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Petroleum System Modeling for (Un)Conventional Hydrocarbon Resources Assessment the Broad Fourteens Basin, The Netherlands*

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Search and Discovery Article #80202 (2011)
Posted November 30, 2011

*Adapted from extended abstract prepared in conjunction with poster presentation at AAPG International Conference and Exhibition, Milan, Italy, October 23-26, 2011

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Abstract

The Broad Fourteens Basin is a northwest-southeast trending structure in the Dutch part of the Southern North Sea area. The basin is one of the most prolific petroleum areas in the Dutch offshore. It was formed during the Mesozoic and it was subject to major inversion movements during the Late Cretaceous and Early Tertiary. Important commercial hydrocarbon accumulations have been found in the Upper Permian and Upper Jurassic formations. The reservoirs are charged from gas-prone Carboniferous and Jurassic oil-prone source rocks. The basin has been extensively studied since the first successful exploration well in 1968. There is a wide range of information and data available which allows better controls on the 3D models for the basin.

More detailed insight in the timing of hydrocarbon generation of the conventional petroleum systems is much needed as a basis to assess drainage areas of undiscovered prospects. In addition, there is a need for information on burial history, temperature and maturity history of the Jurassic and Carboniferous formations in order to evaluate their prospectivity as shale gas plays.

We use 3D basin modeling to analyze the evolution of the basin as well as the maturity of the main source rock units. For this purpose, we use the latest results of the mapping project of the Dutch offshore, including the newly constructed erosion scenarios and thicknesses. A detailed basal heat-flow study allows us to use heat-flow maps in our model which are derived from detailed tectonic

modeling of the basin. In addition, new surface-water interface temperatures and paleo-water depth data, based on recent geo-biological studies, are used for the upper boundary condition and the tectonic reconstruction. The models are calibrated to field data using the wealth of data available from the basin, including temperature and vitrinite reflectance measurements. This permits the evaluation of different geological scenarios that reflect the evolution of the basin.

Our models show that using detailed heat-flow models, based on tectonic analyses of the basin, provide a more realistic estimation of the maturity evolution of the petroleum systems in the basin. Moreover, the duration and intensity of major uplift and erosion events have significant impact on the maturity of the source rocks. The modeling has provided new ideas on the maturity of the source rocks in the basin which will aid exploration activities for new (un)conventional prospects.

Model Input

The input model consists of 24 layers including a basement. The model covers not only the Broad Fourteens Basin, but also the surrounding structures (Figure 1). Sub-layers are created in order to include different facies within some layers. Layer thicknesses are generally based on seismic and well interpretations. Carboniferous formations are derived from a subcrop map of the Carboniferous formations which was based on well data (Figure 2).

A detailed study was carried out to model the basal heat flow. The tectonic basal heat flow was modeled in six wells covering different structures in the study area. The interpolated heat flow maps were then calibrated with measured temperatures and vitrinite reflectance in a number of wells in over the whole area. The new generated heat flow maps were used for maturity analyses (Figure 3). New surface-water interface temperatures and paleo water depth data, based on recent geo-biological studies, have been used for the upper boundary condition and the tectonic reconstruction.

Six formations have been defined in the model as source rock. In addition to the oil-prone Namurian Unit, three Westphalian age gas-prone source rocks are defined in the Carboniferous (Baarlo, Ruurlo and Maurits). Two Jurassic formations are introduced as oil-prone source rocks; the Aalburg and the Posidonia formations.

The initial erosion thicknesses of the different formations are derived from the present-day thickness maps and the assumed initial depositional thicknesses. The original thicknesses are based on the analysis of well data as well as paleogeographic models from the area.

Erosion Estimation

Erosional thicknesses are crucial for the maturity analysis. Therefore the study focuses on determining the amount of erosion for different layers. An iterative approach is used where calculated maturity, based on initial erosion thicknesses, are calibrated to measured well data (temperature and vitrinite reflectance). Erosion scenarios that give the best fit with the measurements were adopted for further analysis.

