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Generation and flow-path migration modelling of the Fairway Basin, New Caledonia

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EXECUTIVE SUMMARY

This report was commissioned by Service Géologique de la Nouvelle-Calédonie – DIMENC to carry out a basin-wide maturity and prospectivity assessment of the Fairway Basin, to the southwest of New Caledonia. This report describes the basin modelling approaches undertaken, reviews model predictions for the maturity of potential source rocks and volumes of oil and gas expelled, and presents likely petroleum migration pathways for charge of potential reservoir structures.

A series of three coaly source rock and intercalated potential marine source rock intervals within the Late Cretaceous syn-rift succession were modelled and assessed for their oil generation potential. In addition, a hypothetical equivalent of the east Australian Walloon Formation and the hypothetical occurrence of a marine source rock in the pre-rift sequence were modelled. The burial and temperature history of the basin was reconstructed using two different heat flow scenarios and generated and expelled volumes were predicted using different kinetic models. In a second step, migration pathways were modelled and charge of potential traps was assessed, using structure maps and reconstructed facies maps. Maximum values stated below are based on the assumption of relatively productive source rocks and the higher of two heat flow scenarios modelled in this study.

Key findings of this study were:

- Under standard assumptions potential source rocks within the syn-rift sequence are immature to early mature
- Coaly source rocks at the base of the syn-rift interval could have expelled up to 5 Tcf gas, but oil would only have been expelled from source rocks assuming low saturation thresholds
- The generation of significant volumes of oil in the basin depends on the presence of marine source rock intervals in the Late Cretaceous syn-rift sequence, which in our models expelled up to 80 billion bbl of oil
- The postulated Walloon Formation equivalent source rock in the upper portion of the pre-rift unit would have been relatively immature and expelled mostly gas (totalling up to 33 Tcf)
- A hypothetical marine source rock in the lower part of the pre-rift sequence would be relatively mature and could have generated large quantities if oil (more than 100 MMbbl/km^2 predicted by the model)
- The Fairway Basin is characterised by slow maturation during the past 50 Myrs and changes in burial history and heat flow, not included in these models, have the potential to modify the results for the scenarios presented
- Flow-path modelling on structure maps indicated that closures for oil and gas accumulations are present and postulated pinch out of sandy reservoir facies on structure highs may provide additional trap structures
- While coaly source rocks in the syn-rift sequence are unlikely to charge large accumulations, a marine type II source rock could have charged accumulations containing 5 billion bbl oil under ideal conditions.

It is important to note that modelled quantities at this stage are speculative due to limited data on source rock composition, richness and distribution, as well as the presence and quality of reservoir and seal quality. Values provided in this study are therefore intended as a preliminary framework for further assessment of the Fairway Basin.

1.0 INTRODUCTION

1.1 OBJECTIVE

In August 2011, GNS science was commissioned by the Service Géologique de la Nouvelle-Calédonie (DIMENC) to carry out a basin-wide maturity and prospectivity assessment of the Fairway Basin, located 200 km southwest of New Caledonia (Figure 1). The aim of this study is to model volumetrics and timing of expelled petroleum phases and to provide a reconnaissance-level assessment of possible hydrocarbon migration and entrapment.

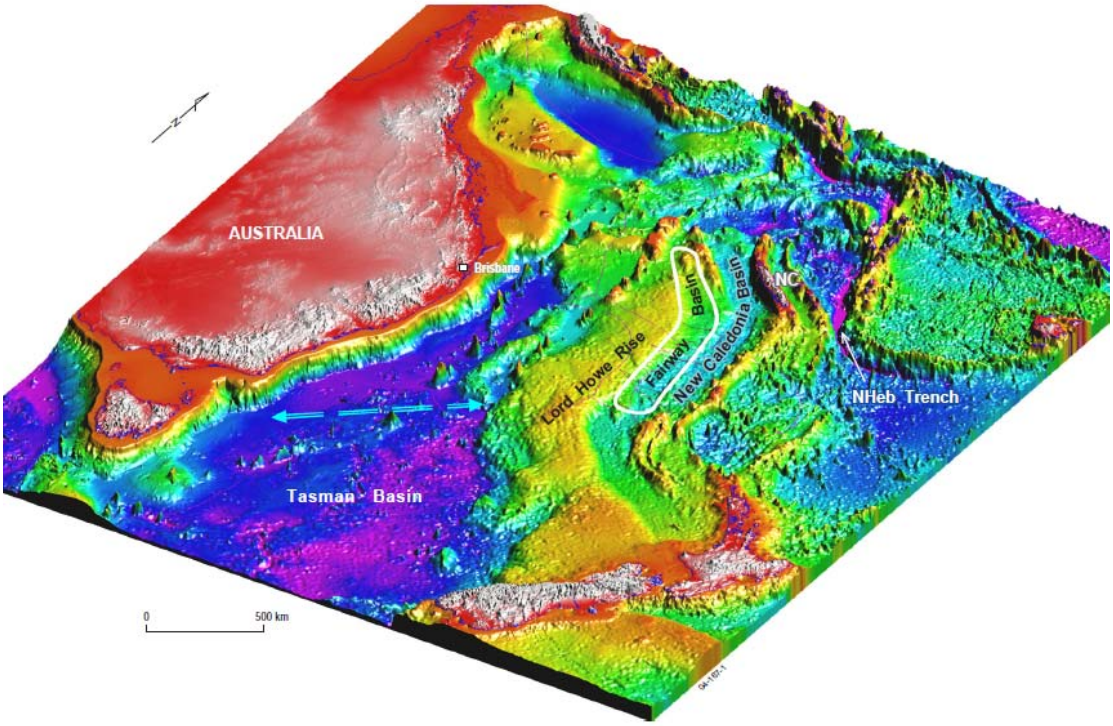

Figure 1 Bathymetric relief of the southwest Pacific Ocean showing Fairway Basin. NC is New Caledonia and NHeb is New Hebrides (Exon et al., 2004).

1.2 BACKGROUND

A series of recent seismic surveys has provided sufficient data to reassess the stratigraphic succession of the Fairway Basin using seismic data tying into DSDP hole 208, onto the Lord Howe Rise to the west (Collot et al., 2008) (Figure 2, Figure 3). This correlation was established by tracing seismic characteristics of the Eocene-Oligocene unconformity or disconformity. The new interpretation of the stratigraphic succession was the basis for mapping of time surfaces carried out by Service Géologique de la Nouvelle-Calédonie – DIMENC that are used in this study.

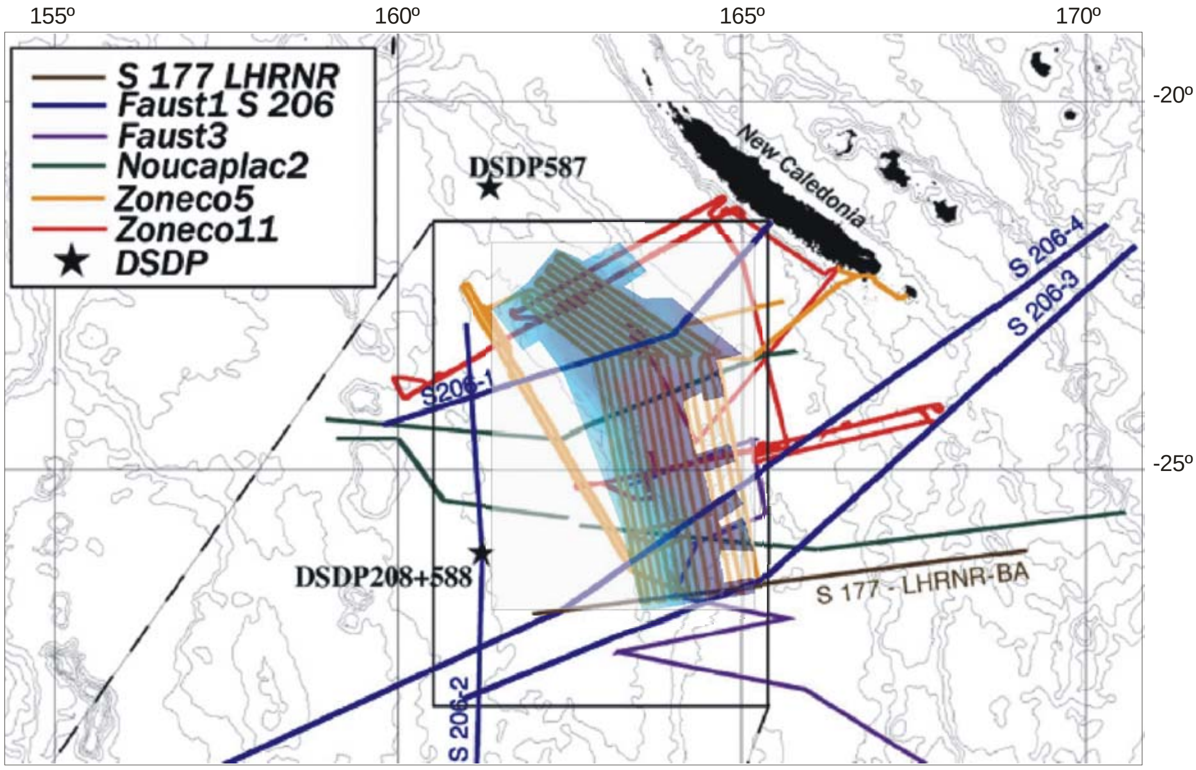

Figure 2 Modelled area and extent of seismic data and interpreted depth surfaces modified from Nouzé et al. (2009). Lines 206-1 and 206-2 tie to DSDP hole 208 on Lord Howe Rise (see Figure 3).

1.3 BASIN GEOLOGY AND SOURCE ROCK POTENTIAL

The stratigraphic succession of the Fairway Basin and surrounding areas consists of Upper Cretaceous and pre-Upper Cretaceous sediments, overlain by Paleocene and Eocene chalks and Upper Oligocene to Middle Miocene calcareous oozes (Exon et al., 2007; Nouzé et al., 2009) (Figure 3). Upper Cretaceous syn-rift sequences that can be traced into the Fairway Basin are known for their content of coaly source rocks in surrounding areas (Exon et al., 2007; Funnell and Stagpoole, 2011). In addition an inferred early rift phase in the Fairway Basin has been proposed to have increased the likelihood for the presence of Cretaceous marine source rocks (Exon et al., 2007). Similar to the adjacent Lord Howe Rise, Upper Cretaceous sediments are interpreted to overlie a rifted Gondwana margin sequence (Klingelhoefer et al., 2007), and analogous to the Clarence-Moreton or Maryborough basins in eastern Australia may contain mid-Jurassic coal measures (Colwell et al., 2006; Funnell and Stagpoole, 2011).

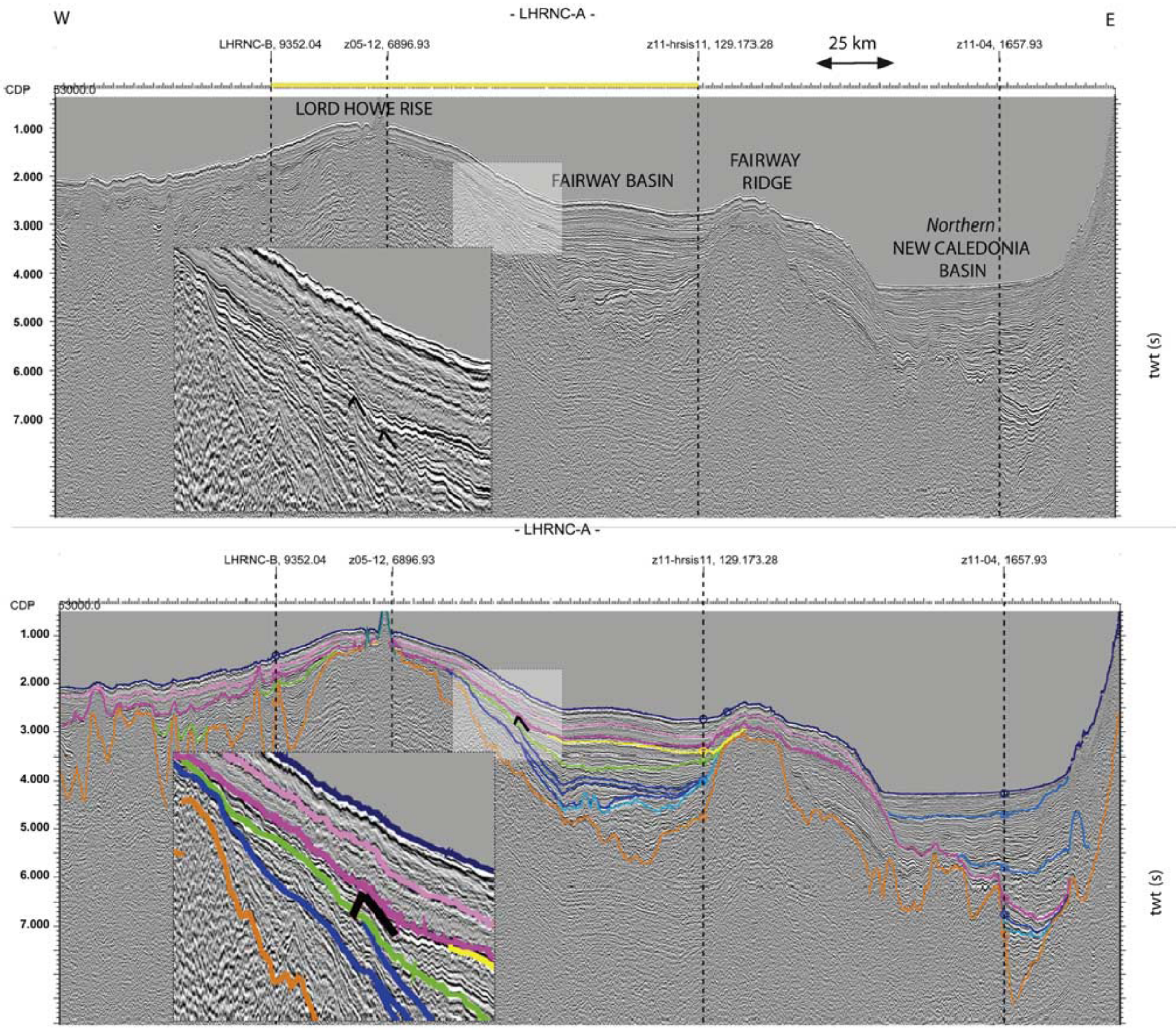

Figure 3 Seismic interpretation (lines S206-1 and -2, see Figure 2 for location) tying the modelled area onto Lord Howe Rise (see Collot et al., 2008 for details and explanation of stratigraphy).

1.4 INPUT DATA AND PROJECT WORKFLOW

The modelling was based on 6 depth grids (Figure 4) and 2 water depth grids (Figure 5) provided by DIMENC (Table 1). Grids were adjusted where necessary and isopach maps were calculated using Trinity software (http://www.zetaware.com). Additional data on source rocks and basin evolution were derived from the input grids and/or published material as well as DIMENC in-house data. Data were assembled in the GNS Science multi-1D (pseudo-3D) modelling software (BM1D) to create grids of the predicted timing and volumes of petroleum phases expelled from the source rock units. These grids were then input into the Zetaware Trinity interactive petroleum system analysis and risking software, to assess petroleum migration pathways and the potential for accumulations at different times during basin evolution. A total of three basin evolution scenarios were computed:

1. using average generation and expulsion parameters for terrestrial source rocks inferred from Cretaceous coaly source rocks studied in other basins such as the Taranaki Basin,

2. using expulsion thresholds at the lower end of values commonly observed in terrestrial source rocks and source rock potential yields at the high end of values typical for Cretaceous coaly source rocks,

3. using a heat flow history that accounts not only for rifting but also for a regional increase in mantle heat flow related to regional Eocene-Miocene magmatism. This scenario assumed both a coaly and a marine pre-rift source rock interval exists.

All models were calibrated to published data on present-day surface heat flow.

