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

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Abstract

Canterbury Basin is one of the frontier basins in 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 Paleocene 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 Clipper sub-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.

Introduction

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). 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 Paleocene 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 ap09 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). 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 characters and igneous intrusions. 2D seismic data are of several vintages and data quality varies. 2D seismic line spacing varies from 1 to 25 km and tends to be of greater density near the wells Galleon-1, Cutter-1 and Clipper-1. 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. 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. Seismic lines reprocessed in 2006 and 2007, part of the Barque seismic survey are of better quality and offer greater interpretation confidence. A 2D PetroMod basin model was then prepared along line cb82-54-3749 through Clipper-1 (Figure 1) using facies maps and well data to understand source rock maturity and migration in the basin.

Seismic Stratigraphy and Facies Characterisation

Five horizons within the Cretaceous, two horizons within the Paleogene and seven horizons within the Neogene were mapped across the basin. Basin evolution can be summarised into three main phases; mid-Cretaceous syn-rift phase, Late Cretaceous to Late Eocene post-rift thermal sag phase and Oligocene to Recent regression phase (Figure 2). Sequences within the syn-rift phase are characterised by active faulting. Horizon K80 (85 Ma) has been mapped at the top of the syn-rift sequence. The post-rift thermal sag phase shows thermal subsidence and overall marine transgression. Some faults continue through K80 during early post-rift thermal sag phase however, these faults are not widespread in the basin. The regression phase is characterised by Neogene foreset progradation. In this study, facies interpretation and paleogeographic mapping were carried out only in the Cretaceous and the Paleogene sections.

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

Continental facies include alluvial fans and fluvial facies. Continental facies are characterised by variable amplitude, discontinuous to low continuity reflectors and chaotic to sub-parallel internal geometry. Lacustrine facies may be possible in the isolated depocentres within syn-rift grabens but it is difficult to identify them based on available seismic data alone. Continental facies are observed in wells Clipper-1 (Figure 3b), Endeavour-1, and Cutter-1.

Coastal environments are transitional environments between continental 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 3a–3c). Coastal sandstone and siltstone facies are characterised by moderate to high amplitude, moderately continuous, parallel to sub parallel reflectors (Figure 3c). Coastal facies are observed in all offshore wells in the basin except Resolution-1.

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 3a). For the purpose of modelling, these facies act as carrier beds and therefore have been merged together 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. Mudstones and siltstone facies of the K80–K90 (Lower Hamurian) 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. Foraminifers indicate dominantly outer shelf environment though, bathyal facies may be interpreted only in the lower most interval of K80–K90 (personal communication with Ian Raine from 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 Clipper sub-basin.

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 and moderate to high continuity. In the Paleocene section, bathyal mudstone and siltstone facies show moderate to high amplitude and moderate continuity. In the Eocene section, they show low to high 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 sharp change in character from surrounding facies (Figure 3d). Volcanics show chaotic internal reflection pattern.

Paleogeographic Maps

To illustrate the areal facies distribution of facies from the Cretaceous to the Eocene, six paleogeographic maps were prepared at 95, 85, 75, 66, 56 and 34 Ma (Figure 4 and Figure 5). These maps depict facies immediately below the top of each time horizon. Paleogeographic maps are expressed broadly as areas of non-deposition/erosion, continental, coastal coal measures, coastal sandstone and siltstone, shoreface–shelfal (sandstone and siltstone), shelfal (mudstone and 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, from continental 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 later part of the mid Cretaceous (95–85 Ma) and was directed from the east. Coal measures include coals and coaly mudstones and are the main source rocks identified in this area (Shell BP Todd, 1984; Sykes and Funnell, 2002). Coastal coal measures are widespread during the mid Cretaceous (Figure 4a and b); however, they are restricted to the western boundary of the study area during the Late Cretaceous (Figure 4c). Potential reservoir rocks (carrier beds) observed at well locations are sandstones and siltstones deposited in coastal and shoreface–shelfal setting. Coastal sandstone and siltstone facies dominate at 95 Ma, while at 85, 75, 66 and 56 Ma, shoreface–shelfal sandstones and siltstones were widespread over the study area. Shelfal mudstones and siltstones and bathyal mudstones are considered as the regional seal rocks, though seal potential will vary with the percentage of clay content. These facies are widely distributed from Late Cretaceous to the Eocene level (Figure 4c and d and Figure 5a and b).

Petroleum systems Modelling

A 2D PetroMod model along seismic line (cb82-54-3749; Figure 2) through Clipper-1 was prepared to understand hydrocarbon maturation and migration in the basin. Basic inputs to build the model were stratal horizons derived from seismic interpretation and their ages based on biostratigraphy, 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 at the end of the Eocene (Munday, 2015) with amount of erosion varying from 0 to 500 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 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), we modelled mid–Late Cretaceous coaly facies 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 (Figure 4), 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 Type III DE kinetics for the mid–Late Cretaceous source rocks and Type II B kinetics for the Paleocene source rock derived from Pepper and Corvi (1995). Kinetics Type III DE is 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) was used for calibration. However, the poor fit of data from Gibbons and Herridge (1984) in Clipper-1 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 intrusion, SWIT and increased thermal conductivity in the Neogene sediments aided to calibrate model with present day temperature and maturity at Clipper-1 (Figure 6a and b). 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, in consistent with timing proposed by O'Leary and Mogg (2008) and is similar to intrusion at Galleon-1 (Haskell and Wylie, 1997). This age is supported by structural bulging of strata extending up to the Paleocene level in seismic interpretation. 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 4000 m (Figure 6b).

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 for the model using β factor and an average crustal thickness of 24 km (Mortimer et al., 2002; Scherwath et al., 2003; Grobys et al., 2008). We assumed 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 maturities (Figure 6).