The geological model comprises four erosional phases, the Saalian (Late Carboniferous-Early Permian), the Late Kimmerian (Late Jurassic), the Subhercynian-Laramide inversion (Late Cretaceous) and the Pyrenean (Late Eocene). During the Late Kimmerian erosion, the Jurassic as well as the Upper Triassic Group were partly eroded. During the Subhercynian-Laramide inversion, the Cretaceous Chalk and the Rijnland Groups were partly eroded.

This initial model is modified through calibration with measured data. The calibration process with selected maturity (vitrinite reflectance) measurements form a selection of wells has resulted in refined erosional thicknesses of various formations. A new erosion scenario is introduced based on a subcrop map of Cretaceous and Jurassic formations in the area. It involves more consideration for the stratigraphic and paleogeographic models from the area which affected the depositional thicknesses of the formations.

In this scenario, it is proposed that the Later Cretaceous inversion in the central part of the Broad Fourteens Basin went deep and reached the Upper Triassic formations. Consequently, Jurassic formations were eroded in two phases; the Later Kimmerian and the Subhercynian-Laramide phases. The Kimmerian erosion is divided into two phases; the Mid-Late Kimmerian I and the Late Kimmerian II. In the Mid-Late Kimmerian I, parts of the Jurassic Altena Group was eroded. During the Late Kimmerian II, the Late Jurassic Schieland Group was eroded in almost the whole area. In the central part of the Broad Fourteens Basin, the Schieland was preserved together with the underlying Altena formations. During the Subhercynian inversion, Cretaceous formations were eroded as well as the remaining patches of Jurassic Schieland and Altena groups in the central part of the study area.

This scenario provides the best fit with measured maturity and temperature data (Figure 4). It is also consistent with new stratigraphic concepts and data. Consequently, this scenario is used for maturity modeling and evaluation of the major source rocks in the Broad Fourteens Basin and the adjacent structures.

Source Rock Maturity Evaluation

The simulation shows that the burial history has a dominating role in temperature and maturity evolution of the area. The model indicates that the Namurian source rock is generally in the gas generating window. It has reached the overmature state in the central part of the Broad Fourteens Basin (Figure 5). Hydrocarbon generation stared in the Permian and increased during the Jurassic rifting phases to reach the present-day status in the Late Cretaceous. Most of its convertible organic matter was consumed during the Permian through gas generation. This gas is likely to have escaped during later tectonic event.

In some places, the remaining organic matter in the Namurian was transformed to hydrocarbons during the Mesozoic. This might have contributed to later the gas accumulations in the area.

The Jurassic and Cretaceous mark an important phase of hydrocarbon generation for the Westphalian formations in the whole area. Maturity of these formations started in the Early Jurassic and experienced a jump in Late Cretaceous. The model indicates that the Baarol Formation is predominantly in the gas window at present-day. The Ruurol and the Maurits formations have entered the gas window only in the basins. At the platforms, both formations appear to be still in the oil generating phase. The Westphalian formations are still capable of hydrocarbon generation as the transformation ratio of the model shows (Figure 6).

Jurassic source rocks (Aalburg and Altena formations) appear to be in the oil window. Some small patches in the basins are in the gas generating window while the northern part of the Broad Fourteens Basin appears to be immature. The maturity started in the Late Jurassic and increased during the Cretaceous to reach a peak at the Late Cretaceous (Figure 6). The maturity has slightly increased during the Tertiary, especially to the south of the Broad Fourteens Basin (the West Netherlands Basin). Jurassic source rocks and the Posidonia shales in particular, are interesting targets for shale gas studies. The new maturity models are used to evaluate these formations for unconventional hydrocarbon resources.

All the modeling results are calibrated to field data including temperature and vitrinite reflectance measurements. This allows us to constrain the erosion thicknesses and erosion scenarios as well as the applied heat flow and lithology parameters.

Conclusions

Our models show that using detailed heat-flow models, based on tectonic analyses of the basin, provide a more realistic estimation of the maturity evolution of the petroleum systems in the basin. Moreover, the duration and intensity of major uplift and erosion events have significant impact on the maturity of the source rocks. The modeling has provided new ideas on the maturity of the source rocks in the basin which will aid exploration activities for new (un)conventional prospects.

