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Seismic Facies Mapping for Source Rock Distribution of the Rakopi Formation in Deep-water Taranaki Basin, New Zealand

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Seismic Facies Mapping for Source Rock Distribution
of the Rakopi Formation in Deep-water Taranaki Basin, New Zealand

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Abstract

The Taranaki Basin is located off the coast of the north island of New Zealand and is currently the only producing basin in New Zealand. Hydrocarbon accumulation in the Tui, Maari, and Maui fields is sourced to the Late Cretaceous and Paleogene units. Exploration of these units has extended from the continental shelf of the Taranaki Basin into the deep-water to the northwest. The Romney 3D survey and Romney–1 well are some the first public exploration projects to supply data from this area. The objective of this study is to estimate source rock quality and distribution of the Rakopi Formation in the Romney 3D survey utilizing seismic facies analysis, log motif, and geochemical evaluations.

The Rakopi Formation records the northwest prograding megasequences of the Taranaki Delta. Seismic facies are defined by internal reflection configuration, reflection amplitude, frequency, continuity, and boundary relationships found in these sequences. Specific depositional environments are interpreted and calibrated using gamma ray log motif and biostratigraphy. These were used to generate paleogeographic reconstructions illustrating areas with the best source potential within the Rakopi Formation. Although seismic stratigraphy does not quantify source rock quality, higher quality organic-rich facies are identified based on geochemical analysis and tied to specific intervals on the Romney–1 well.

The results of this study confirm primary source potential from type II/III, oil and gas prone non-marine coal-rich facies. This source interval contains type II kerogen with excellent total organic content, hydrogen index above 300, and above average generative potential. A potential secondary type I, oil prone, marine algal source facies may also be preserved in the far northwest portion of the Romney 3D and extend westward beyond the survey.

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1. Introduction

The Taranaki Basin is currently the only productive basin in New Zealand and is located off the west coast of the North Island (Figure 1) (Uruski, 2012). The basin encompasses an area of approximately 100,000 km^2 and has production located predominately on the continental shelf and a minor amount on the Taranaki Peninsula (New Zealand, 2014). Estimated reserves for the basin are 534 MMbbl oil and condensate and 7,318 BCF of gas as of 2011(New Zealand, 2014). The source intervals are hydrogen rich coals and mudstones of the Upper Cretaceous Pakawau Group and Paleogene Kapuni Group (Johnston, 1989) (Figure 2). This study will focus on the Taranaki Delta of the Rakopi Formation, which is part of the Pakawau Group. Recent discoveries of more oil prone kerogen in the Cretaceous units at Tui, Maari, and Maui fields (Killops and Sykes 2003; Uruski et al 2003) have led exploration efforts northwest into the Deep-water Taranaki Basin (Figure 1). At the shelf edge favorable facies were found in the Tane-1 well but were thermally immature (Rad, 2015). Basin models indicate the source rock is expected to reach maturity in the Deep-water Taranaki if the known source intervals extend that far into the deep basin (Rad, 2015).

The primary goal of this study is to improve the understanding of Deep-water Taranaki Basin source interval distributions based on seismic stratigraphy and seismic facies analysis of the Romney 3D seismic survey purchased from the New Zealand Ministry of Business, Innovation and Employment. The lateral distribution of potential source intervals will be defined by depositional facies interpretations based on the seismic analysis using IHS Kingdom software. The seismic interpretation will be calibrated by log analysis and evaluation of geochemical reports from the Romney–1 well. Although the Romney-1 well was determined dry, it does not necessarily condemn production potential elsewhere in the deep-water Taranaki Basin. For this

reason, it is essential to understand the distributions of these effective and potential source intervals. Through this process and the review of previous work completed in the Taranaki Basin, this study aims to achieve an improvement on the understanding of source rock types and their distribution in the area of the Romney 3D survey as well as providing the ground work for further exploration projects.

2. Location and Geologic Context

2.1 Study Area

The study area is contained within the Romney-3D survey covering an area of approximately 2000 km^2 situated off the west coast of the north island of New Zealand in Block PEP38451 (Figure 1). The Romney 3D survey and the Romney–1 well it includes is located approximately 180km northwest of the Taranaki Peninsula and 80km from the nearest well, Wainui-1. The Tane-1 exploration well located 115km from Romney-1 encountered the Taranaki Delta and a large reservoir interval but did not contain any significant hydrocarbon shows. The Rakopi Formation outcrops over 200km south and is a proven source rock for the Tui, Maari, and Maui oil and gas fields (Killops and Sykes, 2003; Uruski et al., 2003).

2.2 Tectonics

The Taranaki Basin is predominately offshore and therefore the majority of the exploration efforts have been based on regional 2D seismic surveys and a limited number of well logs. Synrift sediments of the Upper Jurassic (~ 163 Ma) and a range of Cretaceous continental deposits unconformably overly basement rock (Figure 2) (Thrasher, 1992, King and Thrasher

,1996, Uruski et al., 2003, Strogen, 2017). These units were deposited through various tectonic settings resulting in specific depositional responses (Strogen, 2017).

Although the tectonic regime has changed dramatically over the last 150 million years, the plate tectonics provide a roadmap for basic controls on the Taranaki Basin formation and its subsequent stratigraphy (Figure 3). Originally situated in the eastern Gondwana subduction margin (Sutherland et al., 2001), the New Zealand mini-continent remained within the Gondwana margin until the Upper Jurassic (Uruski, 2008). Subduction of the Pacific plate underneath Gondwana created buoyant mantle that gave rise to the opening of the proto-Tasman Sea. The early rift faulting and subsequent extension of the Proto-New Zealand continent from Australia and Antarctica occurred between 150ma to 105ma (Uruski, 2003). The Cretaceous and Paleocene periods (105–55Ma) are defined by two distinct phases of rifting (Laird and Bradshaw, 2004; Strogen, 2017).

The first phase is known as the Zealandia rift phase which produced half-grabens trending northwest during the mid-Cretaceous (105 – 83 Ma) (Uruski et al., 2002 & 2003; Strogen, 2017). These rift basins developed as a result of the tectonic stretching prior to the onset of seafloor spreading in the Tasman Sea (Strogen, 2017; Browne et al., 2008). Shortly after this extensional regime, a period of uplift and erosion that lasted approximately 3 million years occurred between 85–75 Ma (Strogen, 2017). This flexural phase allowed hot asthenospheric material to rise and heat the rift margins resulting in a peripheral bulge (Miall, 2010). Meanwhile, basinward subsidence and thermal sagging commenced creating accommodation space for the deposition of eroded hinterland sediments. The combination of these tectonic events created a post rift sag fill and an overall progradational shoreline. Evidence for these erosional and depositional periods in the Taranaki Basin are represented in the southern region of

the basin as an angular unconformity and the basinward deposition of the Taranaki Delta sequence of the Rakopi Formation (Strogen, 2017). The Taniwha Formation is also a depositional result of these tectonics but is limited to isolated depocenters and occurred earlier during the uplift phase (Uruski, 2007). The second phase of rifting is known as the West Coast-Taranaki rift, which produced north to northeast trending extensional half-grabens within the shelfal Taranaki Basin (Strogen, 2017). This phase occurred approximately 80 – 55Ma and is mainly seen in Southern Taranaki and the west coast of the North Island (Strogen, 2017).

2.3 Stratigraphy

The Late Cretaceous Pakawau Group contains two regionally extensive formations, the North Cape and Rakopi Formation (Thrasher, 1992). The Rakopi Formation is stratigraphically located below the North Cape Formation and above basement rocks (Figure 2). These formations are divided by a regionally extensive hiatus that can be seen in seismic and well logs (Thrasher, 1992; Higgs et al., 2010). This boundary is recognized in the southeastern parts of the basin as local loss of section and in the northwest regions as a transgressive surface overlying prograding delta lobes of the Taranaki Delta (Higgs et al., 2010).

The deposition of the Rakopi Formation occurred between the Campanian (Early Haumurian) and Maastrichtian (Late Haumurian) stages, which coincide with the breakup of eastern Gondwanaland and the formation of the Tasman Sea (King and Thrasher, 1996). This time period was constrained by palynological spore and pollen samples collected by Raine (1984) who found *Tricolpites lilliei* Couper, the index species of the PM2 Zone, and thus restricts the age of the Pakawau group to about 77 – 65 Ma (Kennedy et al., 2001; Kennedy, 2003).

Although the entire Pakawau Group was originally considered non-marine (Titheridge, 1977), it has recently been expanded to include marginal marine facies previously included in the North Cape Formation by Thrasher (1992) and in the Rakopi Formation by Browne et al. (2008) and Sykes et al. (2004). Thrasher (1992) found the presence of dinoflagellates and sedimentary structures such as bidirectional dunes and mud drapes within the North Cape Formation but did not find evidence within the underlying Rakopi. The presence of these sedimentary structures revealed the environments to be tidally influenced shallow marine. More recent studies found dinoflagellate cysts and glauconite in the Upper Rakopi Formation indicating the onset of marine transgression and transition to North Cape deposition (Wizevich, 1994; Browne et al., 2008).

3. Previous Investigations

3.1 Sequence Stratigraphy and Seismic Facies

In the twentieth century, many observations and hypotheses were made in regard to the relationship of sea level and resulting stratigraphy. The original proposal of eustatic concepts was introduced by Suess (1885;1904) who determined that the extent of transgression is measurable by observing the movement of sediment and faunal characteristics with shoreline location (Miall, 2010). Further investigations by Wheeler (1958;1959) and Sloss (1962; 1963) correlated these time synchronous units across geologic sections and improved stratigraphic analysis (Posamentier, 1999). Although most concepts of sequence stratigraphy were proposed by the 1960's (Ross, 1991), it was not until the improvement of seismic reflection data that Peter Vail and his colleagues at the Exxon Production Research Co. observed and defined significant seismic stratigraphic depositional sequences such as regressive-transgressive-regressive sedimentary cycles bounded by unconformities (Posamentier, 1999). Vail presented these ideas at the 1975 meeting of American Association of Petroleum Geologist (Vail, 1975). This was

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followed by two seminal publications that established this sequence stratigraphic paradigm; AAPG memoir 26 (Payton, 1977) and SEPM Special Publication 42 (Wilgus et al., 1988). Since then seismic sequence stratigraphy has greatly improved petroleum exploration and enhanced the understanding and prediction of reservoirs, seal, and source rock facies.

Tectonics, relative sea level, and sediment supply play critical roles in the development of these sequences and seismic facies. As a result, genetically related units are deposited in a conformable succession bounded at the top and bottom by unconformities, erosional surfaces, or correlative conformities (Mitchum et al., 1977; Van Wagoner et al., 1988; Posamentier, 1999; Emery, 2009; Miall, 2010). Depositional successions can be recognized on seismic data through the analysis and visual determination of reflection patterns. This type of analysis is defined by trace amplitude, internal geometry, termination types, and continuity (Mitchum et al., 1977). These characteristics can be attributed to geomorphic structures and lithology (Posamentier, 2007).

Sequences can be further subdivided into distinct depositional packages known as system tracts (Brown and Fisher, 1977; Emery, 2009). System tracts, and their internal seismic facies, are defined as three dimensional units containing internal geometries bounded by depositional terminations such as onlap, downlap, toplap, or truncations (Brown and Fisher 1977, Mitchum et al., 1977; Emery, 2009). Divisions and terminology of system tracts can become unnecessarily complex; therefore, it is important to remember they represent fundamental mapping units for facies prediction (Emery, 2009).

3.2 Regional Seismic Interpretations

To date the lateral extent of the Rakopi Formation is defined predominately through 2D seismic mapping and depositional interpretations based on pollen and spore studies, plant macrofossils, and electric log characteristics. Glenn Paul Thrasher (1990; 1992) was one of the first to comprehensively examine tectonics and the associated sedimentation history of the Late Cretaceous units in the Taranaki Basin. Thrasher (1992) utilized outcrops, well bores, and subsurface 2D seismic mapping to study stratigraphy, facies, and paleogeography of the Pakawau Group. His data consisted of an outcrop located in Northwest Nelson of the South Island, and the Cook-1, Cape Farewell-1, Fresne-1 wells, Rakopi Borehole, UC1, UC2, UC3, UC4 coal exploration wells. He concluded there was a distinct seismic reflection horizon that defined a regional surface, thus separating the Pakawau Group into the North Cape and Rakopi Formations. His study is the first publication in the New Zealand Stratigraphic Lexicon to suggest divisions of the Late Cretaceous Pakawau Group into the North Cape and Rakopi Formations. The characterization of the Rakopi Formation was defined seismically by high amplitude, hummocky, and laterally discontinuous reflectors in contrast to the North Cape Formation that displays more uniform, parallel-layered reflectors (Thrasher, 1992).

The stratigraphic evolution of the Taranaki Basin is heavily influenced by the development of the regional tectonics. Evidence of the rift megasequences system in the Taranaki Basin begins with the Jurassic and Early Cretaceous synrift sediments followed by the post rift progradation of the Taranaki Delta of the Late Cretaceous Rakopi Formation. The presence of the Taranaki Delta in the deep-water basin demonstrates that there were sufficient erosion and fluvial conduits transporting sediments from the uplifted hinterlands to the restricted seaway at the head of the New Caldonia Basin (Uruski et al., 2003; Strogen, 2017).

Uruski et al. (2003) expounded upon these facies defined on the continental shelf out into the Deep-water Taranaki. Techniques included sequence stratigraphy combined with seismic character tied to well stratigraphy near the shelf edge. The results were regional paleogeographic maps of depositional facies that suggest the presence of a range of source rocks within the Late to Early Cretaceous successions. Results of this model were then compared to analogous basins that originated from the Tasman rift such as the Gippsland Basin of Australia. Conclusions of the study revealed similar depositional environments of the Late Cretaceous and Paleogene units in the Australian and New Zealand Basins.

Large late Cretaceous deltas containing extensive coal-bearing units exist at both locations. These units in the Gippsland Basin are known as the Emperor sub-group and are located in the Taranaki Delta of the Taranaki Basin (Uruski et al., 2003). Interestingly this subgroup of the Gippsland Basin contains proven petroleum accumulations (Megallaa et al., 1998; Baillie et al., 2004). Their study resulted in definition of a series of 4 megasequences known as A, B, C and D used to define the systems tracts of the Pakawau Group and Paleogene units (Figure 2 and 4) (Uruski et al., 2003; Baillie et al., 2004).

3.3 Megasequences

Two megasequences and the lower portion of a third megasequence defined by Uruski et al. (2003) and Baillie et al. (2004) known as A, B, and C fall within the Cretaceous time period (Figures 2; 3). The megasequences are characterized as follows: A, a syn-rift succession and transgression of Jurassic to Early Cretaceous age; B, a prograding deltaic succession known as the Taranaki Delta; C, a transgressive coastal plain succession, and D, a regressive system that is direct result of modern day plate boundary development (Uruski, 2007). In addition, the term

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"Basement" has been informally utilized in the region to name the rocks that unconformably underlie Megasequence A. Although this unit varies in composition, within the Taranaki Basin it is called the Separation Point Granite and is generally classified as Paleozoic metamorphic, submetamorphic granitic rocks (Bishop, 1992).

3.3.1 Megasequence A

Megasequence A took place 160 to 105Ma (Oxfordian – Albian) (Uruski, 2007). These syn-rift sediments are thought to have been derived from local fault scarps initiated by the rifting of the nearby New Caldonia Basin (Suggate, 1990). As a result, these units are dominated by coarse clastic rocks and interwoven fluvial deposits that transported sediments from the Gondwana hinterland (Uruski, 2007). Low-lying areas are likely to have contained swamps, marshes, and lacustrine environments depositing organics and fine-grained sediments (Uruski, 2007). The presence of Jurassic age sediments has been a subject of debate in the region, but the discovery of high bituminous coals from a core of the Huriwai Beds in the Wakanui-1 well (Figure 1) core dated to the Jurassic have proved its presence on the northern continental shelf (Suggate, 1990). Little is known about the Jurassic and Early Cretaceous succession except that the sediments are likely to be terrestrial and contain coals and coaly mudstones (Uruski, 2015). The upper boundary of this succession is defined by a hiatus at approximately 105 Ma and is seismically recognized by a downlap by the overlying megasequence B (Uruski, 2007).

3.3.2 Megasequence B

Megasequence B took place approximately 105 to 75Ma (Cenomanian-late Campanian) and contains the most effective source rocks in the basin. This megasequence coincides with the

end of rifting in the New Caldonia basin and the onset of extension in the proto-Tasman Sea (Uruski, 2015). This overall regressive phase was interpreted by Uruski et al. (2003) and Uruski (2007) to have four 2nd order sequences within the Taranaki Delta sequence. Sequence B1 represents a highstand system tract that thickens to the northwest and then tapers to zero near the center of the deep-water basin (Figure 4) (Uruski et al., 2003). Also, a highstand systems tract, B2 resembles a typical "slug model" thickening (Vail, 1977) basinward from zero to approximately 750 milliseconds twt (Uruski et al., 2003). Eventually B2 tappers to zero approximately 50 km away from the shelf edge as it downlaps onto B1(Uruski et al. ,2003). A relative sea level rise is recorded B1 and B2 that is related to tectonic driven subsidence from the extension of Tasman Rift (100 – 80 Ma) (King et al., 1999; Norvick et al., 2001; Uruski et al., 2003; Uruski, 2007). These units are interpreted to be the time equivalent of the Emperor subgroup in the Gippsland Basin (Uruski, 2015). A low stand systems tract, B3 is identified with high-amplitude reflectivity that onlaps onto B2 with complex internal reflectors that may be representative of turbidite sandstones (Uruski et al., 2003). Following a transgression or rise in relative sea level, B4 continues a renewed progradation across B2 and the lowstand wedge of B3. High amplitude topset beds are prominent and tie to the Rakopi Formation coal measures of Tane-1 well (Uruski et al., 2003; Uruski, 2007). B5 is a distal lowstand wedge located northwest of B4 and onlaps onto B4 (Uruski et al., 2003)

The lowstand B3 unit of the Rakopi Formation in the Maui-4 well, which is located approximately 30 km east of the Maari field, is split into two coaly units and separated by a thick 35m marine sand unit (Uruski, 2007). Palynological evidence suggests the presence of abundant vegetation occupying the delta and transported across the basin floor by turbidites during these low stands (Uruski, 2007). The Mahakam and Sabah deltas of offshore Kalimantan are

analogous examples of these delta systems that have carried large volumes of plant material into the deep-water during low stands (Sykes, 2007). Therefore, most parts of the Taranaki delta should contain significant amounts of organic matter for kerogen formation (Uruski, 2007; Uruski, 2015).

3.3.3 Megasequence C

Megasequence C spans 75 to 25Ma (Campanian – Chattian) (Uruski, 2007) and was deposited during the intracontinental rifting which slowed and eventually initiated subsidence that persisted into the Paleogene (Thrasher, 1992). Transgression reached peak flooding stage around 66.5 Ma and was soon followed by a Paleocene regression that was restricted to the southern part of the basin (Thrasher, 1990). The previously established depositional basins of the Rakopi Formation were flooded and became depocenters for the marginal marine clastics of the North Cape Formation (Thrasher, 1990).

3.4 Source Rocks and Petroleum Potential

The temporal relation between geologic events and the burial–temperature history of the source interval controls generative potential for oil and gas. Elements such as favorable depositional environments and types of organic matter define the dominate type of hydrocarbons that might be expelled from a potential source interval (Table 1; Figure 5). The generative process begins with the accumulation and preservation of organic matter, and proper thermal maturation to create polymers and macerals known as kerogen (Walters, 2007). Since the generation of these compounds requires a considerable amount of time, a source rock can be classified as potential, effective, relic effective or spent (Law, 1999). The two classifications of

interest in petroleum exploration are potential and effective source rocks. Potential source rocks contain the necessary organic matter in sufficient quantity but require additional thermal maturation, whereas effective source rock is currently generating and expelling hydrocarbons to form commercial accumulations (Law, 1999). The level of maturation reached for effective production can vary depending on the kerogen type present.

The Rakopi Formation in the Taranaki Basin has been proven on the continental shelf and is dominantly Type III, gas-prone in composition (Table1) (Killops and Sykes, 2003), but recent discoveries in the Maui field have revealed the Rakopi Formation to be more Type II oil and gas-prone than initially believed (Uruski et al., 2003). Based on the kerogen type, thermal maturity is reached at a specific temperature of thermal cracking. This is typically evaluated by Rock-Eval Pyrolysis as S1 and S2 peaks (Espitalie et al., 1977, Hunt, 1979, Peters, 1986). The amount of generated hydrocarbons within the source rock sample is known as the S1 peak and the S2 peak indicates the remaining generative potential based on additional heating of the sample.