Thermal History, Maturity and Petroleum Expulsion

At Clipper-1, maximum temperature was predicted during the Paleocene due to the modelled igneous intrusion (Figure 7a). In areas unaffected by intrusive heating, modelling results suggest that the highest temperatures at source rock level were also reached during the Late Paleocene–Eocene (Figure 7b). 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 for the Great South Basin to the south of the study area (Kroeger and Funnell, 2012). The present model suggests that basin temperature decreased in the Late Eocene–Early Oligocene due to erosion and cooler water temperature.

At present day, the calibrated model shows temperatures of >1500C for most of the section below 85 Ma. These data suggest that most of the mid Cretaceous source rocks (below 85 Ma) are within the gas window at present day (Figure 8a). Late Cretaceous source rocks are restricted to the western boundary of the basin (Figure 4c and d). Some of the Late Cretaceous source rocks are predicted to be within the oil window below the Neogene foreset progradation but most of them are in the early oil window (Figure 8a). Paleocene source rocks (Tartan Formation) have not reached sufficient maturity to generate hydrocarbons. In general, higher maturities are observed beneath the Neogene foresets while igneous intrusions influence localised high maturity (Figure 8a).

Mid-Cretaceous rocks are considered the primary source rocks in the Clipper sub-basin as they have reached sufficient maturity to expel hydrocarbons. Predicted cumulative expelled petroleum is shown for three locations (Figure 8a); at pseudo well-1 (away from Neogene foreset progradation and igneous intrusion), Clipper-1 and pseudo well-2 (under Neogene foreset progradation and away from intrusion). At pseudo well-1, expulsion is predicted to have started in the Early Paleocene and peaked by the end of the Eocene (Figure 8b). Expulsion at Clipper-1 is predicted to have started slightly later but to then have occurred rapidly during the time of igneous intrusion (Paleocene). 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. Lithological compositions were derived from Clipper-1 well log and cuttings lithology information. 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 %). Well data suggest that there is reasonably good seal present overlying the 85 Ma interval. Due to the lack of good reservoir, modelling predicts no accumulation at Clipper-1 despite the presence of charge from a mature mid Cretaceous source rock. Source rocks at Clipper-1 are predicted to reach > 85 % transformation ratio at Paleocene during the time of igneous intrusion. 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 9). Petroleum accumulations (flashed volume) are predicted in the deeper parts of the basin at present day assuming good regional seals exist within the 84 Ma and Paleocene intervals, and good reservoir facies (70% sandstone and 30% siltstone) in the shoreface–shelfal facies in the 95–85 Ma interval.

Assuming a regional seal rock composition of 70% shale and 30% silt, models suggest that these accumulations have been in place from the end of Late Paleocene to the present day. Sufficient overburden and seal quality is predicted to be present to at least partially preserve early-expelled petroleum accumulations in the deeper part of the basin since the Paleocene. However, sufficient seal overlying 75 Ma reservoirs (Figure 9) was not developed in the western part of the basin until the Late Miocene. Therefore, most of the expelled hydrocarbon during the Paleocene and Eocene time (Figure 8b) in the western part of the basin may have escaped through vertical migration before further burial by the Neogene foresets. Expelled hydrocarbons from the mid Cretaceous source rocks during Neogene foreset development (pseudo well-2 in Figure 8b) may have led to accumulations in the Late Cretaceous reservoirs (75 Ma reservoir in this model) after Late Miocene time in the western part of the basin. However, only small accumulations are predicted in the western part of the basin at present day (Figure 9).

Conclusion

The Canterbury Basin has a well-defined petroleum system, with mature source, reservoir, seal rocks and traps. 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 are restricted to the southwestern part of the basin (Figure 4c) and may have generated petroleum beneath the prograding Neogene foresets. Reservoir facies include fluvial, coastal and shoreface-shelfal sandstones in the mid Cretaceous sequences, and mainly shoreface–shelfal sandstones in the Late Cretaceous to Paleocene section. Reservoir quality in the coastal facies may be limited, but could be better in the shoreface–shelfal facies. 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 broadly distributed in the Late Cretaceous and in the Paleocene section and have the potential to act as a seal rock for underlying reservoir units. Modelling results suggest that sufficient seal capacity of the mudstone interval at top of 85 Ma reservoir to trap hydrocarbons had been developed since the Paleocene.

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 one of the major risks for the mid Cretaceous interval in this part of the basin. 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 75 Ma reservoir interval started to develop towards 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. While these results suggest that plays fairways both in the area of Neogene foreset progadation and further offshore could be viable, a multi 2D or 3D basin model analysis would be useful to better understand the impact of burial history and facies distribution on basin prospectivity.