The maturity and the timing of hydrocarbon generation can be related to the major tectonic events and the associated structures to understand the distribution of oil and gas fields. The Kimmerian rifting and the Late Cretaceous inversion have caused faulting and folding that might have created conditions for hydrocarbon migration and trapping. Later generation phases, during the Tertiary, might have plays a crucial role in charging the traps in the area from various source rock units. A more detailed migration study is required for understanding the trapping and distribution of the current fields.

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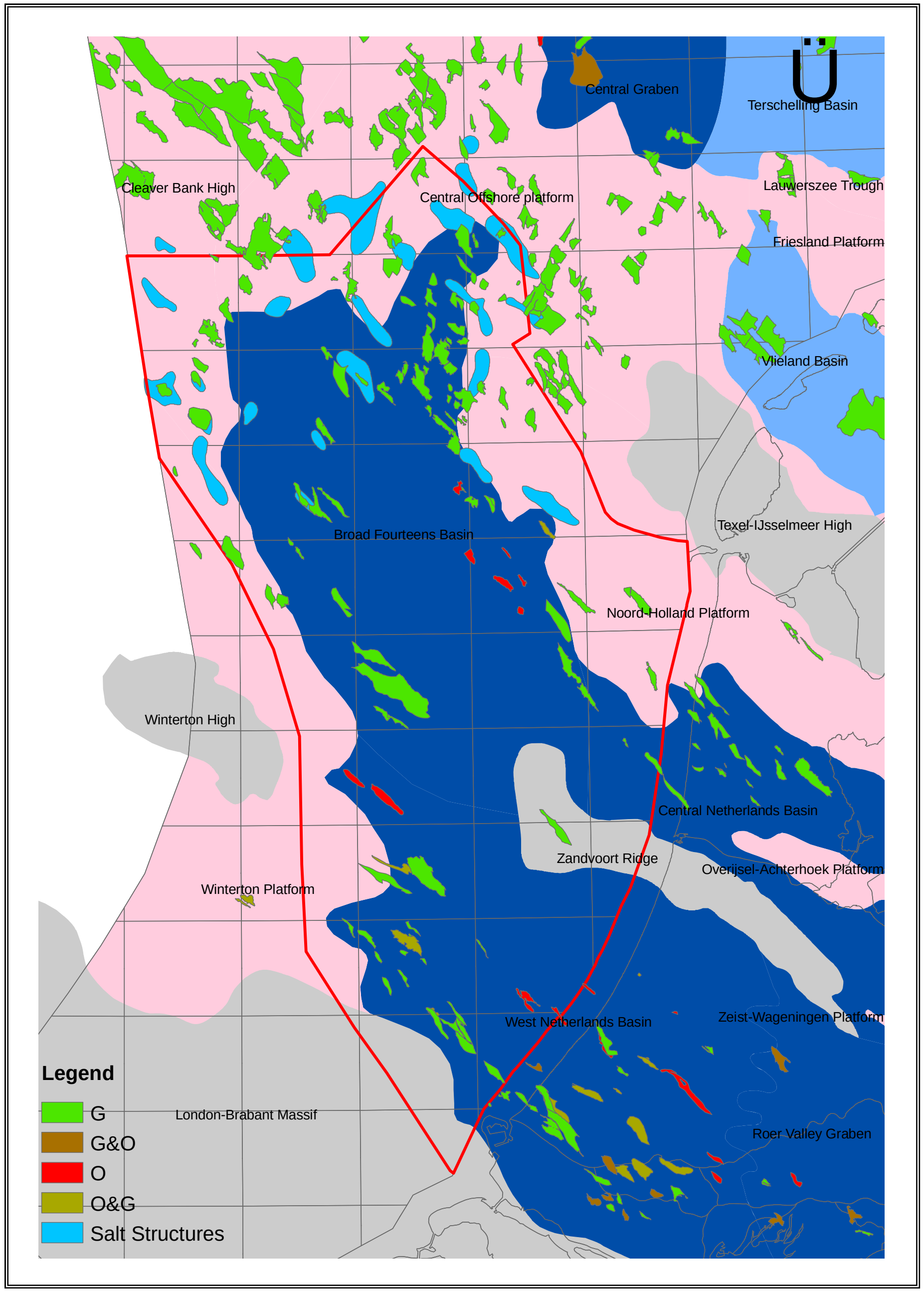

Figure 1. The distribution of oil and gas fields in the Broad Fourteens Basin in the Dutch offshore.