Table 1. Types of effective source rocks

Type	Kerogen Type	Origin	Hydrocarbon Potential	Environment
I	Sapropelic	Algal and Spores	Oil Prone	Marine and Lacustrine Settings
II	Mixed Origin	Phytoplankton, Zooplankton, and some land-derived plants	Oil and Gas Prone	Shelf breaks and Delta fronts, and at base of shelf slope break
III	Humic	Predominately land -derived plants	Gas Prone	Delta plain and Estuaries
IV	Inertinite	Recycled land plants	None	Oxidizing

The Rakopi Formation is expected to improve in source rock quality and maturation following a northwest trend from the outcrop to the proven source in the Tui, Maari, and Maui fields (Browne et al., 2008; Killops and Sykes, 2003; Uruski et al., 2003) and basinward into the

deeper region of the basin (Figure 1). Following this same trend, the Rakopi Formation's depositional environment transitioned from terrestrial coastal plain swamps to lower delta plain swamps and finally prodelta slope as the Taranaki Delta prograded into the Tasman Rift (Figure 4) (Brown et al., 2008; Sykes et al., 2004). If the distal environments exist in the deeper regions of the basin, then the Rakopi Formation is likely to be influenced by saline rich marine waters where anoxia preservation of organic matter may have enhanced the source rock preservation and generative potential (Browne et al., 2008). These deeper facies may contain Type I, oil-prone, marine algal source facies in contrast to the non-marine, coal-rich Type III source facies previously described.

The Rakopi Formation was not considered a significant source for oil and gas until production at the Tui, Maari, and Maui fields found more oil prone kerogen than anticipated (Killops and Sykes, 2003; Uruski et al., 2003). This led Sykes et al. (2004) to improve the understanding of organic facies controls on generation and expulsion of oil and gas in the Rakopi Formation through analysis of an outcrop adjacent to the Paturau River. A multivariate analysis of bulk chemistry, petrography, and pyrolysis-gas chromatography of the Rakopi humic coal seams revealed substantial evidence for marine influence (Sykes et al., 2004). Sykes (2001) defined an upper limit of total sulfur content for regional coals that accumulated in entirely terrestrial environments as 0.5%. The 10 Paturau River coal seams had total sulfur contents of 0.51–0.78% and followed a trend of decreasing to increasing total percent of sulfur, which suggests a low degree of downward percolation of sulfate-rich waters following a marine transgression (Sykes, 2004).

In addition to Sykes et al. (2003) and Sykes (2004), Browne et al. (2008) conducted a predominately outcrop-based study utilizing sedimentology, petrography, stratigraphy, and

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depositional environment interpretations to investigate preliminary insights and evaluate a newly exposed outcrop of the Pakawau Group at the Paturau River. Browne et al. (2008) rejects the hypothesis of downward percolation as an unreasonable assumption due to the interbedded mudstones that exist in the Rakopi that would present significant barriers to fluid flow. This trend is more likely caused by the brackishness of successive peat mires that resulted from marine influences shortly after deposition (Browne et al., 2008). The palynological sampling found dinoflagellate cysts at the Forestry Block location, which confirms this marine influence in the Upper Rakopi Formation (Browne et al., 2008). Interestingly, dinoflagellate cysts were not detected at the Paturau River location where Sykes (2004) discovered elevated sulfur values. Browne et al., (2008) determined that the sulfur content of coals is a better indicator for marine influence than fossils in coastal plain settings because dinoflagellate cysts require higher salinity to exist.

Contrasting King and Thrasher's (1996) statement of no evident marine influence in the Rakopi Formation, Browne et al. (2008) concluded that there is irrefutable evidence from three different marine sources at several locations within the Rakopi Formation. If there are sulfate influences such as a transgression of the shoreface, the generative potential and oil-proneness would be enhanced. This potential can be attributed to the higher hydrogen indices and organic sulfur contents of the coal seams in the Rakopi Formation that would result in an earlier generation of oil and a greater proportion of oil to gas (Sykes, 2004; Browne et al., 2008). There should be a significantly greater chance of marine influence in the Rakopi Formation north of the outcrop area and into the present day offshore region (Browne et al., 2008). The location of this outcrop is proximal to uplifted areas that occurred between the two rifting phases. Initial observations can be made that the location of the Romney Survey will be an extension of the

depositional system seen in outcrop. This investigation plans to support this hypothesis, but it may be an oversimplification due to the dramatic lateral variability that can exist in extensional basins.

4. Data

The primary data for this study is the Romney 3D pre-stack time migration (PSTM) seismic survey, Rock-Eval Pyrolysis data, and the Romney-1 gamma ray and mud log. The data is included in the 2016 New Zealand Petroleum Exploration Data Pack that was curated for sale by the New Zealand Ministry of Business, Innovation and Employment (New Zealand, 2016). Additional information and data such as biostratigraphic and petroleum reports were acquired through the publicly accessible Petroleum Exploration Database maintained by the New Zealand Government.

Seismic parameters for the Romney survey within the Rakopi Formation interval are located in Table 2. The Romney–1 well was operated by Anadarko NZ Taranaki Co. and is located in the northwest quadrant of the Petroleum Exploration Permit block (PEP) 38451 approximately 80km northeast of the Wainui-1 well (Figure 1). The spud date was November 26, 2013 and was drilled by Noble Drilling Corporation. Reaching a measured depth of 4619m MD and a true vertical depth from the sea surface of 4594m TVDSS on January 20, 2014.

The Romney – 1 well report was published February 10, 2015 (Rad, 2015). The well bore reached the Rakopi Formation at 3784m MDRT where a sequence of graded and sandstone and carbonaceous siltstones was encountered. This sequence is composed primarily of fluvio-deltaic sediments with coal seams. The coals and carbonaceous material are the secondary source interval and have been a proven source in the upper part of the sequence (Rad, 2015). The

primary source target for the Romney-1 well was the marine shales located at the base of the Taranaki Delta (Rad, 2015).

The Romney-1 well was classified a dry hole and plugged and abandoned (Rad, 2015). There was no indication of moveable hydrocarbons and the primary and secondary reservoirs were close to or on the regional water gradient. Although the well was dry, it does not necessarily condemn production potential elsewhere in the basin.

The top of the Rakopi Formation or Taranaki Delta was intersected at depths of 3780 m MD and the base of the unit was reached at 4415m MD. Wireline gamma logs were recorded through the entire Rakopi Formation. The primary source intervals were anticipated to be the transgressive prograding delta shales near the base of the Taranaki Delta (Rad 2015). The Romney-1 well is the first to drill this interval in the deep-water and was expected to be charged as it was deposited during the global anoxic event and is the Taranaki equivalent to Gippsland Basin analogs. The Late Cretaceous Rakopi fluvio-deltaic section that contains coal measures are seismically correlative to the Tane-1 well where it was proven to be immature (Rad 2015).

A geochemical analysis was conducted by Intertek Geotech providing an evaluation of hydrocarbons from gases and cuttings recovered while drilling. Evaluations consisted of thermal maturity, total organic carbon (TOC), Hydrogen Index (HI), Oxygen Index (OI), and Rock-Eval Pyrolysis. A total of 32 rotary sidewall core samples were taken from depths 3365m – 4615m and were submitted for (TOC) and Rock Eval Pyrolysis (Phillips 2014). Out of the 32 samples only 16 were collected from the Rakopi Formation (3784 m – 4441 m). These samples were extracted with organic solvent in order to negate alterations or contaminations from drilling fluids or additives (Phillips, 2014). Cutting sample results were not used for the geochemical analysis in this study due to the contamination from the mud additive 'Ecotrol' which alters any

potential oil shows. By using sidewall cores, any contamination from additives is minimized. Values of TOC were recorded as weight percent, and S1 and S2 values were given in milligrams of distilled hydrocarbons per one gram of rock; S1 is representative of the free hydrocarbons and S2 as kerogen with remaining potential hydrocarbon yield upon further heating.

5. Methods

5.1 Seismic

The Romney 3D survey was uploaded to a Kingdom project along with a previously constructed synthetic seismogram of the Romney–1 well tied to the Romney 3D survey. Depth is converted using time-depth curve supplied in the purchased Data Pack (Figure 6). Resolution calculations are shown in Table 2 and were done using the average interval velocity as 3486 m/s. Frequency values of 25 – 35 Hz were gathered from spectral analysis for a seismic volume below the top of the Rakopi Formation at 4.6 – 5.6 ms. Dominant frequency is 30Hz and the dominate wavelength is approximately 116.2 m. Vertical resolution was calculated using $\lambda/4$ and is therefore 34.8 m and theoretical lateral resolution using $\lambda/2$ is 69.7m. The Romney 3D inline bin (NE-SW) dimension is 25 m, so the lateral resolution in that direction is 25 m and the crossline (NW-SE) bin is 12.5 m, so the crossline lateral resolution is 22.5 m.

The Rakopi interval was found to be particularly noisy due to seismic anisotropy caused by the coal beds in the upper section (Gray, 2005). Analysis of the Romney 3D survey was conducted after noise reduction processing. A bandpass filter was applied within the Taranaki Delta interval using a high pass value of 40 and cut value of 55.

Key horizons were identified such as the top of the North Cape Formation (top of Pakawau Group), top of Rakopi Formation, syn-rift units, and basement (Figure 7). Within the

Rakopi Formation seismic stratigraphic interpretation was based on the recognition of regional

structures, internal reflection configuration, reflection amplitude, frequency, continuity, and

boundary relationships.

Table 2. Main parameters for the Romney 3D survey

Seismic Survey			
Name	Romney 3D	Sample rate	4 ms
Survey type	3D	Record length	8.04 s
Environment	Marine	Dominant frequency	30Hz
Acquisition year	2011	Rakopi interval velocity	3486m/s
Area	35x55 km	Rakopi vertical resolution	34.8 m
Bin size	12.5x25 m	Rakopi lateral resolution	22.5 m

Distinctive terminations such as toplap, downlap, onlap, and truncations define structures

in the Taranaki Delta of the Rakopi Formation such as topsets, foresets, bottomsets, and

condensed sections. These definitions lead to an understanding of depositional history such as

stratigraphic responses to sea level and accommodation space. Seismic geometries and

geomorphological characteristics are used to further define seismic facies and extrapolate

interpreted depositional environments beyond the well bore within the Taranaki Delta

succession. Seismic facies were defined on the basis of reflection continuity, amplitude, and

relative frequency as described by Mitchum et al. (1977). A set of thickness maps for each of the

horizon time intervals T1, T2, and T3 were generated using the following equation:

$$H_{interval} = V_{interval} \left(\frac{T_2 - T_1}{2000} \right) \qquad (1)$$

Where $H_{interval}$ is the thickness of the interval, $V_{interval}$ is the interval velocity, T_2 is the two-way

time at bottom boundary, and T_1 is the two-way time at the top boundary

The Pakawau Group was initially divided into megasequences as defined by Uruski and Baillie (2003) (Figures 2 and 4). Sequences within megasequence B were then identified in the Romney 3D survey. Clinoforms of sequence B1 were found on the 2D seismic lines, DTB01-17 (Figures 4 and 8) and DTB01-15. DTB01-15 intersects the Romney survey allowing for the correlation of megasequence B between the surveys. Figures generated will be thickness maps between time horizons, facie distributions and paleogeographic maps at time horizons.

5.2 Well Log

Log motif analysis was used to define gamma ray log facies, identify representative stacking patterns, and interpret environmental associations. The summary for the well information is shown in Table 3. Five motif types were observed in the Rakopi Formation between 3784 m and 4441 m: Funnel-, bell-, barrel-, box car- and serrated-shaped (Figure 9). Motif shapes are non-unique and may indicate more than one depositional environment, therefore lithologic and biostratigraphic interpretations from the well report are utilized in this study to calibrate motifs to a relative depositional environment. Motif analysis is a powerful tool as long as there is a regional context within which to interpret their characteristics and distribution.

Ideally a conventional core would be used to calibrate the log facies interpretations, but unfortunately core was not extracted from the Romney-1 well. The lithologic interpretations in this study utilized well cuttings descriptions provided in the petroleum report PR4951. Morgan Goodall Palaeo Pty Ltd conducted biostratigraphic interpretations such as relative proportions of dinoflagellates (marine) to miospores (terrestrial) as paleoenvironment indicators that were provided in the petroleum report PR4935 (Phillips, 2014).

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Gamma ray motif definitions are illustrated in Figure 9 and defined as follows: bell-shaped responses have a thickness of approximately 12m – 15m and are found in the lower to middle sections of the Rakopi interval. This shape is usually indicative of a transgressive shoreface, tidal channels, or fluvial deltaic channels (Selly, 1998). Tidal channels typically have associated limestone deposits from shell debris accumulation (Nelson and James, 2000), whereas carbonaceous material is typically found in the fluvial or deltaic channels (Selly, 1998).

Funnel-shaped gamma responses have a thickness range of 10 m – 20 m and are found throughout the section. Representative of coarsening and/or thickening upward profiles suggesting a shallowing environment, the funnel shape motif can be divided into three categories: regressive barrier bars, prograding marine shelf fans and prograding deltas (Selly, 1998).

The box car-shaped gamma motif is characterized by a sharp base and top and is typical of fluvial channel sands, distributary channel-fill, turbidites, and aeolian sands (Emery, 2009). Relative thickness of these depositional environments can vary significantly, and the overlying and underlying environments in the section aid in distinction of these sand-rich systems.

Serrated motifs can be indicative of aggradational muds and silts deposited in deep-water, fluvial flood plains, or distal lower shoreface (Emery, 2009). It is difficult to distinguish these depositional environments solely from the gamma response. As a result, paleoenvironment indicators such as miospore and dinoflagellates proportions, mud log lithologies, and relative position along seismic profiles allows for the distinction between marine versus terrestrial deposits. Finally, barrel shaped motifs are indicative of progradation followed by a regression. This can occur in a proximal or distal location; therefore, grain size and proportions of paleoenvironment indicators must be considered in order to determine this shape's relative

location. Accumulation and preservation of varying types of organic matter with unique

geochemical responses can be tied to associated depositional facies based in part on these gamma

ray motifs. Figures generated will be a butterfly log of the gamma ray with selected motif

descriptions and a percent lithology of the lithology log.

Table 3: Well Summary

Romney-1 Well	
Name	Romney-1
Well Type	Vertical wildcat exploration
Spud date	26-Nov-2013
Completion date	20-Jan-2014
Rig type	Drillship
Latitude	37° 53' 39.337" S
Longitude	172° 43' 52.719" E
Drilling floor	25 m above sea level
Water depth	1546.6 m lowest astronomical tide
Total depth	4619 m measured depth
Total depth	4594 m TVD subsea
Result	Dry hole
Logs	Gamma/Resistivity/Sonic
Side Wall Samples	32 total

5.3 Source Rock

Hydrogen Index (HI) and Oxygen Index (OI) are used to determine kerogen type (Tissot,

1974; Durand et al., 1974; Espitalie, 1977; Hunt, 1979; Sabin, 2004). Typically, higher hydrogen

index values are attributed to lipid and protein rich marine organic matter whereas the

carbohydrate-rich land plants have a lower hydrogen index (Tissot et al., 1984). Type III, gas

prone kerogen typically has a HI range of 50 – 200 HC/ g TOC; Type II/III gas and oil prone

kerogen has an HI range of 200 – 300 HC/g TOC, and Type I, oil prone kerogen is generally greater than 300 mg HC/g TOC (Pepper et al., 1995).

Rock Eval Pyrolysis records the S1, S2, and S3 peaks at increasing relative temperatures. S1 is representative of free hydrocarbons within the source rock at 300°C. S2 is the percentage of additional, generated hydrocarbons and is measured at "maximum output." The temperature at S2 peak is recorded as Tmax, while S3 is the release of organic bound CO_2 at temperatures beyond the S2 Tmax between 300°C to 550°C (Espitalie et al., 1985; Hunt, 1979; Phillips, 2014).

In addition, the quantity of organic matter referenced as total organic carbon (TOC) is measured in weight percent. Source rock TOC can be described as poor, fair, good, very good, or excellent depending on the weight percentage of TOC in the samples (Peters et al., 1994). Poor source rock typically has TOC values below 0.5% while a fair TOC value ranges from 0.5 – 1% weight percent. Good source rock has a weight percent value between 1 – 2%, very good 2 - 4 %, and excellent typically has values greater than 4% (Peters, 1994).

Furthermore, the Production Index (PI = S1/(S1+S2)) assesses the overall maturity for a homogenous section (Hunt 1979). The generative potential (GP) is determined by comparing the S1+S2 relative to TOC percent (Hunt, 1979). Originally, Hunt (1979) combined S1 and S2 and compared to TOC on a cartesian coordinate system. This method was not used for coaly source rocks but rather marine organic rich shales. In this study the utilization of S1 + S2 is divided by TOC (GP = (S1+S2)/TOC) to gain a quantitative comparison and estimation of producible hydrocarbons out of the entire organic constituents of the coals. Figures generated will be a geochemical evaluation table and a modified Van Krevelin diagram.

6. Analysis

6.1 Seismic Analysis

The B1, B2, and B4 subdivisions of megasequence B are contained in the Romney survey but they all do not exist throughout the entire survey (Figure 4). These sequences are illustrated in the idealized cross section of Figure 10. The base of B1 was defined by the downlap surfaces onto the basement. Sequence B1 was identified by divergent reflection patterns that exist in the southwest corner of the survey. The base of B4 and the top of B2 were defined by their contrasting reflection continuities and amplitudes. These sequences change from high amplitude and semi continuous seismic facies to low impedance contrast and continuous seismic facies. The top of sequence B4 was selected on a peak above high amplitude events and corresponds to the top of the Rakopi Formation. Sequence B3 is defined by Uruski et al. (2003) to be a lowstand systems tract and is not deposited in the Romney 3D Survey illustrated by its pinch out to the southeast (Figure 4).

Five seismic facies were defined within these sequences: 1, 2, 3, 4, and 5 (Figure 11). The type section in which all five facies are encountered is shown in the crossline of Figure 12. Seismic facies maps and associated paleogeographic reconstructions were generated along three time slices indicated as T1, T2, and T3 on Figure 10. The paleoenvironment interpretations of facies 1, 2, and 3 are supported by log motif and biostratigraphic data from the Romney–1 well. Facies 4 and 5 occur basinward of the well location and are only developed in a stratigraphic interval deeper than the well TD (Figure 10). Figures 6 and 13 illustrates the seismic facies tie at the Romney–1 well tie. The lateral distributions of seismic facies 1 – 5 are illustrated on a series of facies maps for T1 through T3 (Figure 14, 15, and 16). The thickness maps at the time horizons define relative stratigraphic strike and dip directions as well as areas of high and low

accommodation (Equation 1; Figures 17, 18, and 19). Paleogeographic reconstruction of the T1

through T3 time slices based on these maps calibrated with log motif and biostratigraphic data is

presented on Figures 20, 21, and 22.

Facies 1 is characterized by high amplitude, high frequency, and variable to low

continuity which is consistent with coaly delta plain to coastal plain environments (Figure 11).

This unit becomes thicker towards the northeast (Figure 17, 18, and 19). The distribution of

facies 1 is most restricted on the T1 map (Figure 14) and expands through time until it dominates

T3 map. (Figures 15 and 16).

Facies 2 is characterized by variable to high amplitude, high continuity and moderate

frequency and is interpreted as sand-rich, marginal marine environments (Figure 11). Marine

conditions and reworking of sediments yield broader, sheet-like depositional elements that

produce a greater degree of continuity. The exact boundary between facies 1 and 2 is difficult to

define due to the variability of reflector continuity resulting from rapid lateral shifts of the

shoreline. Facies 1 locally displays higher continuity near its transition to facies 2 (Figure 12).

The map view shows the extent of regression as facies 2 diminishes between time slices T1 to T2

(Figure 14 and 15). As an overall regression occurs facies 2 is only seen in the westward corner

of the Romney Survey at time T3 (Figure 16).

Facies 3 exhibits low amplitude with variable continuity (Figure 11). This indicates lower

internal impedance contrasts suggesting a lower sand content resulting in an overall low

amplitude. Some degree of continuity is observed due to internal impedance contrasts consistent

with mud-rich inner shelf deposits containing broad sheets of silts and thin sands. In comparison,

facies 4 is characterized by low amplitude and limited to no continuity indicating a near

complete lack of internal impedance contrasts. This suggest a low sand content and minimal

lithologic variability. Facies 4 is dominated by muds on the distal shelf near the shelf break. At time T2, facies 3 dominates the map and facies 4 is not present. This suggests that regression and associated progradation have advanced across the survey replacing the facies 4 and 5 observed on the T1 seismic facies map with facies 3 on the T2 seismic facies map (Figure 15).