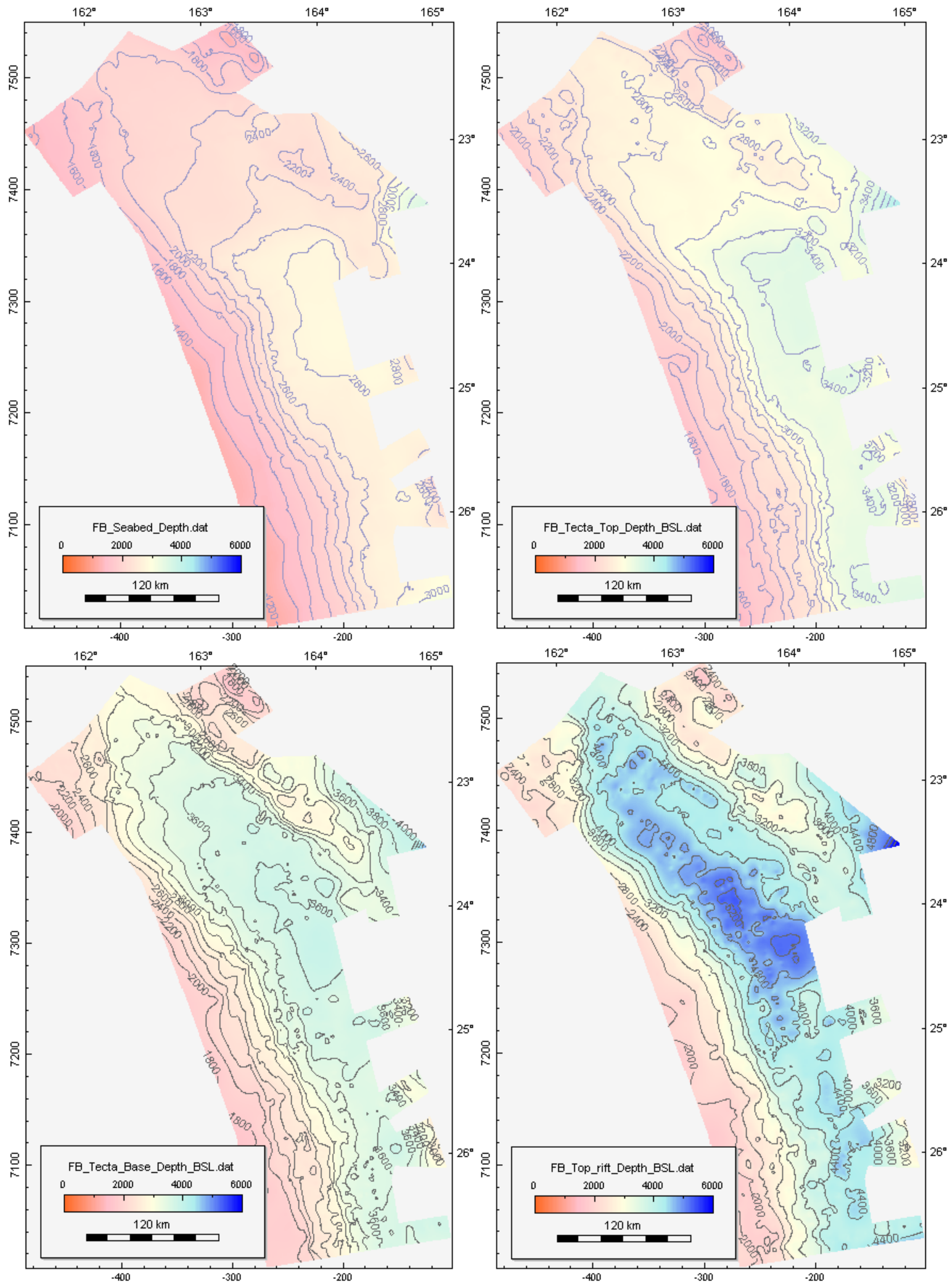

Figure 4 Interpreted depth maps based on grids provided by DIMENC. Smoothing and trimming was applied where necessary. See Table 1 for ages of depth maps and related isopach maps.

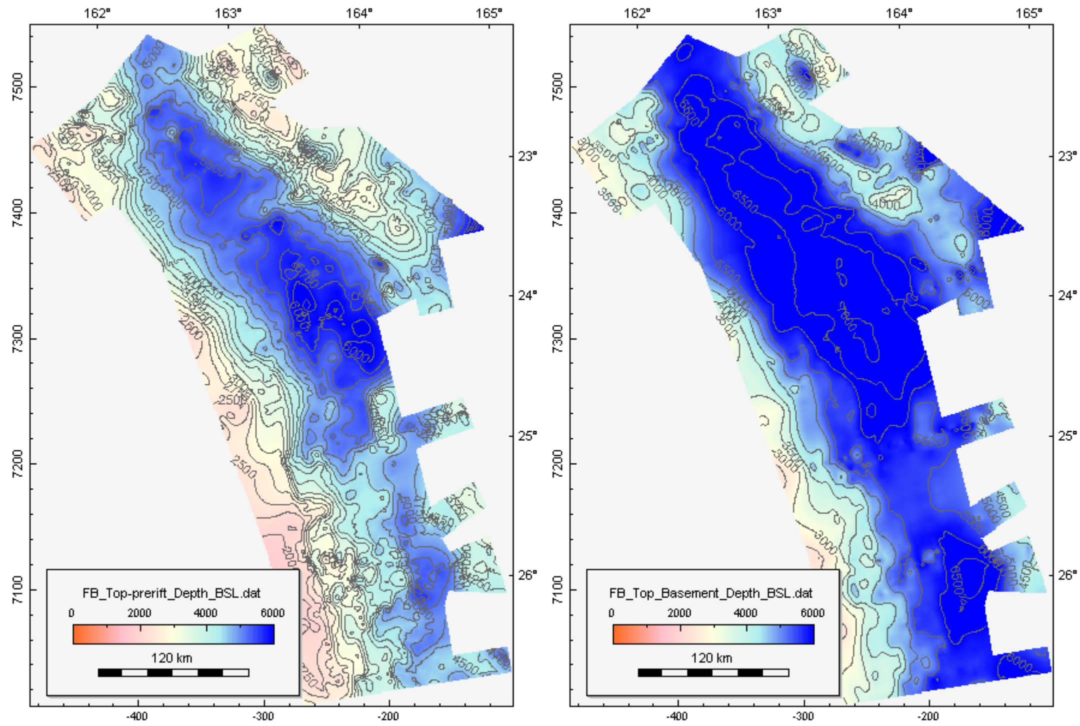

Figure 4 (continued). Interpreted depth maps based on grids provided by DIMENC. Smoothing and trimming was applied where necessary. See Table 1 for ages of depth maps and related isopach maps.

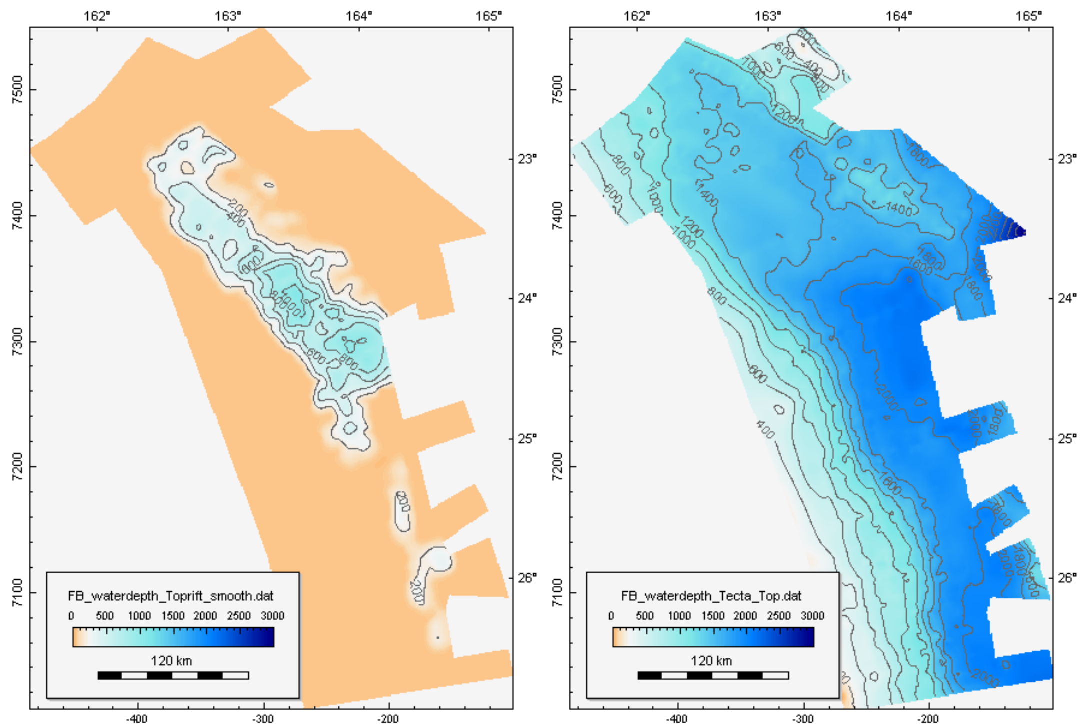

Figure 5 Water depth for top rift (72 Ma) sequence and top Tecta (34 Ma) unit.

Table 1 Interpreted depth structure and paleobathymetry maps used to calculate sediment thickness (isopach) and to interpolate water depth. Lithologies reflect interpreted composition of sediments used to calculate rock property evolution in the basin. Ages and lithology data were provided by DIMENC.

				Estimated	Lithologies					
Horizons	**Unit**	**Isopach**	**Paleobathymetry**	**Age**	**sand**	**silt**	**mud**	**carbonate**	**volcanic**	**coal**
FB_Sea_Bed			FB_Seabed_Depth	0						
	Oligo-Neogene	Isopach_original_Oligo-Neogene			0.1	0.1	0.2	0.45	0.15	0
FB_Top_Tecta			FB_waterdepth_Tecta_Top	34						
	Upper Post-rift	Isopach_original_Upper_postrift			0.2	0.2	0.2	0.4	0	0
FB_Onset_Tecta			interpolated	45						
	Lower Post-rift	Isopach_original_Lower_postrift			0	0	0.4	0.6	0	0
FB_Top_Rift			FB_waterdepth_Toprift_smooth	72						
	Rift	Isopach_10mSR_synrift3			0.1	0.2	0.2	0	0	0.5
			FB_waterdepth_Toprift_smooth	73						
	Rift	Isopach_upper_synrift3			0.2	0.3	0.4	0	0.1	0
			FB_waterdepth_Toprift_smooth	88						
	Rift	Isopach_10mSR_synrift3			0.1	0.2	0.2	0	0	0.5
			FB_waterdepth_Toprift_smooth	89						
	Rift	Isopach_lower_synrift3			0.2	0.3	0.4	0	0.1	0
			FB_waterdepth_Toprift_smooth	104						
	Rift	Isopach_10mSR_synrift3			0.1	0.2	0.2	0	0	0.5
FB_Top_Prerift			FB_waterdepth_Toprift_smooth	105						
	Pre-rift	Hiatus								
			FB_waterdepth_Toprift_smooth	130						
	Pre-rift	Isopach_upper_pre-rift			0.4	0.2	0.2	0	0.2	0
			interpolated	165						
	Pre-rift	Isopach_Walloon-Eq			0.2	0.1	0.1	0	0.1	0.5
			interpolated	175						
	Pre-rift	Isopach_lower_prerift			0.4	0.2	0.2	0	0.2	0
FB_Top_Basement			zero water depth	260						

2.0 MULTI-1D BASIN MODELLING

2.1 METHODOLOGY

The multi-1D (pseudo-3D) BM1D basin modelling code used in this report is a GNS Science development based on the 1D finite-element conductive heat flow package Bassim, the application of which is described in (Wood et al., 1998). The basin simulation code is applied to each 1 km^2 cell across a basin grid covering the region of interest (Figure 2). Stratigraphic thickness, age, temperature and paleobathymetric data are combined with mathematical relationships describing sediment properties during progressive compaction to derive burial and thermal maturity histories for each cell.

Using a one-dimensional conductive heat flow algorithm in a 3-dimensional sense has some limitations, especially in areas where lateral heat transfer exists, and care should be exercised in interpreting model output in areas where heat transfer due to lateral fluid flow and refraction of heat across thermal conductivity boundaries, such as faults, may be significant.

The stack of sedimentary layers is decompacted according to lithological parameters (Table 1) to allow the reconstruction of the basin configuration and sediment fill through time. Geochemical parameters describing source rock properties (e.g., TOC, HI, GOGI and Sth) allow source rock maturity and volumes of expelled petroleum to be predicted as a model output. These outputs are used in map-based migration modelling. Other outputs include predicted heat flow, vitrinite reflectance and temperatures within the basin, as well as paleo-structure maps for the evolving basin, which can be used as surfaces suitable for paleo-charge modelling.

2.2 MODEL CONSTRUCTION

2.2.1 Burial History

Burial history was reconstructed in the model by multi 1D forward modelling of isopach grids derived from depth maps using a computed interval-specific compaction history. The list of grids in the stratigraphic sequence developed for the modelling is shown in Table 1. The Tertiary burial history is defined by three supplied grids: onset Tecta, top Tecta and seabed. Paleocene, Eocene and Oligocene-Recent burial rates are defined by interpolation between these grids (Table 1).

The Upper Cretaceous syn-rift sequence as defined by the top pre-rift and top rift grids was further subdivided into a set of 5 isopachs in order to provide flexibility in the model to account for deposition of a series of interbedded marine organic-rich and coal measure intervals. Analogous to modelling of the Capel and Faust basins (Funnell and Stagpoole, 2011), the pre-rift isopach was subdivided to account for the inferred presence of a terrestrial source rock interval equivalent to the Walloon coal measures in the Clarence-Moreton Basin, eastern Australia (Figure 6).

In addition to structural depth maps, the bathymetric evolution inferred from seismic data interpretation provided by DIMENC reflects the progressive subsidence of the basin since the Late Cretaceous (Figure 5) and tectonic activity and inversion on adjacent areas such as the Lord Howe Rise and Fairway Ridge resulting in basin floor tilting in the New Caledonia Basin and, to a lesser degree, in the Fairway Basin (Collot et al., 2008). Water depth was interpolated between the two water depth maps provided by DIMENC and the present-day seabed map.

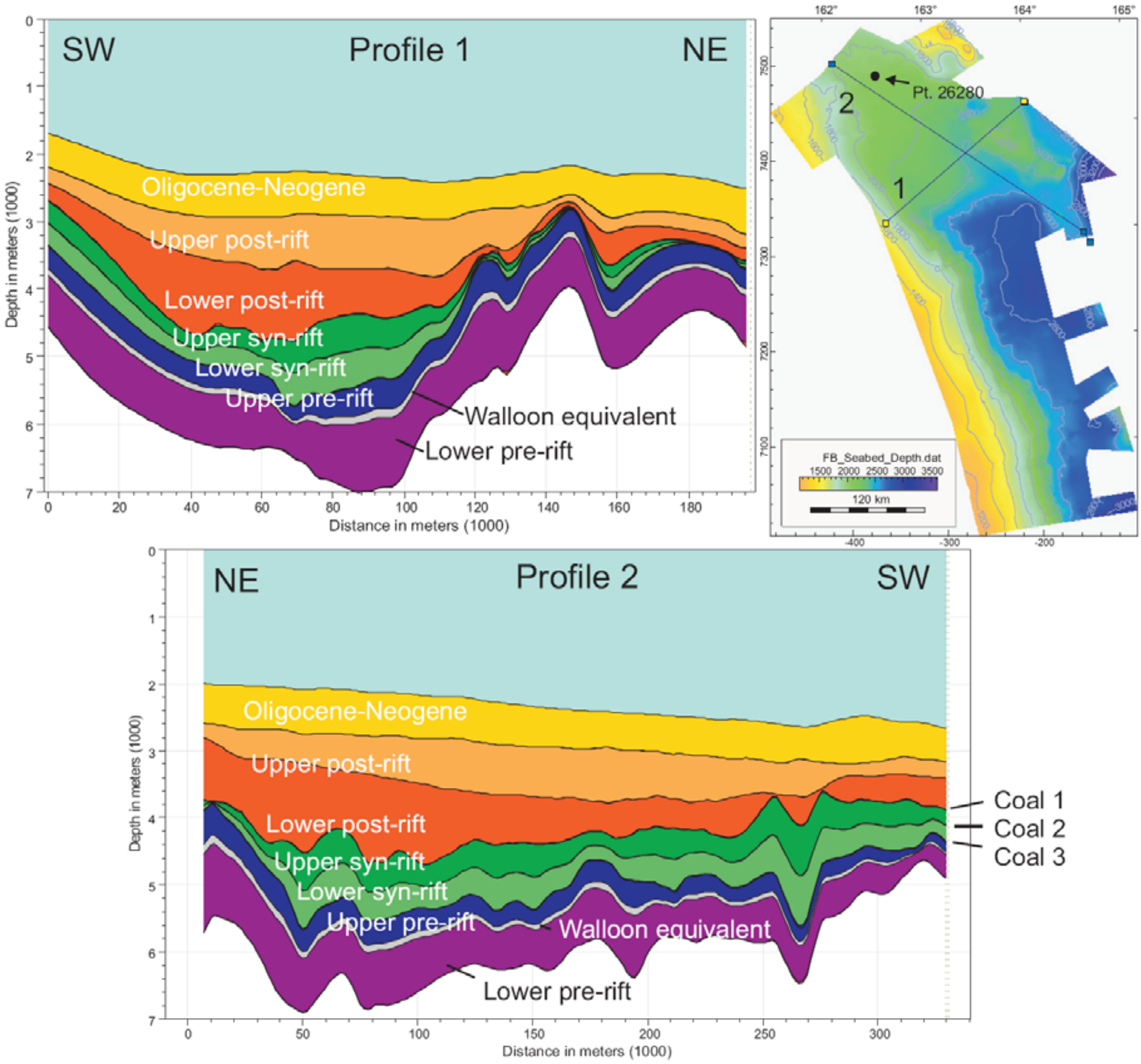

Figure 6 Present day basin architecture as shown by two transects through the model. Point 26280 refers to burial history data presented in Figures 15 and 16.

