Facies Distribution and Impact on Petroleum Migration in the Canterbury Basin, New Zealand

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ABSTRACT

The Canterbury Basin is one of the frontier basins of New Zealand and is under active exploration in multiple permits. Sub-commercial gas and condensate discoveries suggest that it has a working petroleum system. Presence and distribution of petroleum system elements such as source, reservoir and seal rocks within the Cretaceous to Paleocene succession are important components in evaluating the petroleum potential of the basin. This study has used seismic facies analysis to identify these elements. 2D PetroMod modelling has then been used to assess how source rock distribution and carrier bed architecture impacts prospectivity of the offshore Canterbury Basin.

Mapping of key sequence stratigraphic surfaces and seismic facies characterisation was carried out to understand basin evolution, facies distribution and depositional environments. Seismic facies were characterised based on seismic amplitude, reflection continuity, geometry of reflection packages and information from five wells. Results were integrated to map facies distribution and to reconstruct source, reservoir and seal rock architecture for petroleum migration modelling.

Facies distribution maps illustrate the mid Cretaceous to Eocene evolution of the basin from initial rifting to a subsequent post-rift sag phase. Reservoir facies include fluvial and coastal sandstones in the Cretaceous syn-rift sequences, and mainly shoreface–shelfal sandstones in the Late Cretaceous to Paleocene post-rift section. Late Cretaceous coastal sandstones are restricted to the western margin of the basin whereas shoreface–shelfal sandstones are widely distributed. In accordance with previous studies, Cretaceous coaly facies are modelled to be the primary mature source rocks in the basin. Widely distributed mid Cretaceous coaly source rocks are mature and peak expulsion is predicted to have occurred during the Paleogene. Late Cretaceous coaly source facies are restricted to the southwestern part of the basin and have likely generated petroleum beneath the Plio-Pleistocene shelf margin offlap. Transgressive marine mudstones within the Cretaceous to Eocene sedimentary succession may act as potential seals for underlying reservoirs. 2D petroleum systems modelling along a line in the basin suggests that carrier bed distribution within the Cretaceous succession and the timing of expulsion relative to seal quality development are key factors controlling the prospectivity in this part of the basin.

KEYWORDS New Zealand, Canterbury Basin, facies distribution, paleogeographic maps, seismic facies characterisation, petroleum system modelling and basin prospectivity.

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INTRODUCTION

The Canterbury Basin is an intra-continental rift and subsequent sag basin located east of New Zealand's South Island. The general geology, basin evolution, and paleogeographic development since the Cretaceous have been described by several authors (Shell BP Todd, 1984; Field and Browne, 1989; Constable and Crookbain, 2011; Sahoo et al, 2014a). The intent of this study is to update these earlier efforts using the most recent publicly available seismic data and seismic facies mapping.

Exploration in offshore Canterbury Basin started in 1965 with the granting of a licence area to a BP Shell Todd consortium (Wilding and Sweetman, 1971). A considerable amount of 2D seismic data was acquired and/or reprocessed between 1974 and 2000 by multiple operators. However, most of the data was restricted to the present day Canterbury shelf area. In 2005 and 2006 Origin Energy was awarded two exploration permits. Origin Energy acquired 3670 line kilometres (lkm) of 2D seismic data and further reprocessed around 5760 lkm of data during 2006–2007 (Mogg et al, 2008). Origin Energy also acquired 1151 km^2 of 3D seismic data (Waka 3D survey) over part of PEP 38262 in the offshore Canterbury Basin. In 2010, Anadarko Petroleum joined exploration in the Canterbury Basin in partnership with Origin Energy. They relinquished 13570 km^2 of the permits in 2011 and retained an area of 6742 km^2. Other seismic data acquired since 2006 include AP256-06 (Austral Pacific Energy Ltd, 2006) and Barque 2D seismic lines (Dayboro Geophysical, 2010).

Six offshore petroleum wells (Endeavour-1, Resolution-1, Clipper-1, Galleon-1, Cutter-1 and Caravel-1) have been drilled so far in the basin. Clipper-1 and Galleon-1 are non-commercial gas-condensate discoveries. In Cutter-1, gas shows were reported in tight Eocene sands and minor shows were recorded in the Late Cretaceous. Recently in 2014, Caravel-1 was drilled under operatorship of Anadarko Petroleum and gas shows were observed in the Paleocene section (Blanke, 2015). Additional information (location, biostratigraphy, cuttings lithology and wireline logs) from this well was not available for this study.

As part of the present study, an updated series of paleogeographic maps in the offshore Canterbury Basin (Figure 1) were produced to show source, reservoir, and seal rock distribution within the Cretaceous to Eocene succession. This study utilised the most recent biostratigraphy and paleoenvironmental interpretations in wells compiled by Griffin (2013) and newly available seismic data, including the Waka 3D, Barque survey and AP256-06 seismic lines. These paleogeographic maps were then used to build a 2D PetroMod model to understand how source rock distribution and carrier bed architecture impacts prospectivity of the offshore Canterbury Basin.

DATA AND METHODS

2D and 3D seismic data (Waka 3D) and information from five offshore wells available in the public domain were used for this study (Figure 1). Results of the recently drilled well Caravel-1 are still confidential and were not used in this study. We have mainly used 2D seismic data for the facies interpretation because of its larger areal extent. The Waka 3D seismic volume has been used to understand the distribution of facies types and igneous intrusions. 2D seismic data are of multiple vintages and data quality varies. Seismic lines reprocessed in 2006 and 2007, and seismic lines acquired since 2006 are of better quality and offer greater interpretation confidence. Horizons and faults were mapped across the Canterbury Basin to understand basin evolution and facies distribution (Figure 2). Age was assigned to each horizon using the most recent biostratigraphy from drilled wells and well correlation along seismic lines.

Recently, seismic facies mapping and paleogeographic maps have been prepared in the contiguous Great South Basin by Sahoo et al (2014b). Following facies interpretations by Sahoo et al (2014b), seismic amplitude, continuity, and geometry of reflection packages were analysed to categorise different seismic facies types, and these were then calibrated with wells for age, gross lithology, and depositional environment. We have used seismic facies characterisation, well data, and isochron maps to prepare a series of updated paleogeographic maps. A 2D PetroMod basin model was then prepared along line cb82-54 through Clipper-1 (Figure 1) using facies maps and well data to understand source rock maturity and migration in the basin. Overall, confidence in our seismic facies interpretation is greatest in areas near the wells, and it decreases away from wells and in areas with poor seismic data quality and coverage.

TECTONO-SEDIMENTARY EVOLUTION

The Canterbury Basin was initiated in the mid Cretaceous during the rifting of New Zealand from West Antarctica (Field and Browne, 1989). Basement rocks of the Canterbury Basin exposed in outcrop in the South Island are mainly composed of metasediments of the Torlesse Terrane. Details of basement rocks observed in outcrop are described in Field and Browne (1989) and references therein. Basement rocks in the offshore Canterbury Basin are also considered to be related to the Torlesse Terrane, although localised igneous basement rocks may be present. Lithologies of basement rocks include schist, metasediments, localised volcanics and gabbros. For this study the basement pick has been tied to the Haast Schist top at Clipper-1 and top gabbro at Galleon-1, although the latter is believed to be an intrusive body rather than true basement. Basin evolution of the mid Cretaceous to the present day sedimentary succession can be simplified into three main phases (O'Leary and Mogg, 2008): syn-rift phase, post-rift thermal sag phase and regression phase (Figure 2).