Finally, Facies 5 is a moderate to high amplitude, moderate continuity seismic facies that exhibits inclined reflectivity as a seismic foreset geometry. It is bounded at its base by a downlap surface and a toplap surface at its top boundary (Figure 12). This downlap surface is the beginning of the condensed section that continues beyond the Romney 3D Survey to the northwest (Figure 10). The inclined internal reflector geometry indicates a progradational stratigraphic architecture consistent with an advancing delta slope setting. It is restricted to the northwest corner of the T1 facies map (Figure 14) and does not exist on the T2 and T3 maps. Since facies 5 was deposited at the prodelta slope it marks the up-dip transition to deep marine environments to the west. Consequently, at time T1 water depth shallows toward the east and deposition proceeds through facies 4, 3, 2, and 1 in that eastward direction (Figures 14 and 17). These seismic facies are indicative of specific lithologic responses and were calibrated using the following mudlogs and biostratigraphic environment interpretations.

6.1 Well Log Motif and Lithology

The Romney – 1 well penetrated seismic facies 1, 2, and 3 (Figure 9). The gamma-ray log exhibits 5 log motif geometries that can be linked to individual depositional elements within the seismic facies. These motifs include: bell (confined flow channels), box car (sand rich with sharp base and top such as fluvial or distributary channel fills), funnel (unconfined, upward coarsening/thickening such as progradational shore or deltaic deposits), barrel (upward

thickening overlain by upward thinning such as in distal shelf or fluvial overbank settings) and serrated (vertically aggradation, mud-rich intervals such as outer shelf or distal fluvial overbank). Log motif is a non-unique solution but when integrated with seismic facies can provide a degree of calibration to the overall depositional and paleogeographic interpretations.

Observed lithology integrated with the ratio of miospores to dinoflagellates is used to further analyze the depositional environment through the section. Figure 23 presents the percent lithology with depth through the Rakopi Formation. The initial report interpreted the depositional environment of the Rakopi Formation to transition from marine at the base to terrestrial at the top (Phillips, 2014; Schioler et al., 2014). This is punctuated by multiple higher frequency cycles of transgressions and regressions in between. Log motif results and depositional environment interpretations are as follows and were complimentary to the biostratigraphic interpretations.

Beginning at the base of the section the Romney–1 well seismic facies 3 transitions from open marine to marginal marine environments. Higher frequency events occur in this facies as alternating bell and funnel shaped geometries (Figure 9). This indicates a transgressive shoreline followed by prograding shelf fans. Specifically, the bell shape located at 4352 m is likely to be a small-scale channel in transgressive pro-delta environment due to the dominant siltstones and minor carbonaceous material with little to no calcareous material (Figure 23).

Log motifs from 4460 m up to 4185 m characterize seismic facies 3. The depositional environment in the lower half of seismic facies 3 is more indicative of an inner shelf, distal prodelta because it is dominated by siltstone and has local carbonaceous stringers (Figure 5, 9 and 23). Based on the depositional scale of the funnel shapes in this section they are likely the result of a prograding delta. Crevasse splays have a much smaller scale of 1 m-6 m. A maximum flooding surface occurs at 4390 m and contains increased organic matter that defines source

interval 3. The lithology becomes dominated by sandstone and exhibits a barrel shaped motif in the upper half of seismic facies 3 (Figures 9 and 23). Since this motif is dominated by sandier lithologies it indicates a more proximal environment in the delta front and an overall advance of the shoreface (Figure 5). Source interval 2 spans the boundary of seismic facies 3 and 2 at 4190 m and indicates a high frequency transgression with associated base level rise.

Log motifs from 4185 m up to 4030 m characterize seismic facies 2 which is interpreted as a band of marginal marine deposits separating the inner shelf deposits of seismic facies 3 and the terrestrial coastal plain deposits of seismic facies 1. Seismic facies 2 suggests an overall shallowing of base level. The transition from marginal marine to terrestrial coastal plain environments is illustrated by the dominate small scale bell and funnel shaped motifs (Figure 9). Successively stacked bell and funnel-shapes indicate high frequency regressive - transgressive cyclicity in the lower half of seismic facies 2 (4110 m – 4200 m) (Figure 9). This section contains graded beds of sandstone and carbonaceous siltstone with persistent coal seams ranging from .5 – 1m thick making up 5 – 20% of the lithology (Figure 23). This reflects the gradational nature of the contacts between the seismic facies 2 and 3. This gradational character suggests a local advance of a proximal delta front environments overlain by lower delta plain indicated by abundant carbonaceous material, lack of shell debris, and numerous coal beds (Figures 9 and 23)

Two large successive bell-shaped geometries that contain graded beds of sandstone and siltstone capped with limestone lithologies are developed in the upper half of seismic facies 2 (Figures 9 and 23). Although the decrease in grain size and the presence of an overlying limestone show an overall transgression for this interval, a dominate amount of miospores relative to dinoflagellates suggests a more near shore environment.

The log motifs from 4110 m up to 3780 m (Top of Rakopi) characterize the depositional environments of seismic facies 1. This interval is interpreted to be marginal marine to terrestrial based on the low proportion of dinoflagellates to miospore counts. This interval contains two serrated motifs and single box car geometry. The serrate motifs reflect aggradational fluvial flood plain deposits. These are locally cut by sand filled fluvial channels indicated by bell and box car motifs (Figure 9). This facies is dominantly terrestrial coals and siltstone and contains the primary source interval 1, in the upper half of its thickness (Figure 23).

Interestingly there is a limestone bed capping the uppermost coaly unit defined as source interval 1 (Figure 23). This overlying limestone indicates an up-dip transgression that affected the lower delta plain ecosystem as marine water infiltrated the swamp environments allowing more saline organisms to thrive. Since this higher frequency transgression occurred directly over coal beds the marine incursion enhanced the hydrogen of these coal units (Figure 24) and allowed more marine algal organic matter to accumulate. The mixed depositional environment and type of organic matter deposited by these sequences impacts the generation of specific kerogen types (Table 1) and can be analyzed for indicative geochemical responses through Rock-Eval Pyrolysis (Table 4).

6.2 Source Rock Quality and Lithology

The accumulation and preservation of organic matter depends on the source rocks relative depositional environments and can be quantitatively evaluated through geochemical analysis. The level of organic maturation and overall quality of the source rock at the Romney–1 location can be approximated from TOC, the relative HI to OI, the production index (PI), generation potential (GP), and Tmax at the S2 peak (Table 4) (Hunt, 1979).

TOC values in the Taranaki Delta are highly variable between 1.04% – 70% which indicates good to excellent source rock quality (Figure 24). TOC weight percent ranges from 1.22% at 3903 m to 70% at 3865m where coals were identified. The TOC content within all samples is within the good source rock richness trend (>1wt. %) (Phillips, 2014).

The HI values range from 138 to 400 HC/g TOC over the entire Rakopi section, indicating that parts of the section have potential for both liquid and gas generation (Hunt, 1979; Pepper, 1995; Sabin, 2004). The large variability in TOC values is due to differing amounts of coal throughout the section. In addition, the presence of liptonite maceral rich coals which are known as boghead coals (Hunt, 1979; Phillips, 2014) shows elevated HI. Boghead coals exhibit elevated hydrogen content due to a unique marine algal population present during deposition (Thiessen, 1923). This marine algal contribution may reflect periods of transgression and local marine incursions along the Rakopi coastline at that time. These HI responses are typically indicative of type I to type II kerogen (Figure 25), but in this case they are a result of higher concentrations of liptonite macerals and increased generative potential of type II/III coaly source rocks (Waples, 1985).

Three primary source intervals were selected based on their distinctive source rock characteristics. Two are coal-rich, marginal marine to non-marine deposits within seismic facies 1 and 2. These coal-rich facies are consistent with source intervals described by previous workers. The third may have a greater algal marine organic content linked to a period of transgression and highstand in seismic facies 3.

Source interval 1 extends from 3865 m to 3920 m (MD) and resides in seismic facies 1. It is highlighted in green in Table 4 and indicated on Figures 9, 23, and 24. This source interval is a coal rich interbedded siltstone and sandstone (Figure 23). Two samples at depths 3890m and

3870m have particularly good source qualities (Figure 24). Both samples are mature and have excellent TOC and type II kerogen (HI >300) (Figure 25) and maintain generative potential against their overall TOC. There are additional coal beds located in seismic facies 1 and 2 (Figure 23) that do not show as favorable source rock characteristics (Figure 21). Although the TOC is good, the HI is too low (HI <200) (Figure 25). These coals tend to occur in lower percentages and are more than likely deposited in an oxidizing environment in which most of the coals are disseminated into the sediments reducing organic matter preservation. Evidence for this is the dominance of carbonaceous siltstone throughout the facies (Figure 23).

Source interval 2 extends from 4175 m to 4180 m (MD). This interval is highlighted in red in Table 4 and shows excellent TOC, type II kerogen, and moderate generative potential. The limited generative potential relative to source interval 1 can be attributed to the degree of dissemination of organic matter deposited. Source interval 2 is dominantly carbonaceous siltstones with a low percentage of thin coals (Figure 23). Local marine incursions result in local deposition of marine algal kerogens combined with type III humic woody kerogen resulting in high hydrogen coals.

Source interval 3 extends from 4370 m to 4385 m (MD) and is shown in blue on Table 4 and Figures 9, 16 and 23. This interval is located just above the flooding surface identified by the fining upwards then coarsening upward log motif (Figure 9). The source rock characteristics of this unit are more indicative of marine shales rather than terrestrial coals such as source intervals 1 and 2. TOC values are good with HI values and are within the type II range (Figures 24 and 25). These marine shales are consistent with the maximum flooding surfaces interpreted within seismic facies 3 and log motif (Figure 9).

Table 4: Total organic carbon (TOC) and Rock-Eval Pyrolysis data for the analyzed samples (Data source: Phillips 2014). S1 and S2 values are in mg hydrocarbon/ g rock, S3 in mg CO_2/g rock, Tmax in °C, Hydrogen Index (HI) in mg hydrocarbon/ g TOC, Oxygen Index OI in mg CO_2/ g TOC, Production Index (PI) is equal to (S1/S2+S2), and Transformation Index (TI) is equal to (S1/TOC), and Generative potential or Source potential (GP) is equal to S1+S2/TOC. Source interval 1 is highlighted in green, source interval 2 is highlighted in red, and source interval 3 is highlighted in blue.

Depth (m)	TOC (wt.%)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	OI	HI	PI	TI	GP
3725.00	2.07	16.91	6.15	0.10	428.00	5	297	0.73	8.17	11.14
3865.00	69.90	52.93	246.94	4.76	422.00	7	353	0.18	0.76	4.29
3871.00	2.04	7.31	4.57	0.06	437.00	3	224	0.62	3.58	5.82
3895.00	9.73	7.29	30.93	0.46	429.00	5	318	0.19	0.75	3.93
3903.00	1.22	4.77	3.55	0.15	437.00	12	291	0.57	3.91	6.82
3919.00	29.81	9.22	58.13	2.04	429.00	7	195	0.14	0.31	2.26
4033.00	1.51	12.79	2.69	0.43	437.00	28	178	0.83	8.47	10.25
4075.00	1.63	6.01	3.11	0.32	429.00	20	191	0.66	3.69	5.60
4178.00	3.06	1.98	7.97	0.28	433.00	9	260	0.20	0.65	3.25
4197.00	10.49	4.51	39.44	0.24	435.00	2	376	0.10	0.43	4.19
4298.00	1.53	3.56	3.21	0.39	437.00	25	210	0.53	2.33	4.42
4303.00	2.15	1.98	5.40	0.66	434.00	31	251	0.27	0.92	3.43
4351.00	1.16	0.68	2.75	0.17	439.00	15	237	0.20	0.59	2.96
4370.00	1.17	1.95	2.66	0.42	437.00	36	227	0.42	1.67	3.94
4385.00	1.04	1.38	2.66	0.55	442.00	53	256	0.34	1.33	3.88
4442.00	1.36	0.60	2.48	0.15	441.00	11	182	0.19	0.44	2.26
								Average:	2.37	4.90

There is yet another potential source interval based on seismic stratigraphy alone. It is linked to a regional downlap surface at the base of seismic facies 5 (Figures 8 and 12). The distribution of this potential source interval is illustrated by seismic facies 5 on the T1 seismic facies map (Figures 14 and 20). The greater extent of this potential source facies can be inferred by the regional downlap surface at the base of sequence B1, B2, and B3 on the regional 2D profile (Figure 4). This is a typical seismic geometry related to condensed section that is generally characterized by type I (marine algal) kerogens. This suggests that the coal-rich source intervals that are considered the primary source facies for the proven hydrocarbon accumulations may be replaced by deep marine source facies as exploration progresses into the deep-water Taranaki Basin.

6.3 Integrated Interpretation

The Romney–1 is located in proximal depositional environments and reveals that there is significant potential for effective source rocks westward. Increased maturity and favorable source rock environments such as condensed section of sequences B1 and B2 are likely to exist westward of the Romney 3D Survey.

The Romney–1 well intersects seismic facies 1, 2, and 3 (Figure 13) and encountered three source intervals. Source interval 1 is terrestrial in origin, resides in seismic facies 1, and has the potential to be widely distributed (Figure 14, 15, and 16). This facies is relatively thick in the eastern half of the survey and thins to the west. Based on the available data in the Romney–1 well the uppermost coal-rich units exhibit good source potential given their high HI characteristics attributed to the higher liptonite maceral content relative to other coals in the Taranaki Delta. The liptonite rich coals are likely to occur between time T1 and T2 as the highly variable base level increases the likelihood of frequent incursions between facies 1 and 2. This would allow saline waters to inundate landward promoting production of algal organisms generating higher hydrogen content organics and improving the quality of organic matter.

Source interval 2 is marginal marine in origin and is located at the boundary between facies 2 and 3 (Figures 15 and 18). This source interval may extend northwest to southeast paralleling the paleo-shoreline at T2 (Figure 21) but is difficult to determine as it may be a local distribution of a tidal dominated delta. The distribution of this interval will be heavily influenced by local variables that are beyond the resolution of this study. A critical evaluation of the local structural influences during deposition will aid in future evaluation of this unit.

Source interval 3 is marine in origin and is located near the base of seismic facies 3 (Figures 14 and 23). The depositional environment for seismic facies 3 and source interval 3 is

the semi-proximal top sets of sequence B2. Beyond the western boundaries of the Romney 3D survey facies 3 is likely to transition into facies 4, and then facies 5, eventually transitioning into bottom sets creating a condensed section similar to sequence B1.

The construction of paleogeographic maps were made at horizons T1, T2, and T3 (Figures 20, 21, 22). At time horizon T1 the paleogeography reveals a westward progradation of the delta as the facies grade into deeper depositional environments (Figure 20). Large clinoforms are located in the northwest corner of the Romney survey indicating a deep marine environment as accommodation space is necessary to create divergent traces which characterize seismic facies 5. The paleo-shelf edge is located between facies 4 and 5 (Figures 14 and 20), and both foresets and top sets are present at this time.

At time T2 the Romney Survey contains three depositional environments: terrestrial, marginal marine, and nearshore/inner shelf (Figure 15). The terrestrial environment expanded westward relative to T1 and the marginal marine environment begins to narrow (Figure 21). By time T3 the Romney survey is dominated by terrestrial deposition with a small area of a marginal marine deposition in the northwest corner (Figures 16 and 22).

Since the Romney–1 was drilled on a basement high, sequence B1 was not intersected by the well. As a result, lithologic or geochemical analysis for these units could not be conducted, and therefore source rock quality cannot be evaluated. Even though these facies do not tie to the well bore, indicative seismic responses and Walther's Law (Gerard, 1973) allow for the interpretation of relative depositional environments. It is likely that sequence B1 would lack significant amounts of the established, coal bearing source facies in the area of the Romney 3D. However, it may contain marine source interval in the corner of the survey to the southwest.

Considering all three analyses of seismic facies, log motif interpretations, and geochemical analysis, a source rock distribution map has been constructed two distinct kerogen types (Figure 26). In the western most corner of the Romney 3D Survey there is the potential for type I marine algal deposition as the seismic facies 5 clinoforms downlap onto the underlying units and create a condensed section. The second source is type II/III terrestrial coal influenced by marine incursions located in the eastern most region of the Romney 3D survey.

Based on Figure 26, the Taranaki Delta has significant source rock potential and the addition of data from future deep-water wells will help refine the Taranaki Basin's effective source rock distribution and quality. The source rocks at the Romney-1 location are just reaching maturity and source interval 1 has a favorable depositional environment leading to preservation of organic matter and improved kerogen type. Source interval 2 is a potential source rock and may reach effective levels of maturity in deeper, basinward locations north of the Romney Survey. Source interval 3 is within the effective maturity range and has significant potential for westward development of distal, deep-water depositional environments such as the condensed sections of potential source interval 4.

7. Summary

Previous studies have defined the regional distribution of the Taranaki Delta (Uruski et al 2003; Baillie et al. 2004; Uruski 2007) and discovered similarities to the analogous Gippsland Basin of Australia. These studies utilized 2D seismic grids with well ties on the continental shelf to extend the Taranaki Delta's distribution into the deeper water (Uruski et al 2003; Baillie et al. 2004; Uruski 2007). The current study applies the most recent data from the deep-water region of the Taranaki Basin for initial source rock analysis and utilizes a finer seismic grid for facies

characterization and mapping depositional distributional facies within the boundaries of the Romney 3D survey.

This interdisciplinary approach revealed a similar conclusion to Brown et al (2008) which suggest a northwest deepening of depositional facies (Sykes 2004) would lead to improved oil generation from marine dominated source facies. The relative location and higher resolution 3D used in the current study allowed for the interpretation of depositional facies and the construction of local paleogeographic maps, whereas previous studies have generalized the regional stratigraphy of the basin (Figure 4). Furthermore, other investigations suggested this region to be charged by the same source units that are found in the Tui, Maari, and Maui fields (Killops and Sykes 2003; Uruski et al 2003). Previous basin modelling suggested the Taranaki Delta facies found at the Tane–1 well to be more mature and within the oil window (Killops and Sykes 2003; Rad 2015). Based on the Tmax values through the Rakopi section this study proved the previous statement to be true with the exception that not all the units seem to be within peak generation. The upper half of the Taranaki Delta is immature-mature whereas the lower half is mature (Figure 24).

The Romney 3D survey boundaries do not extend into the distal regions of the Taranaki Delta system, rather it contains the upper to lower delta plain topsets of sequences B4 and B2 with underlying delta front and lower delta plain of sequence B1 (Figure 4). This study has developed an exploration framework in the Deep-water Taranaki Basin by expanding upon previously defined sequences, defining their internal seismic facies, and linking those to depositional facies and associated source rock potential. Five seismic facies were defined and mapped across the Romney 3D survey (Figure 11). A series of three seismic facies and inter thickness maps were generated (Figures 14 - 19) to provide the foundation for three time slice

paleogeographic reconstructions (Figures 20 – 22). The internal facies interpretations were further supported by gamma ray log motif analysis and detailed lithologic characterization from existing sample descriptions (Figures 9 and 23). These maps illustrate the paleogeographic evolution through three time steps in the overall regressive/progradational history of the Taranaki Delta. This provided the framework for the analysis of potential source rock intervals within the Romney 3D survey.

The generative potential of the Taranaki Delta in the Deep-water Taranaki Basin has been a topic of debate. Geochemical analysis allows for the quantification of potential and effective source rock intervals (Table 4, Figures 24 and 25). Four potential source intervals are located in the Taranaki Delta of the Rakopi Formation and show potential for oil and gas generation. Source intervals 1 through 3 in the upper Taranaki Delta succession are confirmed with geochemical and log analysis. Source interval 4 is a potential deep-water source facies associated with condensed sections along downlap surfaces defined by seismic stratigraphic characteristics (Figure 8 and 12). Source rock intervals 1 and 2 contain type II/III kerogen within environments of the proximal delta front and the upper delta plain. Source intervals 3 and 4 contain type I kerogen within deep marine deposits. Considering that the Rakopi Formation is predominately terrestrial in nature the coal-rich units are generally assumed to be type III gas-prone source rocks. However, this study revealed the favorable depositional environments that accommodated improved kerogen development and preservation of liptonite macerals in the upper coaly units of the Taranaki Delta. This is consistent with the high hydrogen coals and supports the interpretation in this study of an oil and gas prone type II/III kerogen composition within the shallower, more proximal source intervals.