Acknowledgements

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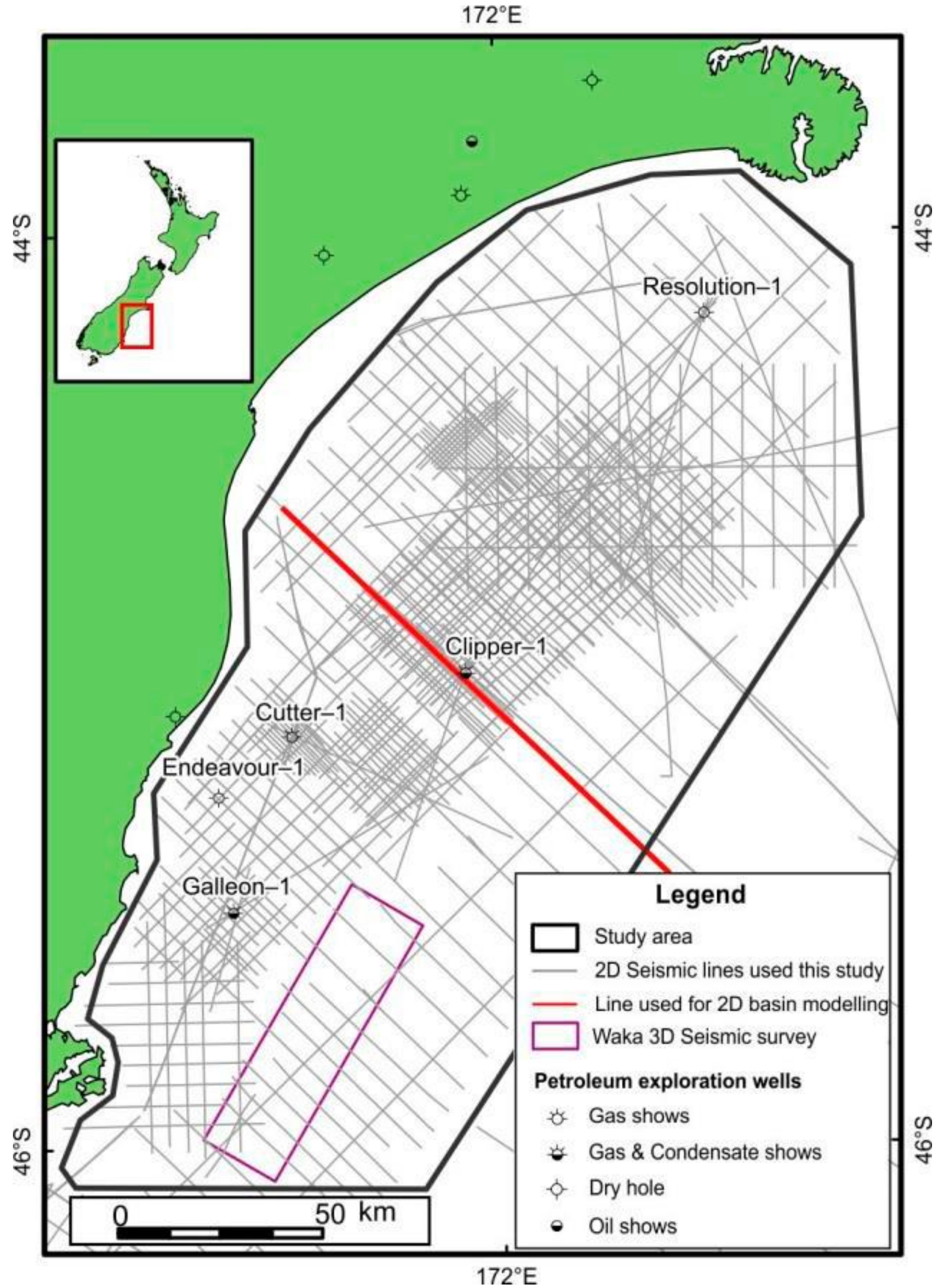

Figure 1. Location map of the study area showing drilled wells and seismic data coverage.

