attribute Maps - Zero Crossing Count

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 1 Amplitude Maps show a strong visual correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). The description of the attribute calculation is given below (taken from SeiswareTM).

Zero Crossing Count (ZCC):

This will compute the number of zero crossings in the sample set.

Please note that peak or trough horizons work best with this attribute when using a one or two horizon window.

Figure 9.11 Type 2 Amplitude Attribute Maps - Average Absolute

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 2 Amplitude Maps still show a visual correlation with the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2), but have some variations which it does not predict. The description of the attribute calculation is given below (taken from SeiswareTM).

Average Absolute (ABS):

This attributes will sum the absolute value for all samples within the window and divide by the number of samples. The threshold is ignored.

Figure 9.12 Type 2 Amplitude Attribute Maps - Average Energy Value

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 2 Amplitude Maps still show a visual correlation with the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2), but have some variations which it does not predict. The description of the attribute calculation is given below (taken from SeiswareTM).

Average Energy Value:

This will compute the average of the squared amplitudes.

$$x_{ae} = \frac{x_1^2 + x_2^2 + x_3^2 + \dots + x_n^2}{n}$$

Figure 9.13 Type 2 Amplitude Attribute Maps - Maximum Value

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 2 Amplitude Maps still show a visual correlation with the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2), but have some variations which it does not predict. The description of the attribute calculation is given below (taken from Seisware™).

Maximum Value (MAX):

This will determine the largest value within the window. The threshold is ignored. The blue area indicates the maximum sample.

Figure 9.14 Type 2 Amplitude Attribute Maps - Max Negative Value

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 2 Amplitude Maps still show a visual correlation with the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2), but have some variations which it does not predict. The description of the attribute calculation is given below (taken from SeiswareTM).

Max Negative Value (MAXN):

This will determine the largest negative value within the window. A negative value is any value that is less than zero. The threshold is ignored. The blue area indicates the maximum negative sample.

Figure 9.15 Type 2 Amplitude Attribute Maps - Max Positive Value

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 2 Amplitude Maps still show a visual correlation with the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2), but have some variations which it does not predict. The description of the attribute calculation is given below (taken from SeiswareTM).

Max Positive Value (MAXP):

This will determine the largest positive value within the window. A positive value is any value that is greater than zero. The threshold is ignored. The blue area indicates the maximum positive sample.

Figure 9.16 Type 2 Amplitude Attribute Maps - Minimum Value

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 2 Amplitude Maps still show a visual correlation with the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2), but have some variations which it does not predict. The description of the attribute calculation is given below (taken from SeiswareTM).

Minimum Value (MIN):

This will determine the smallest value within the window. The threshold is ignored. The blue area indicates the minimum sample.

Figure 9.17 Type 2 Amplitude Attribute Maps - RMS Value

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 2 Amplitude Maps still show a visual correlation with the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2), but have some variations which it does not predict. The description of the attribute calculation is given below (taken from SeiswareTM).

RMS Value (RMS):

This will compute the RMS of all the data within the window using the formula:

$$x_{rms} = \sqrt{\frac{x_1^2 + x_2^2 + \dots + x_n^2}{n}}$$

Figure 9.18 Type 3 Amplitude Attribute Maps - Sum of Amplitudes

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 3 Amplitude Maps show no observable correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). As such, they are likely responding to a lithological feature. The description of the attribute calculation is given below (taken from SeiswareTM).

Sum of Amplitudes:

Sum of all amplitudes in the window.

$$x_{sa} = x_1 + x_2 + x_3 + \dots + x_n$$

Figure 9.19 Type 3 Amplitude Attribute Maps - Zero Crossing Frequency

Shown is the horizon generated by this attribute calculation on the Rakopi Formation interval of the Pipeline (left), and Maari (right) 3D seismic volumes, which have their own scales either side of the inset colour bar. Type 3 Amplitude Maps show no observable correlation to the Rakopi Formation thickness (see Appendix A section 9.1), as given by the Rakopi Formation Isochron Map (Figure 4.2). As such, they are likely responding to a lithological feature. The description of the attribute calculation is given below (taken from SeiswareTM).

Zero Crossing Frequency (ZCF):

This will compute the number of zero crossings in the sample set divided by the number of samples.

Please note that peak or trough horizons work best with this attribute when using a one or two horizon window.