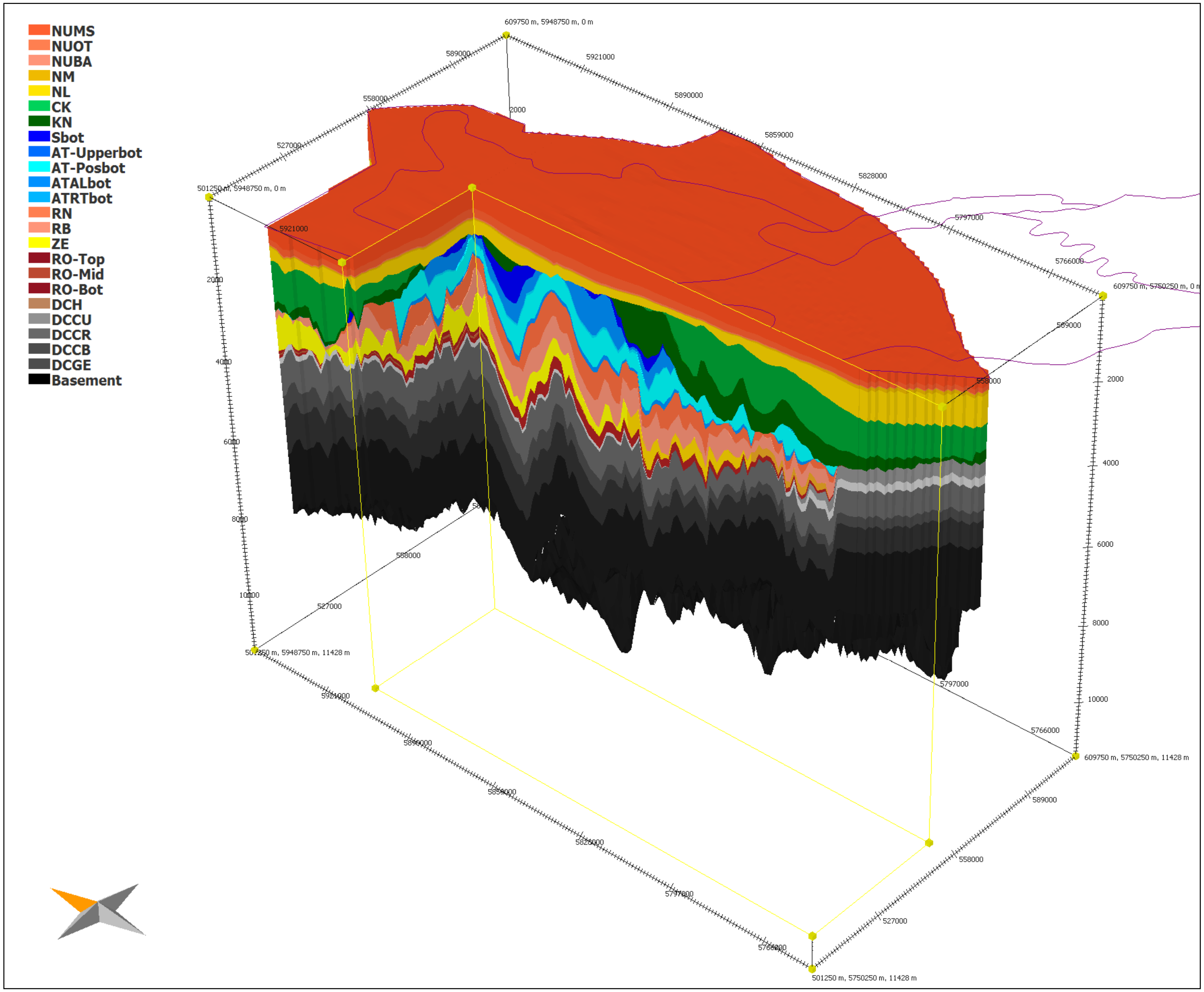

Figure 2. The 3D input model of the Broad Fourteens Basin and the adjacent structures.

