Assessing the Organic Nature, Potentials and Distribution of Source Rocks, within the Pletmos Basin (Offshore of South Africa): A 3D Modelling Study*

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Abstract

Source rock identification and parameter quantification is a key aspect of petroleum prospect assessment and play risking. Intriguingly, despite the occurrence of exploration activities throughout the recent decades within the relatively frontier Pletmos basin, prior to this study, understandings of the potential source rocks that might have ensued to charging remained enigmatic. Likewise, information related to their subsurface 3-D geometries and architectural configurations was unestablished. This heightened the need to identify the characteristics, petroleum generative potentials, and existing source rock(s) configurations. Likewise, establish the critical moment(s) of hydrocarbon generation, expulsion and charge within the basin. To redress such snags, this study, in a first attempt integrated geochemical source rock analysis with basin-modelling techniques.

Based on analysis results from Rock-Eval data (acquired by SOEKOR Ltd) of 89 samples, five Mesozoic source rocks units were identified, whose TOC values decreases northwards with a general southerly increase with strata thicknesses along the modelled. The source rock units are predominated by type III (gas-prone) kerogens, and to a lesser extent contain mixed type II/III (oil/gas-prone). Reconstructed burial and thermal histories permitted modelling of their thermal maturation and transformation ratio distributions. The results show that maturity trends are in accordance with transformation ratios and they both increase away from the Superior High and generally attain a maximum at the southern portions of the modelled area. At present-day, maturities range from immature – late mature (dry gas) in accordance with the preliminary source rock evaluation results. As expected, the highest extent of kerogen transformation is exhibited by the deepest (oldest) buried Kimmeridgian source rock; the reverse is true for the youngest (mostly-immature) Turonian source rock. Three periods (i.e. ~98Ma, ~80Ma and ~60Ma) are projected as critical moments for the Kimmeridgian, Valanginian/Hauterivan, and Aptian respectively, implying that hydrocarbon generation preceded charging and the modelled source rocks probably contributed to the hydrocarbons within the area.

Introduction

The Pletmos Basin is an Atlantic-type passive margin basin that was later modified by transformed movements of the passive continental margin. It has a circa 18,000 km^2 area that is confined by fault-bounded basement arches; and is structurally more complex than the other four sub-basins which together constitute the great 'Outeniqua Basin'. The Basin encompasses several structural highs (particularly the notorious Superior High) and asymmetrical troughs, within which there was deposition of up to ~ 7 km of Mesozoic - Cenozoic sedimentary rock packages comprising several marine organic-rich shales that have been characterized as potential source rocks. Exploration for hydrocarbons within the depression has existed during the last few decades. Though this activity has been less intensive, there have been some significant advances that has ensued to the establishment of proven working petroleum system(s), along with discoveries measures of gas and condensate by Soekor (Pty) Ltd, particularly within Block 11A that constitutes our study area (Figure 1).

There is availability of adequate information and data that permitted the creation and better-quality controls on the 3D models for the basin. Accordingly, the integration of source rock analyses with basin modelling techniques provide the detailed understandings required to retort the associated questions of source rock attributes, petroleum generation, expulsion, timing and charging within the basin. Our modelling was predominantly focused on the geochemical aspects that ensued to maturation and transformation, as it is of great interest to know when hydrocarbons (oil, gas, or condensate) were generated in the region.

Methodology

We employed a multi-step integrated modelling workflow in the study. To ascertain the hydrocarbon source characteristics and potential, we utilized the results from Rock-Eval data (acquired by SOEKOR Ltd). Well logs correlation and analysis, along with detailed structural and seismic mapping; ensued for the determination of rock properties (lithological composition and thickness variability) and the construction of a conceptual model that enabled a proper understanding and knowledge of the subsurface deposition. The main lithological characteristics of the input stratigraphic units were interpreted from the control wells and augmented by literature from prior studies.

Using the Petrel software suite of Schlumberger, depth-converted surfaces along with faults were modelled and incorporated to reconstruct the 3D tectonostratigraphic framework; to aid our understanding of the possible variations in structural regimes, main tectonic phases and geometries (particularly of the associated source rock formations) that served as an input for subsequent construction of the 3D dynamic basin model. Structural cross sections along a series of control transects were generated from which stratigraphic physiognomies, depth and thickness were obtained.