10 Appendix B

10.1 Rakopi Formation RSA Amplitude Maps

This appendix displays the full results of the Rock Solid Attributes (RSAs) which were extracted from the Rakopi Formation interval in the study area, as described in Section 5.2. The list of RSAs which were extracted from the data, along with their brief descriptions, is given by Table 4.1. For more information about RSAs, see Taner (2003) or Rock Solid Images (2016).

The following attribute output images all display the same information. The basemaps within the Pipeline and Maari 3D volumes are displaying the averaged values of the RSAs extracted from the Rakopi interval of the Cretaceous strata. Note that the colour scales are different for the 2 volumes respectively, but the scales are annotated on each side. The representative 2D lines below the volumes show the attribute as it is displayed, and their location within the 3D is shown by the horizontal yellow lines. In most cases, the gain has been adjusted on the 2D lines, and the range of displayed values on the basemaps, have been altered in order to best represent any variations. The Maui-4 and Pukeko-1 wells are shown by the red crosses underneath the yellow seismic lines.

Figure 10.8 Rakopi Formation RSA Data - Spectral Bandwidth

Shown are the values of this attribute, temporally averaged within the Rakopi Formation interval of the Pipeline (top left), and Maari (top right) 3D seismic volumes, which have individual colour scales (see inset colour bar). The representative 2D lines below the basemaps show the attribute outputs when viewed in 2D. For more information on the averaging process, see Figure 5.1, and for the map location, see Figure 1.1.

Figure 10.10 Rakopi Formation RSA Data - Time Derivative of Envelope

Shown are the values of this attribute, temporally averaged within the Rakopi Formation interval of the Pipeline (top left), and Maari (top right) 3D seismic volumes, which have individual colour scales (see inset colour bar). The representative 2D lines below the basemaps show the attribute outputs when viewed in 2D. For more information on the averaging process, see Figure 5.1, and for the map location, see Figure 1.1.

Figure 10.14 Rakopi Formation RSA Data – Semblance

Shown are the values of this attribute, temporally averaged within the Rakopi Formation interval of the Pipeline (top left), and Maari (top right) 3D seismic volumes, which have individual colour scales (see inset colour bar). The representative 2D lines below the basemaps show the attribute outputs when viewed in 2D. For more information on the averaging process, see Figure 5.1, and for the map location, see Figure 1.1.

Note: The Pipeline 3D volume was not able to be loaded correctly into Seisware™. Every second trace was nulled, which was not a problem for most of the work done, but since Semblance compares adjacent traces, it was not able to be displayed properly as an attribute amplitude map.

Figure 10.18 Rakopi Formation RSA Data - Dominant Frequency

Shown are the values of this attribute, temporally averaged within the Rakopi Formation interval of the Pipeline (top left), and Maari (top right) 3D seismic volumes, which have individual colour scales (see inset colour bar). The representative 2D lines below the basemaps show the attribute outputs when viewed in 2D. For more information on the averaging process, see Figure 5.1, and for the map location, see Figure 1.1.

Figure 10.19 Rakopi Formation RSA Data – Bandwidth

Shown are the values of this attribute, temporally averaged within the Rakopi Formation interval of the Pipeline (top left), and Maari (top right) 3D seismic volumes, which have individual colour scales (see inset colour bar). The representative 2D lines below the basemaps show the attribute outputs when viewed in 2D. For more information on the averaging process, see Figure 5.1, and for the map location, see Figure 1.1.

Figure 10.21 Rakopi Formation RSA Data - Normalised Amplitude

Shown are the values of this attribute, temporally averaged within the Rakopi Formation interval of the Pipeline (top left), and Maari (top right) 3D seismic volumes, which have individual colour scales (see inset colour bar). The representative 2D lines below the basemaps show the attribute outputs when viewed in 2D. For more information on the averaging process, see Figure 5.1, and for the map location, see Figure 1.1.

Figure 10.24 Rakopi Formation RSA Data – Similarity

Shown are the values of this attribute, temporally averaged within the Rakopi Formation interval of the Pipeline (top left), and Maari (top right) 3D seismic volumes, which have individual colour scales (see inset colour bar). The representative 2D lines below the basemaps show the attribute outputs when viewed in 2D. For more information on the averaging process, see Figure 5.1, and for the map location, see Figure 1.1.

Figure 10.33 Rakopi Formation RSA Data - Maximum Subband of Envelope

Shown are the values of this attribute, temporally averaged within the Rakopi Formation interval of the Pipeline (top left), and Maari (top right) 3D seismic volumes, which have individual colour scales (see inset colour bar). The representative 2D lines below the basemaps show the attribute outputs when viewed in 2D. For more information on the averaging process, see Figure 5.1, and for the map location, see Figure 1.1.