2.2.2 Source rocks and hydrocarbon generation parameters

There are no proven source rocks in the Fairway Basin. Source rock distribution has been inferred from seismic interpretation and inferences based on analogue basins and regional tectonic reconstructions. Coal intervals in the Upper Cretaceous syn-rift sequence were modelled as 3 layers each 10 m thick extending across the basin (Coal 1-3, Table 1; Figure 6). General source rock parameters, similar to those of the Taranaki Basin were used. In scenario 1 hydrogen indices (HI) of 300 mg_{HC}/g_{TOC} and total organic carbon (TOC) contents of 35% were implemented (Table 2) based on each 10 m unit consisting of an equivalent 5 m thick coal seam. In the centre of the basin, a marine source rock was modelled under the assumption that westward of the main terrigenous input, a restricted marine basin had formed with high organic matter preservation (Figure 7). The richness of such a source rock was interpreted to increase basinward. A TOC map was therefore calculated using the thickness of the Late Cretaceous syn-rift interval as an analogue for water depth evolution and organic carbon sedimentation. In an additional scenario (scenario 2) source rock productivity at the high end of values typical for Cretaceous coaly source rocks with a HI of

350 mg_{HC}/g_{TOC} was used. A typically higher total HI of 545 mg_{HC}/g_{TOC} was used for the syn-rift marine source rocks. An alternative option (scenario 3) was also included using scenario 2 source rock properties for the syn-rift, but adding marine source rock potential (with 2% TOC) to the whole pre-rift sequence, and replacing the Walloon equivalent coaly source rock.

Table 2 Source rock properties implemented in the three modelling scenarios. In scenario 3, the model was run with a terrestrial source rock for the Walloon equivalent and, in addition, assuming a low (2%) TOC marine sequence in the pre-rift interval.

Interval	**Scenario 1**			
	Type	**TOC**	**Sth**	**HI**
		%	**(mg oil/gTOC)**	**(mgHC/gTOC)**
Syn-rift coal1	III	35	100	300
Upper syn-rift	II	0-4	80	548
Syn-rift coal2	III	35	100	300
Lower syn-rift	II	0-4	80	548
Syn-rift coal3	III	35	100	300
Upper pre-rift				
Walloon equivalent	III	15	100	300
Lower pre-rift				

Interval	**Scenario 2**			
	Type	**TOC**	**Sth**	**HI**
		%	**(mg oil/gTOC)**	**(mgHC/gTOC)**
Syn-rift coal1	III	35	80	350
Upper syn-rift	II	0-4	80	548
Syn-rift coal2	III	35	80	350
Lower syn-rift	II	0-4	80	548
Syn-rift coal3	III	35	80	350
Upper pre-rift				
Walloon equivalent	III	15	80	350
Lower pre-rift				

Interval	**Scenario 3**			
	Type	**TOC**	**Sth**	**HI**
		%	**(mg oil/gTOC)**	**(mgHC/gTOC)**
Syn-rift coal1	III	35	80	350
Upper syn-rift	II	0-4	80	548
Syn-rift coal2	III	35	80	350
Lower syn-rift	II	0-4	80	548
Syn-rift coal3	III	35	80	350
Upper pre-rift	II	2	80	548
Walloon equivalent	II/III	2/15	80	350/548
Lower pre-rift	II	2	80	548

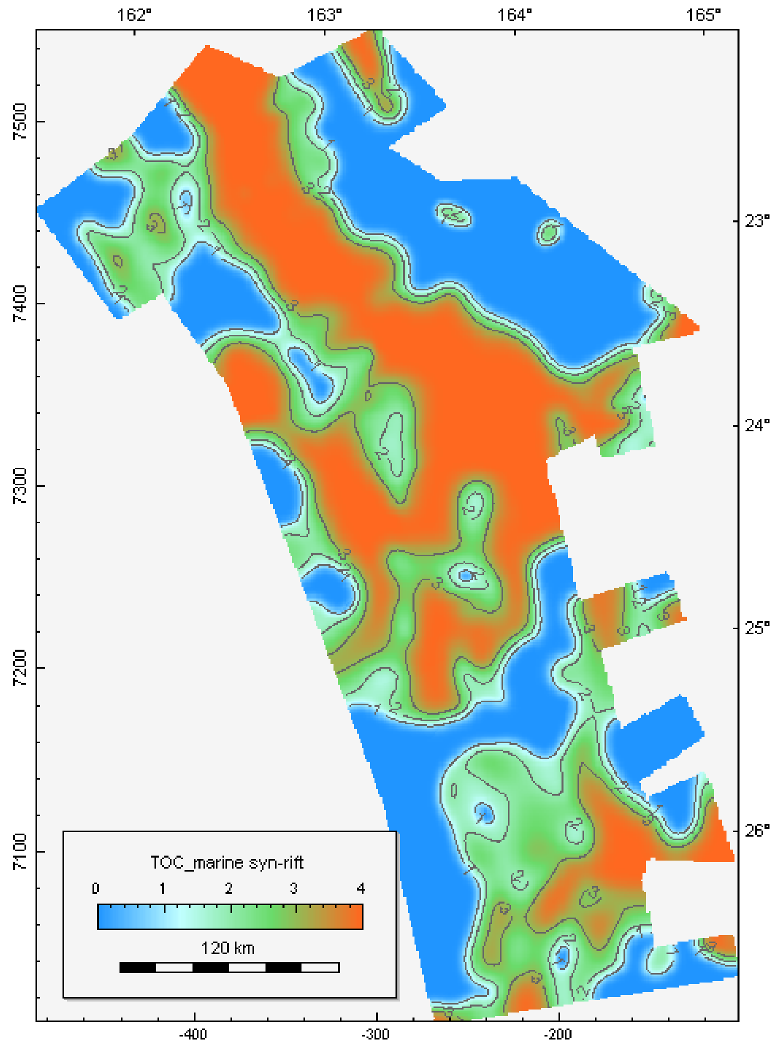

Figure 7 TOC of the marine lower and upper syn-rift units based on the Late Cretaceous isopach.

The rate of transformation of kerogen to oil and gas was modelled using two-component (oil and gas) Arrhenius-type kinetics after Pepper & Corvi (1995a), specified with a single frequency factor and a distribution of activation energies that are widely used for petroleum systems modelling. Coaly source rocks were modelled as sub-type DE organofacies (type III waxy, terrigenous kerogen) for oil and gas generation and cracking of oil to gas (secondary gas generation). For the marine Upper Cretaceous syn-rift sequence source rocks and the modelled marine pre-rift source rock, Pepper and Corvi (1995a) type II (B) kinetics were used. In general, marine source rocks are generating at lower temperatures and are more oil-prone than coaly source rocks (Figure 8). Coals are modelled with a gas-oil generation index (GOGI) of 0.34 compared to 0.16 for the marine source rocks. Terrestrial source rocks are also more gas prone due to their higher adsorption potential. A simple saturation-controlled expulsion threshold (Sth) for oil (Pepper and Corvi, 1995b) was adopted that required the generation of a certain amount of oil to fill pore space and overcome the adsorption capacity before expulsion occurred. In scenario 1, a Sth of 100 mg_{OIL}/g_{TOC} was assumed for coaly source rocks and a Sth of 80 mg_{OIL}/g_{TOC} for marine source rocks, reflecting the lower oil expulsion potential of most terrestrial source rocks, whereas in scenario 2 and 3, a Sth of 80 mg_{OIL}/g_{TOC} was assumed for all source rocks (Funnell & Stagpoole, 2011). See Table 2 for a summary of source rock intervals and parameters used in the three scenarios.

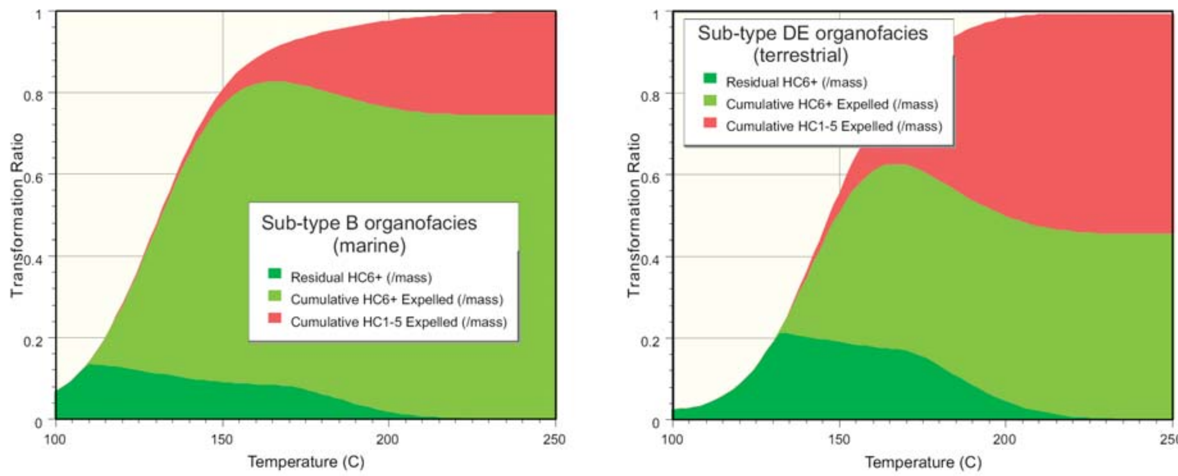

Figure 8 Comparison of transformation ratios for oil and gas for marine and terrestrial source rocks using a linear heating rate of 3°C / My

2.2.3 Lithosphere reconstruction and heat flow calibration

Basin heat flow depends on heat productivity within the crust and heat transfer from the mantle lithosphere. Modelled heat flow is generally conductive and vertical in the case of multi 1D models. However models can also account for an advective heat transfer, for instance implemented as a boundary condition at the base of the model. In addition, BM1D software accounts for upward transport of heat through rifting and relative rock uplift.

According to velocity profiles inferred from deep seismic reflection surveys, the Fairway Basin overlays approximately 15 km thick continental crust (Klingelhoefer et al., 2007). In order to reproduce the history of Cretaceous rifting related to the opening of the Tasman Sea and the thinning of the crust beneath Fairway Basin, stretching factors were computed based on Cretaceous and pre-Cretaceous isopachs (Figure 9). The use of both isopachs enabled a more accurate fit to the Klingelhoefer et al. (2007) data although it is acknowledged that this stretching factor map requires further input. The thermal effects of rifting, including initial heat flow increase due to stretching and following exponential decrease of heat flow, were modelled to occur between 105 and 72 Ma.

Heat production in the crust was modelled to stepwise decrease with depth, corresponding to the age of crustal rocks. In scenario 3, a basin wide increase in heat flow was modelled under the assumption that Eocene-Miocene volcanic activity in the area was related to a regional increase in heat transfer from the mantle. In this scenario, an increase by 20 mW/m^2 was applied at the base of the model (base of the mantle lithosphere). This increase in heat flow is predicted to have reached the base of the sedimentary succession at the end of the Eocene (Figure 10).

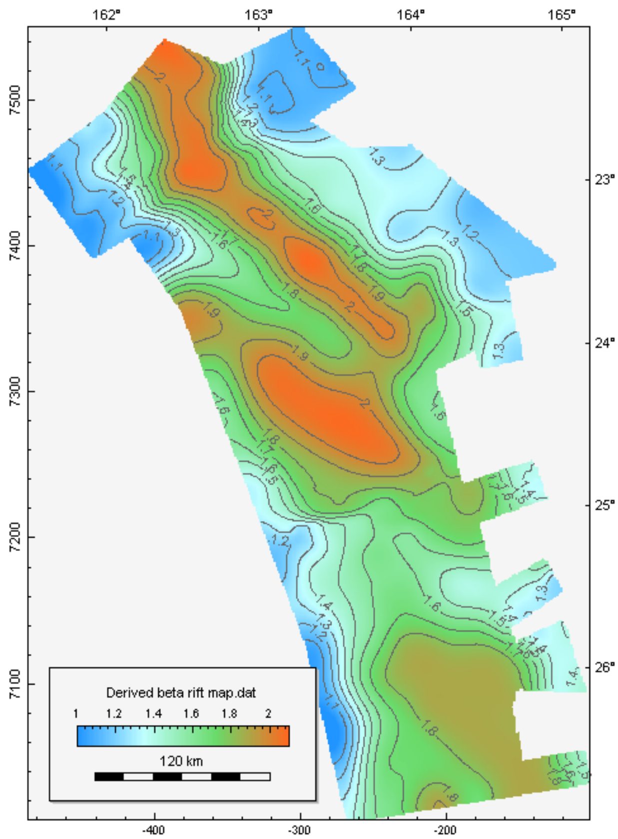

Figure 9 Map of stretching factors derived from a combination of syn- and pre-rift isopachs that was found to best replicate data on crustal thickness of Klingelhoefer et al. (2007).

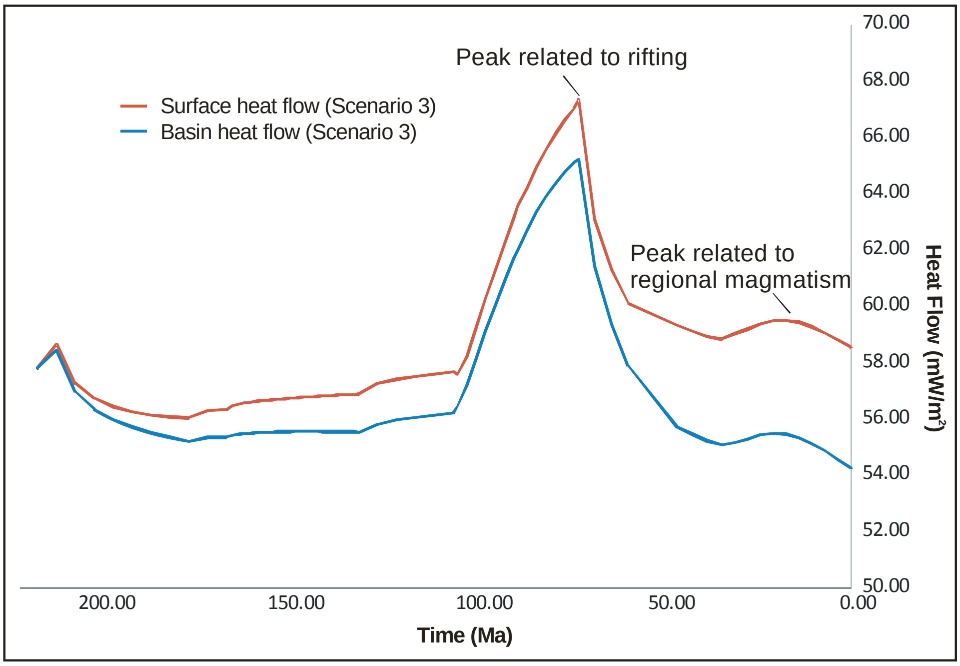

Figure 10 Modelled heat flow history for scenario 3 showing modelled effects for both rifting and increased heat mantle heat transfer.

Heat flow data based on temperature measurements down to 18 m below sea floor are available for the Fairway Basin (Nouzé et al., 2009). These data show a large scatter (49 – 64 mW/m^2) across the central area, probably related to uncertainty in measurements and near surface transient processes such as sedimentation and fluid movement. These data are not reproducible by the basin modelling approach applied in this report (Figure 11; Figure 12). The average heat flow for the Nouzé et al. (2009) data is 52.7 mW/m^2, if the 75 mW/m^2 value is discounted as being unreliable. This average is 3 mW/m^2 below average values in the basin centre as predicted by scenario 1 and 2 and 5 mW/m^2 below modelled values in scenario 3. However, scenario 1 and 2 results are very similar to DSDP hole 587 and 206 values (Figure 11), which are the most recent available data from deeper boreholes in the region. Given that the Fairway Basin measurements are expected to be susceptible to cooling surface influences, which is also a point supported by the large range of values at closely spaced sites (Figure 11), it was decided not to attempt to match these values by the models shown in Figure 12.