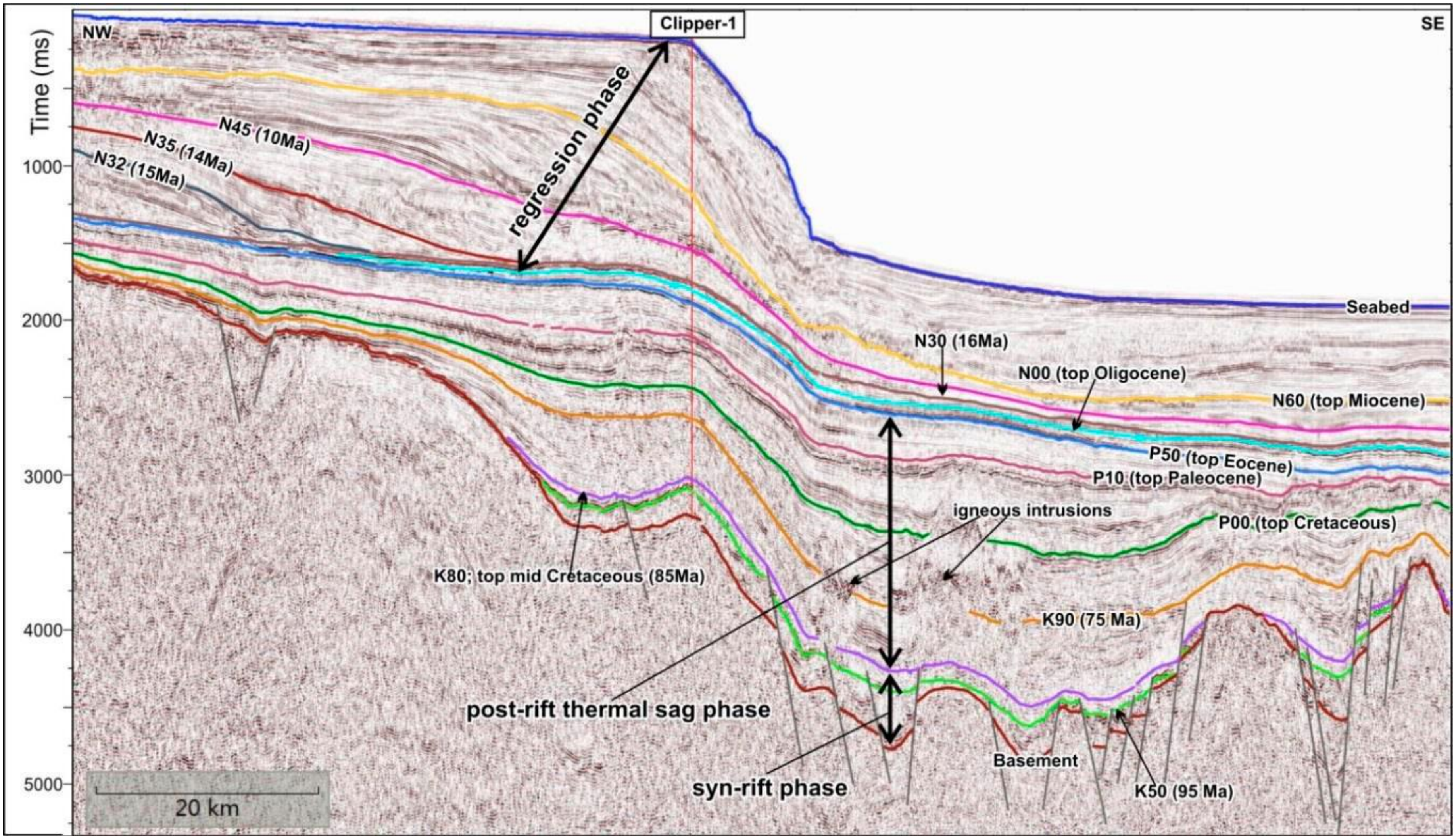

Figure 2. A seismic section along Clipper-1 showing mapped horizon, faults and tectonic phases. For the purpose of the basin modelling absolute age has been assigned to each horizon (shown within brackets).

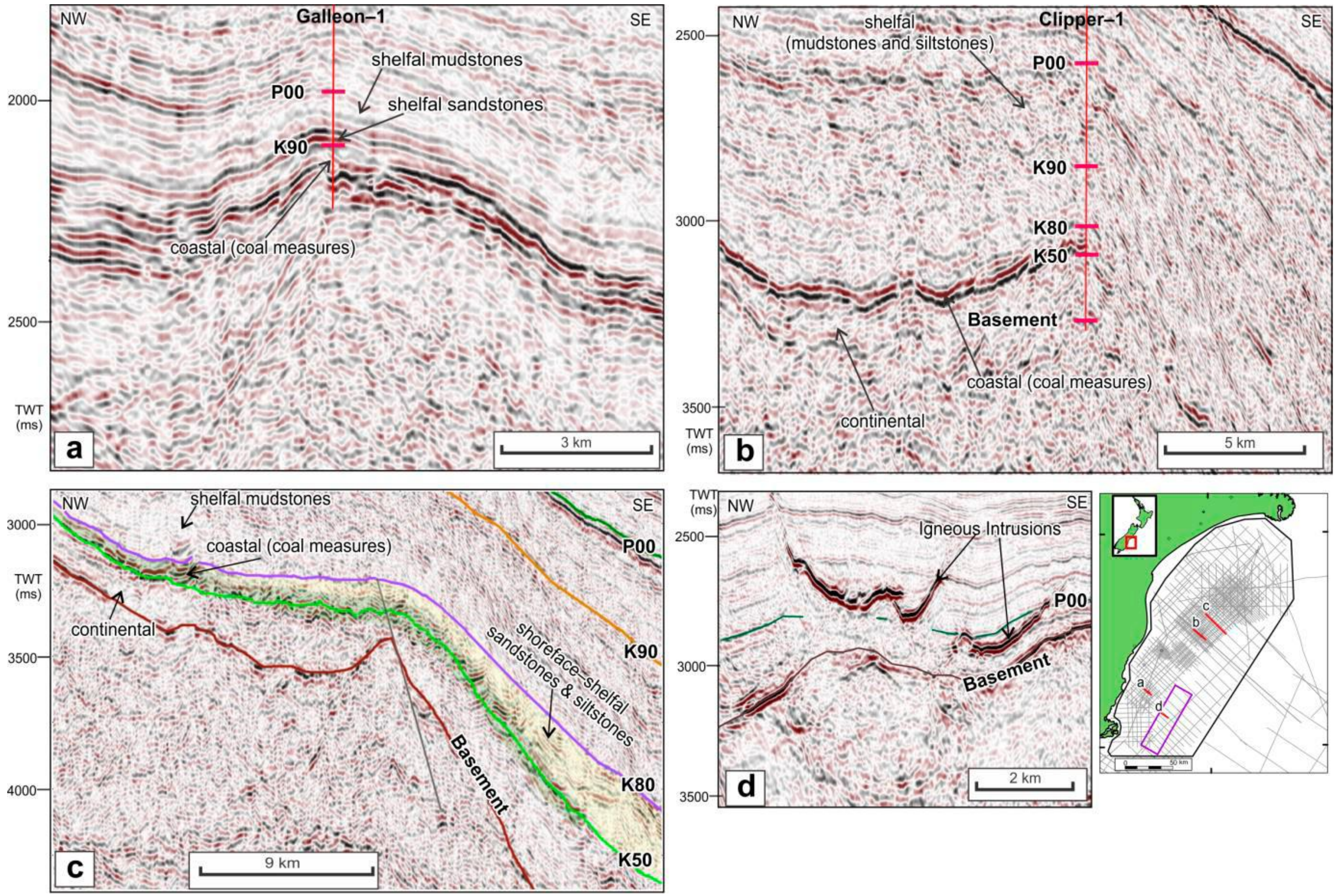

Figure 3. Seismic sections showing examples of facies types and depositional elements identified in the study area. Locations are shown in inset map. a) Seismic section through Galleon-1 showing seismic characters of coastal (coal measures), shelfal mudstone and shelfal sandstone. b) Seismic section through Clipper-1 showing seismic characters of continental facies (fluvial), coastal (coal measures) and shelfal (mudstone & siltstone) facies. c) Seismic section showing 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).