11 Appendix C

11.1 RSA Averages and Frequency Counts within the Rakopi Subdivision

The enclosed figures show the outputted results of the Rock Solid Attribute (RSA) extraction and averaging in the intra-formational seismic packages (Lower Coals, Mid Silts, and Upper Coals, as described by Section 4.5.3, and displayed in Figure 4.4) of the Rakopi Formation, in a small window around the Maui-4 well in the Maari 3D volume (the Rakopi Subdivision) (Figure 6.16).

Note that the following RSA attributes are the 19 which did not show significant difference between the frequency distributions of the 3 seismic packages of the Rakopi Subdivision, with the other 14 being displayed in Figures 6.1-6.15.

Figure 11.1 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Real Part of Complex Trace

Figure 11.2 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Instantaneous Phase

Figure 11.3 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Instantaneous Frequency

Figure 11.4 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Dominant Frequency

Figure 11.5 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Bandwidth

Figure 11.6 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Instantaneous Q Factor

Figure 11.7 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Normalised Amplitude

Figure 11.8 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Dip Similarity

Figure 11.9 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Dip Variance

Figure 11.10 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Similarity

Figure 11.11 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Similarity Variance

Figure 11.12 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Smoothed Dip of Maximum Similarity

Figure 11.13 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Dip Azimuth

Figure 11.14 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Mean Curvature

Figure 11.15 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Maximum Curvature

Figure 11.16 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Minimum Curvature

Figure 11.17 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Most Negative Curvature

Figure 11.18 RSA Averages and Frequency Distributions in the Rakopi Subdivision - Most Positive Curvature

12 Appendix D

12.1 RSA Control Tests Statistical Analysis

This appendix contains all of the results of the RSA control tests carried out in Chapter 6 which did not show enough meaningful variation to be included in the thesis body.

Real Part of Complex Trace - Bi-Exponential Distribution

Figure 12.1 RSA Control Tests Frequency Distributions - Real Part of Complex Trace

Instantaneous Phase - Bi-Exponential Distribution

Figure 12.2 RSA Control Tests Frequency Distributions - Instantaneous Phase

Instantaneous Frequency - Normal Distribution

Figure 12.3 RSA Control Tests Frequency Distributions - Instantaneous Frequency

Dominant Frequency - Log Normal Distribution

Figure 12.4 RSA Control Tests Frequency Distributions - Dominant Frequency

Bandwidth - Log Normal Distribution

Figure 12.5 RSA Control Tests Frequency Distributions - Bandwidth

Instantaneous Q Factor - Log Normal Distribution

Figure 12.6 RSA Control Tests Frequency Distributions - Instantaneous Q Factor

Normalised Amplitude - Bi-Exponential Distribution

Figure 12.7 RSA Control Tests Frequency Distributions - Normalised Amplitude

Dip Similarity - Log Normal Distribution

Figure 12.8 RSA Control Tests Frequency Distributions - Dip Similarity

Dip Variance - Bi-Exponential Distribution

Figure 12.9 RSA Control Tests Frequency Distributions - Dip Variance

Similarity - Log Normal Distribution

Figure 12.10 RSA Control Tests Frequency Distributions - Similarity

Similarity Variance - Bi-Exponential Distribution

Figure 12.11 RSA Control Tests Frequency Distributions - Similarity Variance

Smoothed Dip Similarity - Log Normal Distribution

Figure 12.12 RSA Control Tests Frequency Distributions - Smoothed Dip of Maximum Similarity

Dip Azimuth - Bi-Exponential Distribution

Figure 12.13 RSA Control Tests Frequency Distributions - Dip Azimuth

Mean Curvature - Bi-Exponential Distribution

Figure 12.14 RSA Control Tests Frequency Distributions - Mean Curvature

Maximum Curvature - Log Normal Distribution

Figure 12.15 RSA Control Tests Frequency Distributions - Maximum Curvature

Minimum Curvature - Bi-Exponential Distribution

Figure 12.16 RSA Control Tests Frequency Distributions - Minimum Curvature

Most Negative Curvature - Bi-Exponential Distribution

Figure 12.17 RSA Control Tests Frequency Distributions - Most Negative Curvature

Most Positive Curvature - Bi-Exponential Distribution

Figure 12.18 RSA Control Tests Frequency Distributions - Most Positive Curvature

Maximum Subband Envelope - Log Normal Distribution

Figure 12.19 RSA Control Tests Frequency Distributions - Maximum Subband of Envelope