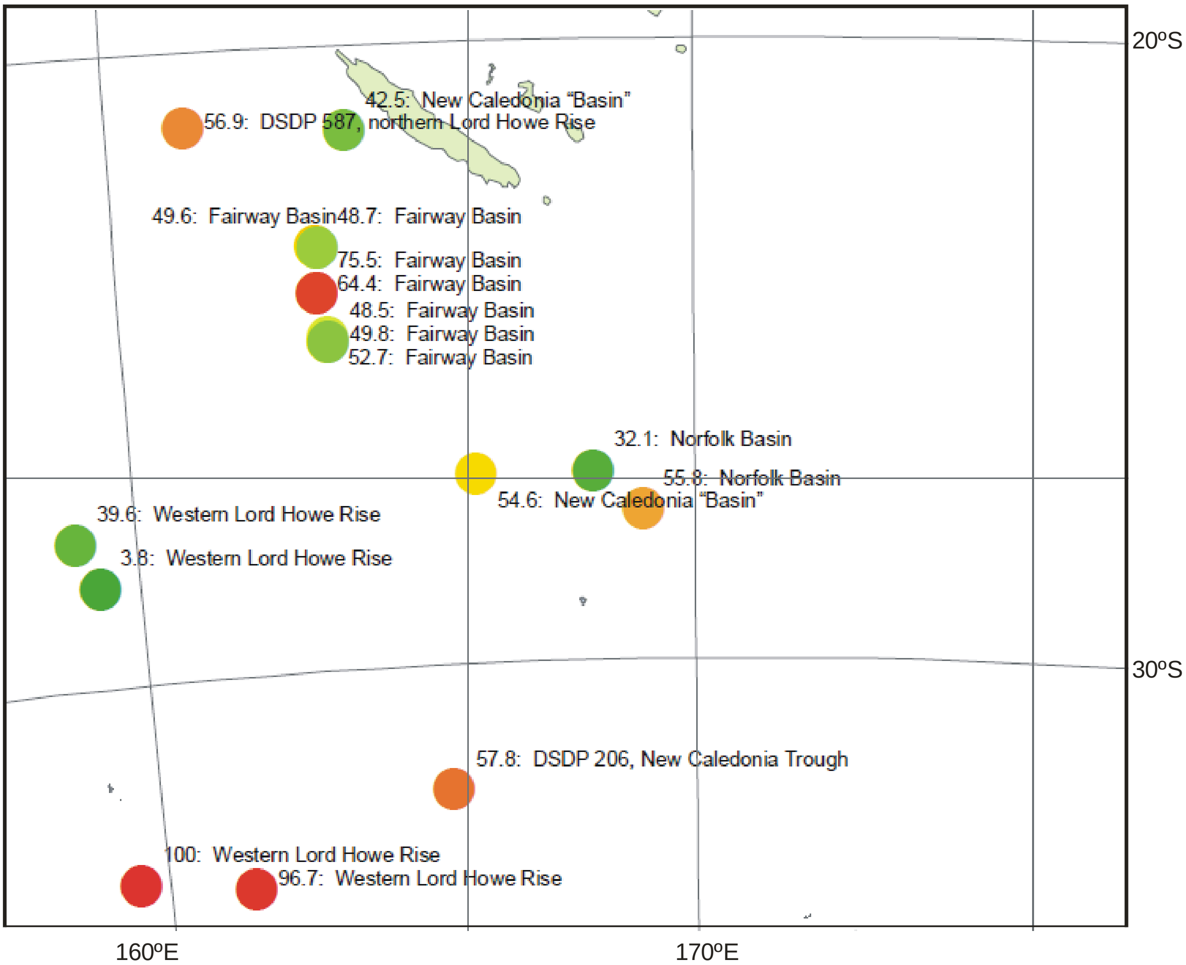

Figure 11 Heat flow data in the region. DSDP hole 587 and 206 as well as Fairway Basin data from Nouzé et al. (2009) were used.

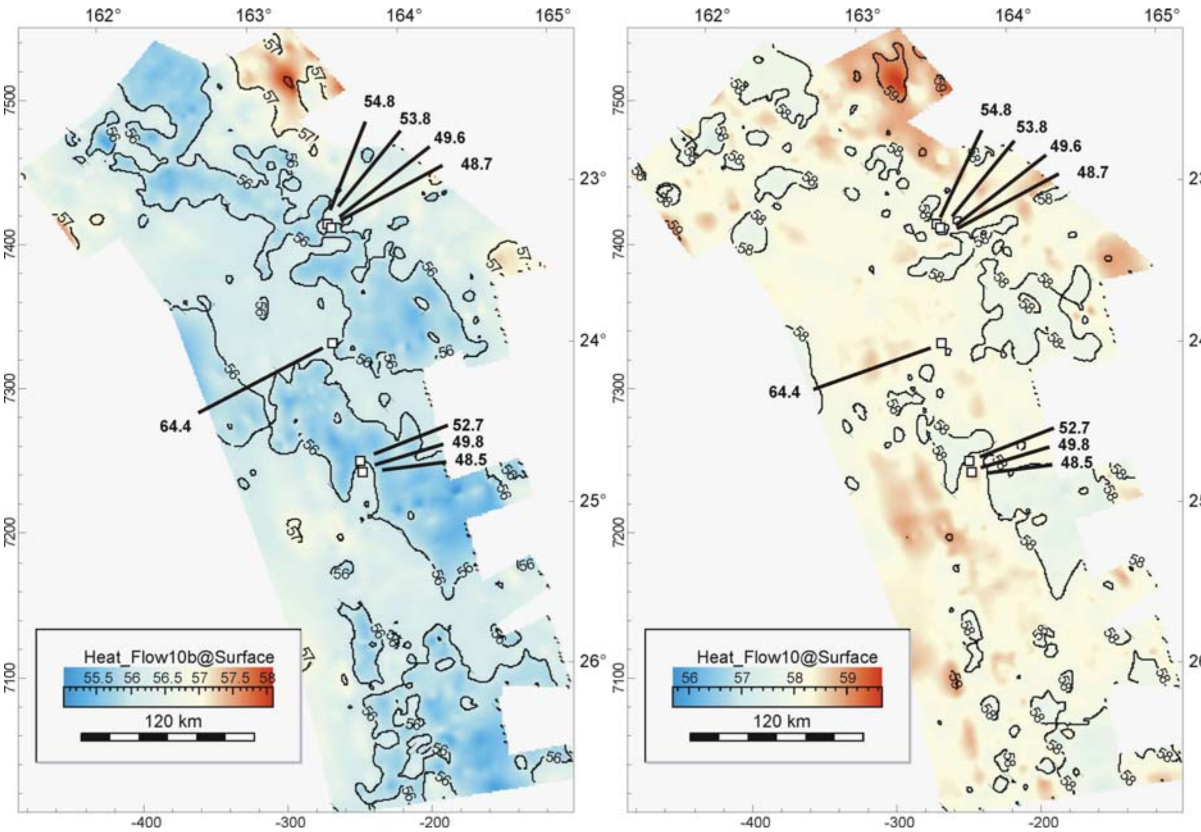

Figure 12 Heat flow data from sub-ocean floor temperature measurements from Nouzé et al. (2009) and maps showing left: surface heat flow prediction by models assuming rifting only (scenario 1 and 2) and right: surface heat flow prediction by a model assuming rifting and a regional heat pulse coeval with volcanic activity (scenario 3).

3.0 RESULTS

3.1 PREDICTED MATURITY

Modelling results for the Fairway Basin indicate maximum present-day temperatures between 110 and 120°C at the level of a hypothetical Walloon Formation equivalent source rock in the lower part of the sedimentary sequence (Figure 13). Predicted temperatures decrease upwards from slightly more than 100°C at the base of the syn-rift sequence to less than 90°C at the top of the syn-rift sequence in the deepest part of the basin. The scenario 3 model, assuming an increase in regional mantle heat flow coeval with widespread Eocene-Miocene volcanism, predicts up to 10°C higher temperatures across the basin (Figure 14). The area of highest temperatures predicted by the model outlines a potential SW-NE oriented petroleum kitchen in the northern part of the basin coinciding with the greatest thickness of syn-rift sediments. However, model predictions indicate temperatures at the lower limit of the oil window (compare Figure 8). Temperatures further back in time are only slightly lower than present-day temperatures for the same horizon (for example base Walloon eq., Figure 13), reflecting relatively low average sedimentation rates since the Eocene (Figure 15; Figure 16). Scenario 3 predicts slightly higher paleo-temperatures than the other scenarios due to the modelled increase in post-Eocene heat flow (Figure 14).

Low maturity of source rock intervals is indicated by modelled vitrinite reflectance which decreases from 0.8 %Ro at the base of the Walloon Formation equivalent to 0.6 %Ro at the top of the syn-rift sequence in the deepest part of the basin (Figure 17). An assumed heat flow increase propagates through the lithosphere into the sedimentary succession by the early Miocene (scenario 3) and results in a predicted increase in vitrinite reflectance of 0.1 %Ro.

3.2 PREDICTED TRANSFORMATION AND EXPULSION

Transformation to oil and gas was modelled using the kinetic parameters (Pepper & Corvi, 1995a) described above and properties presented in Table 2. The fraction of transformed organic material is presented as transformation to both oil and gas, in Figure 18 and Figure 19. Transformation of oil generative kerogen is predicted to have taken place in the lower part of the sedimentary succession. Values for the Walloon equivalent reach transformation ratios of 0.2-0.3 in the deepest part of the basin for scenarios 1 and 2, with a maximum of 0.43 in a small localised area in the northwest of the basin (Figure 18). Scenario 3, assuming increased heat flow due to magmatism, predicts transformation ratios about 0.1 higher.

The difference between terrestrial source rocks and potential marine source rocks becomes apparent in the syn-rift succession, where predicted transformation ratios for marine source rocks at the base of the succession on average are higher than in the underlying Walloon equivalent prediction. However, transformation ratios in the lowermost syn-rift coal unit are predicted to be significantly lower. Transformation to oil within coaly source rocks at higher stratigraphic levels is predicted to be insignificant, although transformation is still predicted to occur in marine source rocks in the upper syn-rift section.

Significant transformation of kerogen to oil, despite relatively shallow burial depth and low present-day temperatures, is a consequence of slow burial and long residence time at elevated temperatures (Figure 16). This emphasizes the importance of time in the Arrhenius equation used to describe the transformation of organic matter to hydrocarbons. However, due to the overall immature to early mature character of the source rocks, transformation of kerogen to gas and cracking of residual oil is small in all scenarios modelled (Figure 19).

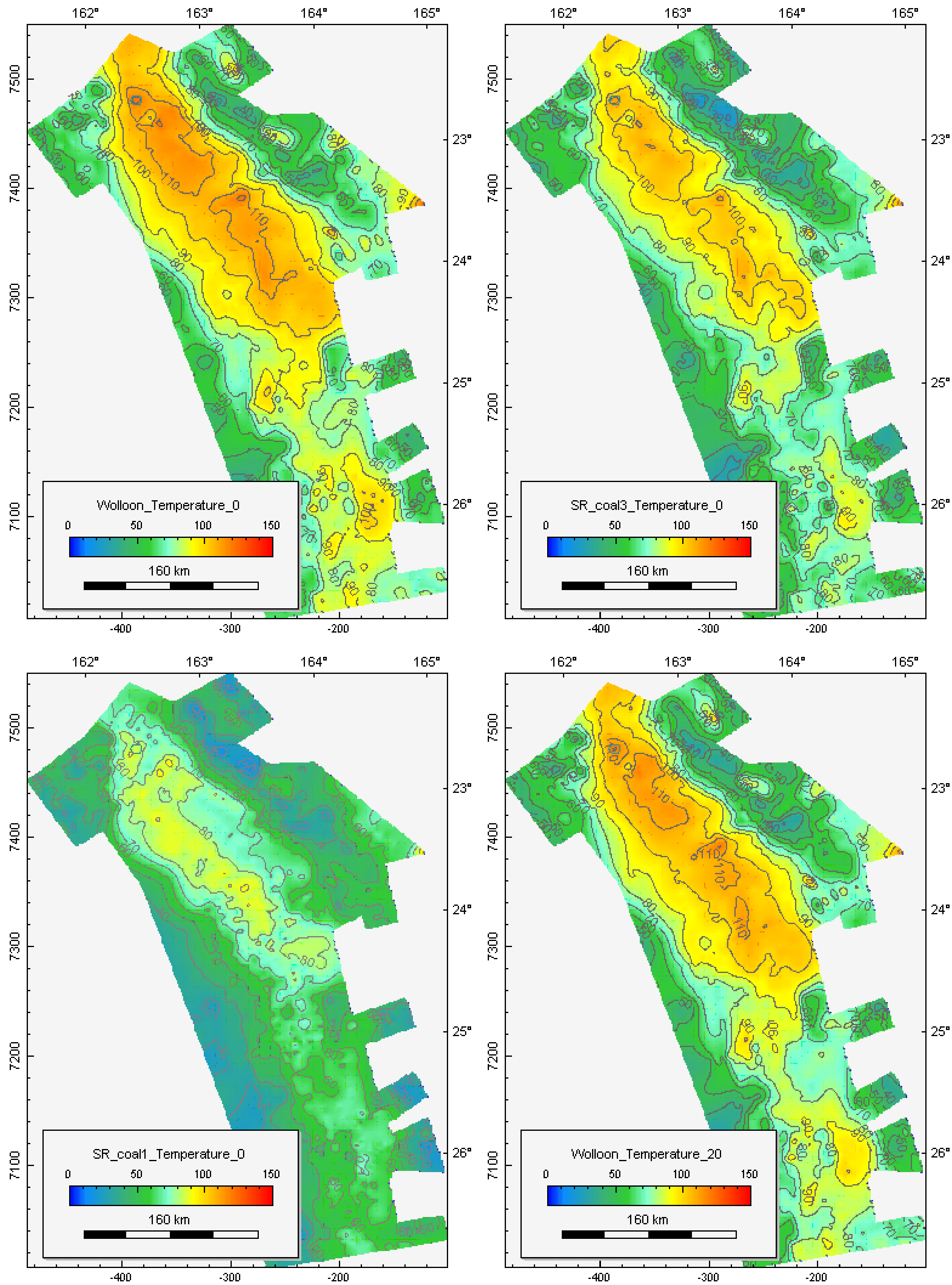

Figure 13 Predicted temperature at base Walloon equivalent (top left), and lower (top right) and uppermost syn-rift coal (bottom left) at present-day for scenario 1 and 2 (no magmatism) and at base Walloon equivalent 20 Myrs ago (bottom right). Coordinates on left and lower axes are UTM 59 in km; the right and upper axes are latitude (S) and longitude (E).

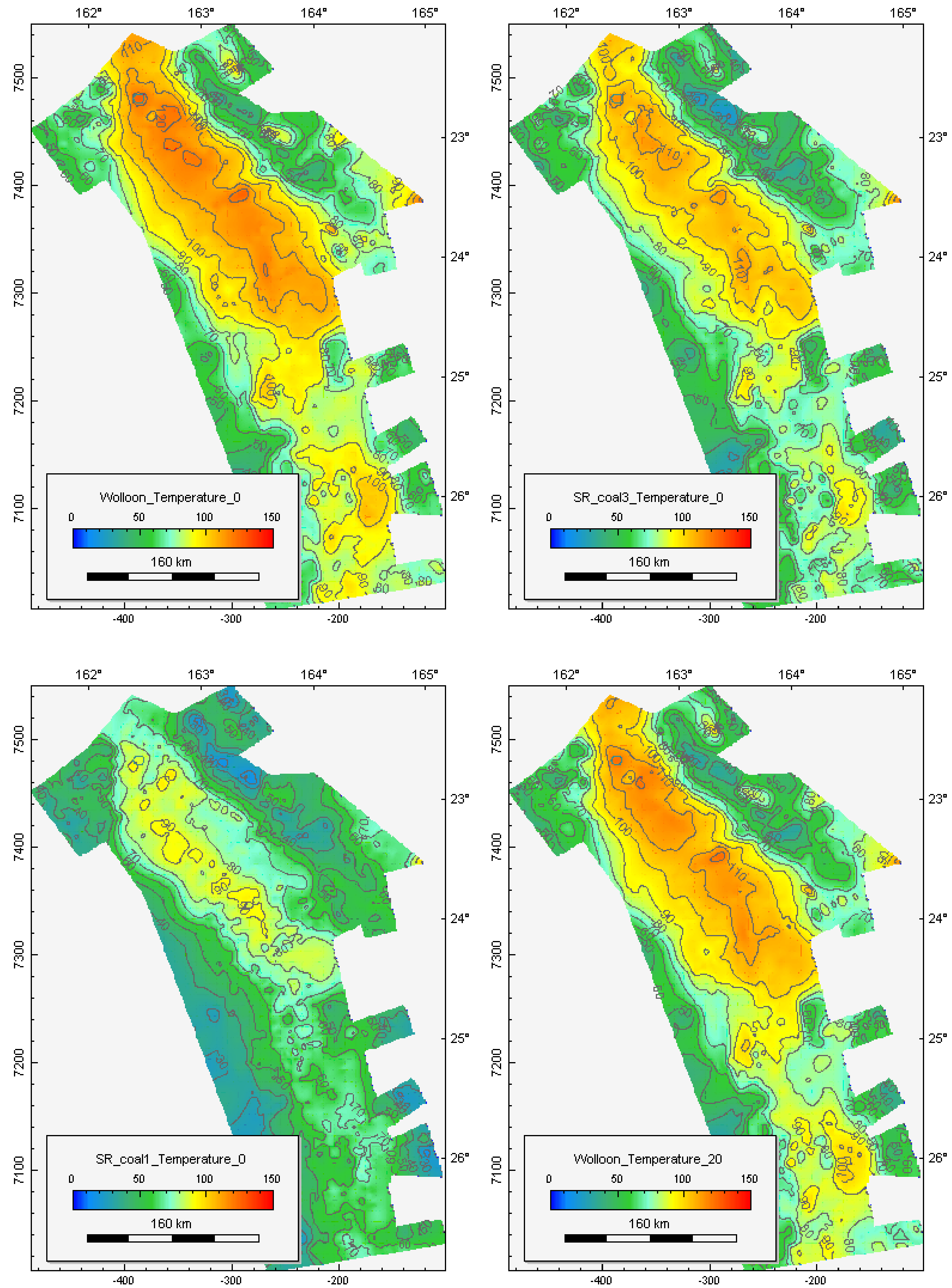

Figure 14 Predicted temperature at base Walloon equivalent (top left), and lower (top right) and uppermost syn-rift coal (bottom left) at present-day for scenario 3 and at base Walloon equivalent 20 Myrs ago (bottom right). Coordinates on left and lower axes are UTM 59 in km; the right and upper axes are latitude (S) and longitude (E).