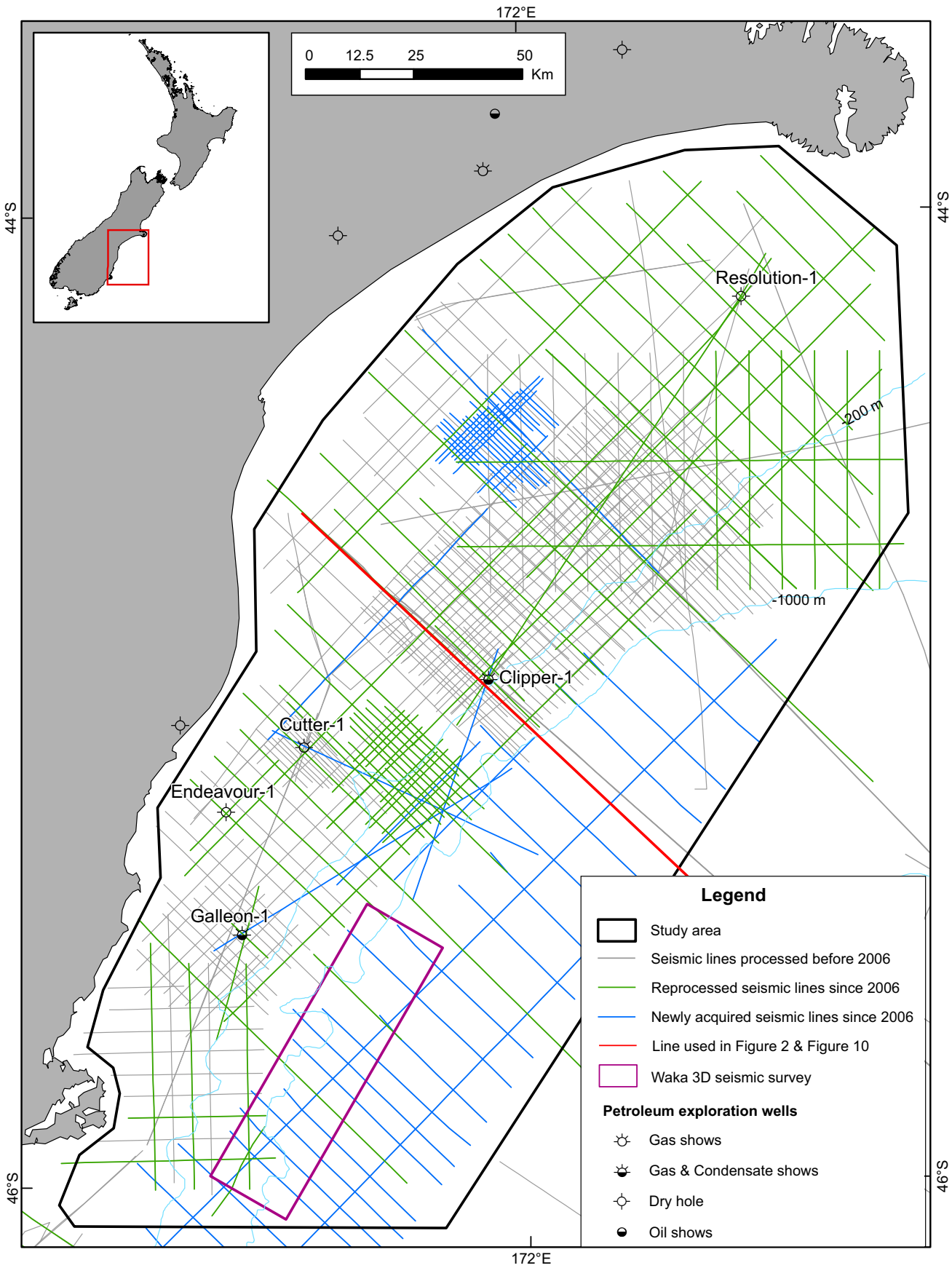

FIGURE 1. Location map of the study area showing drilled wells and seismic data coverage. Line of section shown in Figure 2 and Figure 10 is indicated by the red highlighted line.

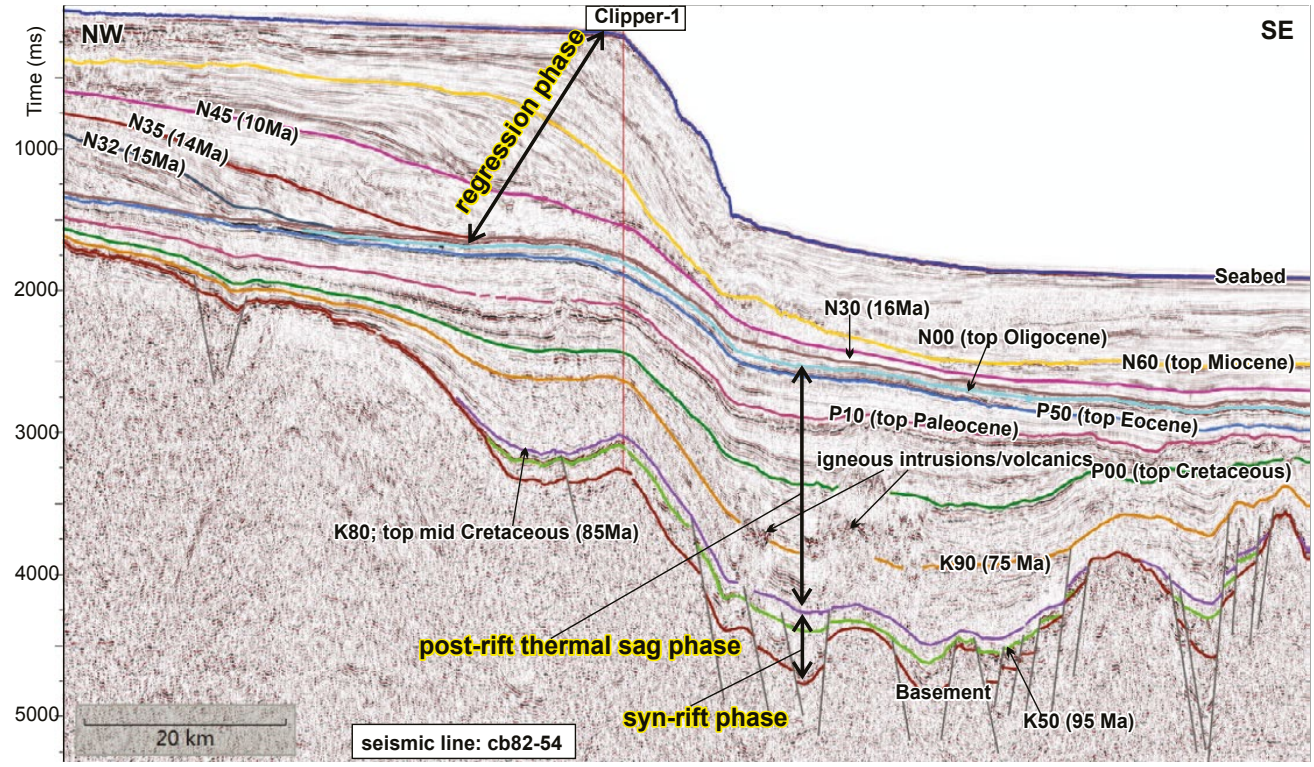

FIGURE 2. A seismic section through Clipper-1 showing mapped horizons, faults and tectonic phases. For the purpose of the basin modelling absolute age has been assigned to each horizon (shown within brackets).

The syn-rift phase is characterised by active normal faulting and widespread horst and graben complexes (Figure 2). These syn-rift fault systems are pronounced in the entire study area except the north western region. Distribution of major fault systems are shown in the paleogeographic maps in the subsequent section (Figures 5a & 5b). Two sets of faults are associated with the syn-rift sediments. Northeast–southwest oriented faults dominate in the basin reflecting the main trend of rifting. East–west trending faults are also observed in the study area but they are not widespread. Sediments deposited in the syn-rift phase range in age from the mid Cretaceous (Albian; ~ 105 Ma) (Davy, 2014) to the middle part of the Late Cretaceous (Santonian; ~ 85 Ma) (O'Leary and Mogg, 2008). Two sequences have been mapped within the syn-rift phase. The earliest syn-rift sequence overlying basement corresponds to Albian–late Cenomanian age (105–95 Ma). Seismic reflectors within this sequence show onlap onto the basin margin and structural highs. Sediments within the lower part of this sequence are often restricted to grabens bounded by fault blocks (Figure 2). Towards the upper part, seismic reflections are more widespread indicating filling of grabens. The sequence in the later part of the syn-rift phase, ranges in age from the late Cenomanian to the Santonian (95–85 Ma). Horizon K80 (85 Ma) has been mapped at the top of the syn-rift sequence and is represented by an unconformity in most places. Seismic units within this sequence also show onlap of reflectors towards structural highs and the basin margin, indicating ongoing infill of the grabens.

The post-rift thermal sag phase is represented by Late Cretaceous to Oligocene sediments (Mogg et al, 2008). During this phase, the basin was largely tectonically quiescent and overall marine transgression occurred during thermal subsidence. Some faults intersect the K80 horizon, indicating some activity during the early post-rift thermal sag phase; however, these faults are not widespread in the basin (Figures 5c, 5d & 6). Maximum flooding of the landmass occurred during the Oligocene (Fulthorpe and Carter, 1991). Five horizons K90 (75 Ma), P00 (top Cretaceous), P10 (top Paleocene), P50 (top Eocene) and N00 (top Oligocene) have been mapped within the post-rift sequence. Top Eocene is an unconformity in most of the region due to erosion caused by younger submarine channel systems. Based on data from the Clipper-1 well, initiation of these channels is interpreted to be around Early Oligocene. Major axial drainage of these channel systems is interpreted to be feeding sediments towards the southeast (Figure 3). Channel systems of this time are also observed in the Waka 3D seismic survey. In Waka 3D channels are flowing from southwest and feeding sediments to the main axial drainage (Figure 3). Lever (2007) postulated that unconformities in the shallow water successions within the Oligocene may have been caused by global sea level falls and sub-Antarctic oceanic current activities. Similar reasons are considered for the Early Oligocene erosion event in the far offshore parts of the basin.