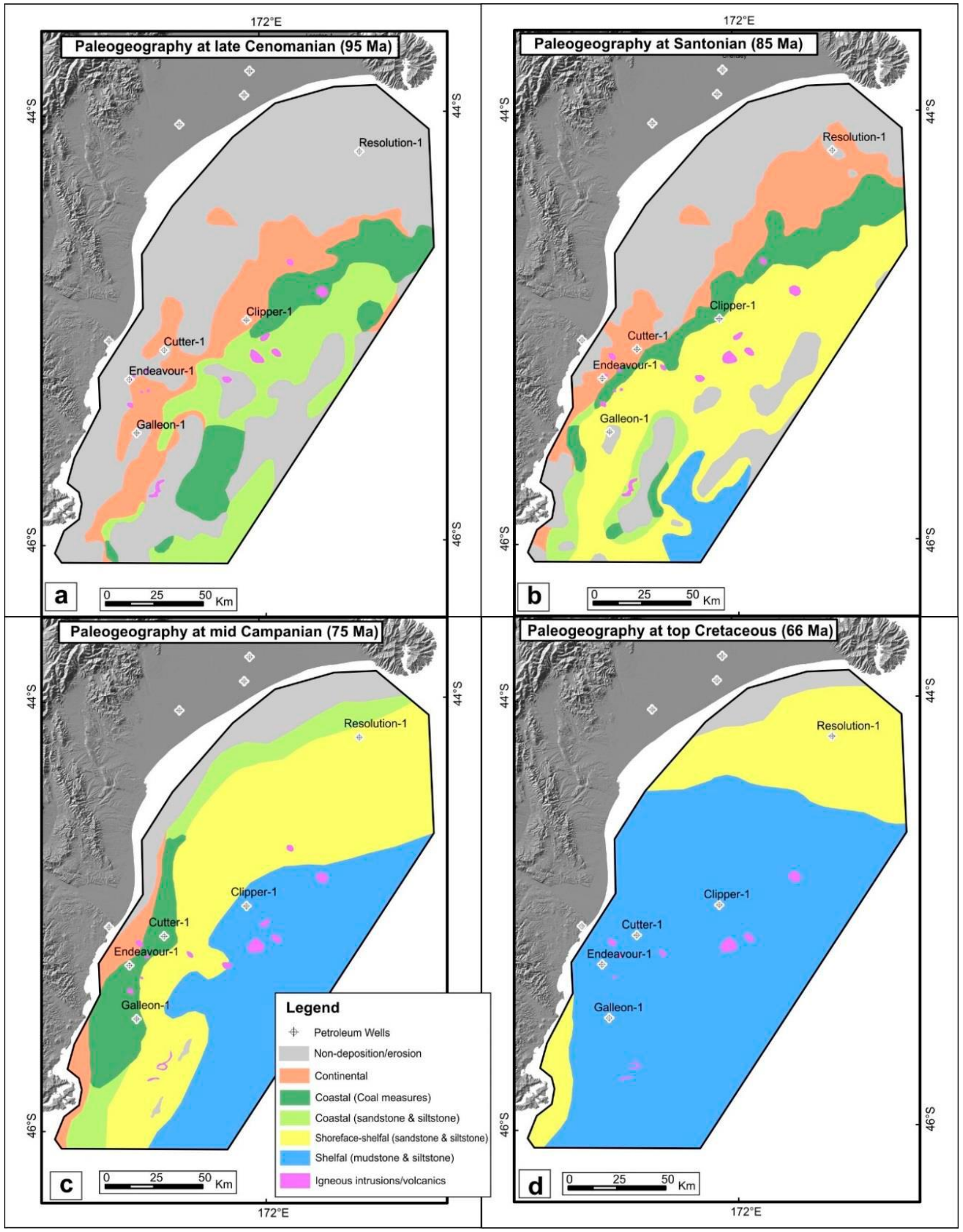

Figure 4. a) Paleogeographic map at late Cenomanian (95 Ma). b) Paleogeographic map at Santonian (85 Ma). c) Paleogeographic map at mid Campanian (75 Ma). d) Paleogeographic map at top Cretaceous (66 Ma).