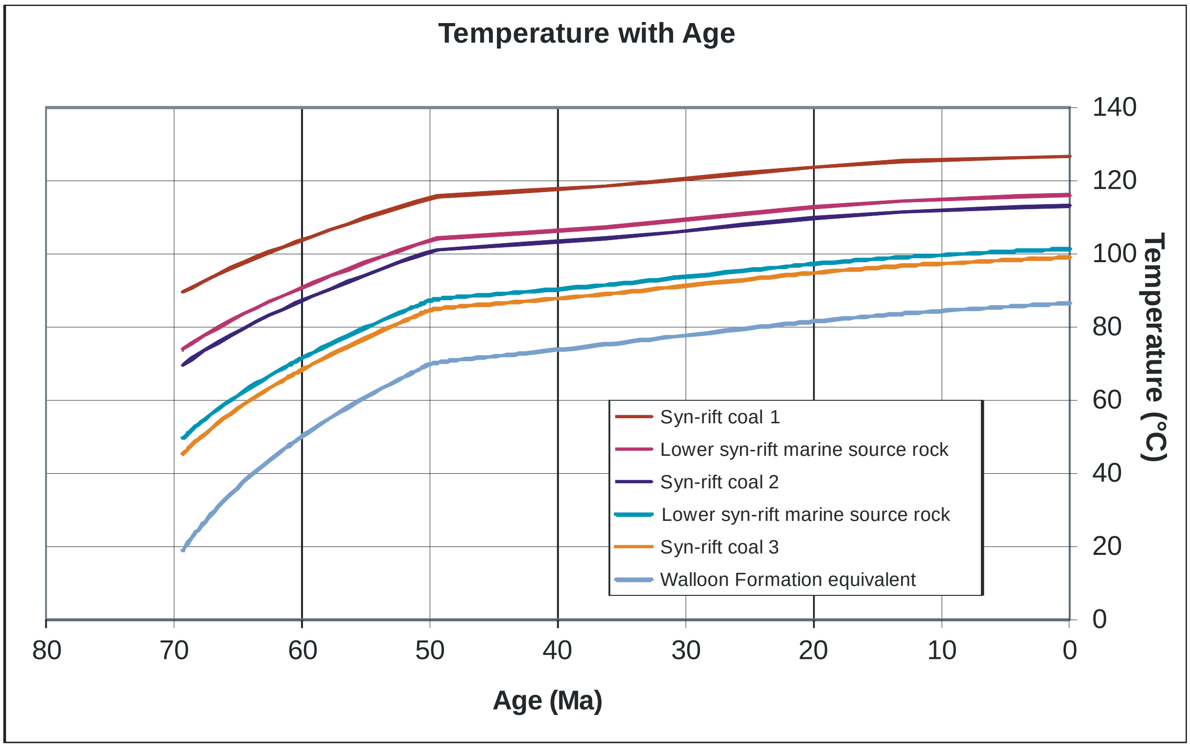

Figure 15 Representative temperature evolution at the level of the modelled source rocks in the Fairway Basin. Location of modelled point shown in Figure 6.

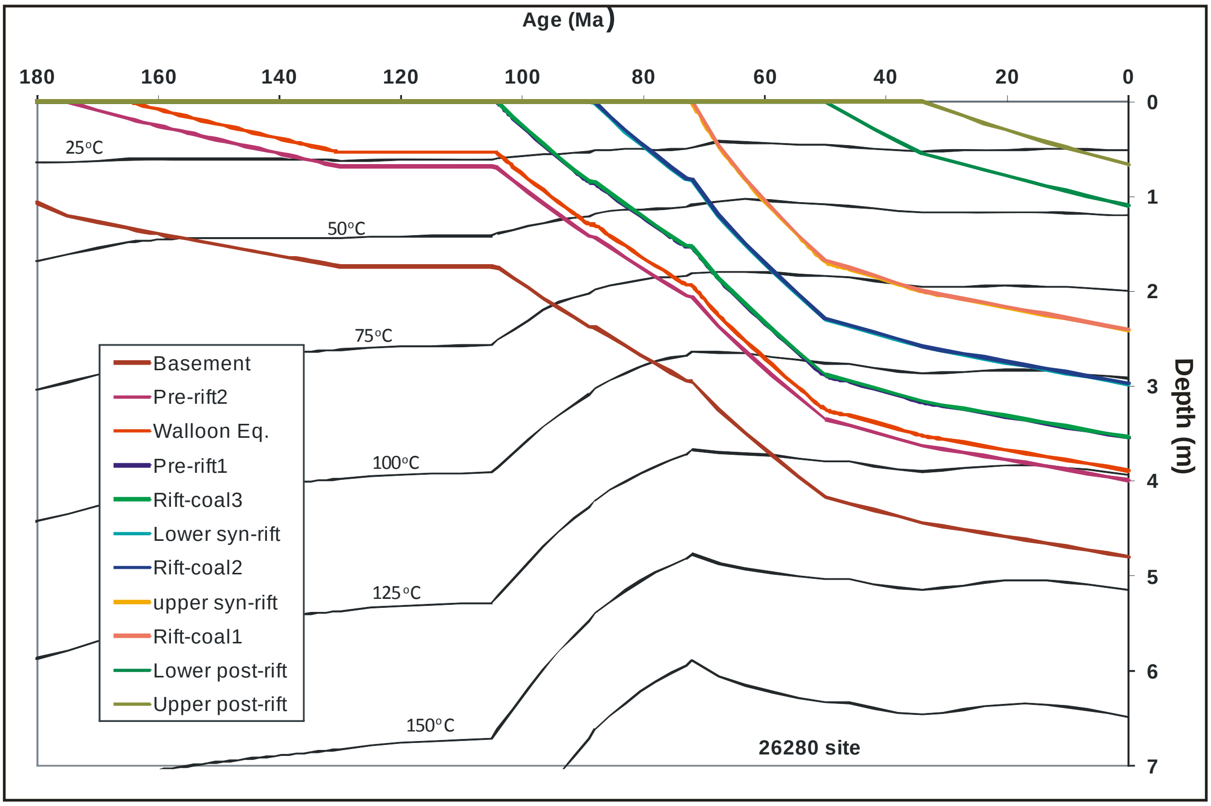

Figure 16 Representative burial history of the main units and basin isotherms in the Fairway Basin (plotted without water depth). Location of modelled point shown in Figure 6. Legend refers to top of each unit indicated.

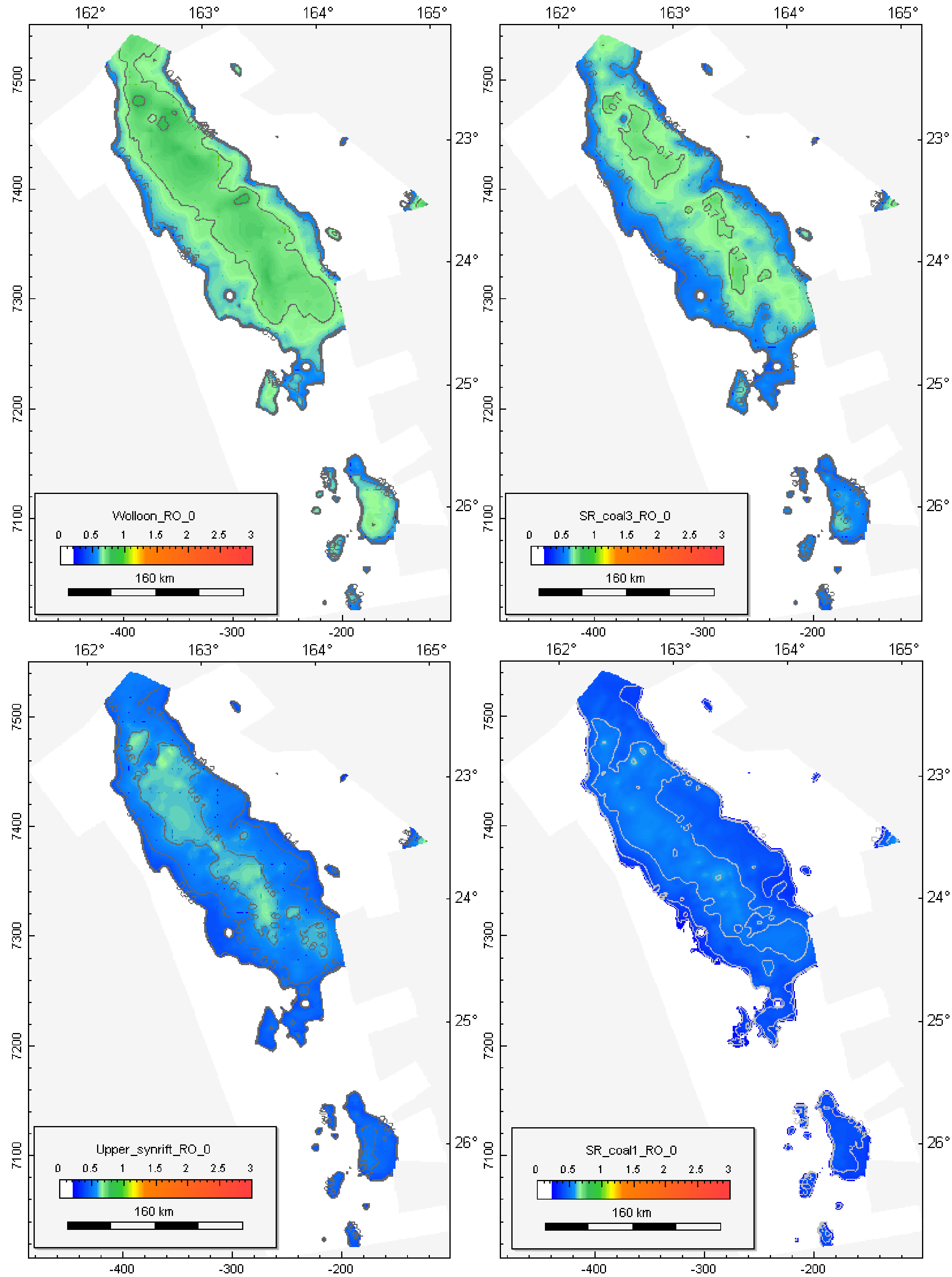

Figure 17 Predicted vitrinite reflectance in %Ro at base Walloon equivalent (top left), base upper syn-rift (bottom left) and lower and uppermost syn-rift coal (top and bottom right) at present-day for scenario 1 and 2. Note that base coal 3 is almost equivalent to base lower syn-rift and base upper syn-rift is almost equivalent to base coal 2 (Table 2). Coordinates on left and lower axes are UTM 59 in km; the right and upper axes are latitude (S) and longitude (E).

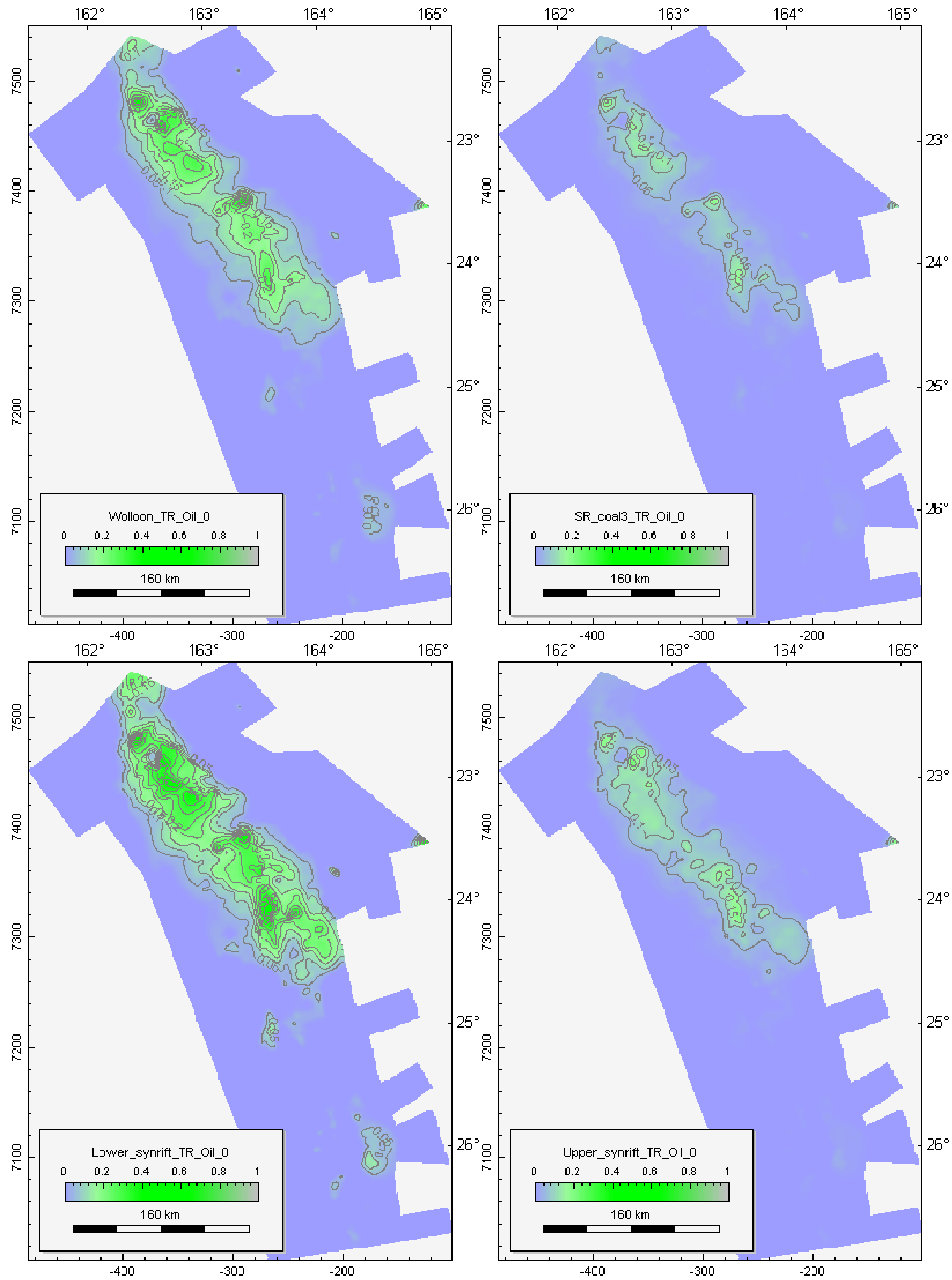

Figure 18 Predicted oil transformation ratio (TR) for syn-rift source rocks. Upper maps show results for coaly source rocks applying organofacies DE (type III) kinetics and lower maps show results for hypothetical marine source rocks, using type II kinetics for scenario 1 and 2. Coordinates on left and lower axes are UTM 59 in km; the right and upper axes are latitude (S) and longitude (E). Coal1 and 2 did not show any significant transformation.

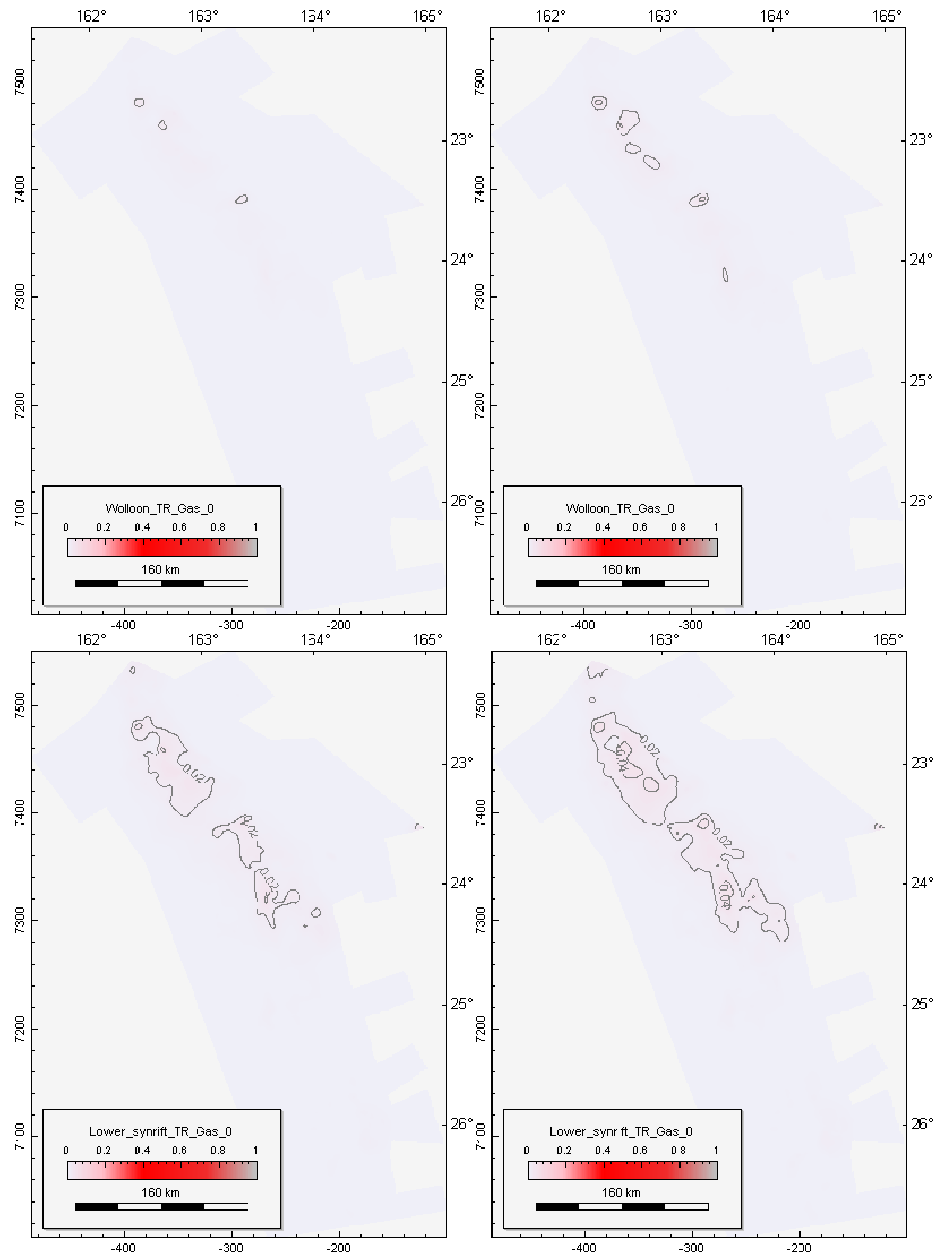

Figure 19 Predicted gas transformation ratio (TR) for the base of the Walloon Formation equivalent using organofacies DE (type III) kinetics (upper maps), and the base of a hypothetical marine source rock in the syn-rift sequence, using type II kinetics. Maps on the left side show predictions from scenario 1 and 2 and maps to the right show predictions for the same layer of scenario 3. Prediction Co-ordinates on left and lower axes are UTM 59 in km; the right and upper axes are latitude (S) and longitude (E). Units overlying the shown layers do not show significant transformation.