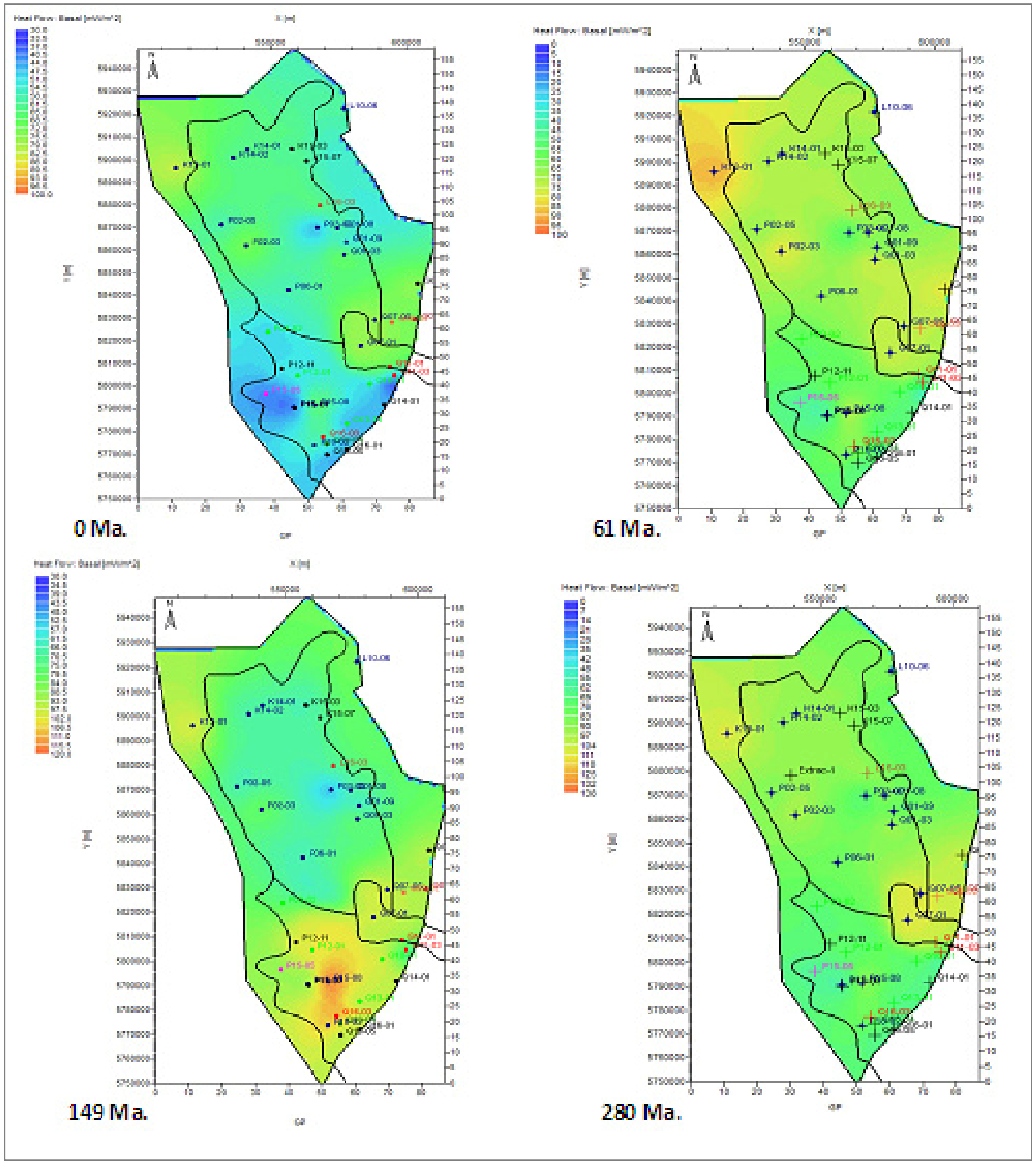

Figure 3. Calibrated basal heat flow maps for selected four time intervals. The maps are calibrated to measured data (temperature and vitrinite reflectance) in the wells shown on the maps.