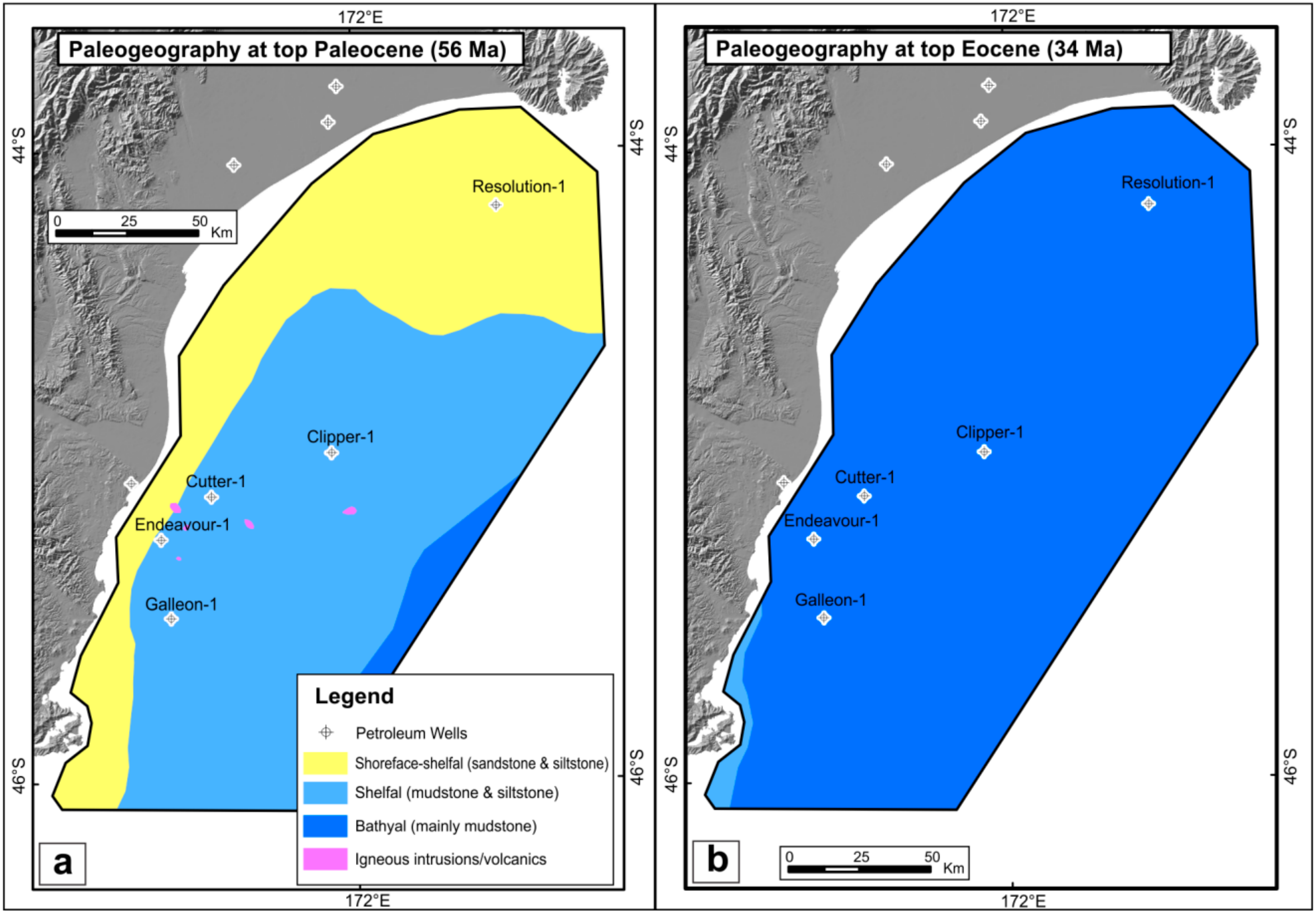

Figure 5. a) Paleogeographic map at top Paleocene (56 Ma). b) Paleogeographic map at top Eocene (34 Ma).