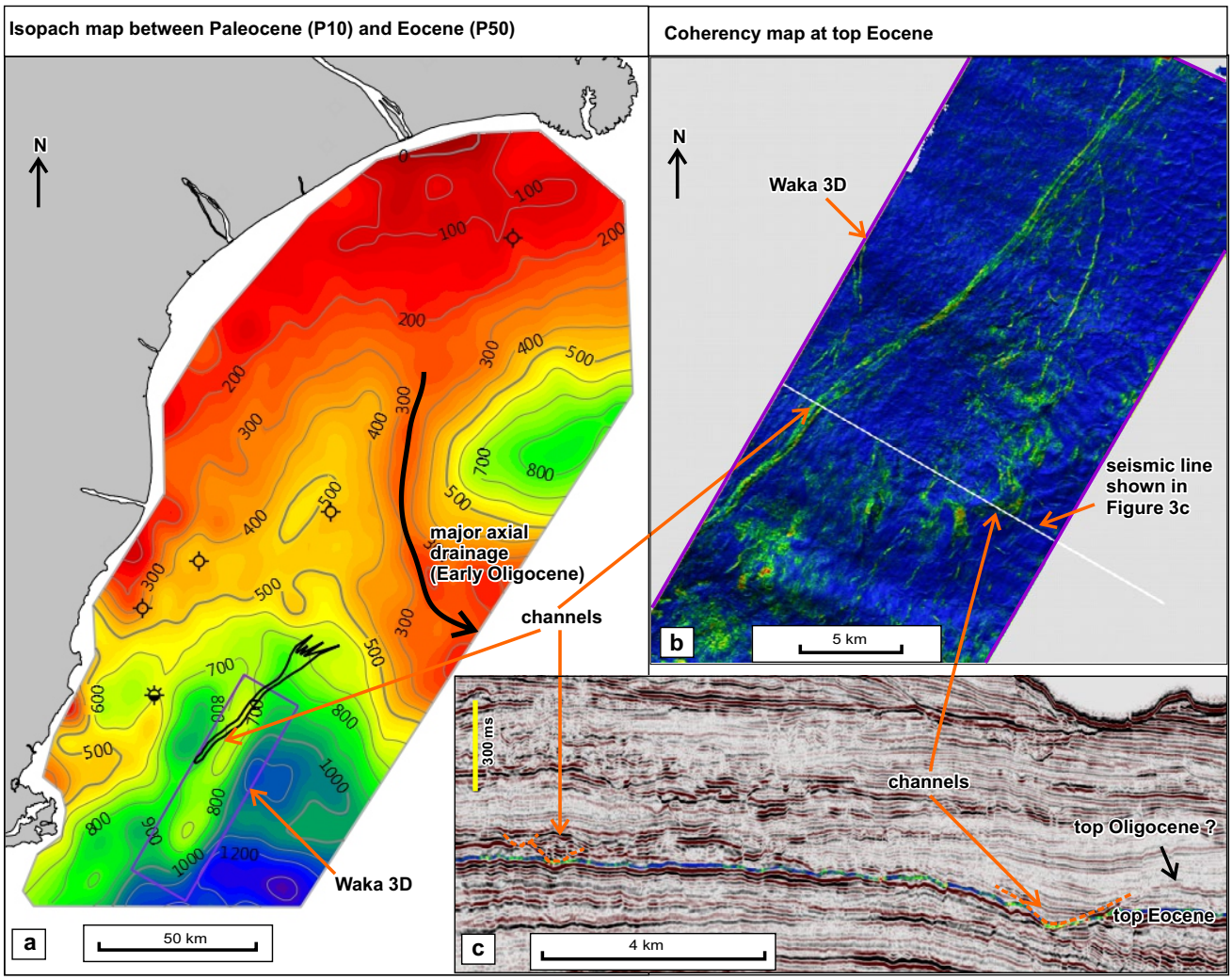

FIGURE 3. a) Isopach map between Paleocene and Eocene showing major axial drainage flowing from the northwest to the southeast.
b) Coherency map at top of the Eocene showing deepwater channel systems flowing from the southwest to the northeast.
c) Seismic examples of the channel systems. Initiation of channel systems and major axial drainage is considered to be during the Early Oligocene.

The regression phase is characterised by Miocene to Recent prograding foresets. The foresets developed due to increased rate of sediment supply during strike slip movement along the Alpine fault (Fulthorpe and Carter, 1991). Six horizons have been interpreted within the Miocene to Recent interval. Among them, top Miocene and seabed have been mapped regionally and the remaining four horizons have been mapped in selected seismic lines to reconstruct the timing of burial. The Oligocene–Early Miocene interval is condensed in the Canterbury Basin and is represented by a thin carbonate-rich interval indicated by a set of high amplitude reflectors in the seismic data.

SEISMIC FACIES CHARACTERISATION

Six broad facies categories were used to define facies in the Cretaceous through Eocene succession. These facies types and related lithologies are terrestrial deposits, coastal coal measures, coastal sandstone and siltstone, shoreface–shelfal sandstone and siltstone, shelfal mudstone and siltstone, and bathyal (mainly mudstone).

Terrestrial facies include alluvial fans and fluvial facies. Terrestrial facies are characterised by variable amplitude, discontinuous to low continuity reflectors and chaotic to sub-parallel internal geometry. Lacustrine facies may occur in isolated depocentres within the syn-rift sequence but it is difficult to identify them based on available seismic data alone. Terrestrial facies are observed in wells Clipper-1 (Figure 4b), Endeavour-1 and Cutter-1.

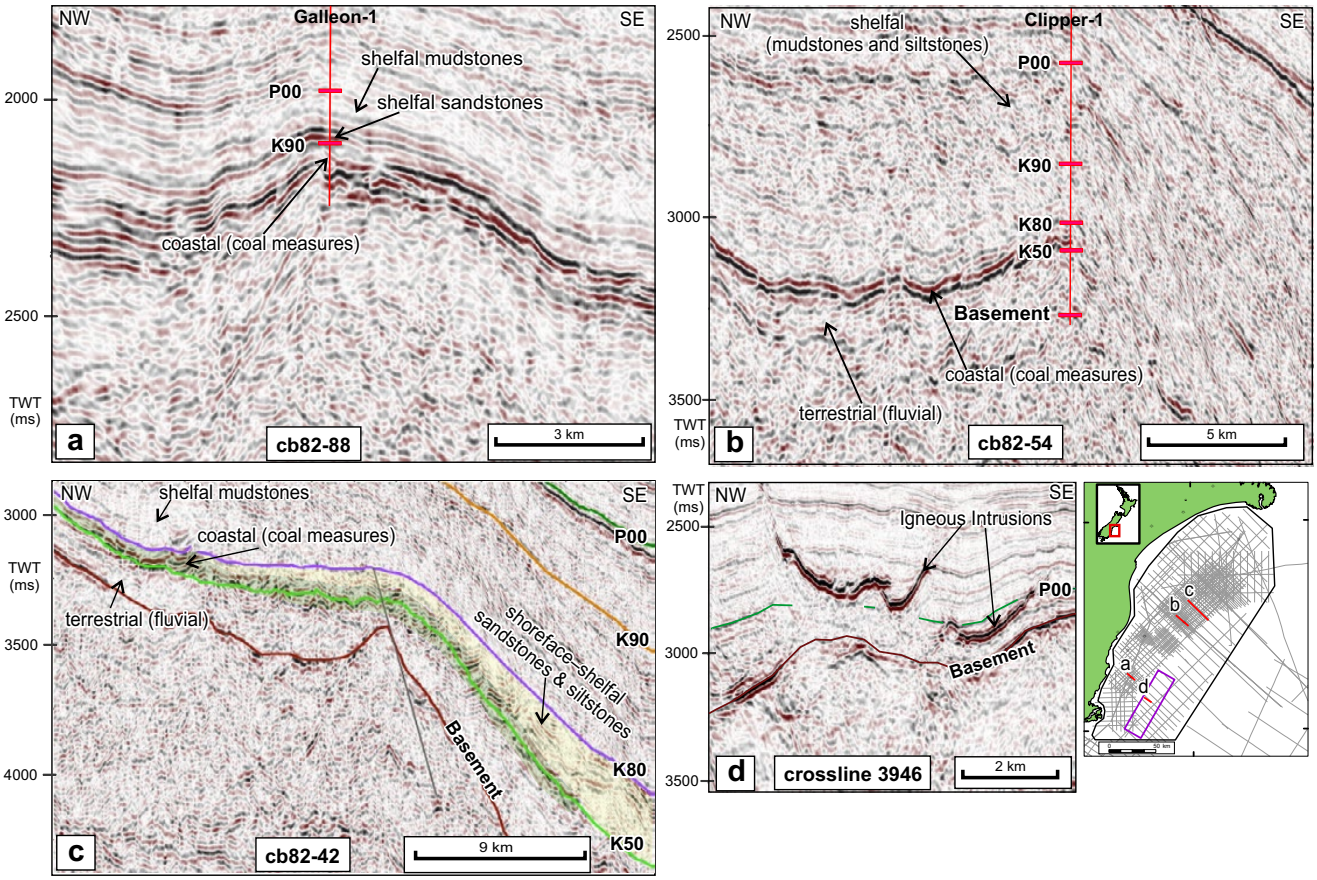

FIGURE 4. Seismic sections showing examples of facies types and depositional elements identified in the study area. Locations are shown in inset map. a) Seismic section through Galleon-1 showing seismic characteristics of coastal coal measures, shelfal mudstone and shelfal sandstone. b) Seismic section through Clipper-1 showing seismic characteristics of terrestrial facies (fluvial), coastal (coal measures) and shelfal (mudstone & siltstone) facies. c) Seismic section showing a change in facies belts from coastal coal measures to shoreface–shelfal sandstones and siltstone within K50 to K80 sequence. d) Seismic examples of igneous intrusions (for further details see Blanke, 2013).

Coastal environments are transitional between terrestrial and marine settings. They include deltas, estuaries and beach environments (Catuneanu, 2006). In this study coastal facies are broadly categorised into coastal coal measures and coastal sandstone and siltstone facies. Coastal coal measures are characterised by high amplitude, moderate to continuous and parallel reflectors (Figures 4a–4c). Coastal sandstone and siltstone facies are characterised by moderate to high amplitude, moderately continuous, parallel to sub parallel reflectors. Commonly the coastal sandstone and siltstone facies are amalgamated with the coastal coal measures. Coastal facies are observed in all offshore wells in the basin except Resolution-1 in the far north.