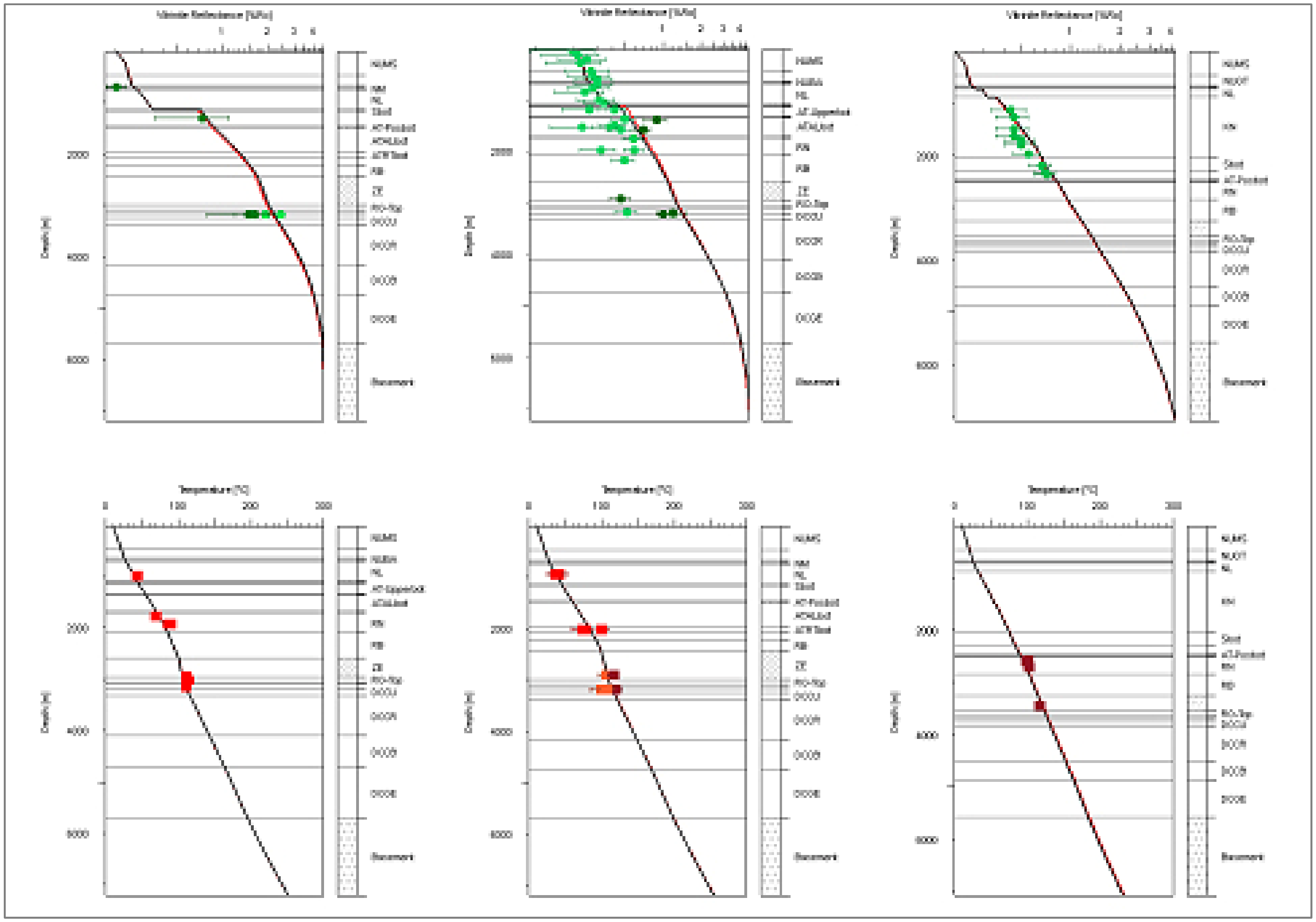

Figure 4. Comparison between modeled and measured maturity (vitrinite reflectance Ro %))(top) and temperature (bottom) in a selection of wells. Improved erosion scenario is implemented. Different colors represent different data source.