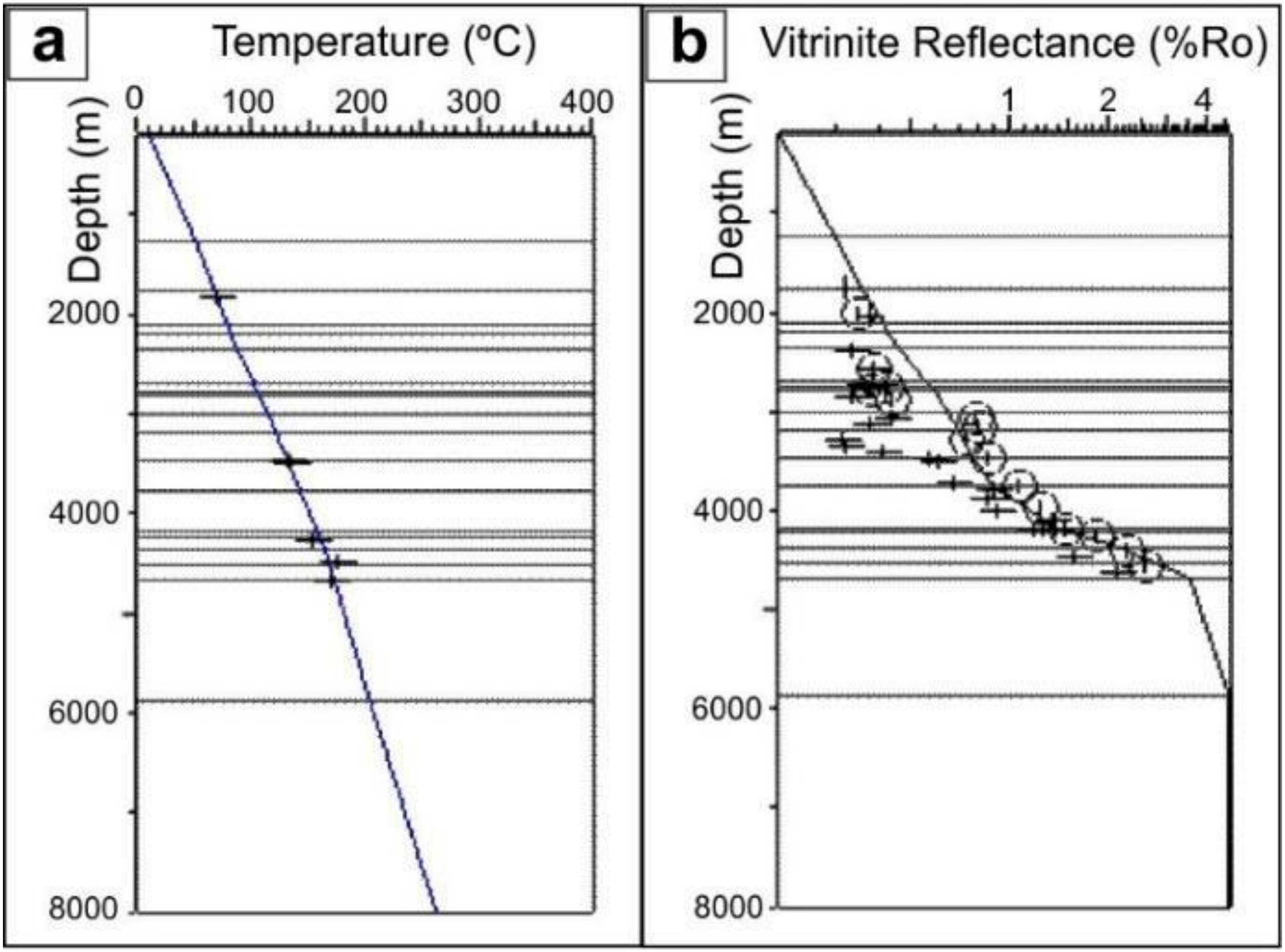

Figure 6. Calibration of model results with a) temperature, b) vitrinite reflectance (data from Gibbons & Herridge (1984) and Newman, et al., (2000) are shown as plus and circle symbols respectively).

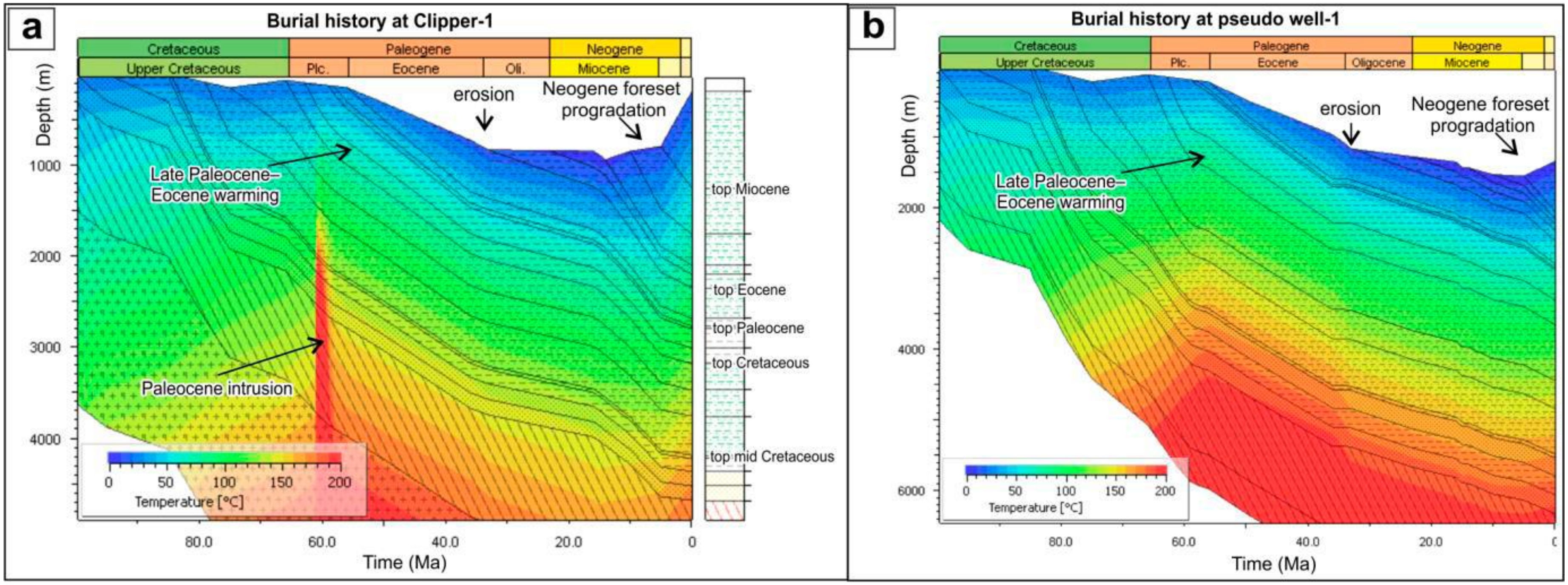

Figure 7. a) Burial history at Clipper-1. b) Burial history at pseudo well-1 (see location in next figure).