Shoreface sandstone and siltstone deposits are characterised by moderate amplitude, low continuity, and parallel to slightly divergent reflectors. Shelfal sandstones are characterised by moderate to high amplitude and continuity, and parallel reflectors (Figure 4a). For the purpose of modelling, these facies act as carrier beds and therefore have been merged to represent a single facies belt. In general, shelfal mudstone and siltstone facies show a low amplitude and low continuity reflector. However, some of the shelfal mudstone and siltstone units within the Late Cretaceous and Paleocene succession show high amplitude and high continuity reflectors. This character may be due to the presence of calcareous or carbonaceous mudstones. High lateral seismic continuity character in shelfal mudstones may indicate outer shelf areas. Mudstone and siltstone facies of the K80–K90 interval in Clipper-1 show a wide range of depositional environments from shelfal to upper bathyal environments (Griffin, 2013) and there is no clear distinction between these two environments based on seismic reflection patterns. Foraminifera indicate a dominantly outer shelf environment, though bathyal facies may be interpreted only in the lower most interval of K80–K90 (personal communication from Ian Raine, GNS Science). In the absence of typical shelf-slope break and slope character in seismic sections, mudstones and siltstones have been assigned to a shelfal environment in the study area. However, it is possible to get upper bathyal facies in the deeper parts of the basin in the K80–K90 interval.

Bathyal facies are observed in the Eocene section in all wells. The Eocene section is dominantly bathyal mudstone, though bathyal sandstones are also observed in Endeavour-1 and Cutter-1 wells within the Eocene section. In general, bathyal mudstone and siltstone facies show variable amplitude, moderate to high continuity and parallel reflectors.

Many volcanic and igneous intrusions are observed within the Cretaceous and Paleocene sequences. It is often difficult to distinguish between igneous intrusions and volcanics using the available 2D seismic data. Intrusions are characterised by high amplitude reflections and often show a sharp change in character from surrounding facies (Figure 4d). Volcanics show a chaotic internal reflection pattern.

PALEOGEOGRAPHIC MAPS

Paleogeographic maps were prepared in the offshore Canterbury Basin using seismic facies character, geometry of reflection packages, isochron maps, well lithology and biostratigraphy. Geological maps from Forsyth et al (2008), Cox and Barrell (2007) and Forsyth (2001) have been used to check the continuity of the offshore paleogeographic maps with the outcrop lithology. To illustrate the areal distribution of facies from the Cretaceous to the Eocene, six paleogeographic maps were prepared at 95, 85, 75, 66, 56 and 34 Ma (Figures 5 & 6). These maps depict facies immediately below the top of each time horizon. Paleogeographic maps are expressed broadly as areas of non-deposition/erosion, terrestrial, coastal coal measures, coastal sandstone and siltstone, shoreface–shelfal (sandstone & siltstone), shelfal (mudstone & siltstone) and bathyal (mainly mudstone) facies types. Numerous igneous intrusions/volcanics are present within the study area; however, only few representative intrusions/volcanics are shown in the paleogeographic maps.

The Cretaceous to Eocene paleogeographic evolution of the Canterbury Basin shows an overall transgressive motif (Figures 5 & 6), from terrestrial and coastal setting during mid Cretaceous (95 Ma) to a bathyal environment during the Late Eocene time (34 Ma). The marine transgression into the study area started during the latter part of the mid Cretaceous (95–85 Ma) and was directed from the east.

At 95 Ma (Figure 5a), the basin was dominated by terrestrial and coastal facies. Source rocks are mainly coastal coal measures. These coal measures are part of the Clipper Formation and distributed mainly in the northeast parts of the basin and east of Zapata Ridge (Figure 5a). These coal measures are present only in the upper part of the basement–K50 interval. Some smaller areas of coal measures are also observed in the southern part of Zapata Ridge. There may be the possibility of development of lacustrine facies within the syn-rift grabens in the basement–K50 interval. Some of the lacustrine facies may have source rock potential; however, it has not yet been established in the basin. Main reservoir rocks at this level are fluvial and coastal sandstones and they are widely distributed in the eastern parts of the basin.

At 85 Ma, the basin shows marine transgression from the east. At this level the basin is dominated by shoreface–shelfal facies (Figure 5b). Source rocks are mainly coastal coal measures of the Clipper Formation. They are widely distributed in the western basin margin. Coal measures are observed in Clipper-1 at this level. Reservoir facies are fluvial sandstones, coastal sandstones, shoreface–shelfal sandstones and siltstones. The eastern, central and southwestern parts of the basin are characterised by sandstone and siltstone dominated facies. However, the low amplitude and low continuity seismic character in the southeastern parts of the basin indicates a lack of coarse clastics and suggest dominance of shelfal mudstone and siltstone facies.

At 75 Ma (Figure 5c), subsidence and marine transgression continues in the western margin of the basin. Shelfal facies are widespread and dominate in most parts of the basin. The northern part of the basin is more marine-dominated compared to the southern part. Coastal coal measures of Pukeiwitahi Formation are the main source rocks at this level and they developed mainly in the south western part of the study area. Northern parts of the basin are dominated by an influx of coarse clastics as evident from cuttings lithology in Resolution-1. Reservoirs are mainly coastal sandstones and shoreface–shelfal sandstone and siltstone. Shelfal mudstone and siltstone facies dominate in the eastern part. These shelfal mudstones may provide some sealing potential for the underlying reservoir units.

At 66 Ma, the study area is dominantly in a marine setting (Figure 5d). The coastal coal measures facies may have moved further west of the basin as many Late Cretaceous coal measures are observed in outcrops west of the study area (Forsyth et al, 2008; Cox and Barrell, 2007; Forsyth, 2001). Reservoirs are shoreface–shelfal sandstone and siltstone facies and they are mainly distributed in the northern part of the basin. Southern and central areas show dominantly shelfal mudstone and siltstone facies. Subsidence and marine transgression also continue at 56 and 34 Ma. At 56 Ma, reservoirs are mainly shoreface–shelfal sandstone and siltstone facies (Figure 6a). They are distributed in the northern and western part of the study area. Shelfal mudstones and siltstone facies are widely distributed in the central and southern area. At 34 Ma, almost the entire basin is dominated by bathyal mudstone facies (Figure 6b).

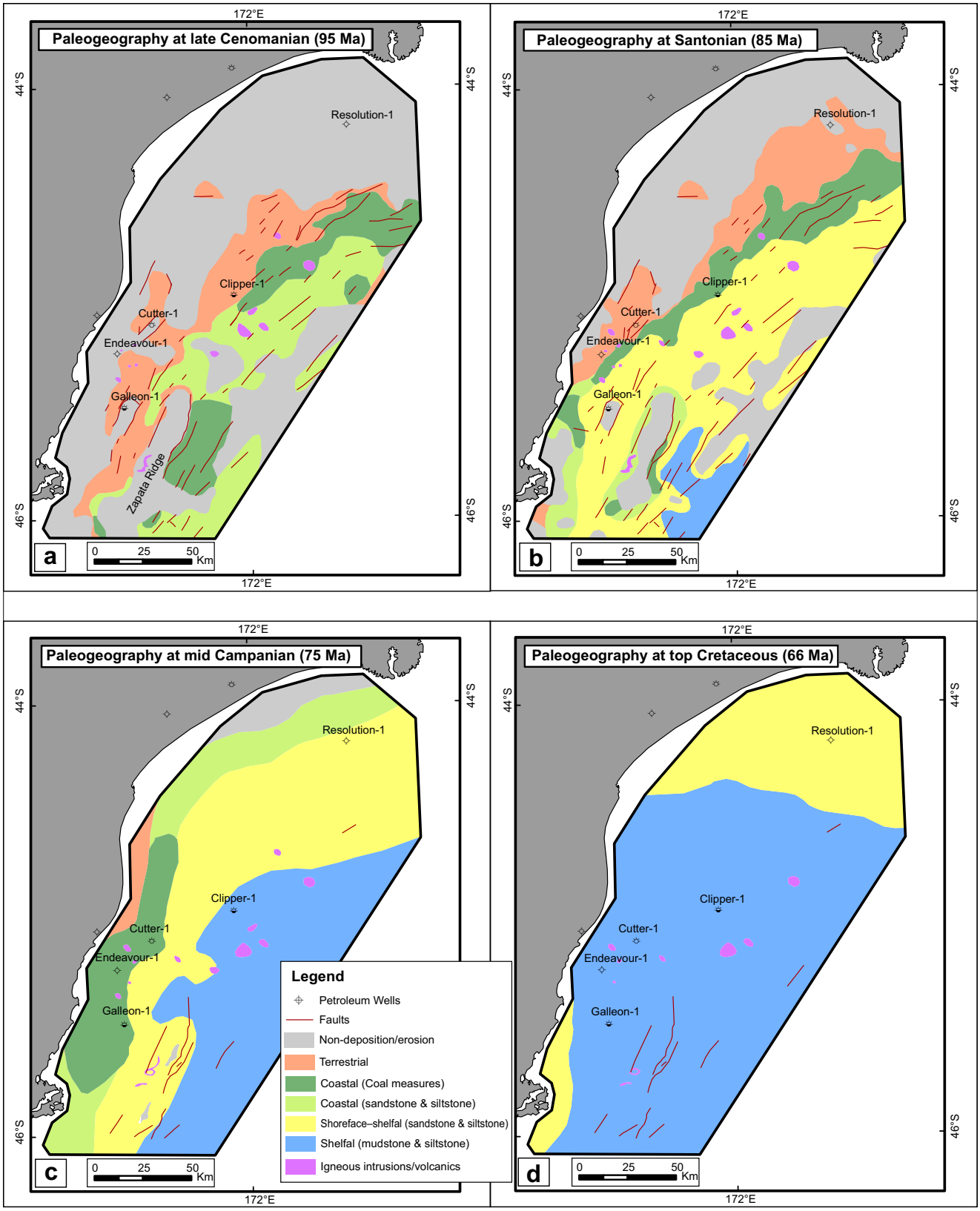

FIGURE 5. a) Paleogeographic map at late Cenomanian (95 Ma). b) Paleogeographic map at Santonian (85 Ma). c) Paleogeographic map at mid Campanian (75 Ma). d) Paleogeographic map at top Cretaceous (66 Ma).