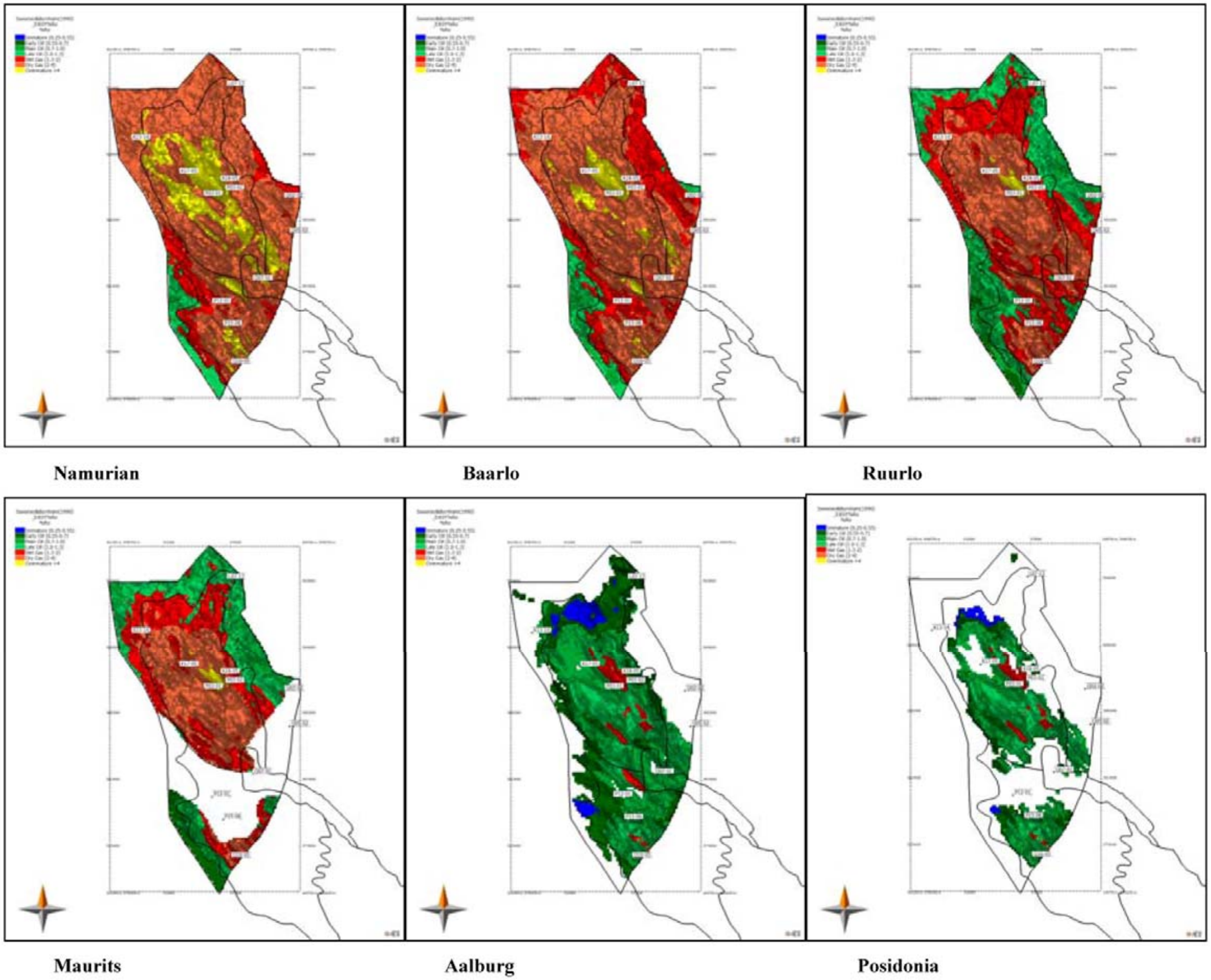

Figure 5. Present-day maturity map of the source rock formations in the area.