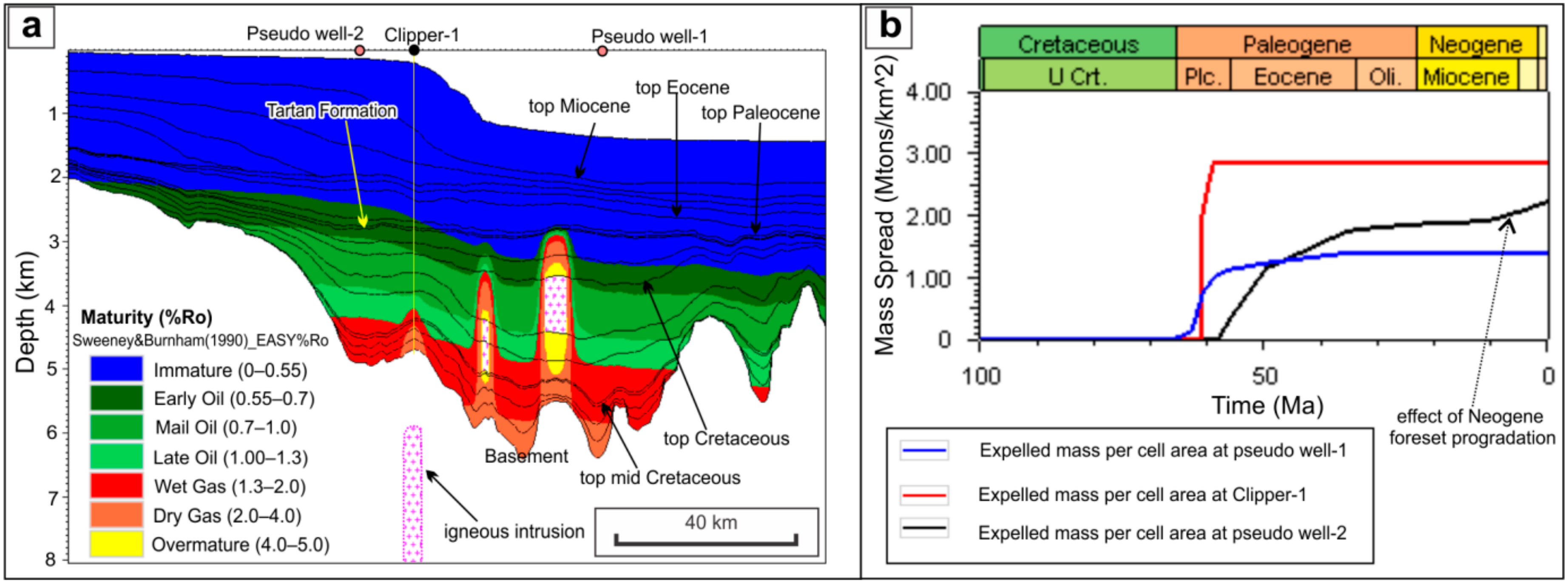

Figure 8. a) Present day maturation along a 2D line through Clipper-1. b) Present day cumulative expelled petroleum from mid Cretaceous source rocks at pseudo well-1, Clipper-1 and pseudo well-2.

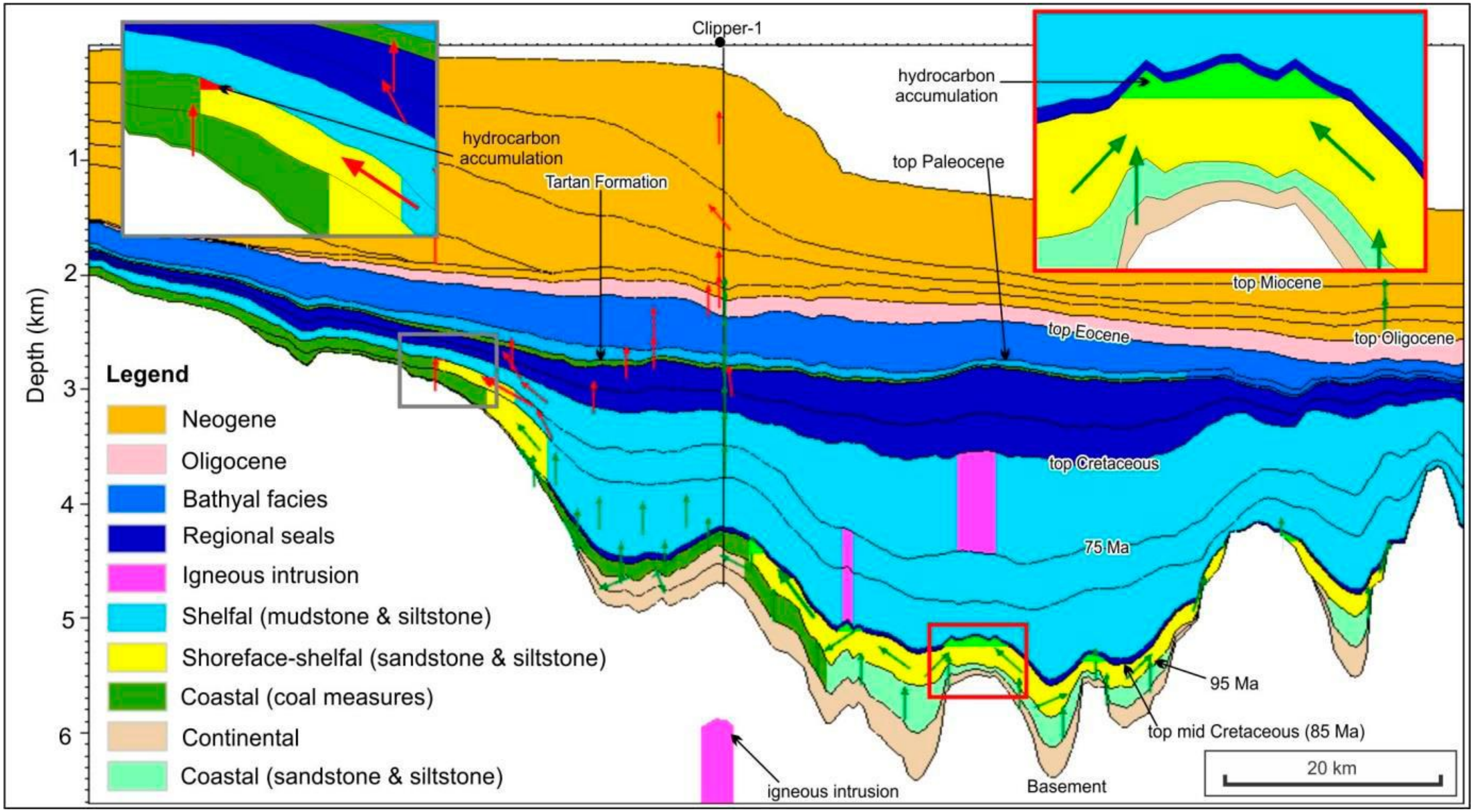

Figure 9. Model showing oil and gas migration pathways from the mid Cretaceous source rocks at present day. Smaller accumulations are observed at 85 Ma and 75 Ma levels at structural closures.

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

Table 1: Source rock parameters used in the 2D PetroMod model