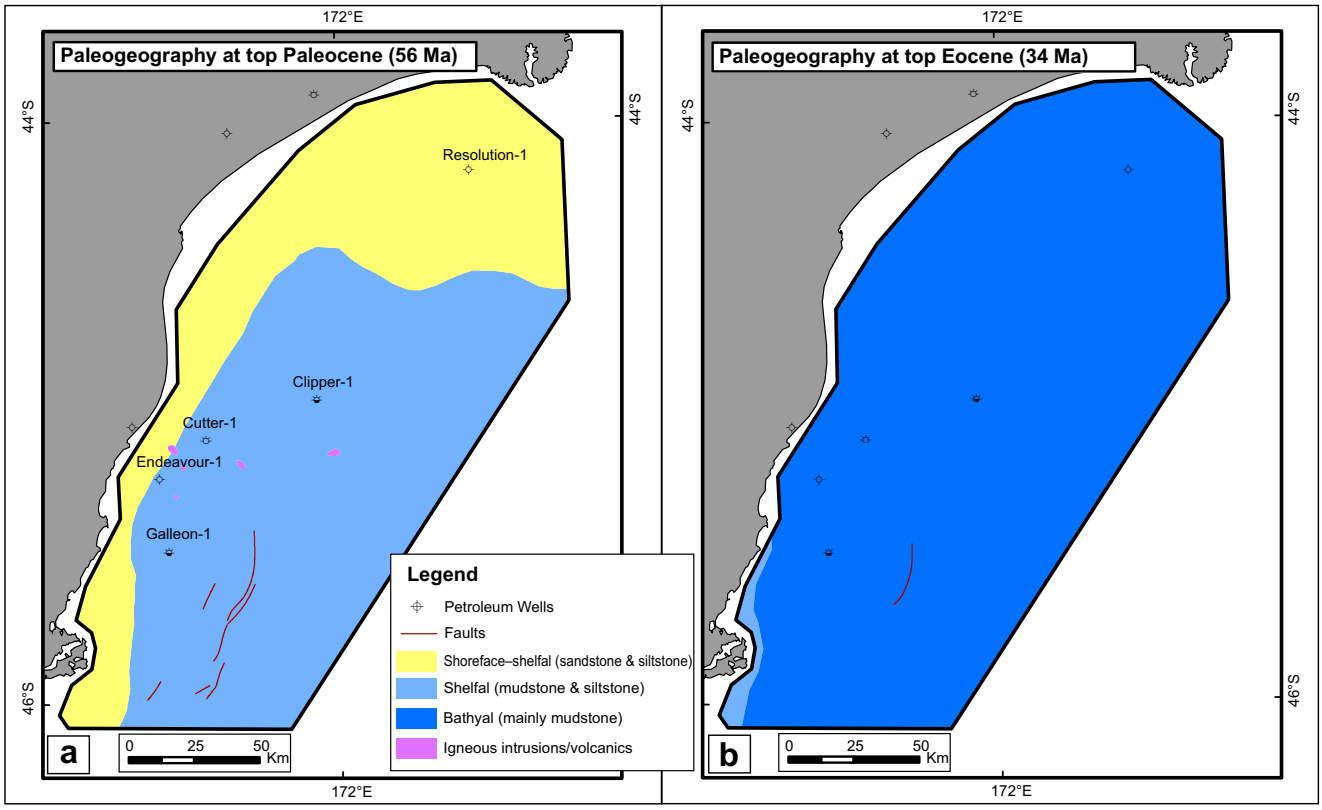

FIGURE 6. a) Paleogeographic map at top Paleocene (56 Ma). b) Paleogeographic map at top Eocene (34 Ma).

PETROLEUM SYSTEM MODELLING

Model input parameters

A 2D PetroMod model along a seismic line (cb82-54; Figure 2) through Clipper-1 was prepared to assess the hydrocarbon maturation and migration potential in the basin. Basic inputs to build the model were stratal horizons derived from seismic interpretation and their ages based on biostratigraphy (Griffin, 2013), and lithologies derived from facies interpretation. Intermediate horizons were added as iso-proportional slices where additional facies details were required. Lithological composition of each facies was defined in terms of sand/silt/shale/coal/limestone percentages from the qualitative analysis of wireline logs and lithology of cuttings available in the well penetrations in the basin. Forward modelling was carried out using paleo-water depth evolution through time derived from the paleogeographic maps, paleoenvironmental information from fossils at well sites and vertical restoration at each time step in PetroMod. In addition, an erosion event during Early Oligocene (Figure 3), with amounts of erosion varying from 0 to 300 m, was introduced in the 2D model. To model the thermal evolution of the basin along the 2D line, sediment water interface temperature (SWIT) was derived from Hollis et al (2012) for the Paleocene–Eocene interval. For the Neogene, bathyal SWIT were considered to be cool (2–3°C). On the shelf SWIT was derived from calibration to IODP borehole 1352 (Fulthorpe et al, 2011). Heat flow at the base of the model was calculated and calibrated to well temperature and vitrinite reflectance data, which is described in detail in the next section.

A detailed study of potential source rocks in the Canterbury Basin has been carried out by Sykes and Funnell (2002). Published source rock properties and kinetic models were used to model petroleum generation and expulsion. In agreement with Sykes and Funnell (2002), mid–Late Cretaceous coaly facies were modelled as the primary source rock in the basin. These facies were deposited in a coastal setting and have been subdivided into a primary coaly facies (coal measures) and a facies consisting mainly of sandstones and siltstones (Figures 5a & 5b), which may also contain a smaller percentage of coaly source rocks. In addition, the Paleocene Tartan Formation (Schiøler et al, 2010) has been considered as a source rock. Considering the substantial thickness of the source rock intervals defined by horizon mapping a conservative average TOC (%) was used for the source rock properties. Source rock parameters used in the 2D PetroMod model are summarised in Table 1. Models were run using kinetic parameters Type III DE (Pepper and Corvi, 1995) for the mid–Late Cretaceous source rocks and Type II B kinetic parameters for the Paleocene source rock. The Type III DE kinetic parameters are widely used to model petroleum generation from waxy non-marine source rocks rich in leaf/cuticle-dominated higher plant material.

Model calibration

Vitrinite reflectance data from Newman et al (2000) and Gibbons and Herridge (1984) were used for calibration. However, the poor fit of data from Gibbons and Herridge (1984) in Clipper-1 (Figure 7) is thought to be due to vitrinite reflectance being suppressed by their perhydrous nature and by the incorrect inclusion of suppressed vitrinite measurements in the older data (Newman et al, 2000; Sykes and Funnell, 2002). Input parameters such as heat flow, timing, dimensions and depth of emplacement of igneous intrusions, SWIT and increased thermal conductivity in the Neogene sediments were used to calibrate the model with present day temperature and maturity at Clipper-1 (Figure 7a & 7b). There is evidence for igneous activity in the offshore Canterbury Basin as observed from maturity data (Newman, et al, 2000) and intrusions are widespread in the basin based on seismic reflection character. Timing of igneous intrusion at Clipper-1 is considered to be 61 Ma, consistent with timing proposed by O'Leary and Mogg (2008) and is similar to the intrusion at Galleon-1 (Haskell and Wylie, 1997). This age is supported by the seismic interpretation of structural bulging of strata extending up to the Paleocene level. An approximately 2 km wide igneous intrusion was emplaced at a depth of around 1100 m below Clipper-1 TD (total depth) in the model. This intrusion helped in achieving the best calibration to vitrinite reflectance data below 3000 m (Figure 7b).

Stretching factors (β) were estimated using the thickness of syn-rift Cetaceous sediments (105–85 Ma) and the crust. Stretching factor (β) varies from 1 to 1.18. Heat flow was calculated within PetroMod using the distribution of β factors and an average crustal thickness of 24 km (Mortimer et al, 2002; Scherwath et al, 2003; Grobys et al, 2008), and assuming a mantle lithosphere thickness of 80 km. Calculated heat flow varying from 60–64 mW/m^2 at the base of the model provided a reasonable fit with the present day temperature and maturity (Figure 7).

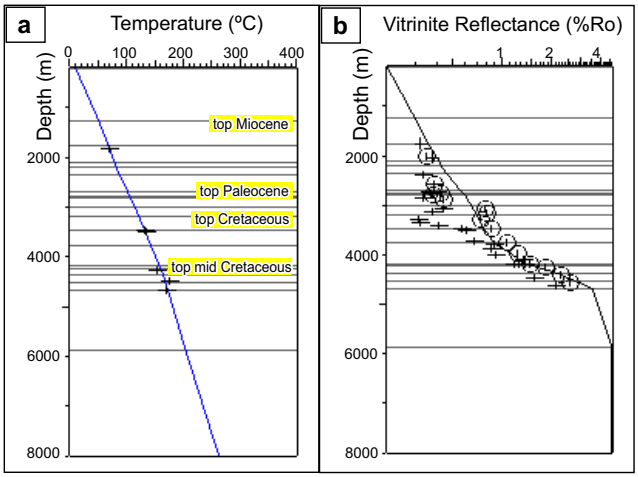

FIGURE 7. Calibration of model results at Clipper-1 with a) temperature, b) vitrinite reflectance (data from Gibbons & Herridge (1984) and Newman et al, (2000) are shown as plus and circle symbols respectively).