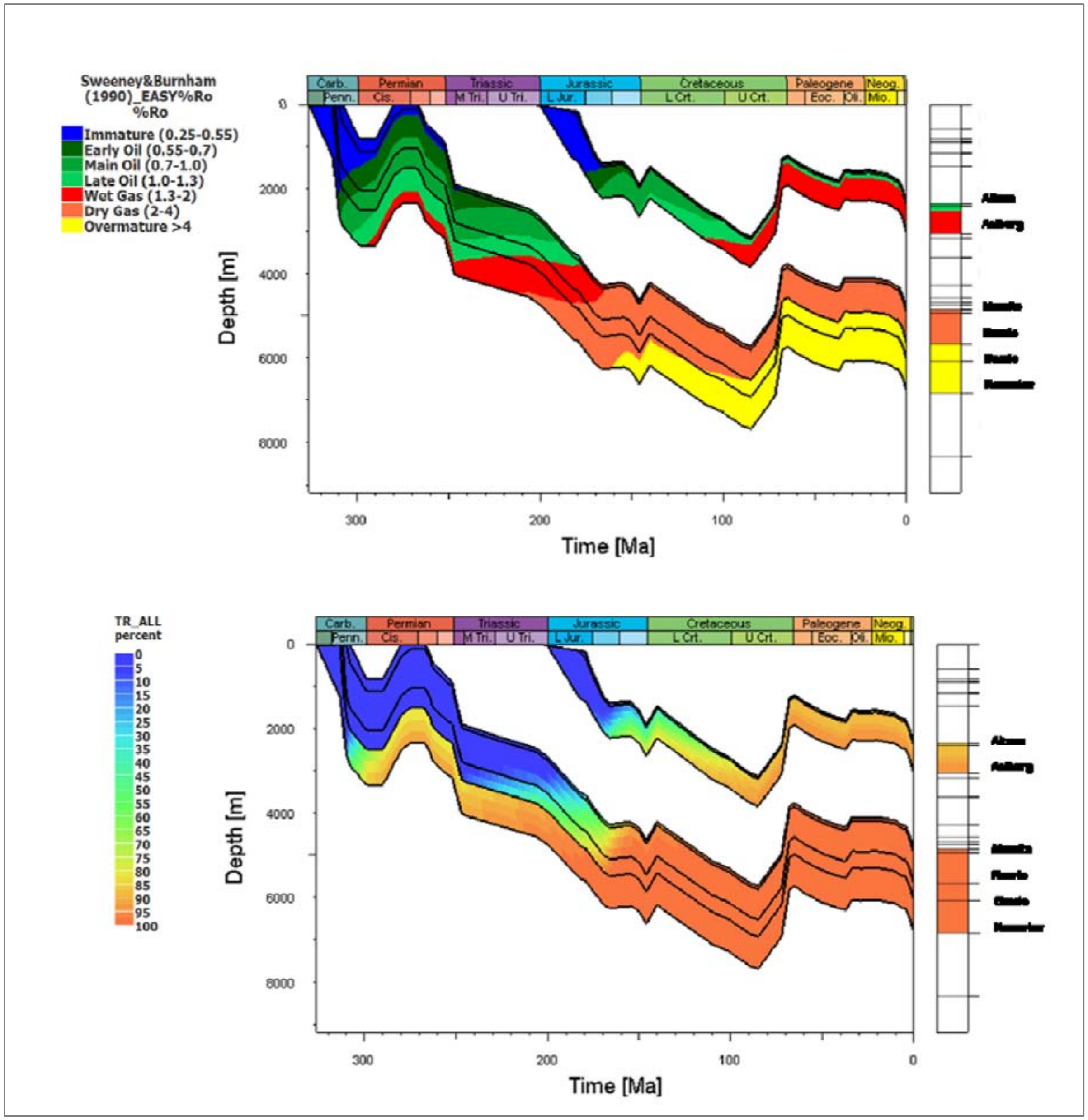

Figure 6. The burial history of the 1D extraction from the central part of the Broad Fourteens Basins. History of maturity (top) and transformation ratio (bottom) of different source rock units are superimposed on the burial history.