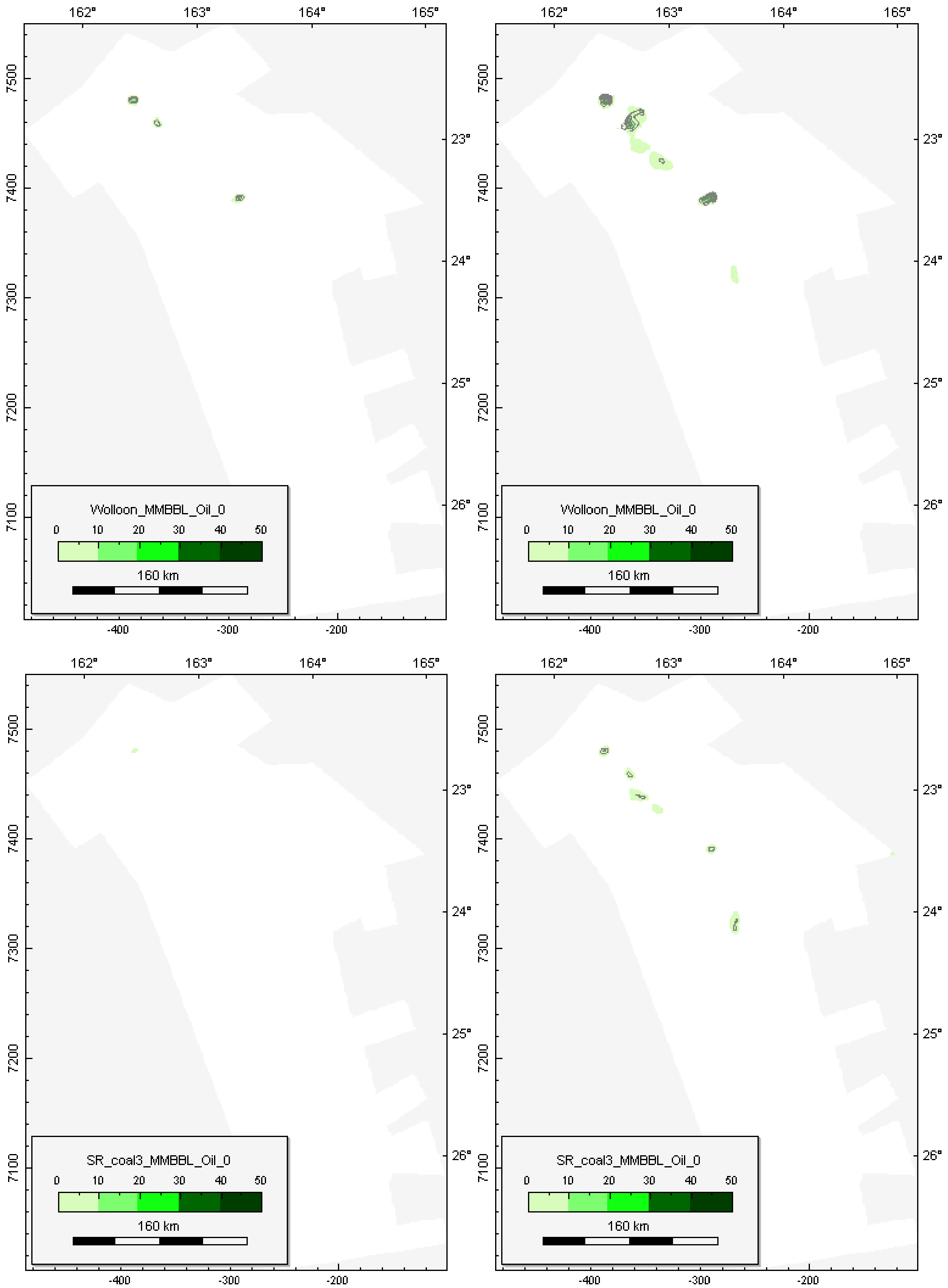

Figure 20 Predicted volumes of oil expelled from coaly source rocks in the Walloon Formation equivalent (upper plots) and coal 3 in the syn-rift sequence for scenario 2 (left) and scenario 3 (right). Stratigraphically higher intervals are not predicted to expel any oil.

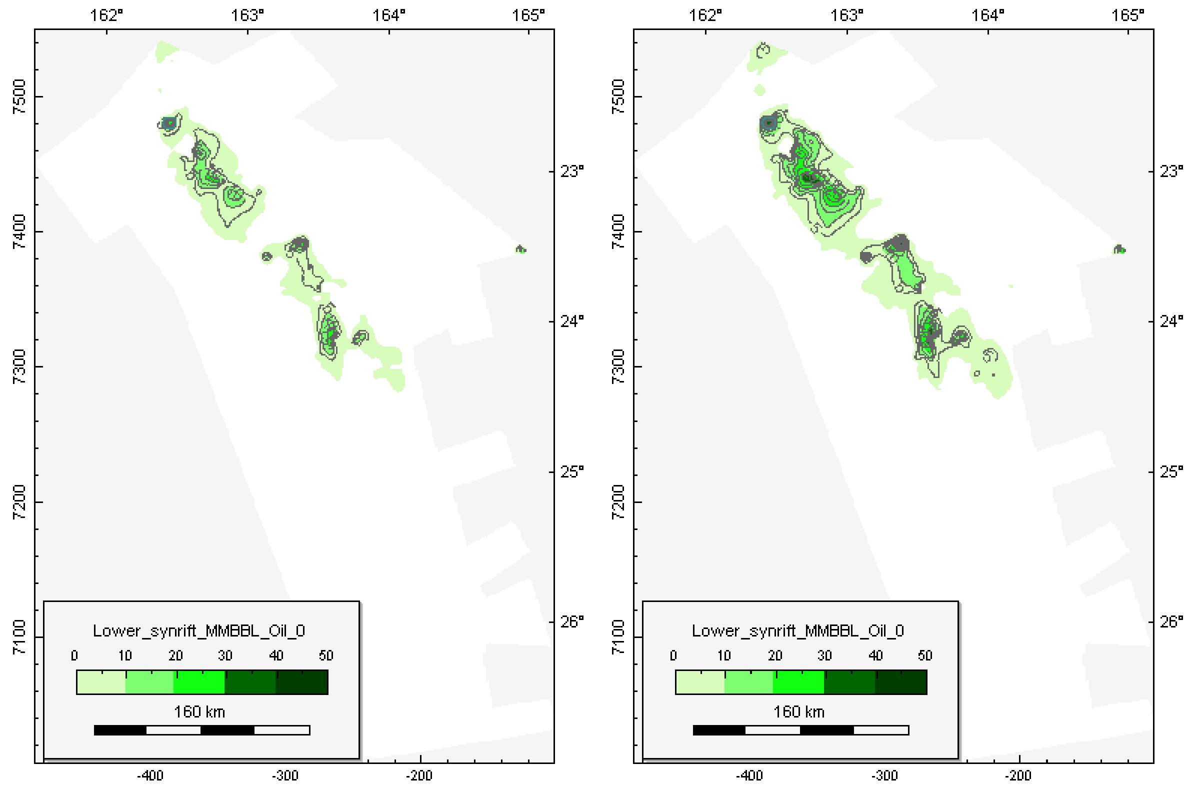

Figure 21 Predicted volumes of oil expelled from hypothetical marine source rocks in the lower syn-rift sequence for scenario 1 and 2 (left) and scenario 3 (right). Stratigraphically higher intervals are not predicted to expel any significant amounts of oil.

The difference in the generation and expulsion potential of terrestrial and marine source rocks has considerable impact on predicted expelled volumes from these source rocks (Figure 20; Figure 21). Predicted expelled volumes of oil from terrestrial source rocks are small, even under optimistic assumptions (scenario 2, 3; Figure 20). Virtually no expulsion takes place using conservative assumptions (scenario 1). This is not only due to lower productivity but most importantly to higher adsorption potential of terrestrial source rock, as reflected by higher saturation thresholds. The modelled Walloon equivalent would only have expelled oil assuming saturation thresholds similar to the marine source rocks (between 1 billion bbl oil in scenario 2 and up to 6.9 billion bbl oil in scenario 3), while the lowermost coal interval in the syn-rift sequence would only have expelled up to 1.7 billion bbl oil in scenario 3. In contrast, between 29 (scenario 1) and 40 MMbbl oil per km^2 (scenario 3) is predicted to have been expelled from the modelled relatively thick marine lower syn-rift sequence (Figure 21). Across the basin, up to 80 billion bbl oil could have been expelled from this interval. Despite generally low transformation to gas, some expulsion is predicted to have occurred from the most deeply buried source rocks, due to low retention potential of gas within the source rocks (Figure 22). Up to 18 Tcf gas are predicted to have been expelled from the marine lower syn-rift unit and between 14 (scenario 1) and 33 Tcf gas (scenario 3) from a Walloon equivalent source rock, while the modelled coaly source rock at the base of the syn-rift sequence (Coal3) is predicted to have expelled 5.1 Tcf gas in scenario 3.

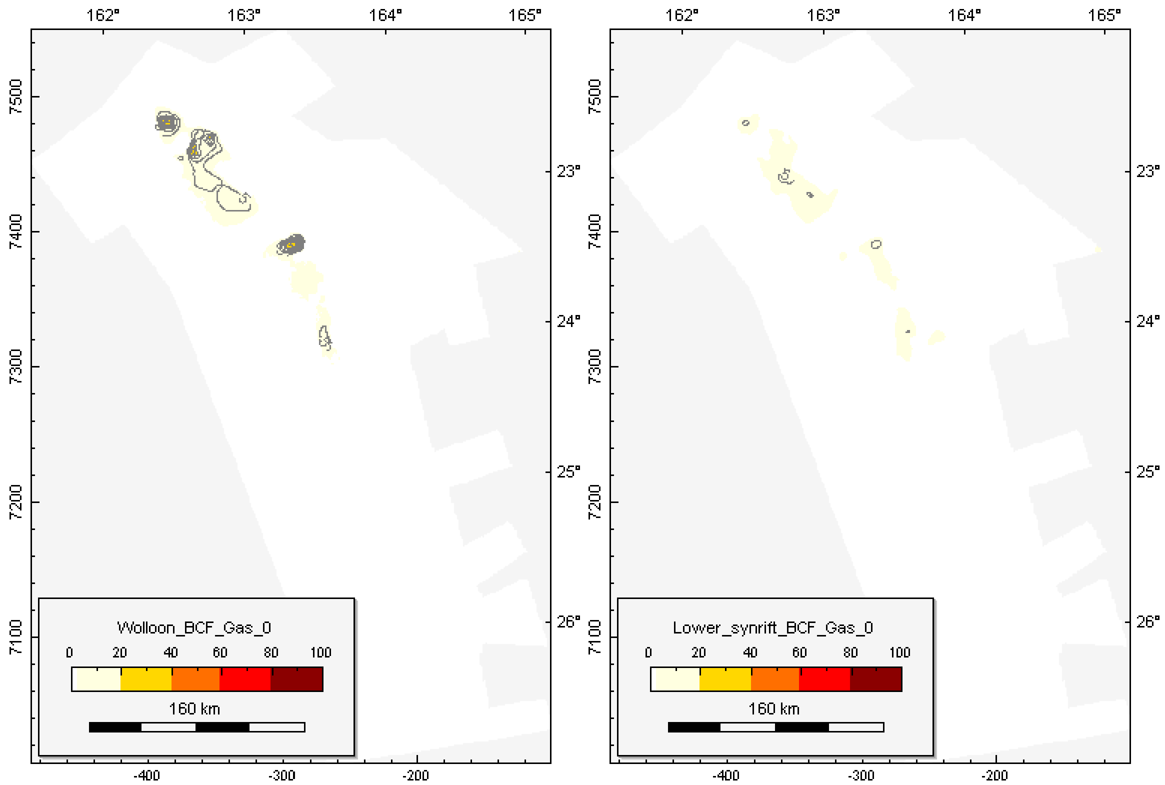

Figure 22 Predicted volumes of gas expelled from a terrestrial Walloon equivalent source rock and from hypothetical marine source rocks in the lower syn-rift sequence for scenario 3. Stratigraphically higher intervals are not predicted to have expelled any significant amounts of gas.

3.3 Marine Pre-Rift Scenario

To further test the potential for oil and gas generation in Fairway Basin an additional hypothetical scenario, assuming the presence of marine source rocks in the pre-rift sequence, was tested. While this scenario is not supported by geological data, it presents an option related to future exploration potential in the Fairway Basin. Similar properties to the marine syn-rift source rock were assumed, with a TOC of 2% throughout the succession. At the base of the pre-rift sequence, the model predicts this source rock to reach almost full transformation to oil, but only 20% transformation to gas. This can be explained by the source rock properties adopted (Table 2) and the predicted maturity at the onset of gas generation. Large volumes of oil (up to 133 MMbbl/km^2) could be expelled from such a source rock (Figure 23).

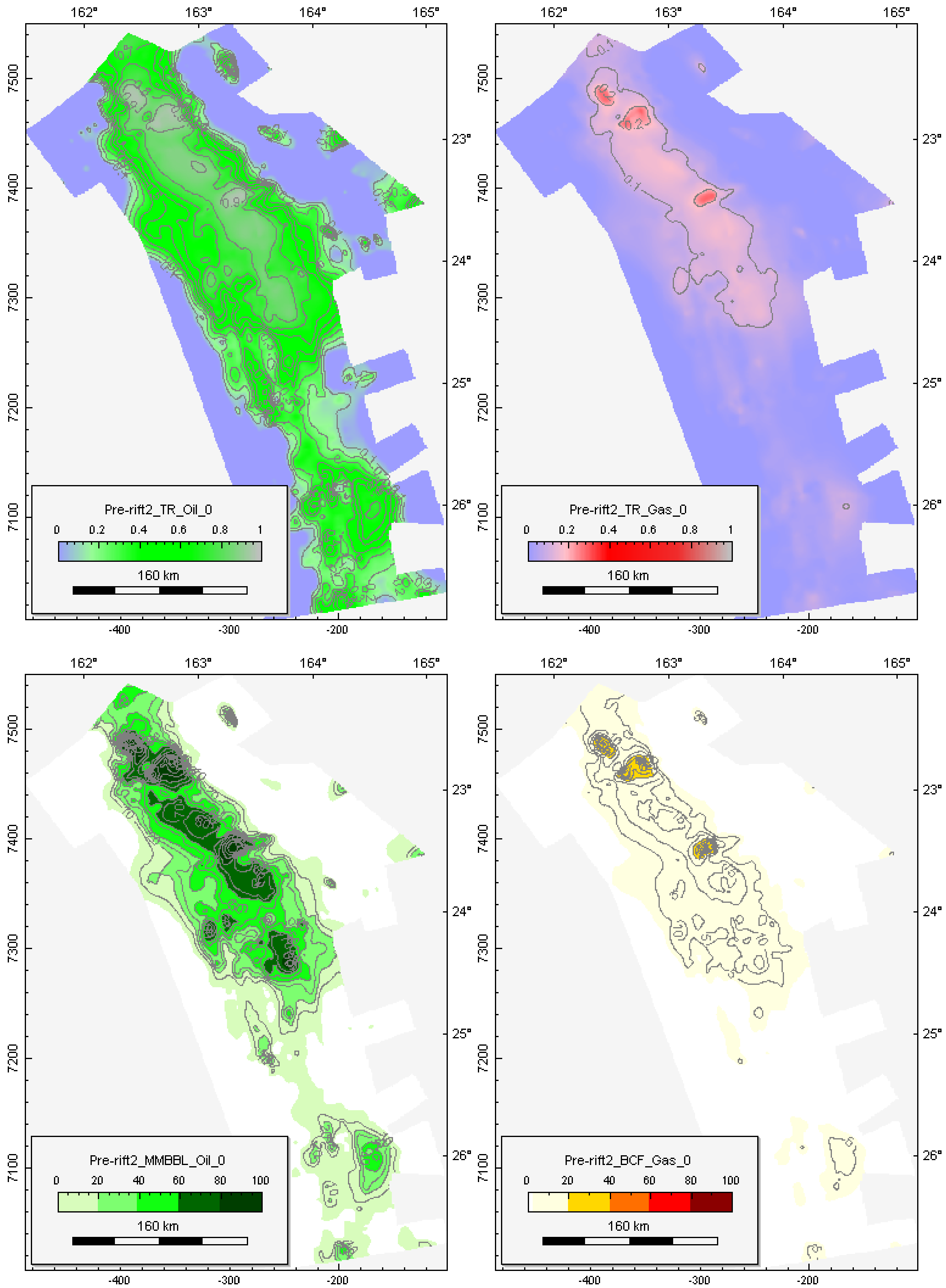

Figure 23 Model results for a postulated marine pre-rift source rock showing maturity in terms of transformation ratio (upper plots) and oil and gas expulsion (lower plots) at the base of the pre-rift sequence.