Thermal history, maturity and petroleum expulsion

At Clipper-1, maximum temperature was predicted during the Paleocene due to the modelled igneous intrusion (Figure 8a). In areas unaffected by intrusive heating, modelling results suggest that the highest temperatures at source rock level were reached during the Late Paleocene–Eocene (Figure 8b). Late Paleocene–Eocene climate warming (Hollis et al, 2012) is predicted to have additionally increased basin temperature. Warmer basin temperatures during this time interval due to climate warming affecting petroleum generation history have previously been postulated in the Great South Basin to the south of the study area (Kroeger and Funnell, 2012). The present model suggests that after Eocene warming, basin temperature decreased in the Late Eocene–Early Oligocene due to erosion and cooler water temperature.

TABLE 1. Source rock parameters used in the 2D PetroMod model.

Source interval	Facies TOC (%)	Hydrogen Index (HI)	Kinetic parameters
Paleocene (Tartan Formation)	3	300	Type II (B) Pepper and Corvi (1995)
75–85 Ma coal measures	5	280	Type III (DE) Pepper and Corvi (1995)
85–95 Ma coal measures	5	300	Type III (DE) Pepper and Corvi (1995)
Older than 95 Ma coal measures	3	300	Type III (DE) Pepper and Corvi (1995)
Mid-Late Cretaceous coastal	2	200	Type III (DE) Pepper and Corvi (1995)

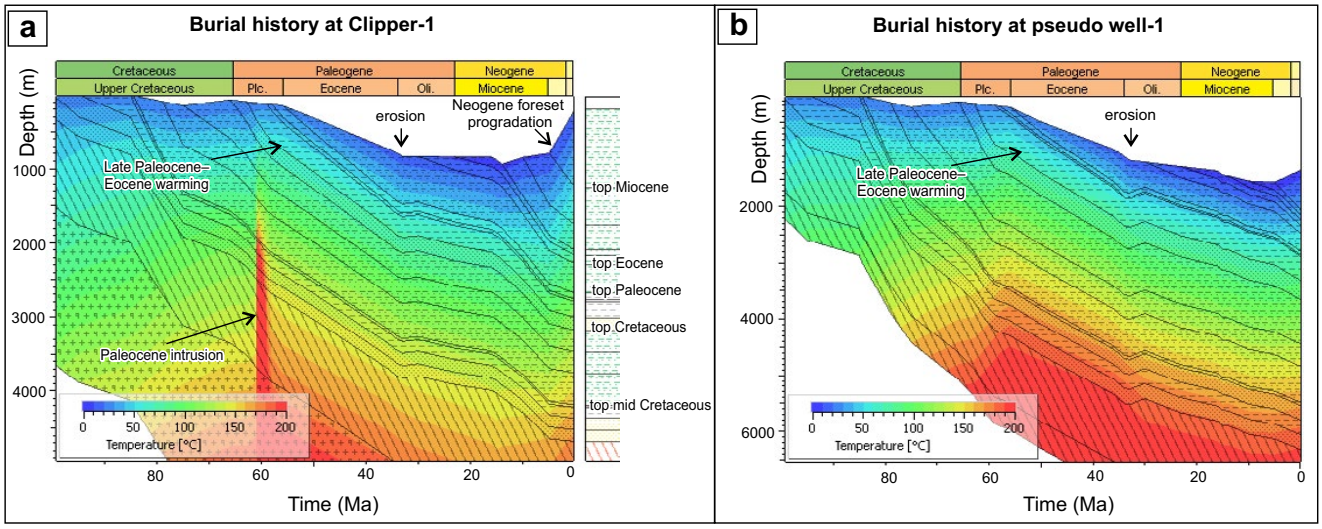

FIGURE 8. a) Burial history at Clipper-1. b) Burial history at pseudo well-1 (see location in next figure).

At present day, the calibrated model shows temperatures of >150°C for most of the section below 85 Ma. These data suggest that most of the mid Cretaceous source rocks (up to ~85 Ma) are within the late maturity window at present day (Figure 9a). Late Cretaceous source rocks younger than 85 Ma are restricted to the western boundary of the basin (Figure 5c). Some of the Late Cretaceous source rocks are predicted to be mature below the prograding Neogene foresets but most of them are in the early maturity window (Figure 9a). Paleocene source rocks (Tartan Formation) have not reached sufficient maturity to generate hydrocarbons. In general, higher maturities at a given depth are predicted beneath the Neogene foresets while igneous intrusions influence localised high maturity (Figure 9a).

Mid Cretaceous rocks are considered to be the primary source rocks in the Clipper sub-basin as they are widely distributed and have reached sufficient maturity to expel hydrocarbons. It is important to consider the expulsion history of this source rock and seal development to understand possible hydrocarbon accumulations in the basin. Predicted cumulative expelled petroleum is shown for three locations (Figure 9a); at pseudo well-1 (away from Neogene foreset progradation and igneous intrusion), Clipper-1 and pseudo well-2 (underneath the Neogene foresets and away from igneous intrusions). At pseudo well-1 expulsion is predicted to have started in the Early Paleocene and peaked by the end of the Eocene (Figure 9b). Expulsion at Clipper-1 is predicted to have started slightly later but to then have occurred rapidly during the time of igneous intrusion (Paleocene). Source rocks at Clipper-1 are predicted to reach > 85% transformation ratio during the Paleocene as a result of igneous intrusion. At pseudo well-2 expulsion started in the Late Paleocene increasing slowly to the end of the Eocene. Petroleum expulsion is predicted to have stopped or been significantly reduced during the Oligocene at all three locations due to cooling related to erosion and incursion of sub-Antarctic cold water masses (Lever, 2007). Further expulsion in the Neogene is predicted to have only occurred beneath the foresets (pseudo well-2), slowly increasing with the increase in burial by Neogene foreset progradation.

Migration and charge modelling

To assess the potential for petroleum accumulation, migration modelling was carried out. For PetroMod modelling we used the hybrid migration modelling approach which uses a combination of flowpath and Darcy flow modelling (Hantschel and Kaurauf, 2009; Kroeger et al, 2009). PetroMod uses a permeability threshold to differentiate between rocks where flow is modelled using Darcy flow and rocks where flowpath migration occurs. We have set this permeability threshold to a value of 100 mD above which petroleum is considered to move through focussed flow rather than saturation fronts and where petroleum can accumulate. Lithological compositions were derived from Clipper-1 well log and cuttings lithology information. Migrating petroleum phases (liquid and vapour, as shown by green and red arrows respectively) are mainly originating from the mid Cretaceous source rocks in the model (Figure 10). In Clipper-1, the interval between top Cretaceous and 95 Ma shows a poor development of reservoir facies and is high in clay and silt content (> 80%). Due to the lack of good reservoir, modelling predicts no petroleum accumulation, which is consistent with the absence of a commercial accumulation at Clipper-1 despite predicted petroleum migration from a mature mid Cretaceous source rock.

In the model, we have considered shoreface–shelfal sandstones and siltstones facies to be good quality reservoirs deposited during 95–85 Ma and 85–75 Ma. Good reservoir facies in the 85–75 Ma interval is considered similar to the reservoirs observed at Galleon-1. At Galleon-1, Late Cretaceous sandstones

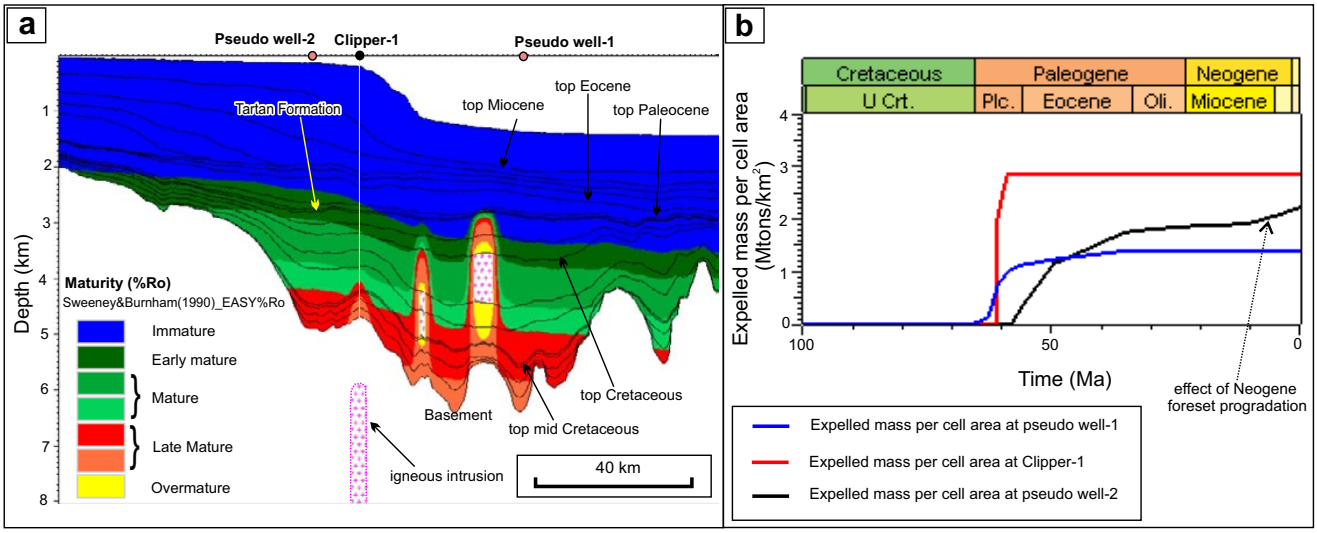

FIGURE 9. a) Present day maturation along a 2D line through Clipper-1. b) Present day cumulative expelled petroleum from mid Cretaceous source rocks at pseudo well-1, Clipper-1 and pseudo well-2.

of the Herbert Formation show reservoir properties with an average porosity around 17% and core permeability ranging from 10 to 100 mD (Mogg et al, 2008). We assumed a lithological composition of 70% sandstone and 30% siltstone for the reservoir facies in the 95–85 Ma and 85–75 Ma intervals, and 50% sandstone, 40% siltstone and 10% claystone in the lower Paleocene section. Presence of a good regional seal (70% shale and 30% siltstone) has been considered overlying the 95–85 Ma reservoir interval.