The geochemical analysis shows that source intervals 1 and 2 at the Romney–1 location are just entering the maturity window. Source potential and organic matter quality is generally good, and the kerogen type has the potential to produce both oil and gas. The Romney-1 was a dry hole due to lack of charge. There are two possibilities 1) migration of the hydrocarbons elsewhere into the basin or 2) a lack of maturity of the source intervals in the area of the well. Despite the limited well control, exploration potential still exists in this region of the Basin. Downlap surfaces of B1 found in the northwest corner of the survey could lead to marine algal, type I source rocks to the northwest of the Romney Survey following the apex of progradation (Figures 10 and 12).

8. Conclusion

The limitations of this study stem from the restricted well control and the placement of the Romney–1 well. It is located in proximal depositional environments and did not penetrate all five sequences present in the Taranaki Delta (Figures 10 and 13). This leads to a limited calibration of all potential source intervals, but it does not eliminate the insights supplied by this study into the nature of these source rocks and the planning benefits for future exploration projects. An improved understanding of the petroleum system in the Deep-water Taranaki Basin was accomplished by creating facies distribution maps and paleogeographic models to better define source potential of the Taranaki Delta.

This thesis confirms the production potential of the defined source intervals found in the Taranaki Delta succession of the Rakopi Formation located in the Deep-water Taranaki Basin. Organic-rich facies were identified by locating the high-quality source rock characteristics in the Taranaki Delta through geochemical analysis such as TOC, HI, OI, PI, GP, Tmax, and Rock-Eval Pyrolysis. In addition, specific depositional environments were interpreted and calibrated

using gamma ray log motif and biostratigraphy. Seismic reflection characteristics were then used to define internal reflection configuration, reflection amplitude, frequency, continuity, and boundary relationships to map depositional facies distributions and interpret the paleogeography.

Results suggest source potential for type II/III, oil and gas prone non-marine, coal-rich and the type I, oil-prone, marginal algal source facies. The majority of the Romney survey contains topset depositional environments with foresets to the northwest in the lower most sequence, B1. By mapping seismic and depositional facies within the survey and quantifying source rock characteristics, it can be concluded that the Taranaki Delta of the Rakopi Formation has potential source rocks in the Romney 3D survey. There is a good possibility of effective source intervals developed to the northwest. By using an interdisciplinary approach this thesis has improved the understanding of source rock quality and distribution of the Rakopi Formation in the Romney 3D survey. This better understanding of source rock distribution has advanced the knowledge of the Taranaki Delta petroleum system and will further enhance future exploration efforts in the deep-water portion of the Taranaki Basin.

9. Future Work

The depositional environment and quality of coaly source rocks are critical aspects to the exploration of a frontier basin such as the Deep-water Taranaki Basin. Therefore, the next step in the source rock analysis is the critical evaluation of the type II/III coals present in the terrestrial coal-rich sections of the upper Rakopi Formation utilizing volatiles and coal ranks (Sr) similar to Suggate (2000; 2006) or total sulfur content measurements similar to Sykes (2004).

Further investigations are needed in analyze the western regions of the basin where the prodelta slope was likely deposited and resulted in condensed sections of type I marine algal kerogen. The equivalent units of seismic facies 4 and 5 can be mapped across a broad area

beyond the limits of the Romney 3D based on the current 2D data as regional downlap surfaces. Additional 3D surveys basinward of the Romney 3D will further define facie distributions and extent of effective type I marine algal and type II/III terrestrial coaly kerogen. Wells drilled in this basinward region will give further insight into the distribution and quality of source intervals 1, 2, and 3 and whether or not these coals have enhanced generative potential similar to the upper Rakopi Formation at the Romney–1.

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11. Appendix
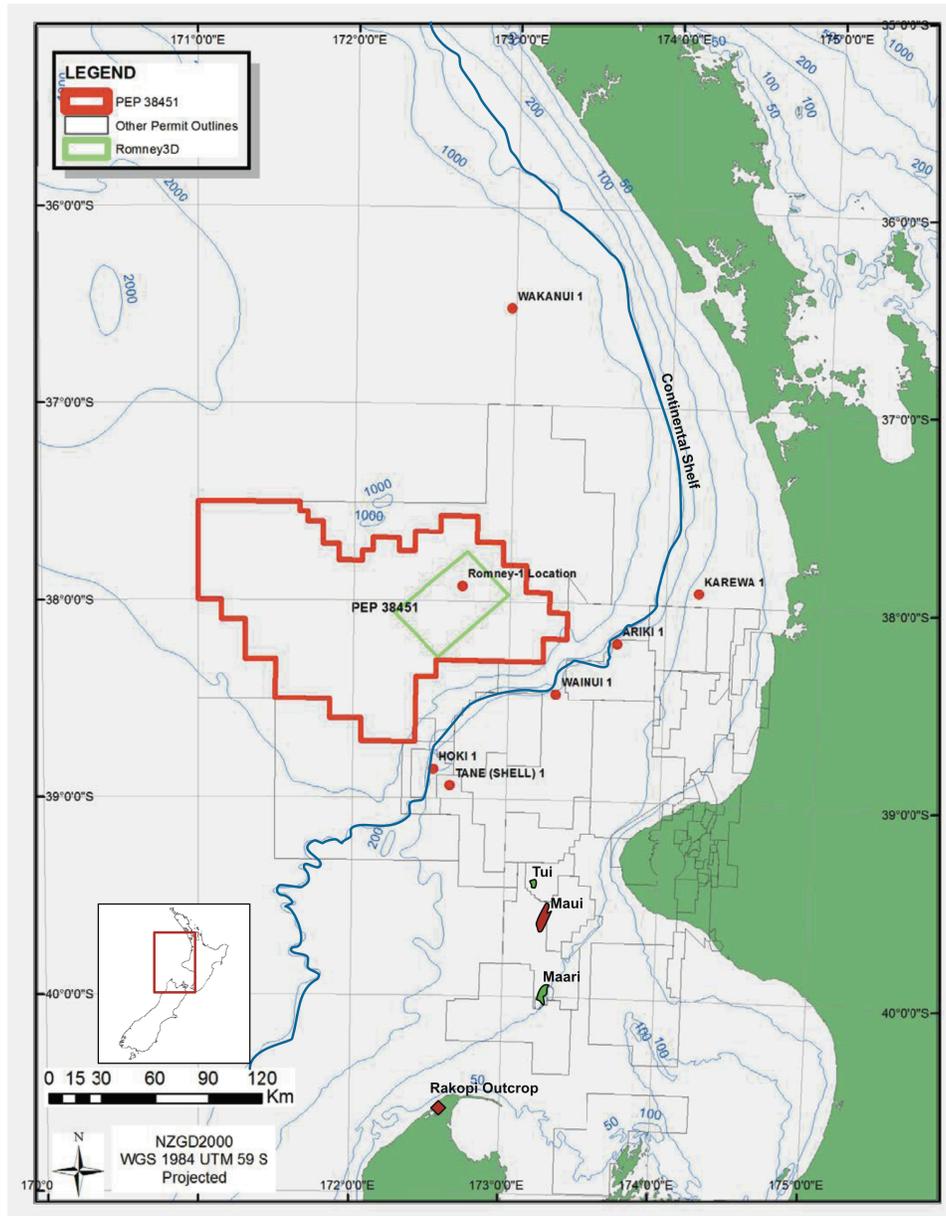
Figure 1: The study area is located west of the North Island of New Zealand. The following points of interest labelled: Rakopi Formation outcrop (red diamond) the Maari, Maui, and Tui oil fields, the Romney – 1 well (red dot) and Romney 3D seismic survey (green outline) location, PEP 38451 (red outline) (Modified from Rad F. 2015).
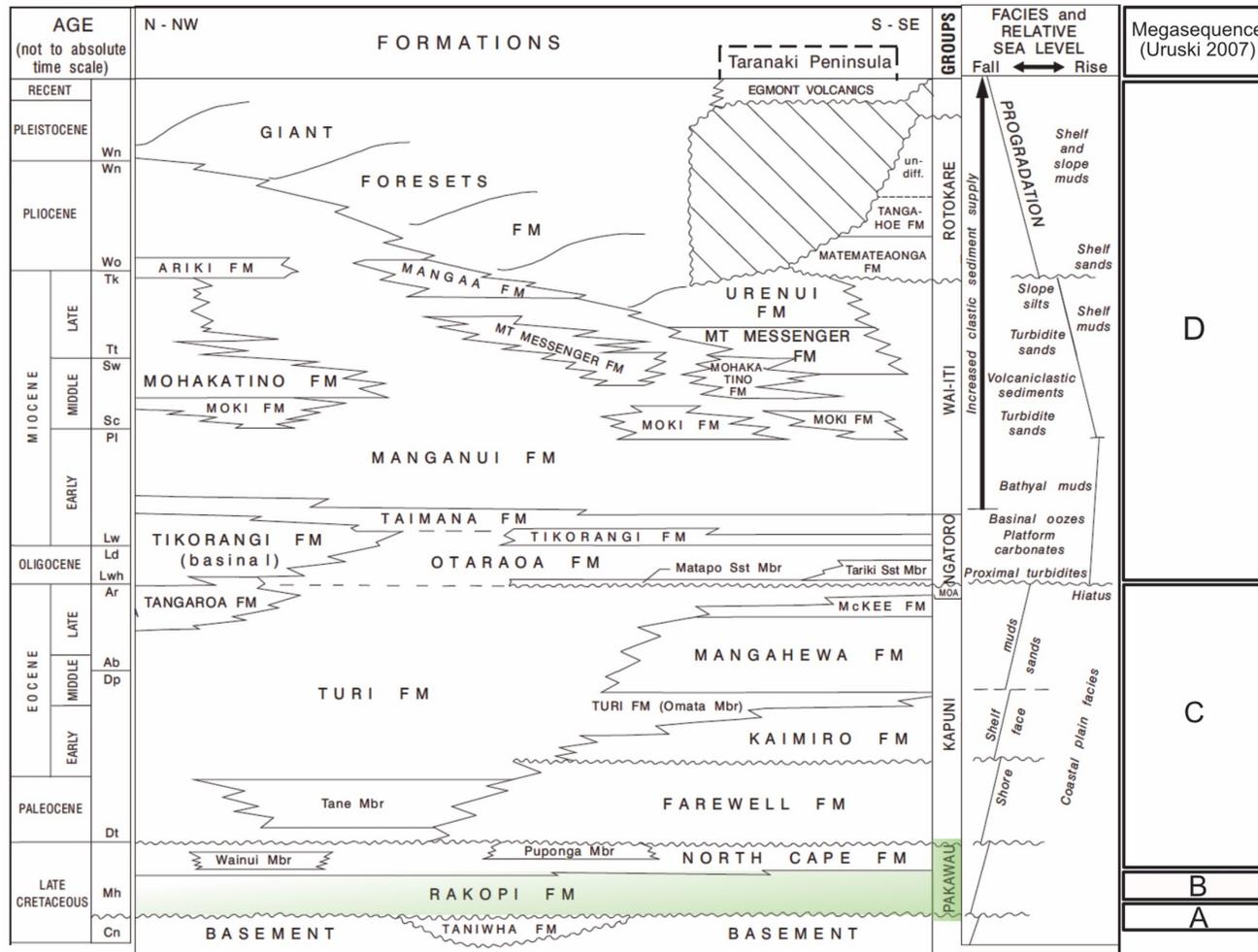
Figure 2: Taranaki Basin stratigraphic column showing the subsurface position of the Late Cretaceous Pakawau Group, Rakopi Formation, and the associated megasequences (Uruski et al 2003). The study interval (highlighted in green) is the stratigraphic location of the informal "Taranaki Delta" of the Rakopi Formation in the Pakawau Group (Modified from King and Thrasher 1996).
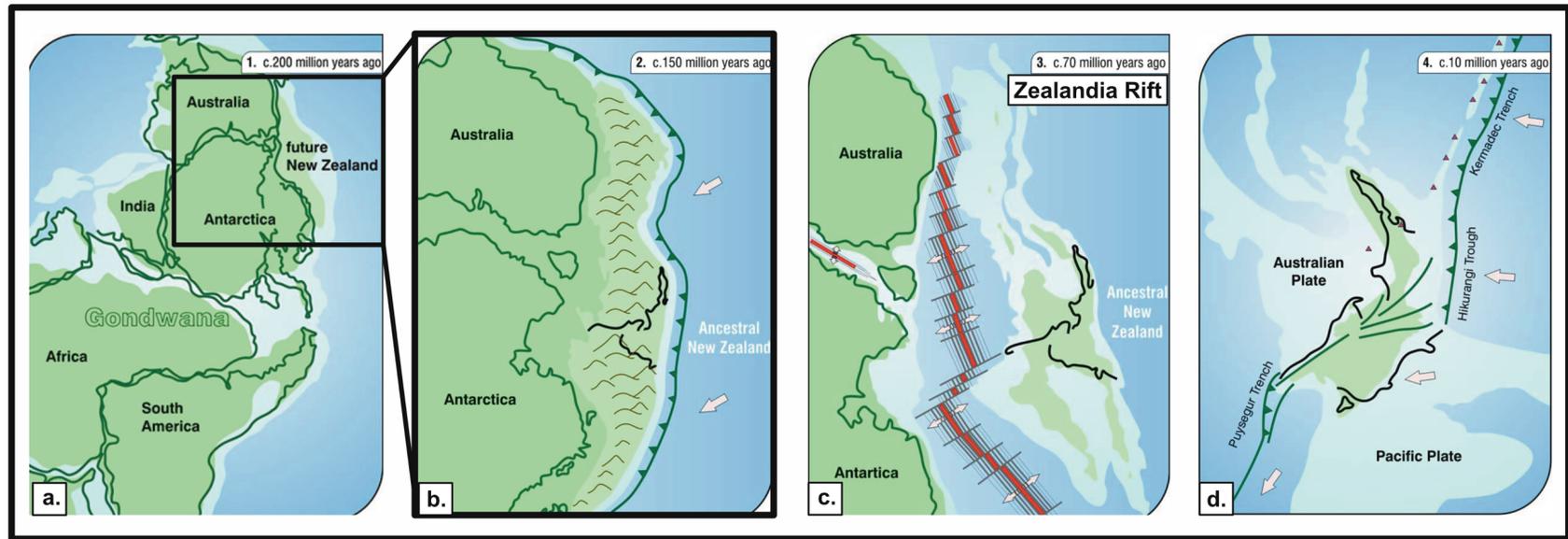
Figure 3: (a.) Continents of Gondwanaland at 200 Ma. **(b.)** zoomed view of the location of ancestral New Zealand at 150 Ma. **(c.)** The formation of the New Zealand Mini-Continent during the Zealandia rift phase at approximately 70 Ma. **(d.)** The beginning of modern day fault formation at 10 Ma. (Modified from McSaveney et al., 2006).
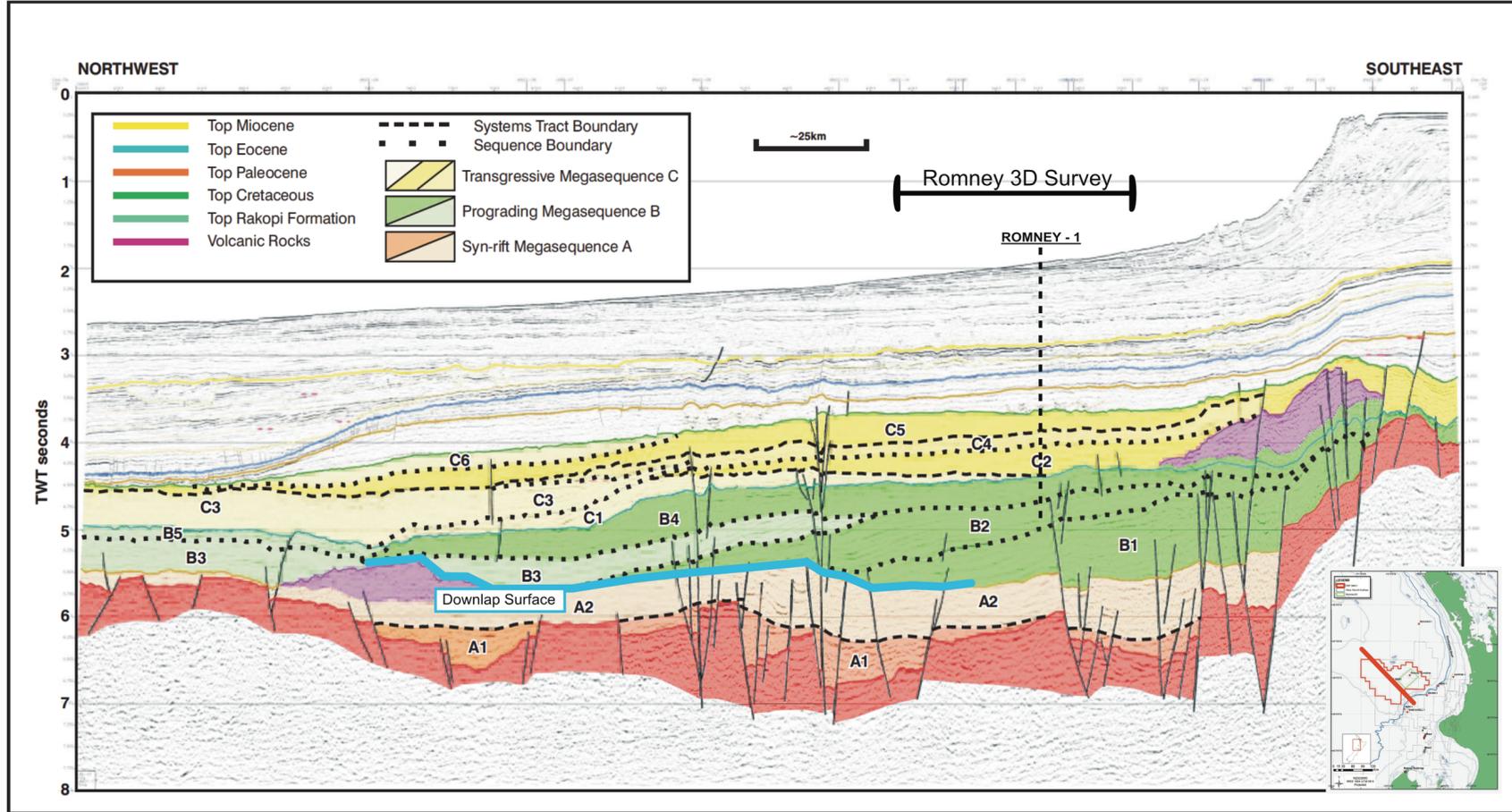
Figure 4: Regional 2D seismic line DTB01-17 with Megasequence A, B, and C interpretations. The boundaries of the Romney 3D survey are shown by the black brackets and the depth of the Romney -1 well by a vertical dashed line. This line does not actually intersect the Romney 3D survey but is used for the correlation of Megasequence B into the Romney Survey. Downlap surface is shown by the light blue line and is the location of the regional condensed section (Modified from Uruski et al. 2003).
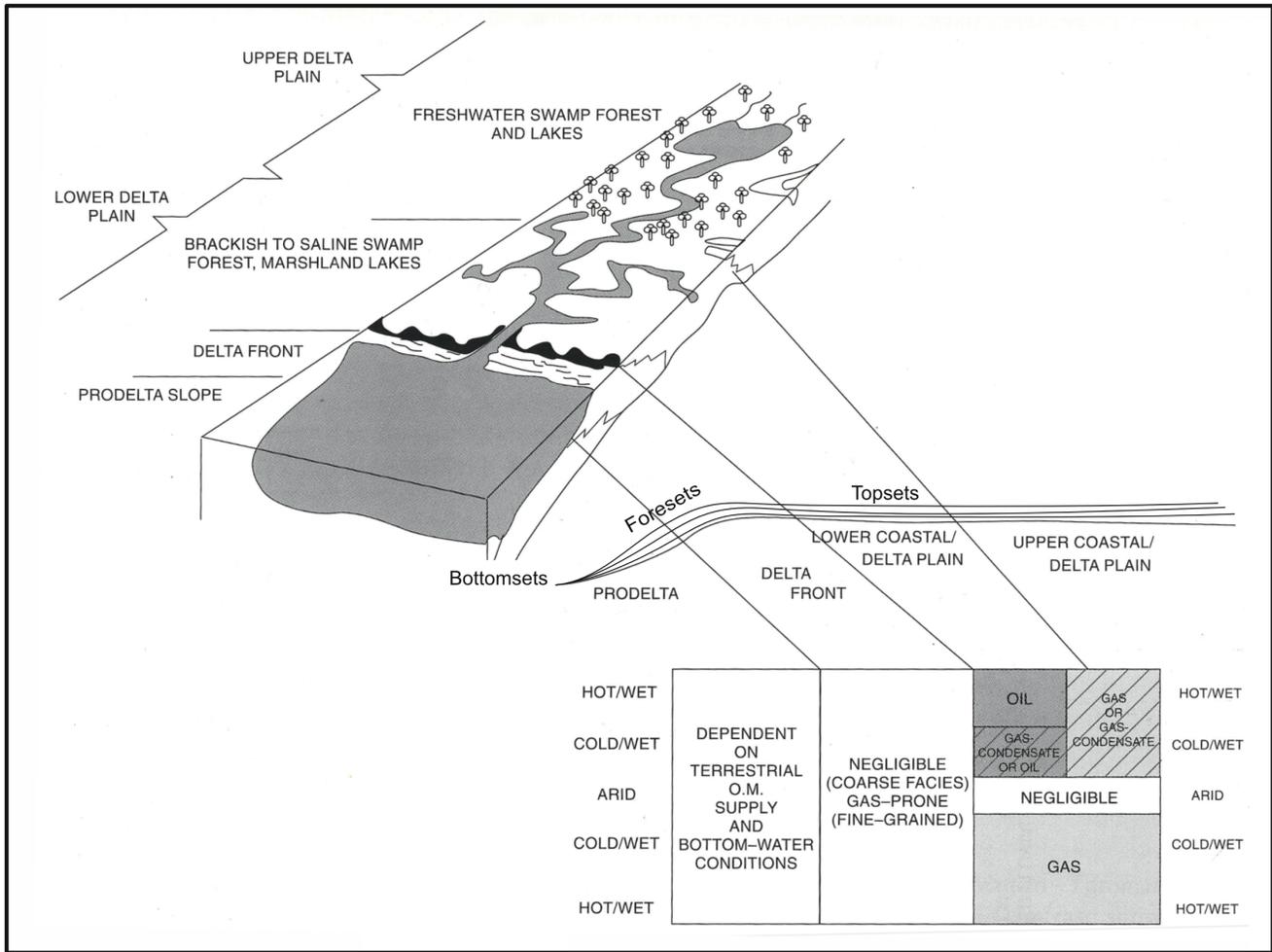
Figure 5: Source rock depositional settings in a typical coastal deltaic system. Lower delta plain environments have a high potential for oil-prone preservation. The hot environments of the Cretaceous era are a favorable environment to foster high foliage to wood ratio communities. As a result, oil prone coaly source rocks such as the Type II kerogens found in the Taranaki Delta can be deposited (Modified from Emery 2009).
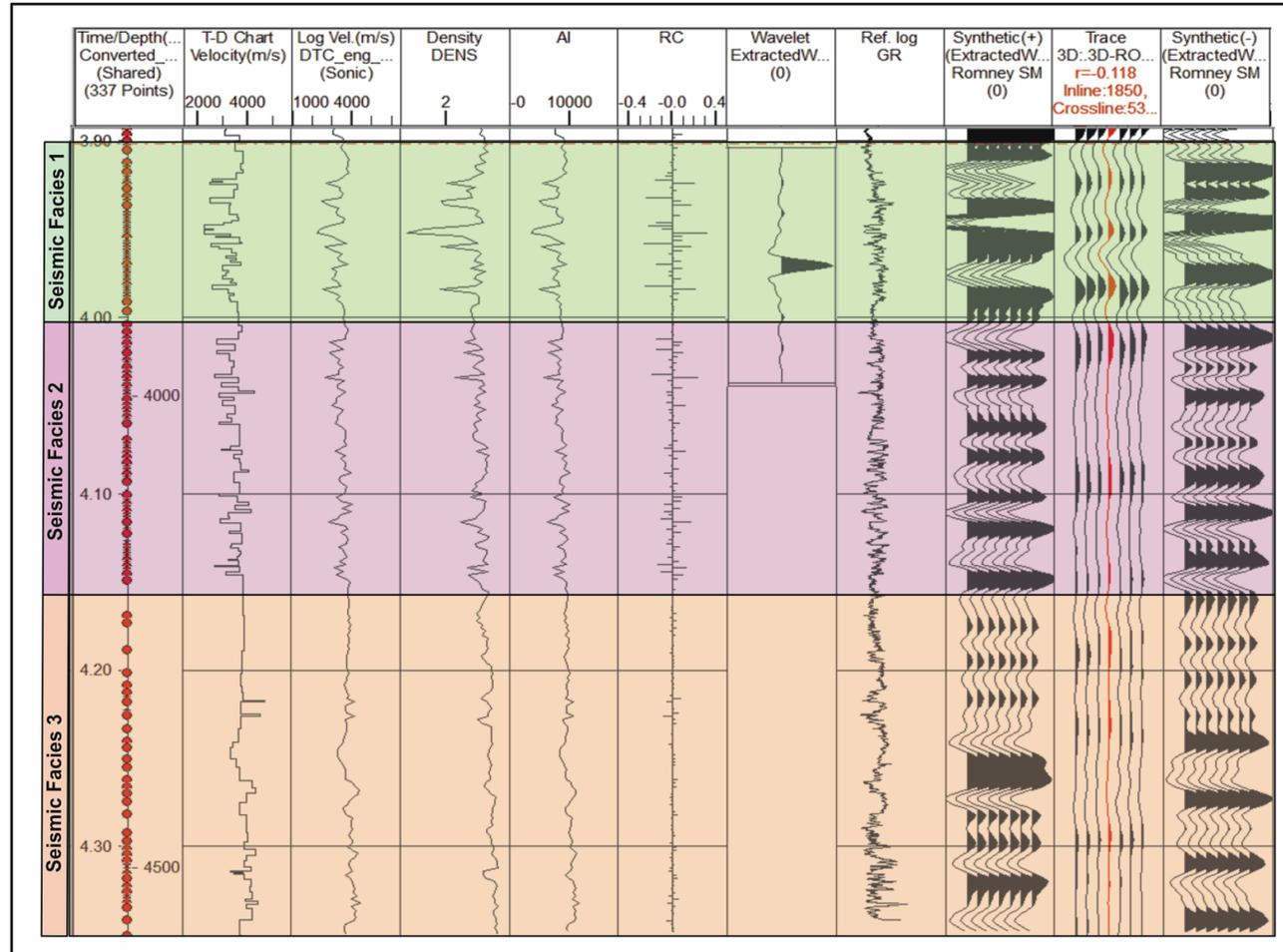
Figure 6: Seismic synthetic supplied with the New Zealand Data Pack for the Romney-1 well and the Romney 3D Survey. Facies illustrated by representative highlights: Seismic Facies 1 (green), Seismic Facies 2 (purple) and Seismic Facies 3 (orange). These facies show unique acoustic impedance signatures with Seismic Facies 1 having highly variable impedance, Seismic Facies 2 show moderately variable impedance and Seismic Facies 3 show low variability in impedance.
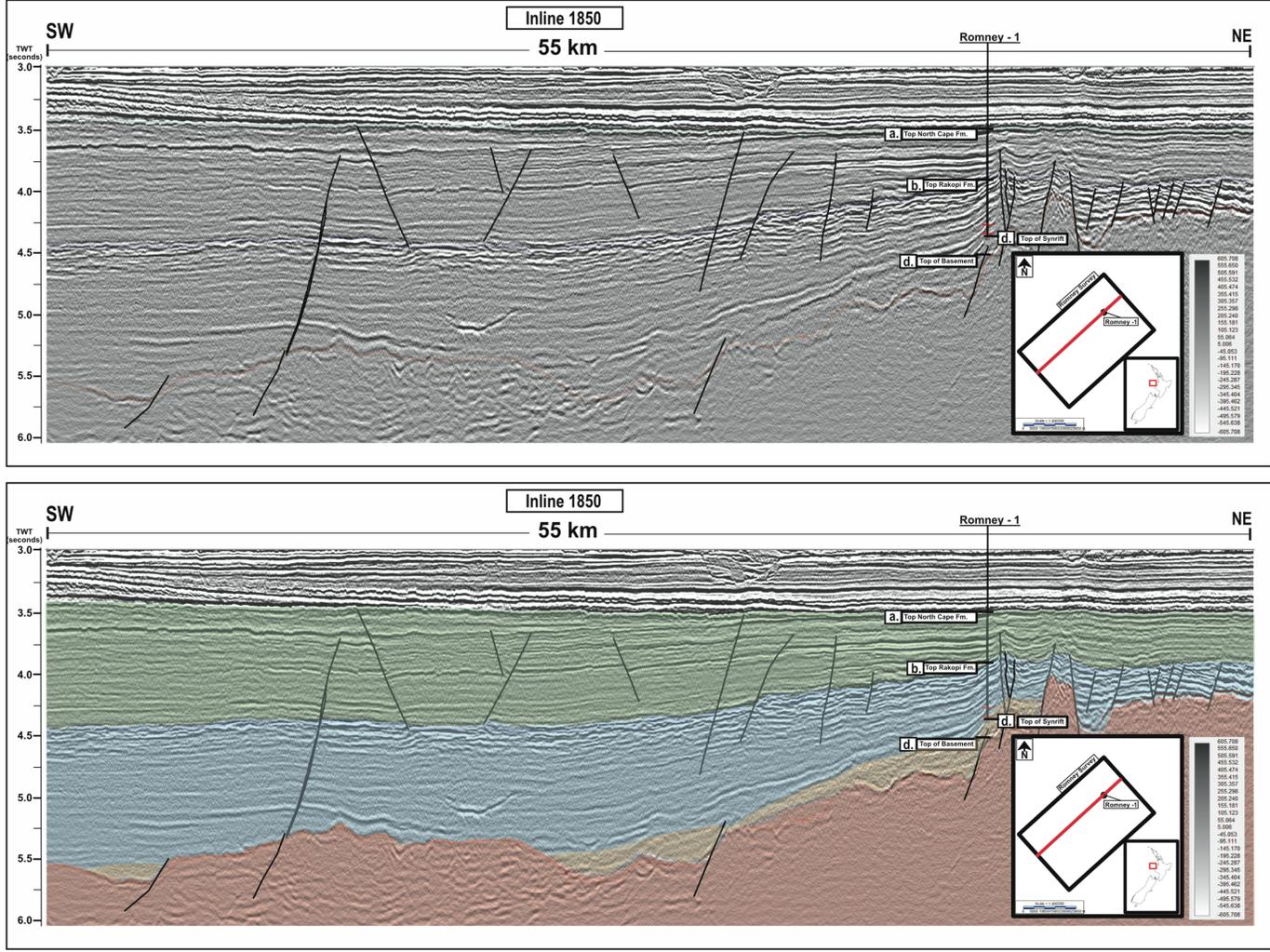
Figure 7: Inline 1850 form the Romney 3D (SW-NE) showing the formation top definitions and the intersection of the Romney–1 well of the Pakawau group which contains the North Cape Formation, Rakopi Formation represented by the green and blue intervals respectively. Yellow represents the Early Cretaceous/Jurassic syn-rift units and red is the basement.