4.0 MAP-BASED CHARGE MODELLING

The objective of the map-based charge modelling (using Zetaware Trinity[1] software) is to provide a reconnaissance level investigation of migration pathways, identifying which traps have access to charge, and possible volumes of expelled petroleum capable of being trapped. Migration is traced on mapped horizons for the top rift sequence and the Tecta-base or top lower post-rift, using potential charge volumes derived from multi-1D models.

The estimates of trapped volumes given here make only simplistic allowance for migration losses (when applied) and are based on the use of simple reservoir properties. They are intended to provide an initial assessment of potential migration pathways and traps that have access to charge. Trap sizes and predicted volume of accumulations are dependent on trap geometry, reservoir properties and seal effectiveness, all of which are generalised and should be considered as approximations in these models.

4.1 METHODOLOGY

The general methodology evaluates migration on individual mapped surfaces based on simple buoyancy-controlled up-dip migration using present-day structure maps. While the software allows for the incorporation of facies control (controlled by a capillary entry pressure values) and pressure effects (from potentiometric surfaces), these data were not available for this frontier region. A simple sand facies map was however developed to replicate possible pinch-out of syn-rift sediments on rift margins. A crucial assumption in this methodology is that petroleum phases migrate vertically from source rock kitchens onto each migration surface, permitting migration to be assessed independently for each surface.

Trinity software was used to compile the input and output grids (1000 x 1000 m cells) for the BM1D modelling because of its flexibility in manipulating and managing grids. Inputs for the charge modelling consist of the following series of maps:

- Present day and paleo-structure (if considered necessary) surfaces on which to migrate petroleum
- Oil and gas expelled volume grids from BM1D software for the last 10 My
- Sand facies migration map for the syn-rift units.

These maps are assembled in a Trinity project that allows the interactive testing of secondary migration and accumulation. The results of these investigations are dependent on the following assumptions with respect to migration:

- The source is limited by the predicted distribution and volume of expelled oil and gas for each time period based on BM1D output
- Migration is controlled by buoyancy driven flow on structural surfaces, unless stated otherwise
- No losses occur during migration, unless stated otherwise
- The sides of the model are open, allowing flow out of the model.

[1] Interactive petroleum system analysis and risking software by Zetaware, Inc. http://www.zetaware.com

The predicted accumulations are dependent on the following assumptions:

- Reservoir properties controlling accumulation size assume 50 m thick sand, 25% porosity and 60% hydrocarbon saturation for all horizons
- Seals are considered adequate to support no more than a 200 m hydrocarbon column, after which they leak
- All quoted volumes are at standard temperature pressure (STP) unless otherwise stated.

The ratio of oil and gas in each trap is defined by the gas-oil ratio (GOR) of fluids initially charging the trap and the contribution of processes leading to seal leakage or trap-volume controlled spillage (e.g., gas tends to leak, oil tends to spill in the model). It should be clearly understood that since the reservoir and seal properties are generalised (using those parameters identified above), this assessment does not provide definitive volume estimates for accumulations, or prove the viability of structural containment.

4.2 FLOW-PATH MODEL

Reservoir intervals have been modelled as being present as land-derived sandstones of the Cretaceous and Paleogene sequence (Exon et al., 2007). Traps may be associated with horsts as overlying anticlines, or pinch-outs against the Lord Howe Rise and the eastern highs on the flanks of the basin (Exon et al., 2007). A trend of sedimentary diapirs penetrating up into the Upper Eocene sequence is present in the north and south of the basin. Auzende et al. (2000) suggest these diapirs were produced by mobilised muds from Cretaceous-aged sediments and may have generated structural traps for accumulating hydrocarbons within the lower post-rift sequence.

The flow-path models are based on supplied grids (1 km^2 cells) and as such are unable to replicate likely accumulation patterns associated with the many diapirs, although some of the larger features are observed in the structural grids with associated accumulations in flow-path models. Given the lack of data on reservoir intervals in this frontier basin, migration models have only been run on the mapped horizons (top pre-rift as 130 Ma, top syn-rift as 72 Ma, and top lower post-rift as 45 Ma) to illustrate likely accumulation patterns. The top rift-sequence horizon has been used in the models as a base-case migration model to compare likely trapped volumes for different source rock scenarios, while the tops of the pre-rift-sequence and the lower post-rift-sequence are primarily used to compare the accumulation patterns at different stratigraphic levels.

A facies map has been developed to guide migration and accumulation modelling in pinch-outs adjacent to the Lord Howe Rise in the west and the eastern margin of the mapped interval. This map was generated by applying high capillary entry pressure zones, where the upper syn-rift isopach thickness was less than 100 m in regions adjacent to structural highs to replicate the onlap and pinch out of sandy facies. The map is presented in Figure 24, as capillary entry pressure quantified in terms of metres of hydrocarbon column. The darker zones are no flow in the model, and the yellow colours represent flow zones associated with expected presence of sands: sediments proximal to highs are predicted to be more coarse grained and have slightly lower capillary entry pressures in the facies map.

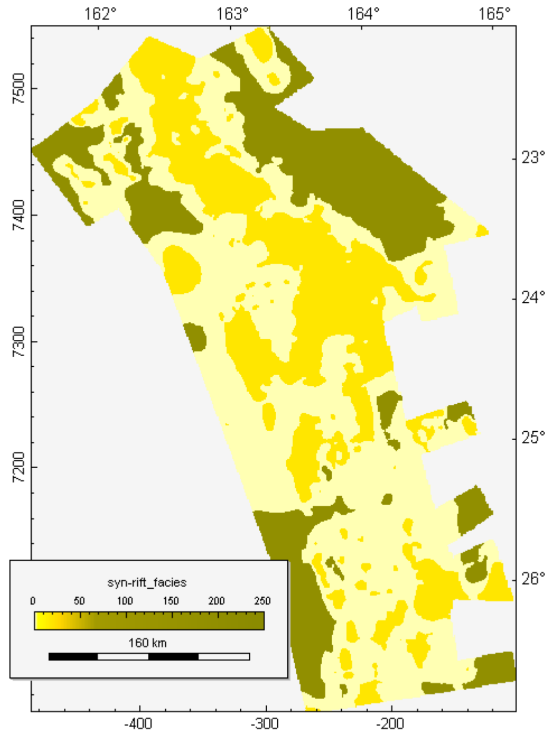

Figure 24 Sand facies map used to predict accumulations in pinch-outs adjacent to highs on the flanks of the basin. Map is presented as capillary entry pressure (metres of hydrocarbon column).

4.3 CHARGE MODEL RESULTS

A series of migration and accumulation figures are presented below illustrating results of the charge modelling. The volumes predicted in modelling scenario 2 to have been expelled from the syn-rift coals (e.g., Coal 3 aged 105 Ma) are relatively small and do not contribute to even moderate-sized accumulations (Figure 25). These models do not account for migration losses; which may be related to residual saturation of pathways, minor accumulations, and blind pathways, and could amount to a significant proportion of the early generation products from such early-mature source rocks.

The deeper pre-rift Walloon equivalent coals (165-175 Ma) are predicted to contribute to widely dispersed gas accumulations on the top rift structure (Figure 25) although once again this is assuming no migration losses. The effect of the modelled facies distribution is most noticeable in the termination of flow-paths and accumulations in the north-eastern flanks of the basin. The volumes applied in all cases are only those predicted to have been generated and expelled in the last 10 My. In general, the maturity levels for coaly source rocks in the scenario 2 heat flow models are not sufficient to predict accumulations in this simple flow-path modelling approach. The lower syn-rift marine source rock does expel sufficient quantities of hydrocarbons to charge traps located along the northern central trend of the basin, with models predicting primarily oil accumulations.

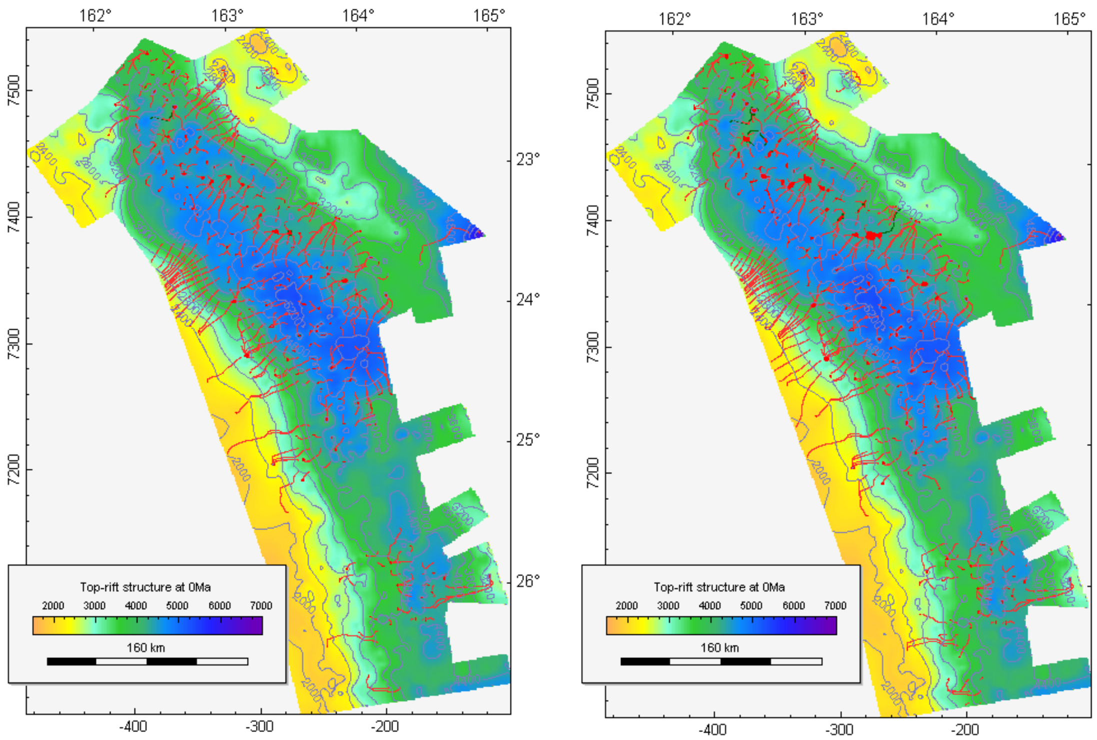

Figure 25 Migration results from flow-path modelling on the top rift structure at the present day based on scenario 2, using volumes expelled up to the present day with facies map and assuming no migration losses from the lower syn-rift coal (coal 3) (left), and from the Walloon equivalent sequence (coaly source rock) (right).

Given the relative immaturity of source rocks predicted by heating scenarios 1 and 2, the remaining flow-path models in this section of the report use the hotter scenario 3 model, including a magmatic heating event in the Eocene (50 Ma to 34 Ma), to be able to assess a wider range of migration and charge scenarios. The predicted migration and accumulation patterns for this hotter scenario are presented in Figure 26 to Figure 30. In Figure 26, a comparison of structural accumulations utilising the same expelled volumes (from the lower syn-rift marine source rock in this case) is presented for the top of the lower post-rift sequence (50 Ma) and the top of the syn-rift sequence (72 Ma) mapped horizons.

Most accumulations are located in the north of the basin with larger predicted accumulations associated with the structure at top syn-rift level. Accumulations range up to 5 billion bbl oil although no migration losses are applied in Figure 26 and the flow-path model has been run without the use of the “pinch-out” facies map. Figure 27 illustrates the impact of firstly applying the facies map (left map) and secondly applying a factor for migration losses for the top syn-rift structure. In this instance an arbitrary loss factor amounting to 4 MMboe/km^2 has been applied (right map in Figure 27). With this relatively moderate loss factor, accumulations of up to 3 billion bbl oil with low GOR of about 150 scf/bbl and column heights of 40 to 80 m for the larger accumulations are predicted.

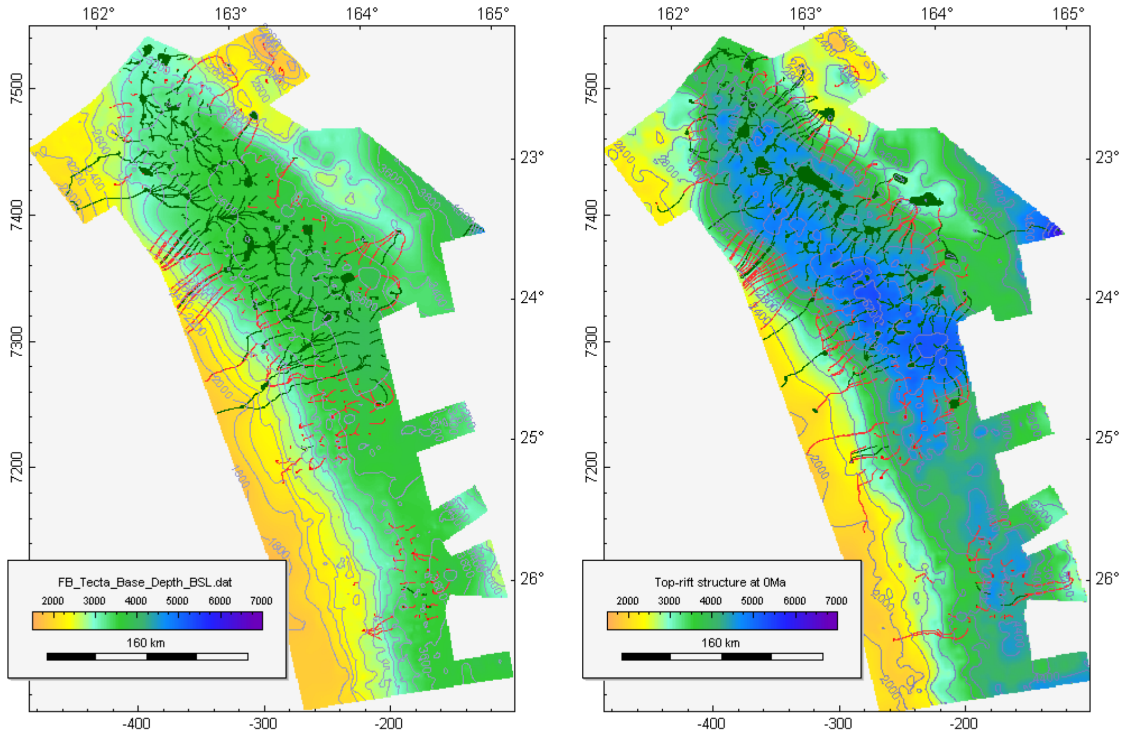

Figure 26 Comparison of flow-path modelling results between the top lower Post-rift structure (left) and the top rift structure at the present day (right) based on the scenario 3 heating model; using volumes expelled from the lower syn-rift sequence (marine source rock) over the last 10 My, with no facies map used and no migration losses modelled.