Modelling results suggest that both oil and gas has been expelled and accumulated in the past; however, at the present day most of the accumulations contain gas. This may be due to replacement of the early oil accumulations by later expelled gas and subsequent leaking through seal at shallower structural levels in the basin. A small oil and gas accumulation is predicted in the 85–75 Ma interval in a stratigraphic trap (see close up section in the left hand side of the Figure 10). This stratal trap reflects the lateral change in modelled reservoir properties from shoreface–shelfal (sandstones & siltstones) facies to coastal facies. Although this lateral change is likely to occur along the section, the modelled boundary is somewhat arbitrary.

Petroleum accumulations are predicted in the shoreface–shelfal (sandstone & siltstone) facies in the 95–85 Ma and 85–75 Ma interval at the present day. Reservoirs within the 95–85 Ma interval are charged from the mid Cretaceous source rocks. Accumulations in the 95–85 Ma interval have been in place from the end of the Late Paleocene to the present day. Sufficient overburden and seal quality of the overlying unit is predicted to be present to at least partially preserve early expelled petroleum in the deeper part of the basin since the Late Paleocene. However, in areas with poor seal, it may lead to significant loss of the early expelled hydrocarbon from the mid Cretaceous source rocks. The model suggests that sufficient seal overlying the 85–75 Ma reservoirs (Figure 10) was not developed in the western part of the basin until the Late Miocene due to lack of overburden. Therefore, most of the expelled hydrocarbon during Paleocene and Eocene time (Figure 9b) in the western part of the basin may have escaped through vertical migration and/or lateral migration out of the basin before further burial by the Neogene foresets. Expelled hydrocarbons from the mid Cretaceous (pseudo well-2 in Figure 9b) and Late Cretaceous source rocks during Neogene foreset development may have led to accumulations in the Late Cretaceous reservoirs (85–75 Ma in this model) after the Late Miocene time in the western part of the basin. However, along the modelled line only small accumulations are predicted in the western part of the basin at the present day (Figure 10).

Modelling predicts charge of potential Paleocene reservoirs from the underlying mid and Late Cretaceous source rocks. However, no sizable hydrocarbon accumulations are predicted at this level due to lack of good seal by the overlying Paleocene mudstones. This modelling result is consistent with the presence of gas shows in the Eocene at Clipper-1 which suggest gas leakage through Paleocene sediments (Hawkes et al, 1985).

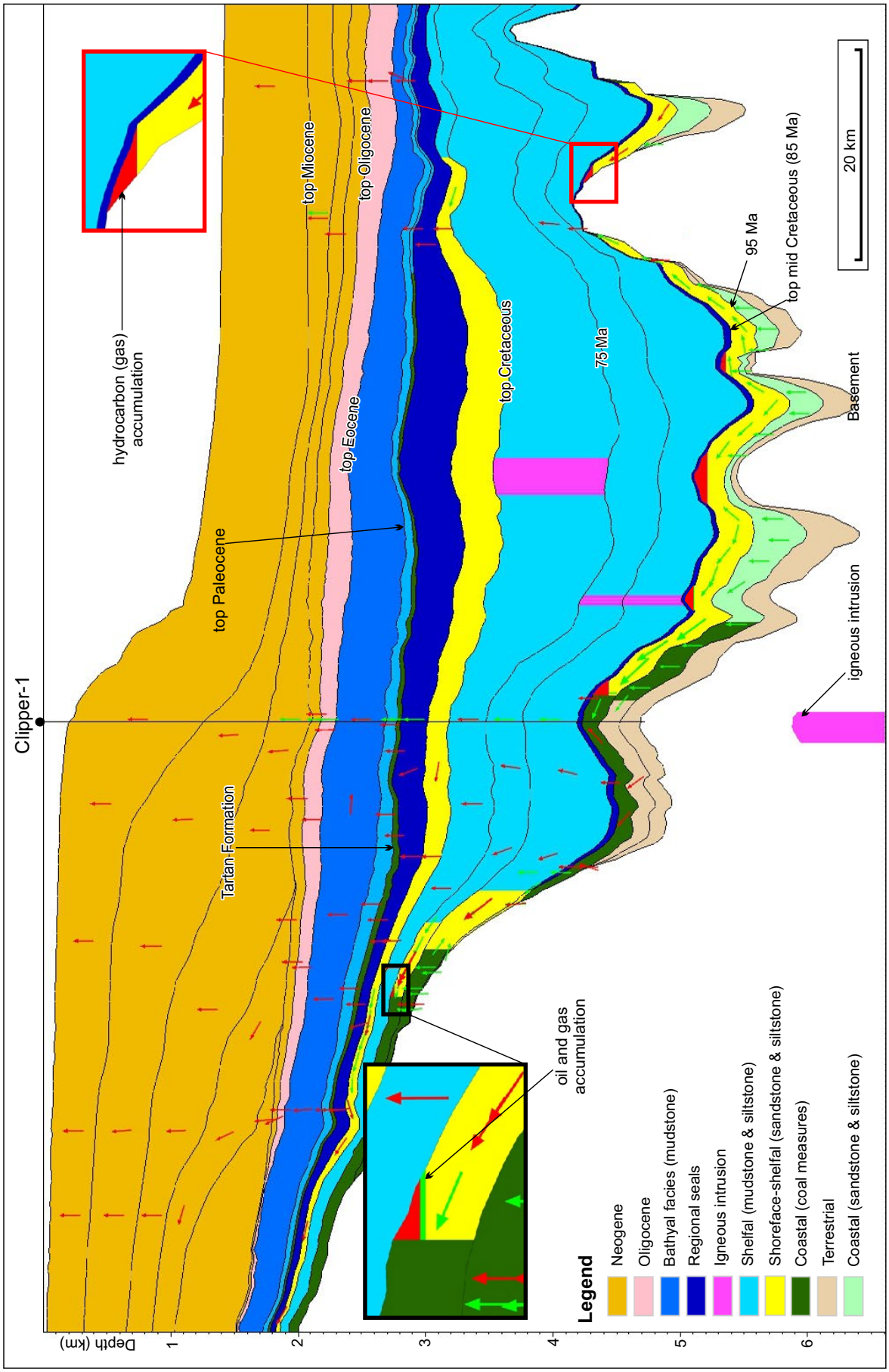

FIGURE 10. Model showing oil and gas migration pathways from the mid Cretaceous source rocks at present day. Small accumulations are observed at 85 Ma and 75 Ma levels at structural closures. Migrating petroleum phases, liquid and vapour are shown by green and red arrows respectively.

PETROLEUM PROSPECTIVITY

The Canterbury Basin has a well-defined petroleum system, with mature source, reservoir, seal rocks and traps. Gas shows at Cutter-1 and gas condensate discoveries at Galleon-1 and Clipper-1 indicate a working source and charge mechanism in the basin. Mid Cretaceous coaly source rocks are widely distributed and are considered to be the primary source rock in the basin, as they are sufficiently mature to expel hydrocarbons. Late Cretaceous coaly source rocks are restricted to the southwestern part of the basin (Figure 5c) and may have generated petroleum beneath the prograding Neogene foresets. Potential reservoir facies include fluvial, coastal and shoreface–shelfal sandstones in the mid Cretaceous sequences, and mainly coastal and shoreface–shelfal sandstones in the Late Cretaceous to Paleocene section. In general, reservoir quality in the fluvial and coastal facies may be limited, and is likely better in the shoreface–shelfal facies. Late Cretaceous shoreface–shelfal reservoirs at Galleon-1 show average porosity of ~17% and permeability of 10–100 mD, whereas mid Cretaceous coastal facies at Clipper-1 show porosities of up to 15% with a very low permeability less than 0.1 mD (Hawkes et al, 1985). Late Cretaceous coastal sandstones are restricted to the western margin of the basin whereas shoreface–shelfal sandstones are widely distributed throughout the basin. Shelfal mudstones are widely distributed in the Late Cretaceous and in the Paleocene section and have the potential to act as a seal rock for underlying reservoir units.

Key risks in the basin are early expulsion from the primary source rock (mid Cretaceous) and associated risk related to the requirement of early seal development to preserve accumulated volumes. Additional risk is related to the heterogeneity in potential reservoir rocks, including shoreface–shelfal rocks within the mid Cretaceous, which so far have not been intercepted in the offshore wells. Plays beneath the present-day shelf, are also at risk due to limited maturity and distribution of Late Cretaceous source rocks.

Mid Cretaceous rocks are predicted to have expelled hydrocarbons since the Early Paleocene, peaking before the end of the Eocene. Early seal development during the Paleocene–Eocene is necessary to trap these expelled hydrocarbons. In areas with absence of good seal at Paleocene–Eocene times loss of these early expelled hydrocarbons may have occurred. The modelling results combined with the absence of an economic hydrocarbon accumulation at Clipper-1 suggest that the presence of a good quality reservoir is also a major risk for the mid Cretaceous interval in this part of the basin. However, reservoir quality of the facies belts may vary in the basin depending on their provenance and sedimentary architecture within the facies belts.