Burial and thermal history reconstructions permitted modelling of the thermal maturation and transformation ratios. The forward modelling process implemented, utilised Basal Heat Flow (HF), Paleo Water Depth (PWD) and Sediment Water Interface Temperatures (SWIT), as the lower and upper boundary conditions. The basal heat-flow (HF) and paleo-water depths were based on prior regional studies, while the surface-water interface temperatures were attained following the approach of Wygrala (1989) that assimilated paleo-latitude variations.

Thermal calibration fully integrated radiogenic heat from the basement, along with those produced by sediments of various assigned facies into all stages. Model predictions were validated with well borehole temperature (BHT) and vitrinite reflectance (%Ro) data measurements from six wells. These allowed for heat-flow modelling and were vital in defining the basic kinetic conditions for thermal development and maturation through time. The first-order compositional kinetic models of Sweeney and Burnham (1990) were utilised for simulation scenarios of kerogen to hydrocarbon conversion reaction rates and a 3D forward modelling evolution approach was employed timing of source rock maturation, and subsequent petroleum generation.

Model Input

The input finite earth model for the 3D modelling consists of seven units that entail a total of 28 Sub-layers, including the top basement. The model covers the entire structural surroundings of block 11A (Figure 1). The sequence and layer thicknesses were largely based on the chronostratigraphic chart (Figure 2), well logs and seismic mapping interpretations. Similarly, the sub-layers were generated to adequately capture and represent layers facies variabilities. A more detailed study is on the way for the basin (Agbor et al., manuscript in prep).

Using the control wells, a series of 1D maturity models were built by means of Schlumberger Petromod software, from which inputs such as paleobathymetry, paleo-erosion and heat flow data were extracted for the stratigraphic units. Accordingly, temperature maps (derive from geothermal gradients) were created during a detailed tectonic reconstruction also served as inputs for the created models. The structural cross sections, depth structural top maps, established source rock geochemical characteristics, thermal parameters, and calibrated boundary conditions were then loaded into Petromod and a 3D forward modelling simulation was achieved using the 3D petroleum systems simulation modules. Five formations were identified as source rocks. The Kimmeridgian and Aptian units were modelled as type II whilst the Valanginian, Hauterivian and Turonian units were modelled as type III source rocks. The thermal calibration process permitted the assessment of various geological scenarios that possibly could reflect the evolution within block 11A, at the southern portion of the Pletmos Basin.

Results and Discussion

The results demonstrate that TOC values range from 0.5 - 4.0 wt. %, indicate that they meet the accepted standard for fair to excellent petroleum generating potentials which increases (from marginal to adequate) with increasing depth. HI values range from 23.7 – 499.5 (mg HC/g TOC) essentially indicating that they are mainly predominated by type III (gas-prone) kerogens and, to a lesser extent contain mixed type II/III (oil/gas-prone) (Figure 3). Thus, they are considered as primarily gas-prone. Tmax values matched with recorded vitrinite reflectance (%Ro); they indicate that source rock maturities range from immature - late mature (dry gas).

Burial and thermal history models exhibit that sedimentation and subsidence rates were faster and more effective during synrift than post-rift times, and there exist a southerly increase in temperatures that is attributed to increasing geothermal gradients due to greater burial depths (Figure 4). The maturity distributions of the Mesozoic source rocks range between immature and the dry gas/overmature windows (Figure 5 and Figure 6) with the Turonian largely remaining immature at present-day. Widespread present-day maturity and transformation ratio (Figure 6) shows a southerly increasing maturity and hydrocarbon generation potential. The Mesozoic source rocks observed to have undergone multi-period tectonism that has ensued to substantial multiple generations.

Petroleum generation onset materialized during the Lower Cretaceous (~135Ma) and peak generation was attained during Late Cretaceous times (~67Ma) (Figure 5). Three main stages of hydrocarbon generation are thus postulated to have occurred with the cumulative peak of generation revealed to have transpired at ~ 23Ma during the Late-Oligocene times because of temperature increase linked to the ‘African Superswell’ plume development.

Conclusions

The results obtained support prior basin evolution studies and concepts. Source rock maturity and hydrocarbon generation timing is related to the major tectonic events in the region. The present-day maturity distribution trends display a southerly increase, indicating a notable influence of burial depths and thickness. Petroleum generation commenced during the Early Cretaceous and four phases of generation are thought to have occurred in the basin. The Aptian source rock has the greatest potential whilst the Kimmeridgian and Valanginian source rocks have contributed the most to the expelled petroleum. The Tertiary generation during the Late-Oligocene, is hereby though to have likely contributed the most to charging of the reservoirs. These results confirm the viability of hydrocarbon plays within the basin, provided all other petroleum system elements and processes are in place. Our models show that using the heat-flow models developed based on tectonic analyses of the basin; provided a more realistic estimation of the maturity evolution, and this study has provided a better understanding of existing petroleum systems.