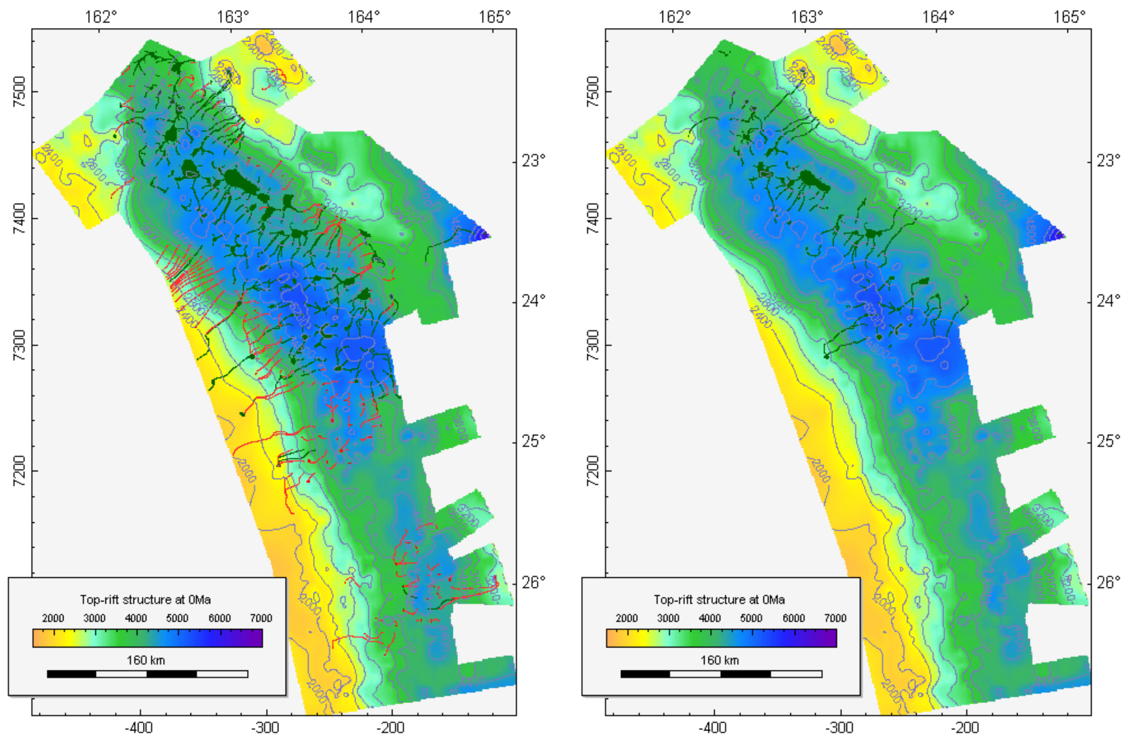

Figure 27 Migration results from flow-path modelling on the top rift structure at the present day, using volumes expelled from the lower syn-rift sequence (marine source rock) over the last 10 My: accumulations using facies map and no losses (left), and using facies map and losses along migration pathways (~4 MMbbl/km) (right).

Figure 28 and Figure 29 show a similar flow-path analysis for the top of the syn-rift sequence horizon using coaly source rocks as the source of expelled volumes of hydrocarbons. In Figure 28, the volumes used are from the coal modelled at the base of the syn-rift sequence (coal 3) and plots are presented for no losses (left) and losses amounting to 4 MMboe/km^2 (right). The predicted accumulations are small compared to those predicted from marine source rocks (Figure 27), amounting up to 300 MMbbl oil and 0.3 Tcf gas with GOR values of 1500 scf/bbl in 20 to 50 m columns. The plot on the right accounting for losses predicts no accumulations.

Figure 29 presents a similar flow-path analysis using volumes expelled from the modelled Walloon equivalent (165-175 Ma) coaly source rock, and migrated on the top syn-rift surface using facies map control. In this case the thicker and more mature modelled coaly source rock is sourcing larger volumes of hydrocarbons and models predict larger accumulations. For the no losses model results presented on the left of Figure 29 the largest predicted accumulations are up to 700 MMbbl oil and 2 Tcf of gas (GOR of 1600 scf/bbl and columns up to 140 m). In comparison, the right plot (Figure 29) with modelled losses of 4 MMboe/km^2 predicts only very few relatively small accumulations.

A general observation from modelling is that coals are generating more gas phase products, partly due to the kinetics used in the model, and partly due to the fact that the marine source rocks are modelled to have much greater oil potential; that is, the coals are modelled with a gas-oil generation index (GOGI) of 0.34 compared to 0.16 for the marine source rocks.

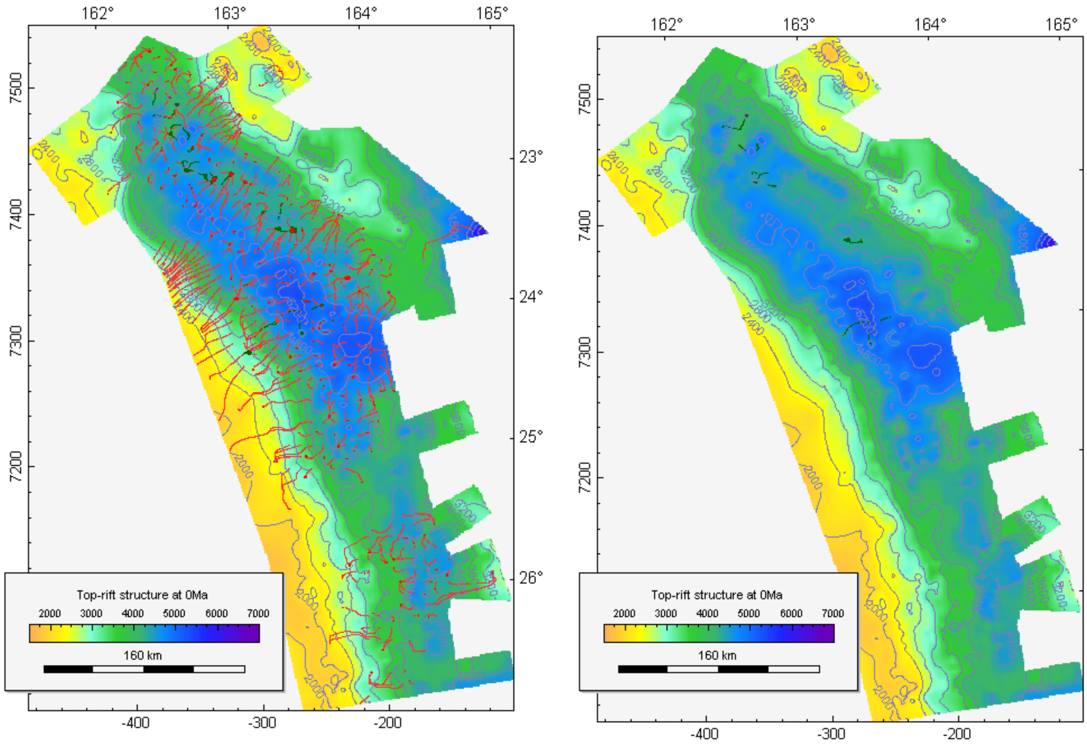

Figure 28 Migration results from flow-path modelling on the top rift structure at the present day, using volumes expelled from the lower syn-rift coal (coaly source rock) over the last 10 My: accumulations using facies map and no losses (left), and using facies map and losses along migration pathways (~4 MMbbl/km) (right).

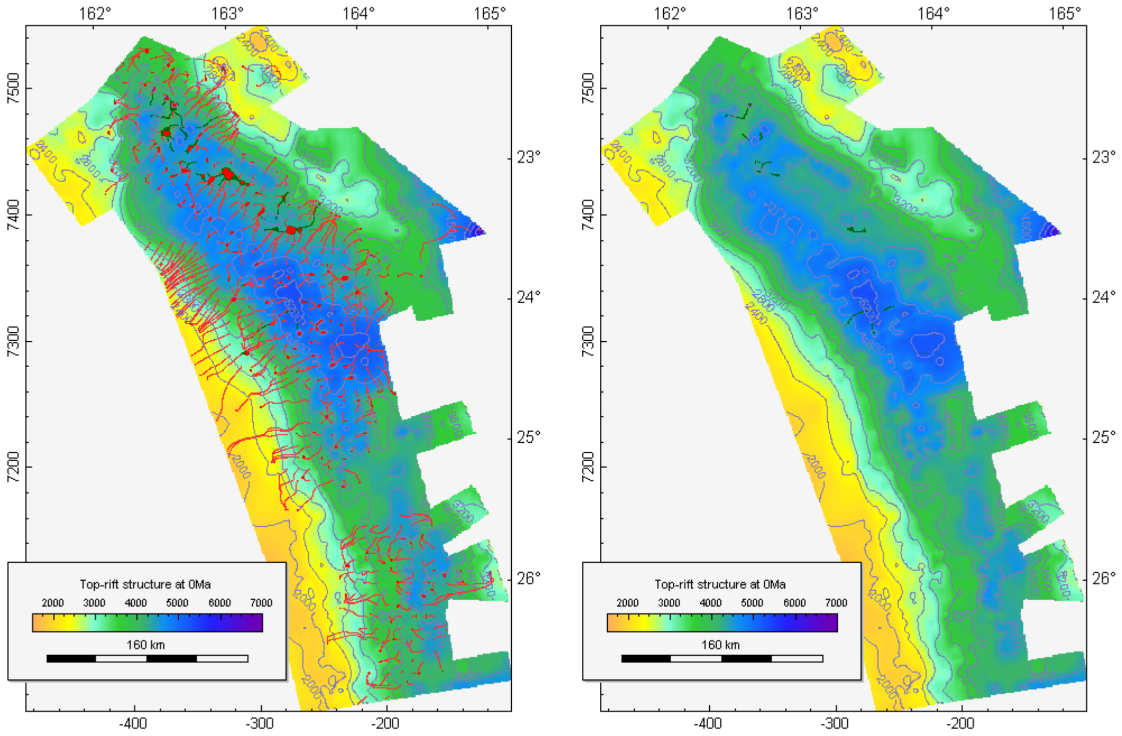

Figure 29 Migration results from flow-path modelling on the top rift structure at the present day, using volumes expelled from the pre-rift Walloon equivalent (coaly source rock) over the last 10 My: accumulations using facies map and no losses (left), and using facies map and losses along migration pathways (~4 MMbbl/km) (right).

The result of the flow-path migration model where the volumes expelled from only the lower section of the pre-rift sequence, modelled as a marine source rock, are allowed to migrate across the top pre-rift surface is shown in Figure 30. As described above, this generation scenario produces the greatest volumes of hydrocarbons, primarily due to the greater burial and hence greater maturity, but also due to the greater thickness of the interval. In this case (Figure 30) the inclusion of losses (right plot) predicts similar amounts to the no losses scenario (left) due to the fact that many accumulations are over-charged with seals leaking after the assumed 200 m column limit has been exceeded. The largest predicted accumulations exceed 5 billion bbl oil and 1.5 Tcf gas (with GOR of 250 – 450 scf/bbl).

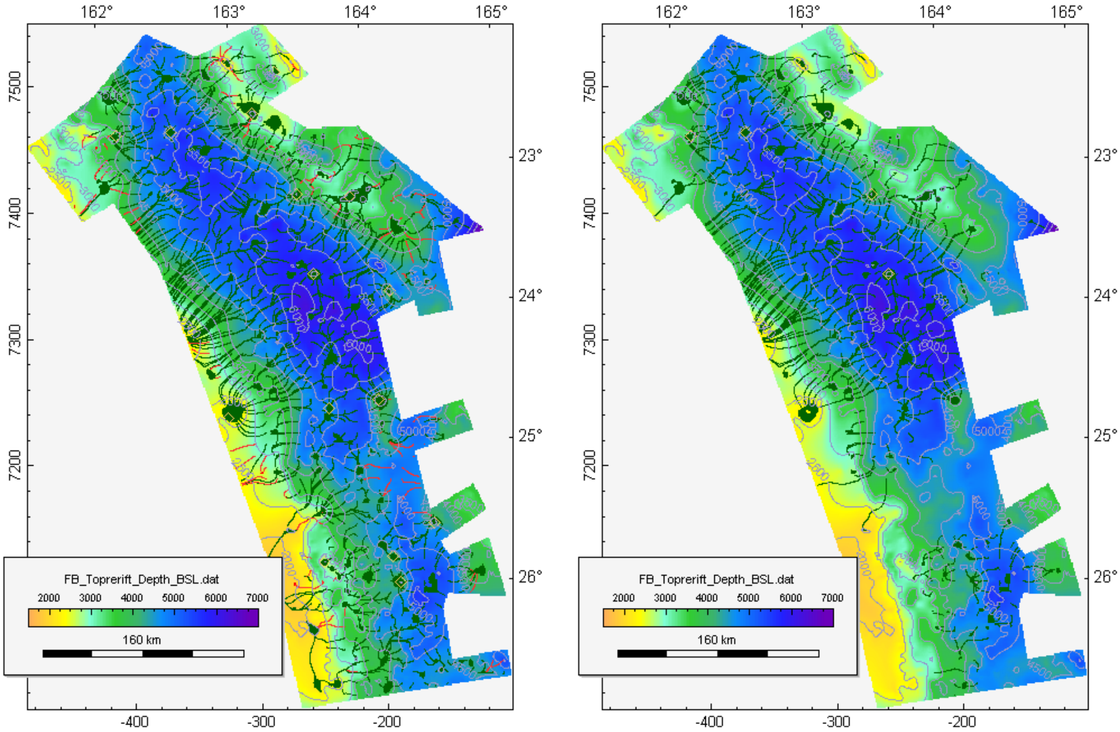

Figure 30 Migration results from flow-path modelling on the top pre-rift structure at the present day, using volumes expelled from the lower pre-rift sequence (marine source rocks) over the last 10 My: accumulations using no facies map and no losses (left), and losses along migration pathways (~4 MMbbl/km) (right).

5.0 SUMMARY AND DISCUSSION

The Fairway Basin is interpreted to contain a rifted Gondwana margin sequence similar to many basins in the east Australian - southwest Pacific region that have proven to contain productive source rocks (Exon et al., 2007). Potential source rocks have been modelled throughout sedimentary sequence, with burial depths ranging up to 5 km (Figure 4). Consequently, the most deeply buried source rocks are only early mature.

The interpretation of seismic data indicates stratigraphic intervals in the Late Cretaceous syn-rift sequence are likely to contain coaly source rocks. These were modelled as three 10 m thick coal measure units spaced throughout the sequence. Models using standard type III kinetics (organofacies DE) to describe oil and gas generation for these intervals indicate that even coals at the base of the syn-rift sequence have generated and expelled very little oil and gas, due to insufficient maturity. This is in part a function of the high adsorption potential of coaly source rocks (Pepper & Corvi, 1995a); and model sensitivity has been tested by lowering the saturation thresholds to allow expulsion of oil. Further sensitivity testing comprised the inclusion of a ‘hypothetical’ marine source rock within the syn-rift sequence. While, such source rocks are modelled to have expelled significant volumes of oil, the volume of expelled gas is predicted to be relatively small due to low maturity.

Model results also indicate that source rock maturity in the Fairway Basin is controlled by comparatively slow burial since the Eocene and maturation at relatively low temperatures over a long time interval. This indicates that even relatively small changes to the burial history reconstruction or in heat transfer into the basin could have a significant impact on volumes of generated petroleum. A modelled regional increase in heat flow results in a measurable increase in predicted expelled volumes. However, possible variations in heat flow scenarios must be constrained by the moderately low present day measured heat flow. Nevertheless, the impact of past magmatism on heat flow has not been fully explored in this study. While in our model changes in heat flow were applied at the base of the mantle lithosphere, rise of magmas to the base of the crust could have resulted in a more pronounced heat flow peak within the sedimentary succession.

An additional option modelled in this study included the presence of a marine source rock within the pre-rift sequence. Admittedly there is no indication that such a source rock exists, however, model results indicate that source rocks within the lower part of the pre-rift sequence containing organic matter of marine algal origin could expel significant volumes of petroleum.

Using the provided structure maps, flow-path and charge modelling suggests structures suitable for petroleum entrapment are present in the basin. In most scenarios structures in the basin are predicted to be under-filled, with petroleum generation and expulsion from source rocks being a key risk for charge. The data used for charge modelling, however, only allowed for a superficial assessment in this case. Modelling of pinch out of sand units at structural highs and the basin margin suggests that these geometries may provide good traps, but the reservoir quality of these deposits and the seal strength of overlying rocks need to be assessed in order to improve charge predictions.

Expulsion, migration and charge modelling emphasises the observation that under current assumptions, coaly source rocks within the syn-rift sequence are immature and are not expected to charge large reservoirs. The amounts expelled are likely to be lost during migration and potential accumulations are probably small. Expulsion from a Walloon equivalent coaly source rock, on the other hand, could lead to more significant accumulations in a hotter heat flow history scenario.

The hypothetical marine (type II) source rocks within the syn-rift sequence could have charged traps with 3-5 billion bbl oil, depending on assumptions about migration losses. A pre-rift marine source rock could have contributed even more significantly to charging structures within the basin. Expulsion and migration modelling thus suggests that under current assumptions the prospectivity of the Fairway Basin depends on the as yet unverified presence of marine source rocks in the basin. However, it is conceivable that Late Cretaceous marine source rocks are present, since Late Cretaceous marine source rocks are known to have been deposited elsewhere in the region. An example is the Whangai Formation source rock in north-east New Zealand (Field and Uruski, 1997).

6.0 OUTLOOK AND RECOMMENDATIONS FOR FURTHER STUDY

Overall modelling results using the supplied depth maps predict that the Farewell Basin is relatively immature for petroleum generation. This could change, however, if the presence of marine source rocks in the basin were confirmed. In addition, uncertainties in the present modelling study are still significant. Using the available heat flow data for calibration, models predict relatively low present-day and paleo-temperatures in the sedimentary succession. However, the effect of Eocene-Miocene magmatism might be underestimated in the models and will depend on the depth at which heating is applied. An additional factor that was not investigated in this study is the influence of climate on the change in water-sediment interface temperature that the consequent impact on source rock maturity for petroleum generation (Kroeger et al., 2011). Due to the long time interval during which source rocks were close to the oil window, any change in basin temperature reconstruction could have a relatively significant impact on petroleum generation. It might therefore be advisable to test a wider range of heat flow and temperature scenarios in future basin prospectivity assessments. Additional data on reservoir facies distribution and seal strength, as well as detailed mapping of potential trapping structures, would improve predictions of petroleum migration and entrapment of hydrocarbon accumulations.

7.0 REFERENCES

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