In the western part of the basin beneath prograding Neogene foresets, development of seal overlying Late Cretaceous reservoirs, plays an important role in the hydrocarbon accumulation potential of Late Cretaceous reservoirs. In the current model, seal capacity above the 85–75 Ma reservoir interval started to develop at the end of the Late Miocene. Based on modelling results, these seals can hold smaller accumulations expelled from the mid or Late Cretaceous source rocks during Neogene foreset progradation. No sizable accumulations are predicted in the Paleocene interval due to lack of good seal quality of the mudstones overlying Paleocene reservoirs. However, larger accumulations may be possible where early cementation has improved seal quality.

Most of the predicted accumulations along the modelled section contain gas because early accumulated oil has been replaced by the later expelled gas. However, small accumulations containing both oil and gas are predicted at Late Cretaceous level (Figure 10) at the present day. Larger oil accumulations may be preserved along fill-spill chains within the Cretaceous interval in other parts of the basin. More detailed basin modeling (multi 2D or 3D modeling) to improve the understanding of three dimensional interactions between facies distribution, migration and charge along local play fairways will be a key component of prospect risk assessment in the Canterbury Basin.

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REFERENCES

AUSTRAL PACIFIC ENERGY LTD, 2006—Seismic survey Canterbury Basin 2006. New Zealand open-file Petroleum Report 3298. Wellington, Ministry of Economic Development.

BLANKE, S.J., 2013—"Saucer sills" of the offshore Canterbury Basin. Auckland, Advantage NZ Petroleum Conference.

BLANKE, S.J., 2015—Caravel-1: Lessons learned in the deepwater Canterbury Basin. Auckland, Advantage NZ Petroleum Summit.

CATUNEANU, O., 2006—Principles of Sequence Stratigraphy. Amsterdam, Elsevier.

CONSTABLE, R. AND CROOKBAIN, R., 2011—A sequence stratigraphic study of the Great South Basin. New Zealand open-file Petroleum Report 4348. Wellington, Ministry of Economic Development.

COX, S.C. AND BARRELL, D.J.A., 2007—Geology of the Aoraki Area. GNS Science, Institute of Geological and Nuclear Sciences, Lower Hutt. 1:250,000 geological map 15.

DAVY, B., 2014—Rotation and offset of the Gondwana convergent margin in the New Zealand region following Cretaceous jamming of Hikurangi Plateau large igneous province subduction. Tectonics, 33, 1577–1595.

DAYBORO GEOPHYSICAL, 2010—Barque 2009 2D seismic processing report. New Zealand open-file Petroleum Report 4257. Wellington, Ministry of Economic Development.

FIELD, B.D. AND BROWNE, G.H., 1989—Cretaceous and Cenozoic sedimentary basins and geological evolution of the Canterbury region, South Island, New Zealand. New Zealand Geological Survey Basin Studies 2. Wellington, Institute of Geological & Nuclear Sciences.

FORSYTH, P.J., 2001—Geology of the Waitaki Area. GNS Science, Institute of Geological and Nuclear Sciences, Lower Hutt. 1:250,000 geological map 19.

FORSYTH, P.J., BARRELL, D.J.A. AND JONGENS, R., 2008—Geology of the Christchurch Area. GNS Science, Institute of Geological and Nuclear Sciences, Lower Hutt. 1:250,000 geological map 16.

FULTHORPE, C.S. AND CARTER, R.M., 1991—Continental-shelf progradation by sediment-drift accretion. Geological Society of America Bulletin, 103, 300–309.

FULTHORPE, C.S., HOYANAGI, K., BLUM, P. AND THE EXPEDITION 317 SCIENTISTS, 2011—Proceedings of the Integrated Ocean Drilling Program, Volume 317.

GIBBONS, M. J. AND HERRIDGE, K.J., 1984—Maturity and source potential of Clipper-1, Canterbury Basin, Offshore New Zealand. New Zealand open-file Petroleum Report PR1044. Wellington, Ministry of Economic Development.

GRIFFIN, A.G., 2013—Petroleum well summary sheets from selected frontier basins, New Zealand: Canterbury, Great South and Northland basins. Wellington, Institute of Geological & Nuclear Sciences.

GROBYS, J.W.G., GOHL, K. AND EAGLES, G., 2008—Quantitative tectonic reconstructions of Zealandia based on crustal thickness estimates. Geochemistry, Geophysics, Geosystems, 9, Q01005.

HANTSCHEL, T. AND KAUERAUF, A.I., 2009—Fundamentals of basin modeling. Springer, Berlin.

HASKELL, T. R. AND WYLIE, I. C., 1997—New Zealand's Canterbury Basin prospects reviewed in a continental Gondwana setting. Oil and Gas Journal, 95(50).

HAWKES, P.W., MOUND, D.G. AND SPICER, P.J., 1985—Clipper-1 evaluation report PPL 38022. New Zealand open-file Petroleum Report 1078. Wellington, Ministry of Economic Development.

HOLLIS, C.J., TAYLOR, K.W.R., HANDLEY, L., PANCOST, R.D., HUBER, M., CREECH, J.B., HINES, B.R., CROUCH, E.M., MORGANS, H.E.G., CRAMPTON, J.S., GIBBS, S., PEARSON, P.N. AND ZACHOS, J.C., 2012—Early Paleogene temperature history of the Southwest Pacific Ocean: Reconciling proxies and models. Earth and Planetary Science Letters 349–350, 53–66.

KROEGER, K.F., DI PRIMIO, R. AND HORSFIELD, B., 2009—Hydrocarbon flow modeling in complex structures (Mackenzie Basin, Canada). AAPG Bulletin 93, 1209-1234.

KROEGER, K.F. AND FUNNELL, R.H., 2012—Warm Eocene climate enhanced petroleum generation from Cretaceous source rocks: A potential climate feedback mechanism? Geophysical Research Letters 39, L04701.

LEVER, H., 2007—Review of unconformities in the late Eocene to early Miocene successions of the South Island, New Zealand: Ages, correlation, and causes. New Zealand Journal of Geology and Geophysics 50:3, 245–261.

MOGG, W.G., AURISCH, K., O'LEARY, R. AND PASS, G.P. 2008—Offshore Canterbury Basin–beyond the shelf edge. Auckland, Advantage NZ Petroleum Conference.

MORTIMER, N., DAVEY, F.J., MELHUISH, A., YU, J. AND GODFREY, N.J., 2002—Geological interpretation of a deep seismic reflection profile across the Eastern Province and Median Batholith, New Zealand: crustal architecture of an extended Phanerozoic convergent orogeny. New Zealand Journal of Geology and Geophysics, 45, 349–363.

NEWMAN, J., ECKERSLEY, K.M., FRANCIS, D.A. AND MOORE, N.A., 2000—Application of vitrinite-inertinite reflectance and fluorescence to maturity assessment in the East Coast and Canterbury Basins of New Zealand. New Zealand, New Zealand Petroleum Conference Proceedings, 314–333.

O'LEARY, R. AND MOGG, W.G., 2008—The petroleum potential of the offshore Canterbury Basin: insights from petroleum systems modelling. PESA Eastern Australian Basins Symposium III, 349–368.

PEPPER, A.S. AND CORVI, P.J., 1995—Simple kinetic models of petroleum formation. Part 1: oil and gas generation from kerogen. Marine Petroleum Geology 12, 291–319.

SAHOO, T.R., BROWNE, G.H. AND HILL M.G., 2014a—Seismic attribute analysis and depositional elements in the Canterbury Basin. Wellington, New Zealand Petroleum Conference.

SAHOO, T.R., KING, P.R., BLAND, K.J., STROGEN, D.P., SYKES, R. AND BACHE, F., 2014b—Tectono-sedimentary evolution and source rock distribution of the mid to Late Cretaceous succession in the Great South Basin, New Zealand. APPEA Journal and Conference Proceedings, 259–274.

SCHERWATH, M., STERN, T., DAVEY, F., OKAYA, D., HOLBROOK, W.S., DAVIES, R. AND KLEFFMANN, S., 2003—Lithospheric structure across oblique continental collision in New Zealand from wide-angle P wave modeling. Journal of Geophysical Research: Solid Earth, 108 (B12), 2566.

SCHIØLER, P., ROGERS, K., SYKES, R., HOLLIS, C.J., ILG, B., MEADOWS, D., RONCAGLIA, L. AND URUSKI, C., 2010—Palynofacies, organic geochemistry and depositional environment of the Tartan Formation (Late Paleocene), a potential source rock in the Great South Basin, New Zealand. Marine and Petroleum Geology, 27, 351–369.

SHELL BP TODD, 1984—Interpretation and prospectivity of PPL 38203 Canterbury Basin New Zealand. New Zealand open-file Petroleum Report 1046. Wellington, Ministry of Economic Development.

SWEENEY, J.J. AND BURNHAM, A.K., 1990—Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. AAPG Bulletin, 74, 1559–1570.

SYKES, R. AND FUNNELL, R.H., 2002—Petroleum source rock potential and generation history in the offshore Canterbury Basin. New Zealand open-file Petroleum Report 2707. Wellington, Ministry of Economic Development.

WILDING, A. AND SWEETMAN, L.A.D., 1971—Endeavour-1 well completion report. New Zealand open-file Petroleum Report 1971. Wellington, Ministry of Economic Development.