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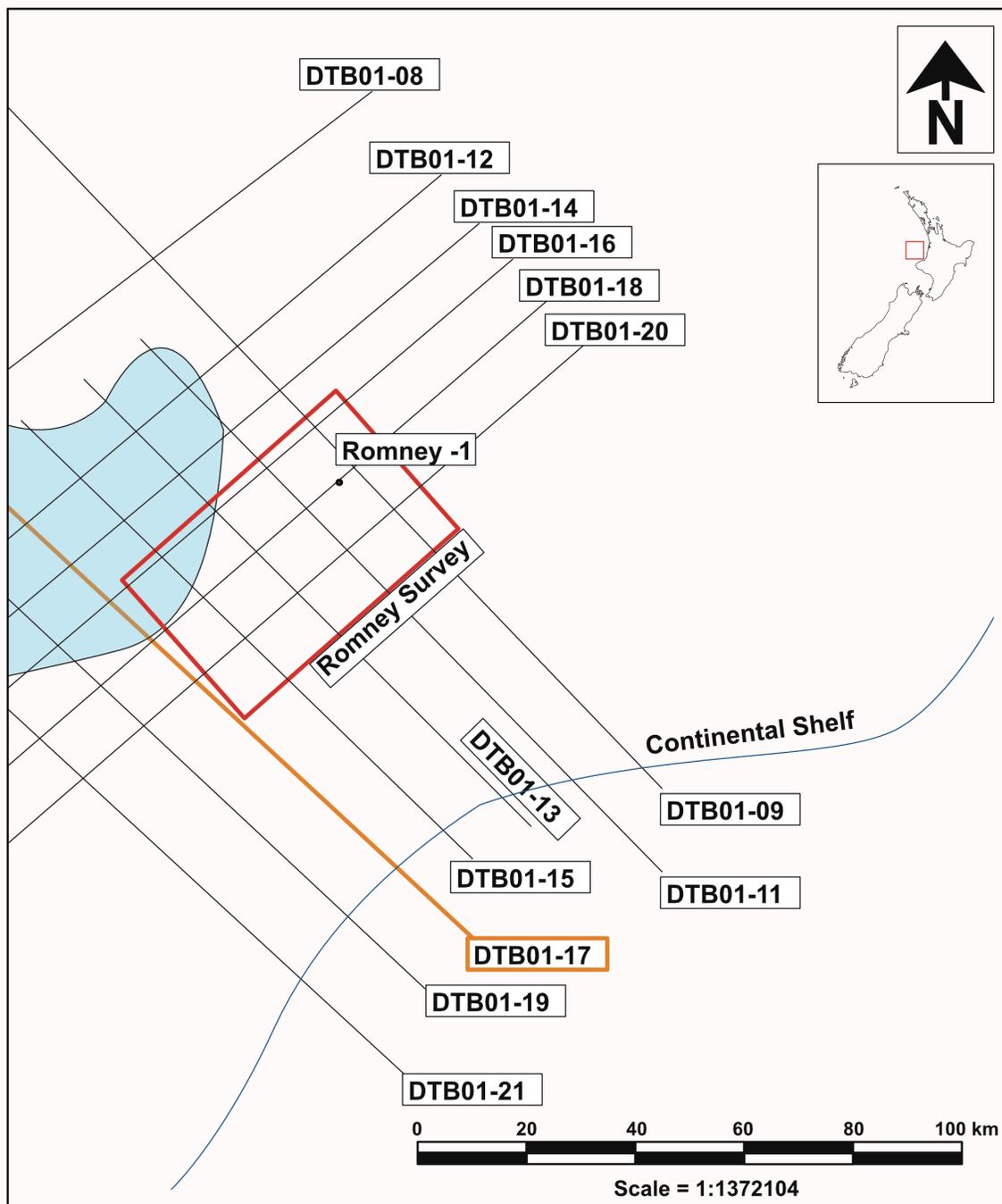
Figure 8: The blue polygon shows where downlap surfaces were identified in regional 2D lines and within the west corner of the Romney 3D survey. DTB01-17 is the show line Uruski et al (2003) (Figure 4).
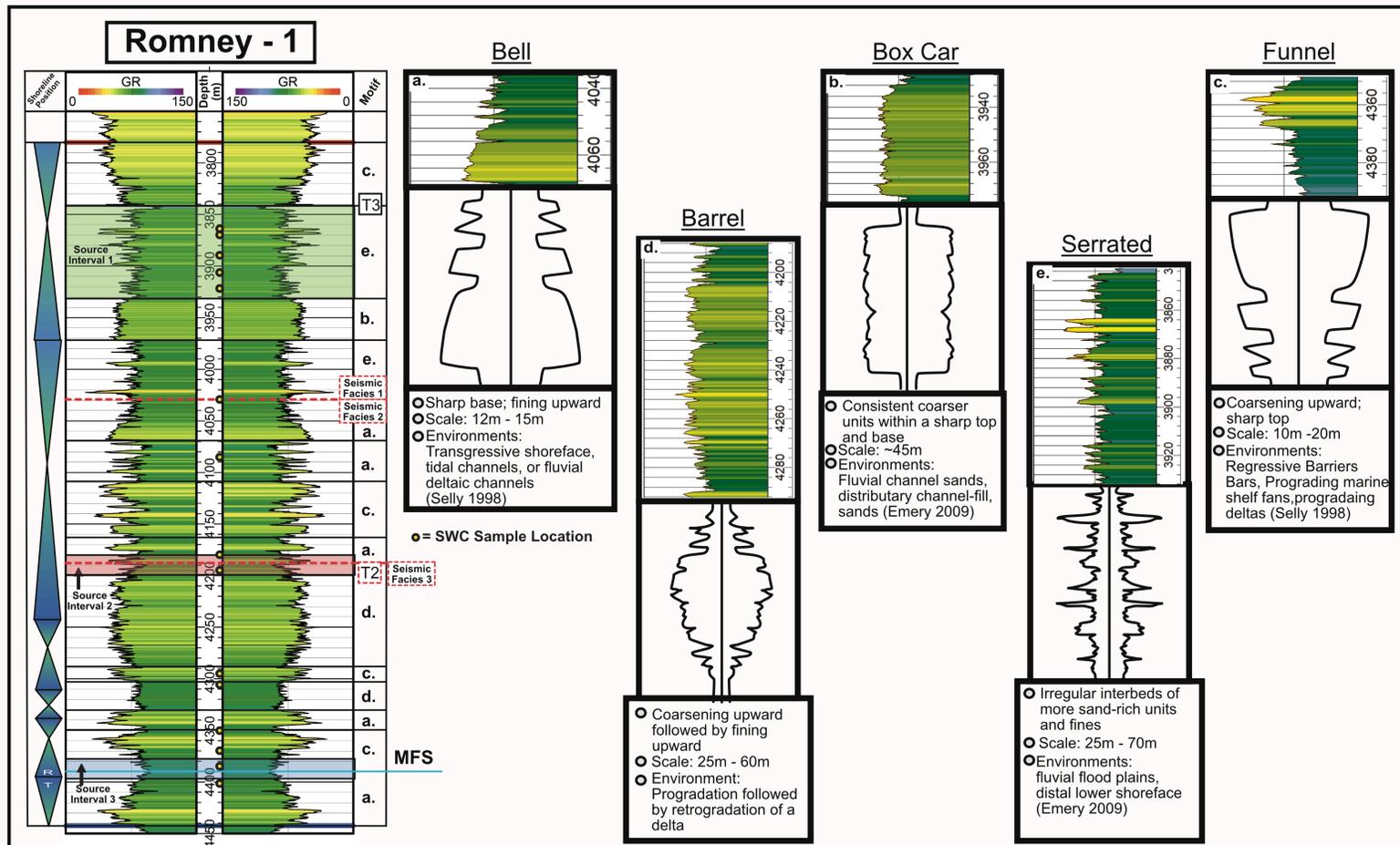
Figure 9: Log motif and motif shape definitions for the Romney -1 well. **a.** Bell shaped motif defined by a sharp base and a fining upward. **b.** Box car shaped motif with a sharp base and top and an overall coarse grain size. **c.** Funnel shaped motif with a coarsen upward and a sharp top cutoff. **d.** Barrel shaped motif defined by a coarsening upward immediately followed by finning upward. **e.** Serrated, or irregular shaped motif defined by irregular thin coarse and fine interbedded units. Source intervals 1, 2, 3 by green, red and blue boxes respectively. Seismic facie boundaries are labelled with dashed red lines.Time slices T1 and T2 are labelled at depths 3850m and 4200m respectively, but T3 does not intersect the Romney – 1 well.
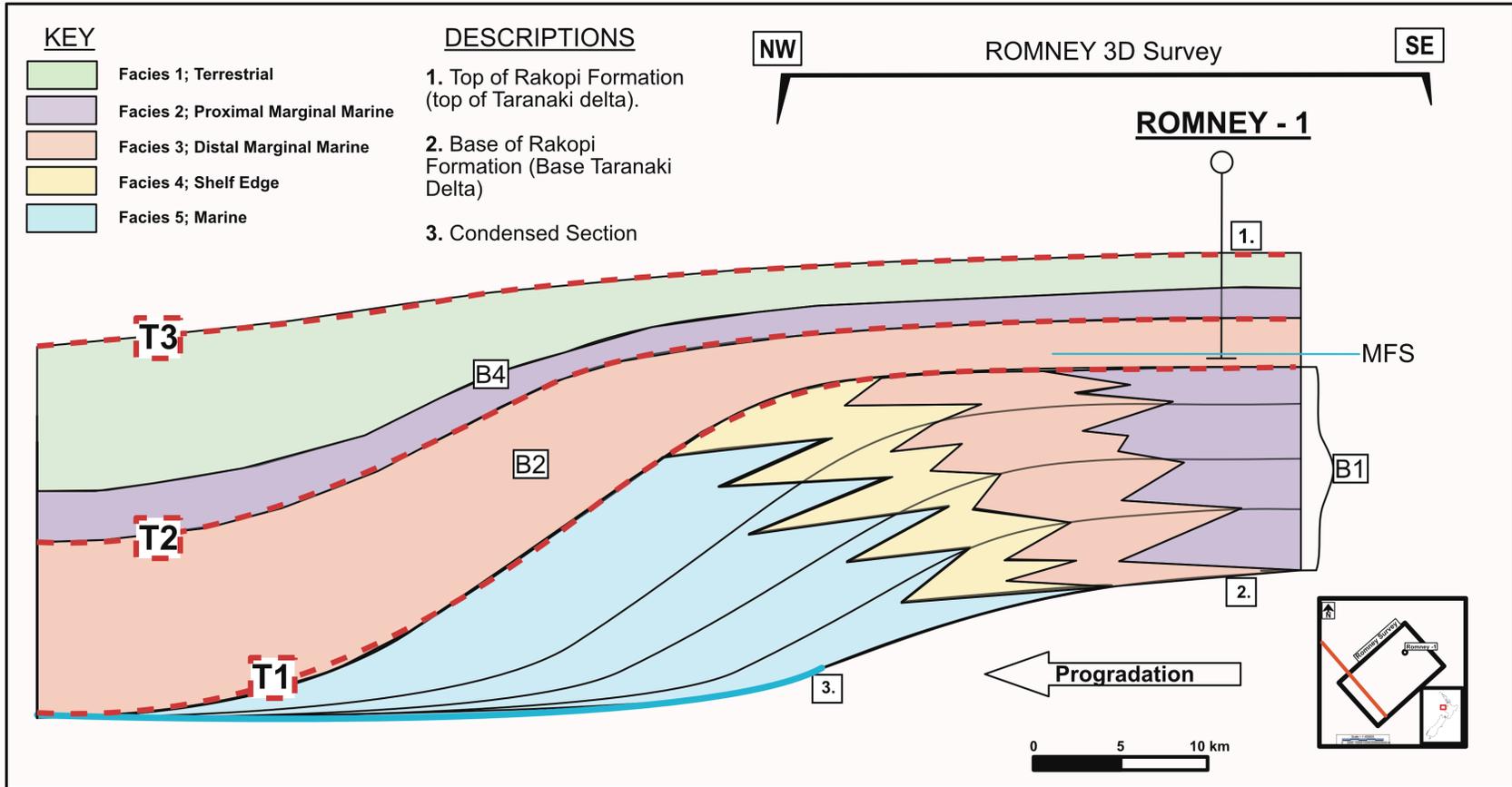
Figure 10: Vertically exaggerated idealized cross section showing the top (1) and base (2) of the Rakopi Formation, downlap surface locations (3), sequences of Megasequence B (Uruski 2003), facies 1 (green), 2 (purple), 3 (orange), 4 (yellow), and 5 (blue) and the corresponding depositional environments.

Facies	Representative Trace	Depositional Environment
<u>Facies 1:</u> Low continuity, High amplitude, High frequency.		Upper - Lower Delta Plain Terrestrial Coal
<u>Facies 2:</u> High continuity, High amplitude, moderate to high frequency.		Lower Delta Plain to Marginal Marine High sand content; Alternating lithologies
<u>Facies 3:</u> Moderate continuity, Low amplitude, Moderate frequency, poor impedance contrast.		Proximal Open Marine; Proximal Delta Front Lower Sand content than facies 2; Alternating lithologies
<u>Facies 4:</u> chaotic, no continuity, Low amplitude, poor impedance contrast.		Distal Delta Front; Open Marine Mud rich; Little to no variation in lithology
<u>Facies 5:</u> Angled, Moderate continuity, Moderate to high amplitude, Moderate frequency.		Prodelta Slope; Open Marine
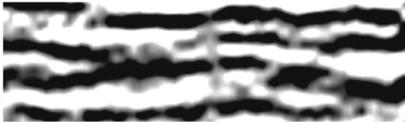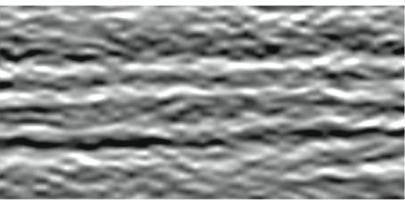
Figure 11: Defined facies 1, 2, 3, 4, and 5 found in the Romney-3D Survey and example images of each taken directly from the Romney survey
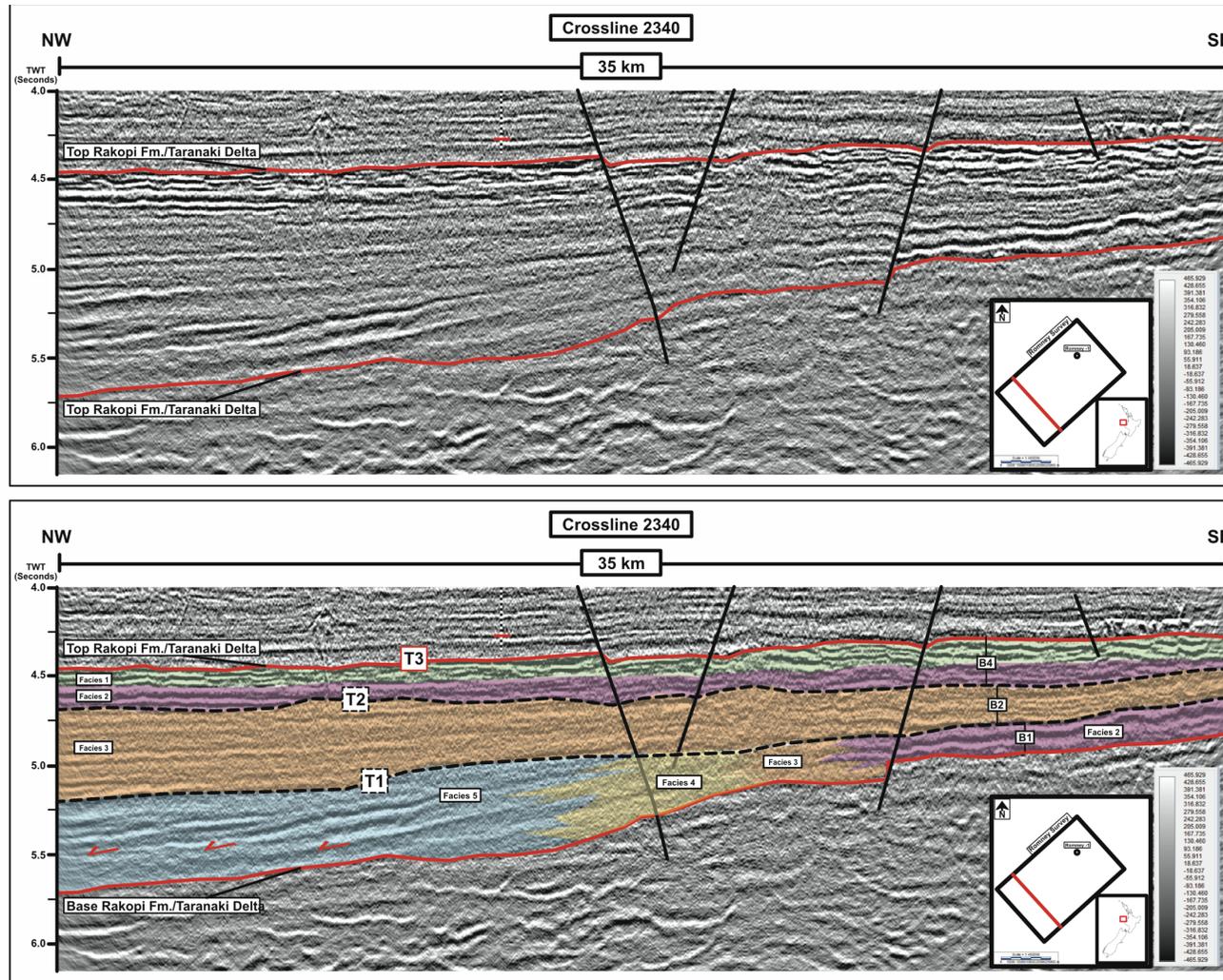
Figure 12: (Top) An uninterpreted crossline located on the southwest end of the Romney-3D Survey. Top and bottom of the Rakopi is defined by a red line. (Below) Interpreted facies are highlighted by their respective colors: 1 (green), 2 (purple), 3 (orange), 4 (yellow), and 5 (blue). T1, T2, and T3 are horizons in which definitive sequence changes occurred within the Taranaki Delta.
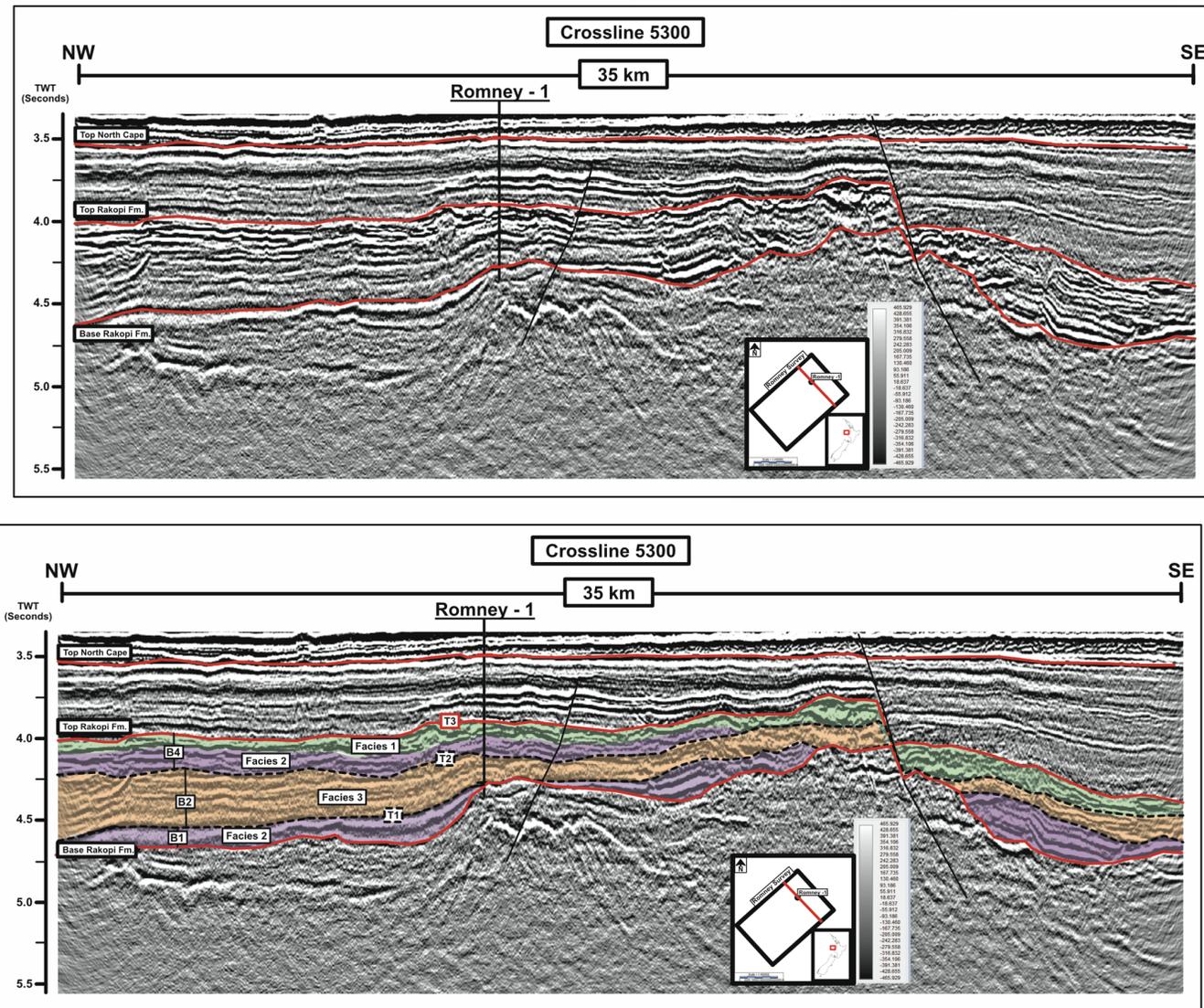
Figure 13: (Top) Uninterpreted crossline 5300 profile intersecting the Romney – 1 well. (Bottom) Interpreted profile of crossline 5300. Only T3 and T2 horizons and three of the five facies are present: facies 1, 2, and 3.
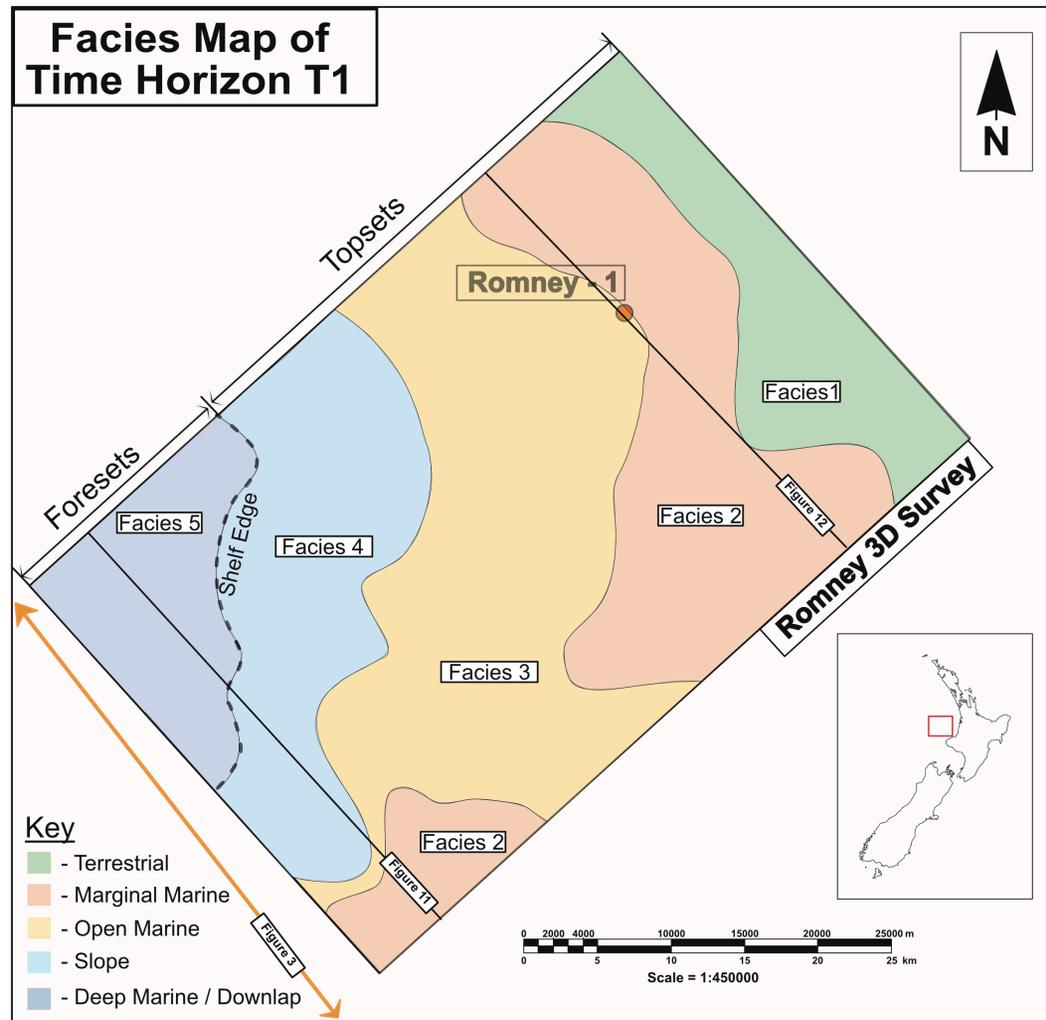
Figure 14: Map view of facies distributions at horizon T1. Facies 1, 2, 3, 4, and 5 are present with both foresets and topsets. The shelf slope break is represented by a dashed line. Both foresets and topsets exist at this time slice. Facies 1 has retreated to the east as base level has risen relative to horizons T2 and T3.
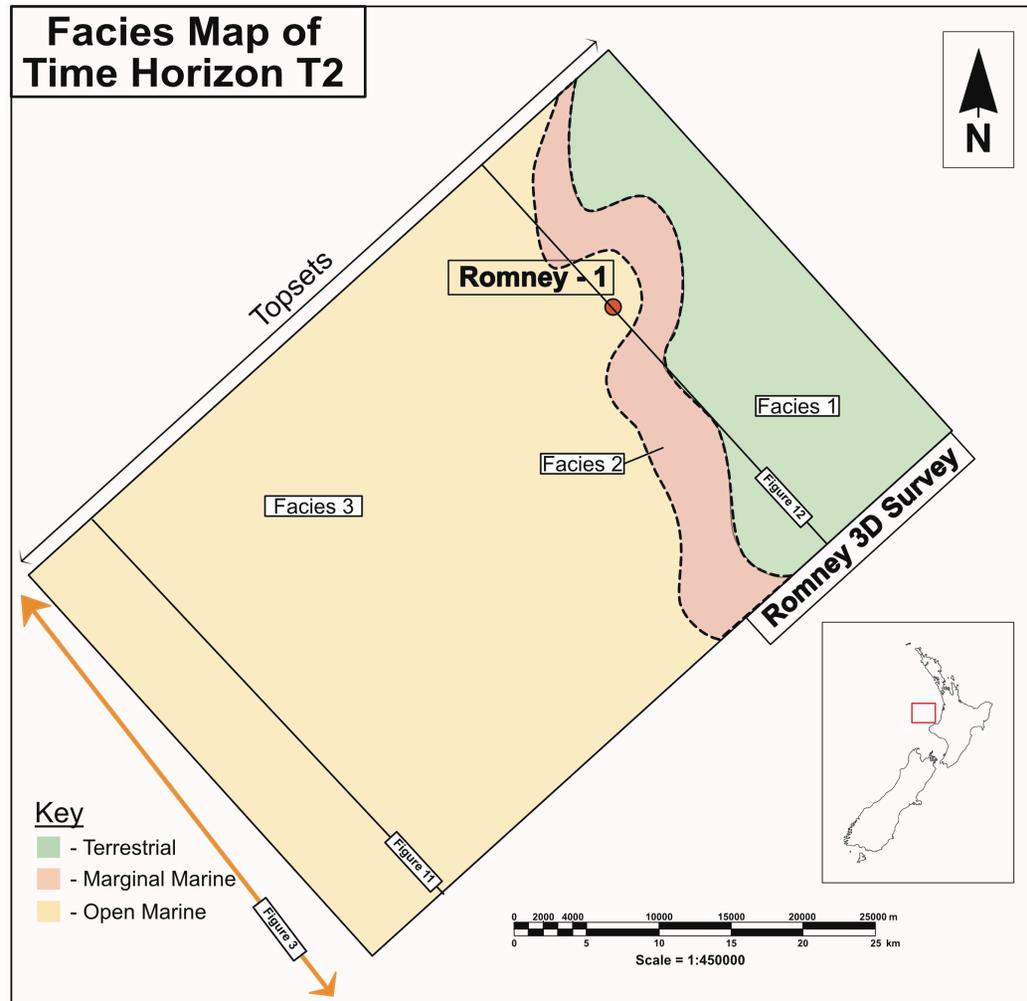
Figure 15: Map view of facies distributions at horizon T2. Facies present are 3, 2, and 1. Relative to horizon T1 the base level has regressed, and terrestrial environment is progressing basinward, and the Romney survey is dominated by topsets. Marginal marine environments were below the resolution of the survey and were not identified. Due to the law of conformable facies, facies 2 more than likely exist between facies 1 and facies 3 and the boundary is represented by a dashed line.
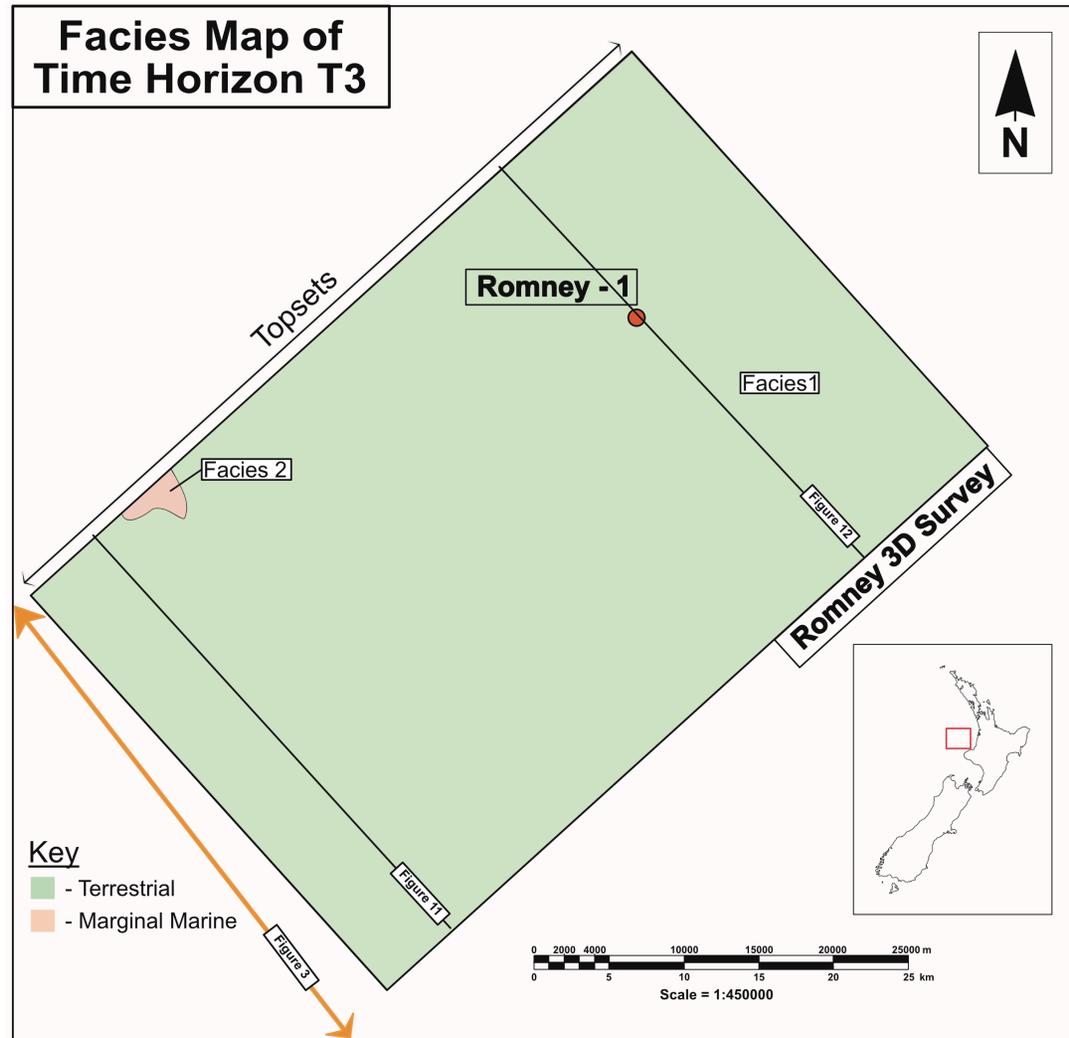
Figure 16: Map view of facies distributions at horizon T3. Facies 1 is laterally extensive with facies 2 appearing in the western quadrant of the Romney 3D Survey.
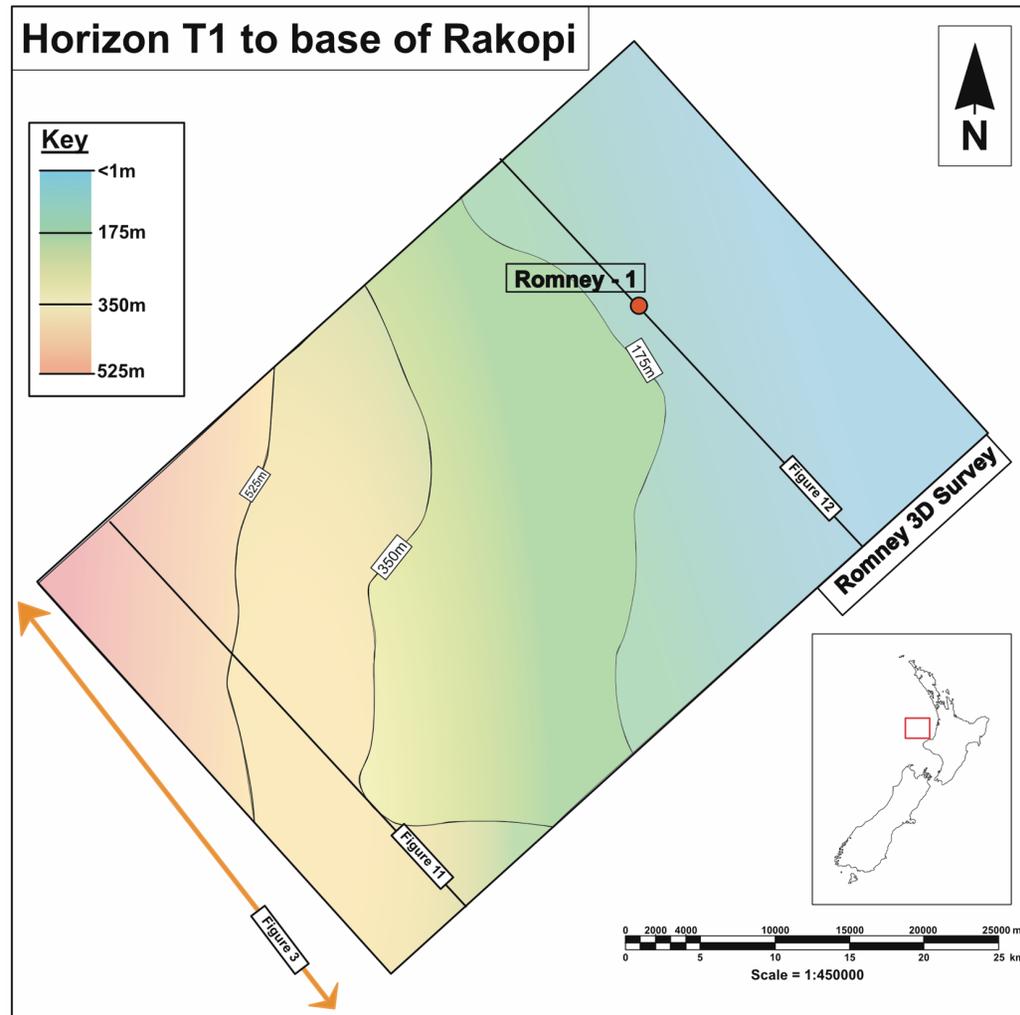
Figure 17: Thickness map of interval T1 to the base of the Rakopi Formation. A western thickening occurs as the foresets prograde basinward and defines relative strike and dip directions north and west respectively.
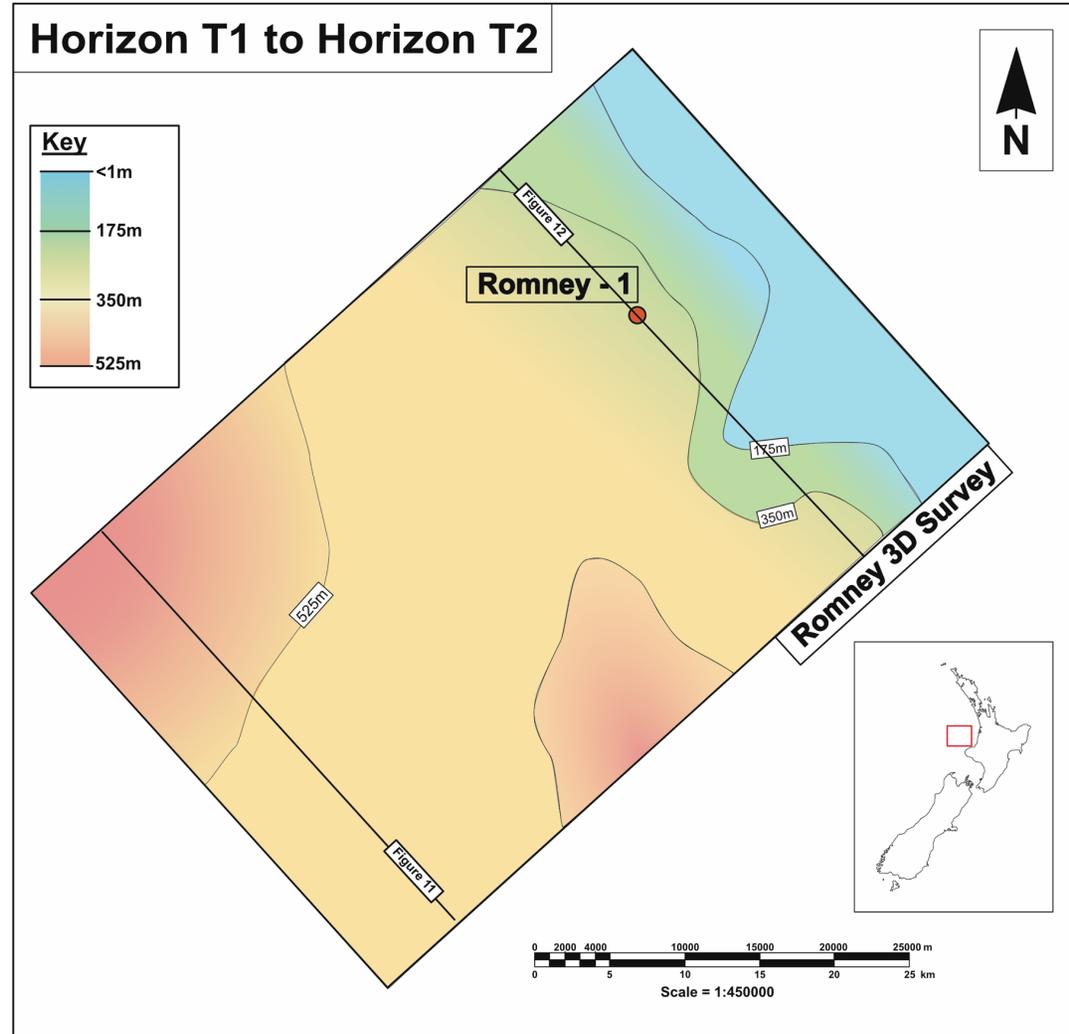
Figure 18: Thickness map of interval T2 to T1. A western thickening and isolated accumulation occurs due to structural or topographical highs during the time of deposition. These isolated accumulations show areas of high accommodation and the areas of low in between the depocenters.
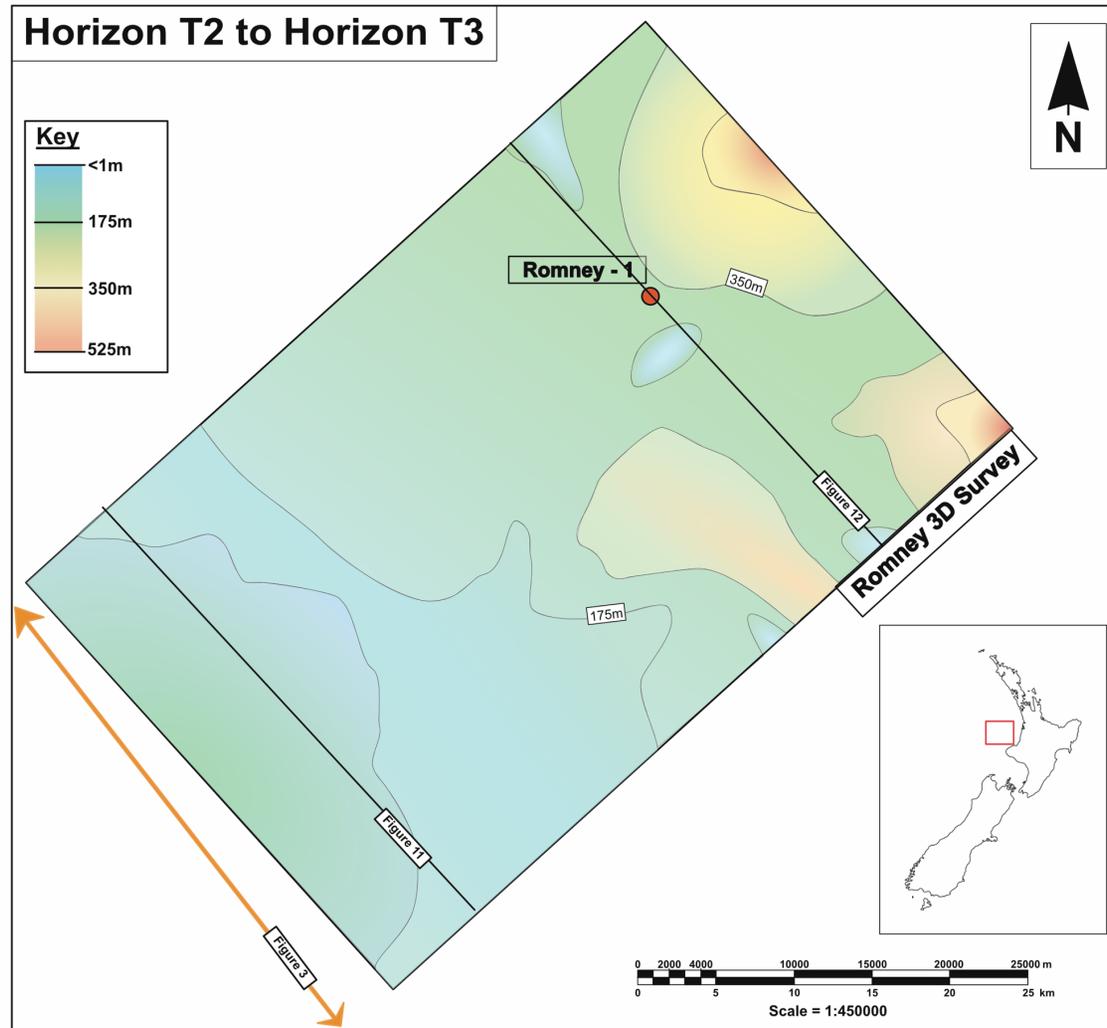
Figure 19: Thickness map of the interval between T3 (Top of Rakopi Formation) and T2. The interval thickens eastward and a thin section occurs in the eastern region.
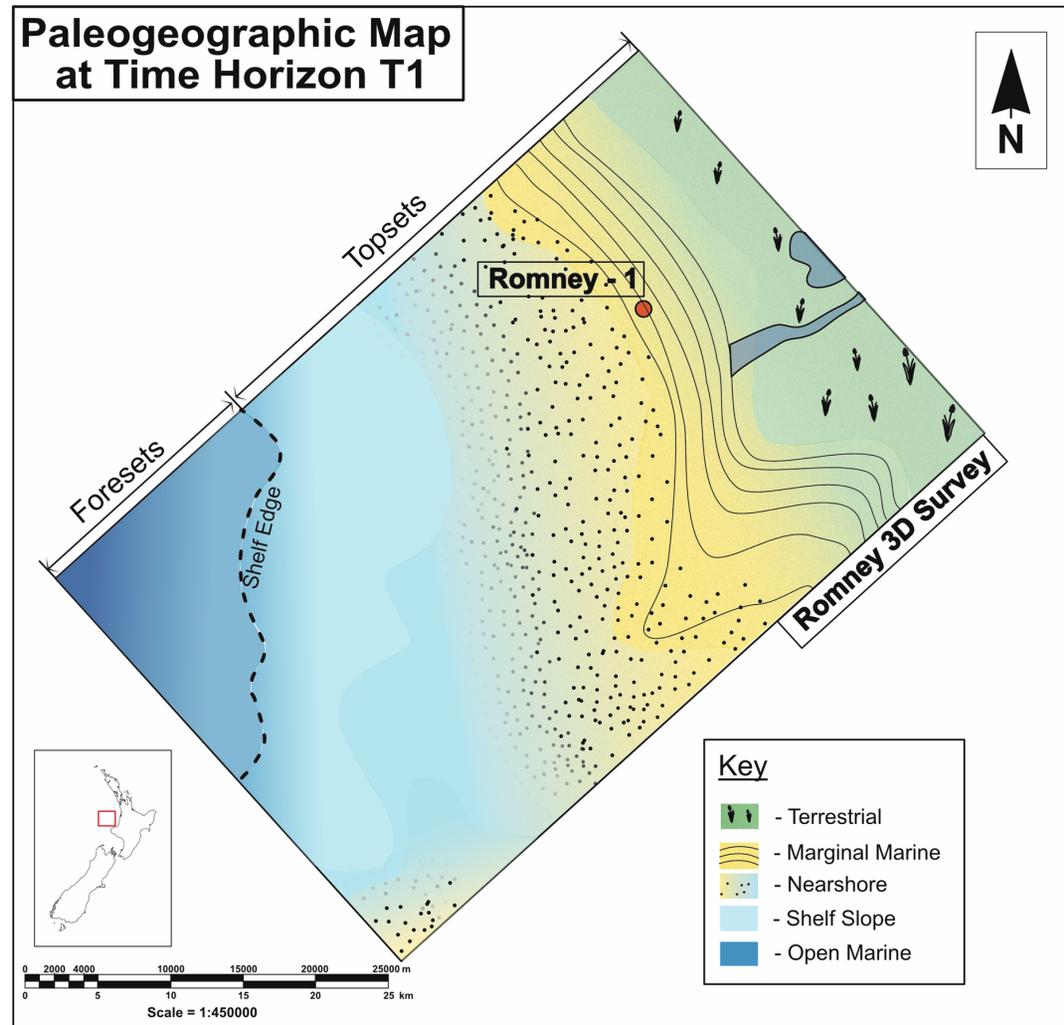
Figure 20: Paleogeographic map at horizon T1. The Romney 3D survey contains all five depositional facies 1, 2, 3, 4, and 5. These facies correlate to respective depositional environments terrestrial, marginal marine, nearshore, shelf slope, and open marine. Both foresets and topsets are present in this time slice showing a general westward progradation of the Taranaki Delta
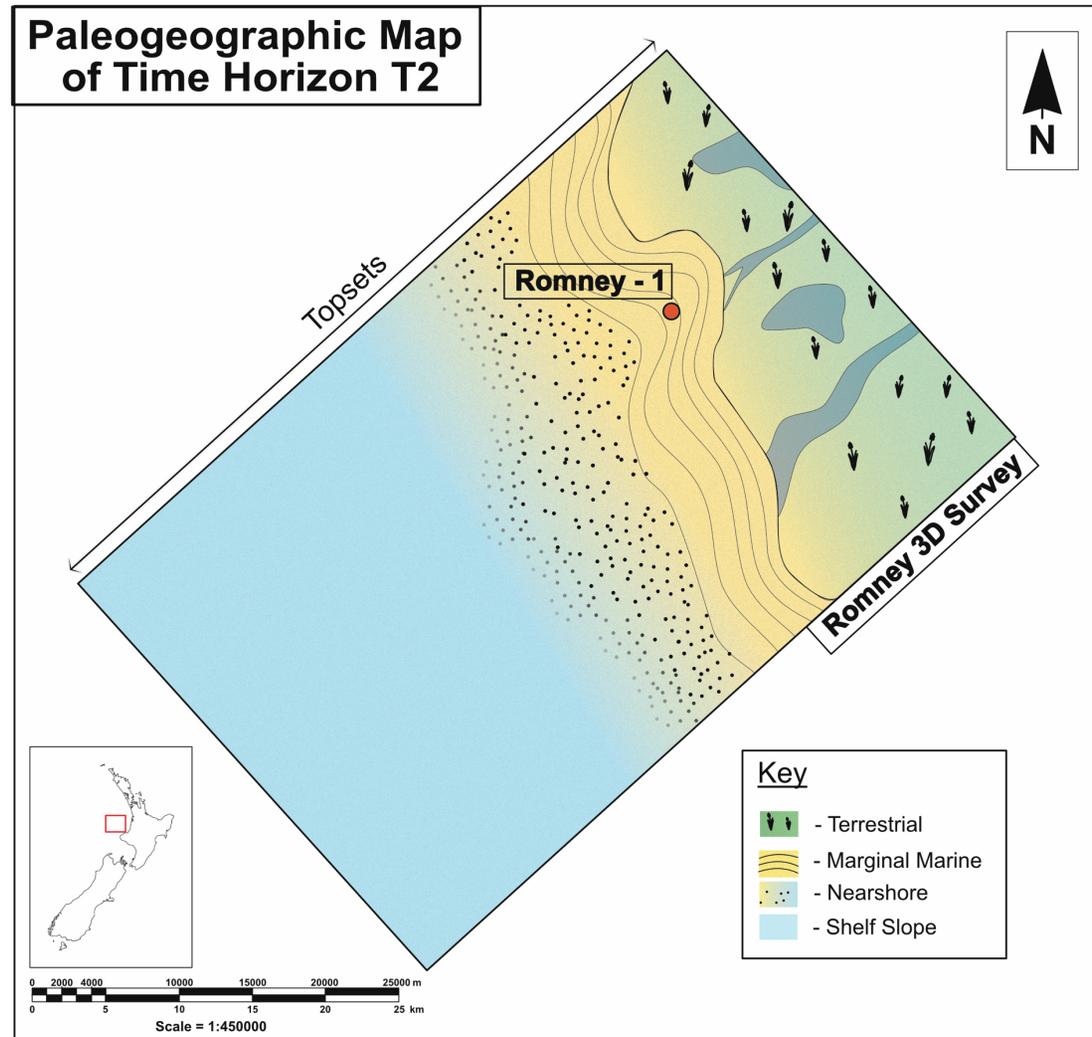
Figure 21: Paleogeographic map of horizon T2. The Romney 3D survey contains 4 depositional environments such as terrestrial, marginal marine, nearshore, the shelf slope. The terrestrial environment has lacustrine environments and fluvial depositional systems. A deepening of depositional environments occurs to the west.
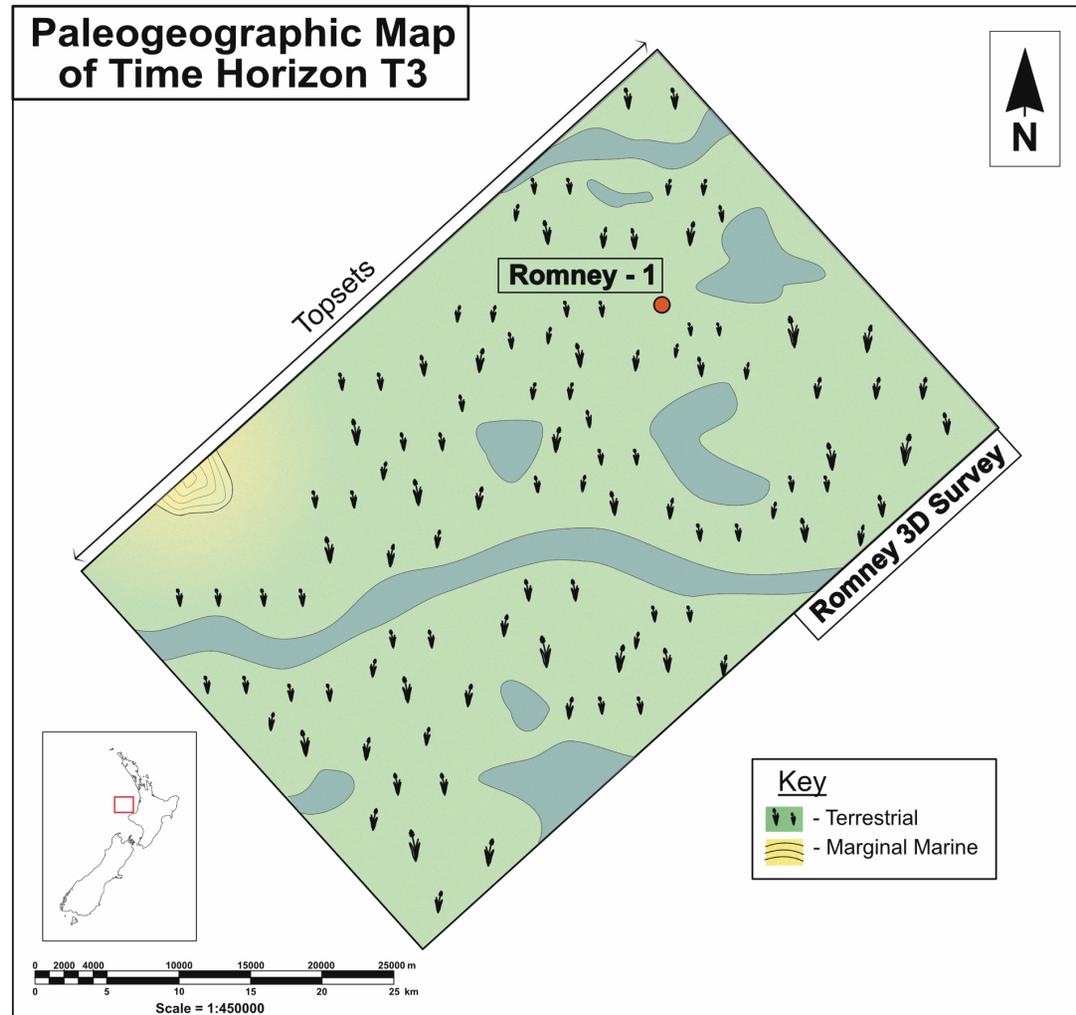
Figure 22: Paleogeographic map of horizon T3 shown in Figure 12. The Romney 3D survey is dominated by a terrestrial environment with the presence of fluvial depositions and lacustrine environments. There is evidence of a small area of marginal marine in the westward corner of the survey illustrated by the yellow gradient.
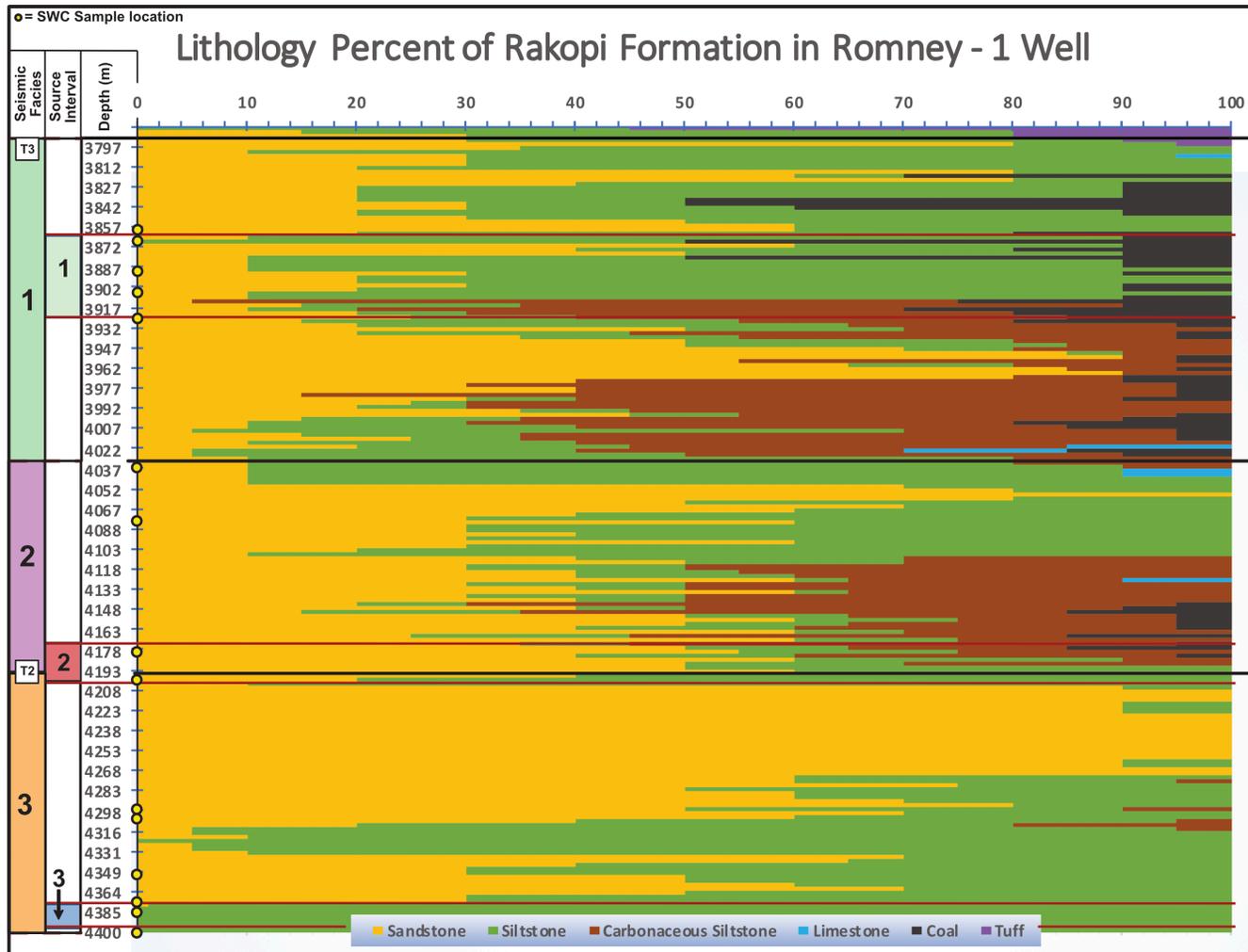
Figure 23: Percent lithology through the entire Rakopi Formation at the Romney – 1 well. Yellow = sandstone, green = siltstone, brown = carbonaceous siltstone, blue = limestone, black = coal, and purple = volcanic tuff. Facies 1, 2, and 3 are defined by dashed red lines and source intervals 1, 2, 3 by green, red and blue boxes respectively. Additionally, time slices T1 and T2 are annotated at their respective depths (3850m and 4200m). Yellow circles located at the 0% line are the depth locations of geochemical samples taken within the Rakopi Formation.
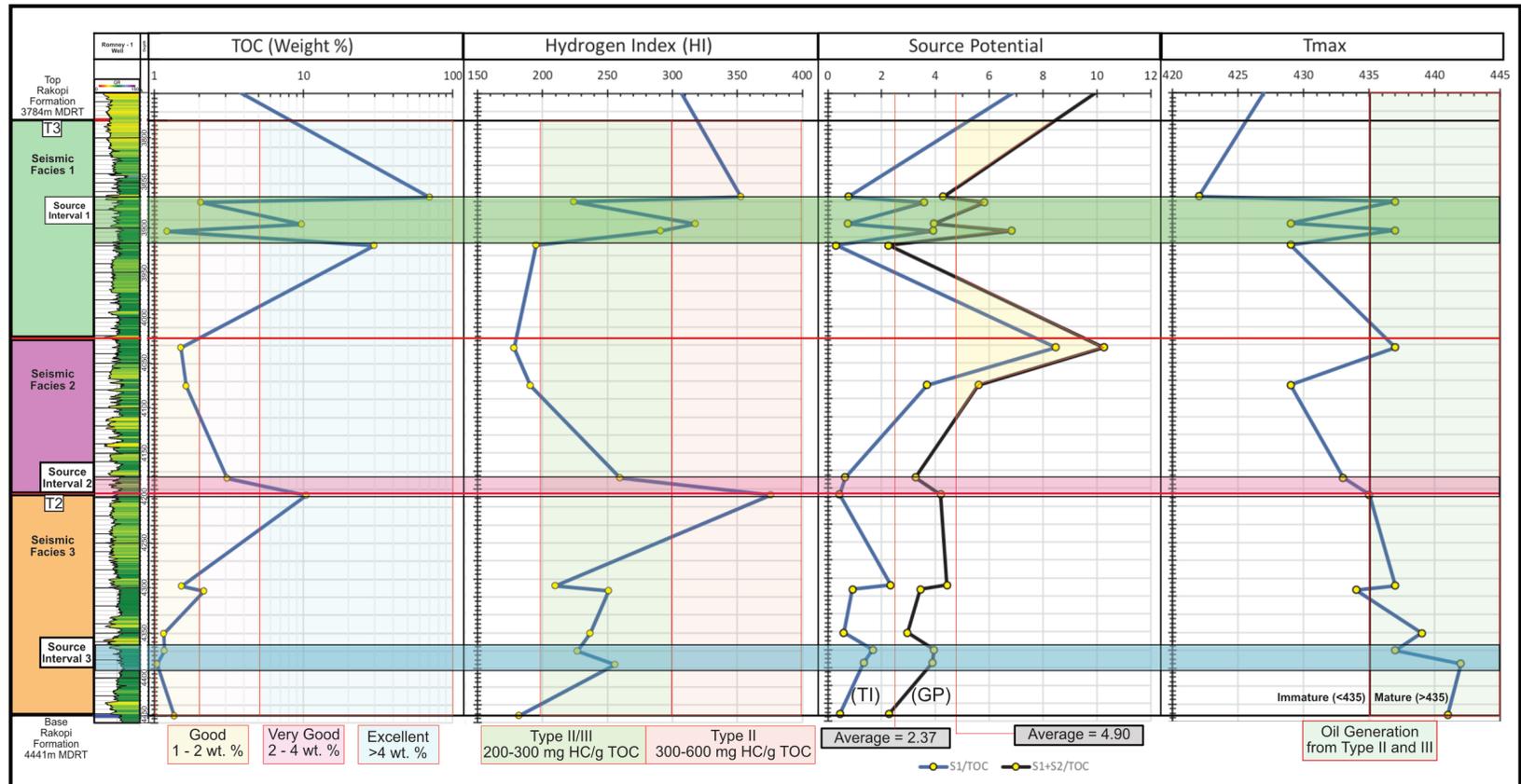
Figure 24: Geochemical analysis of the Rakopi Formation showing the samples taken throughout the section (yellow points) and measure for TOC, HI, TI, GP, and Tmax. Interpreted source intervals are highlighted in the well bore as Source 1 (green), Source 2 (red), and Source (3). In addition, boundaries between facies are illustrated by red lines. Additionally, time slices T1 and T2 are labelled at their respective depths (3850m and 4200m).
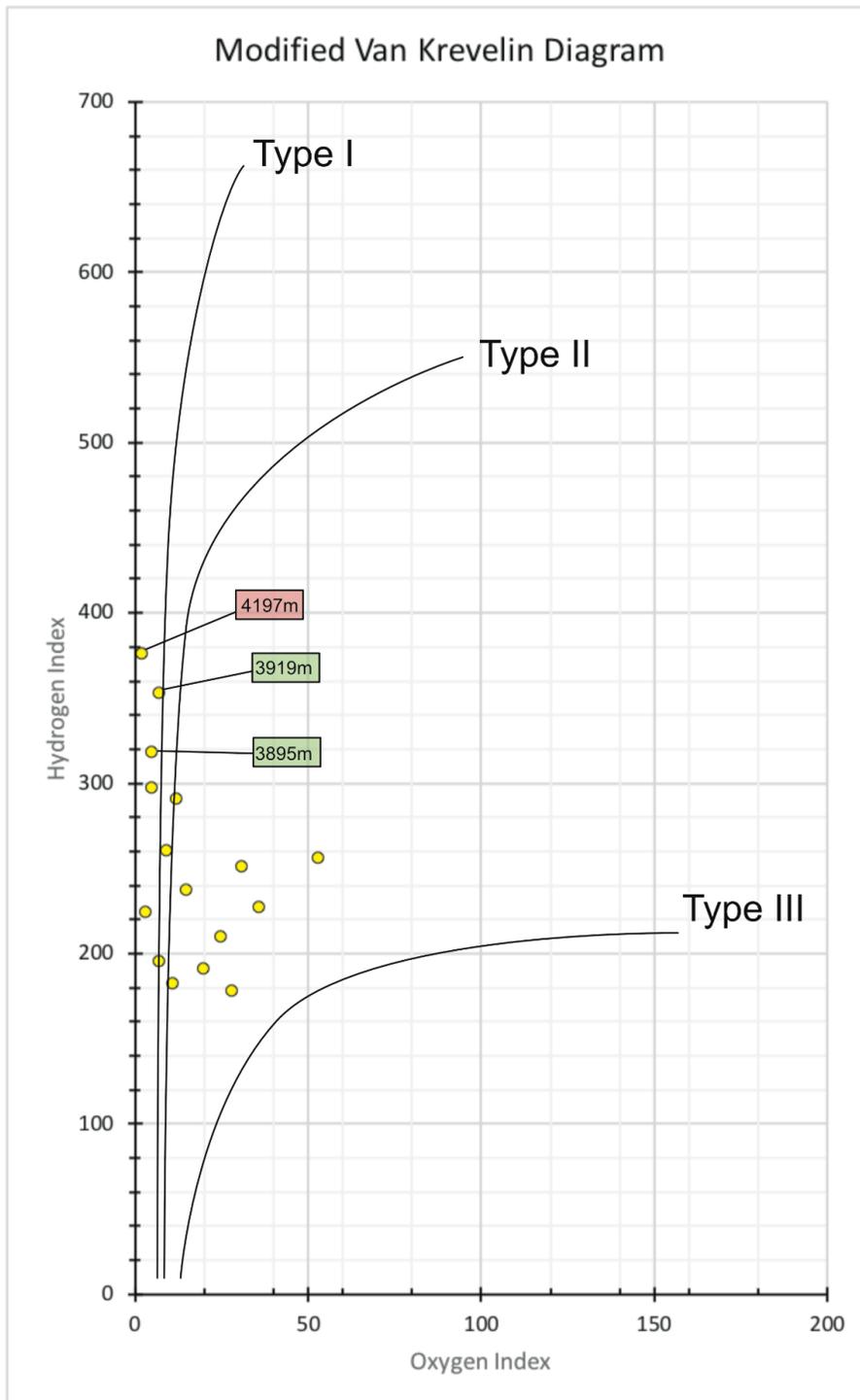
Figure 25: Modified Van Krevelin diagram showing majority of the samples residing in the Type II/III and the higher HI samples trending towards Type I/II with their respective depths and associated source intervals 1 (green) and 2 (red).
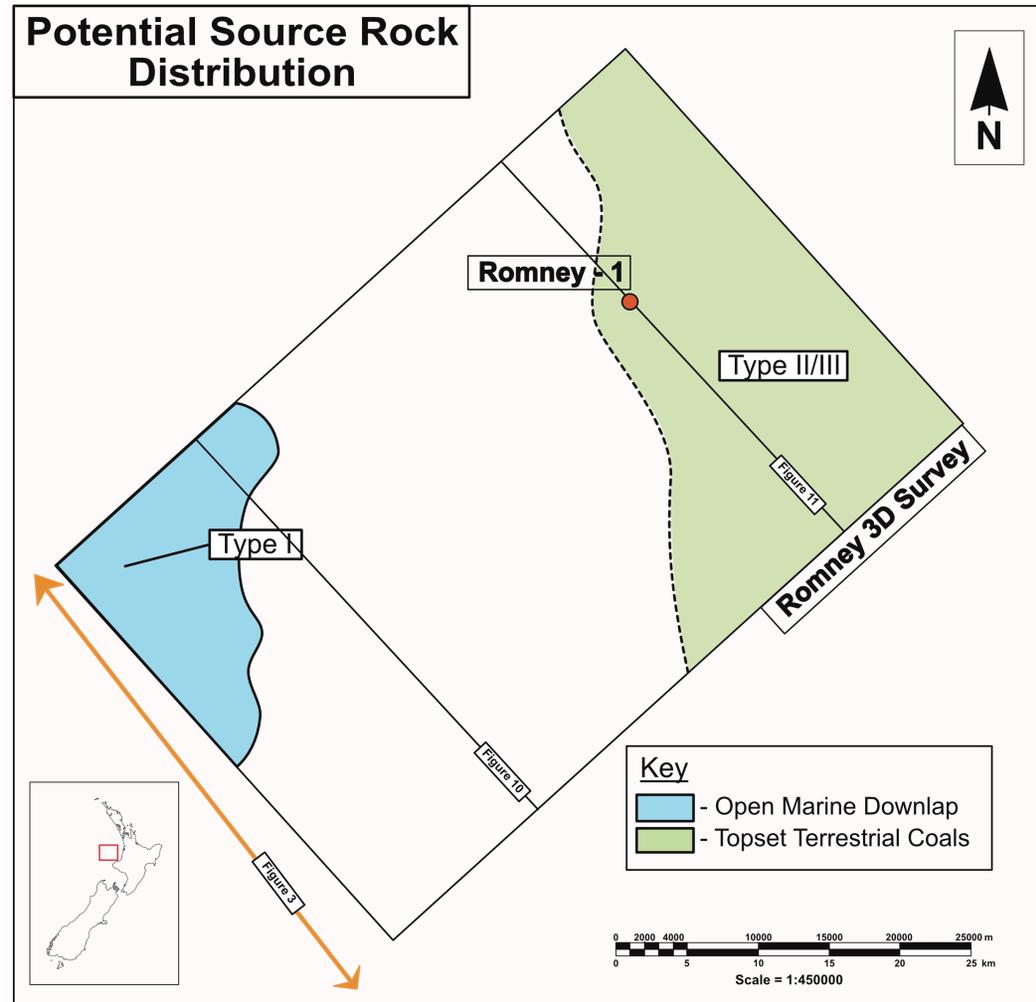
Figure 26: Source rock distribution map illustrating the relative distribution of defined source rock intervals within the Romney 3D survey. Type I is the result of open marine algal accumulation and the Type II/III is the result of marine influenced coaly source rocks.