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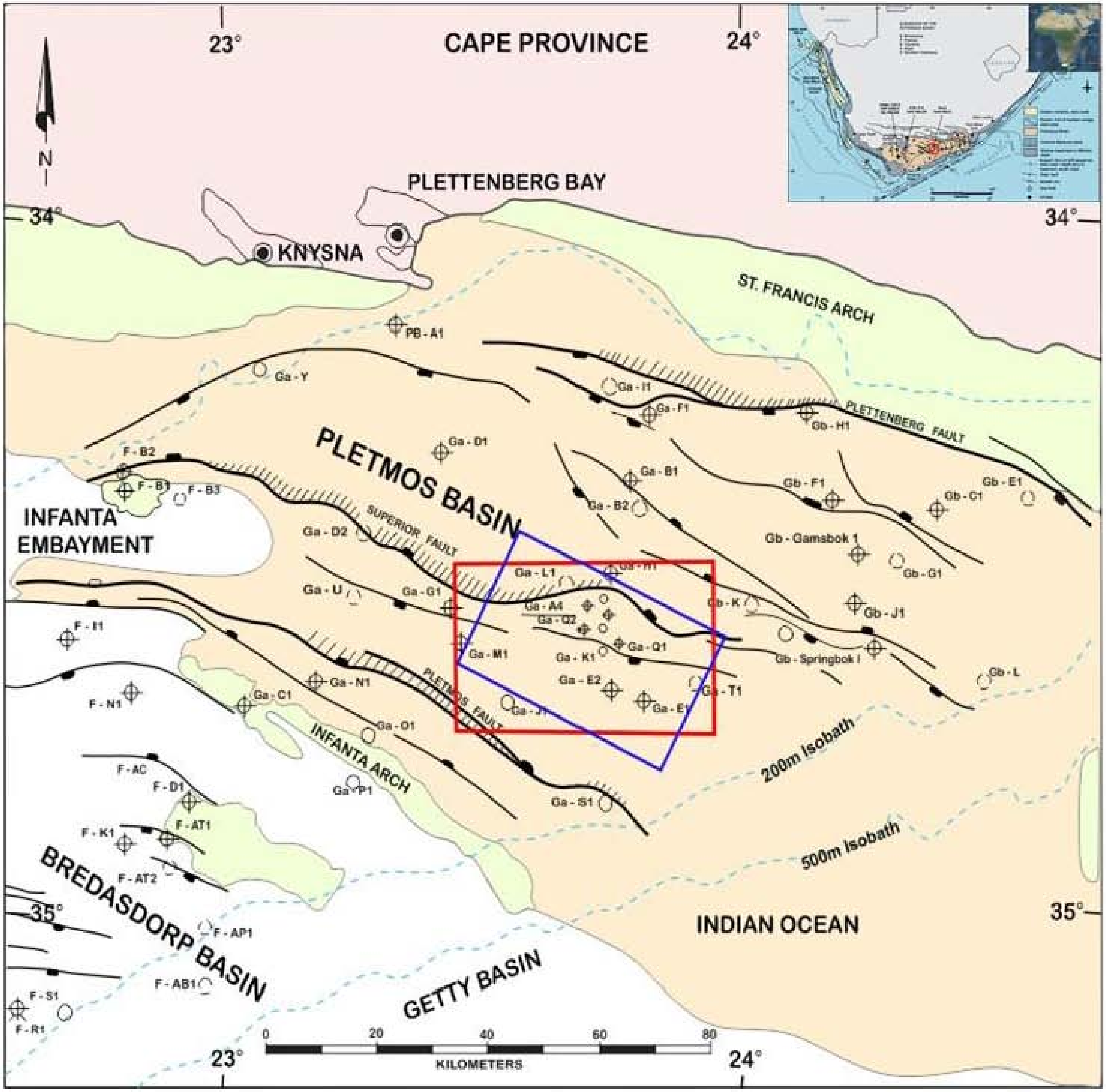

Figure 1. Generalised map outlining the provincial extents and structural features of the Outeniqua Basin, after Broad et al., (2006). Along with, a location map showing control wells and 3D model boundary of the study area within the Pletmos sub-basin.

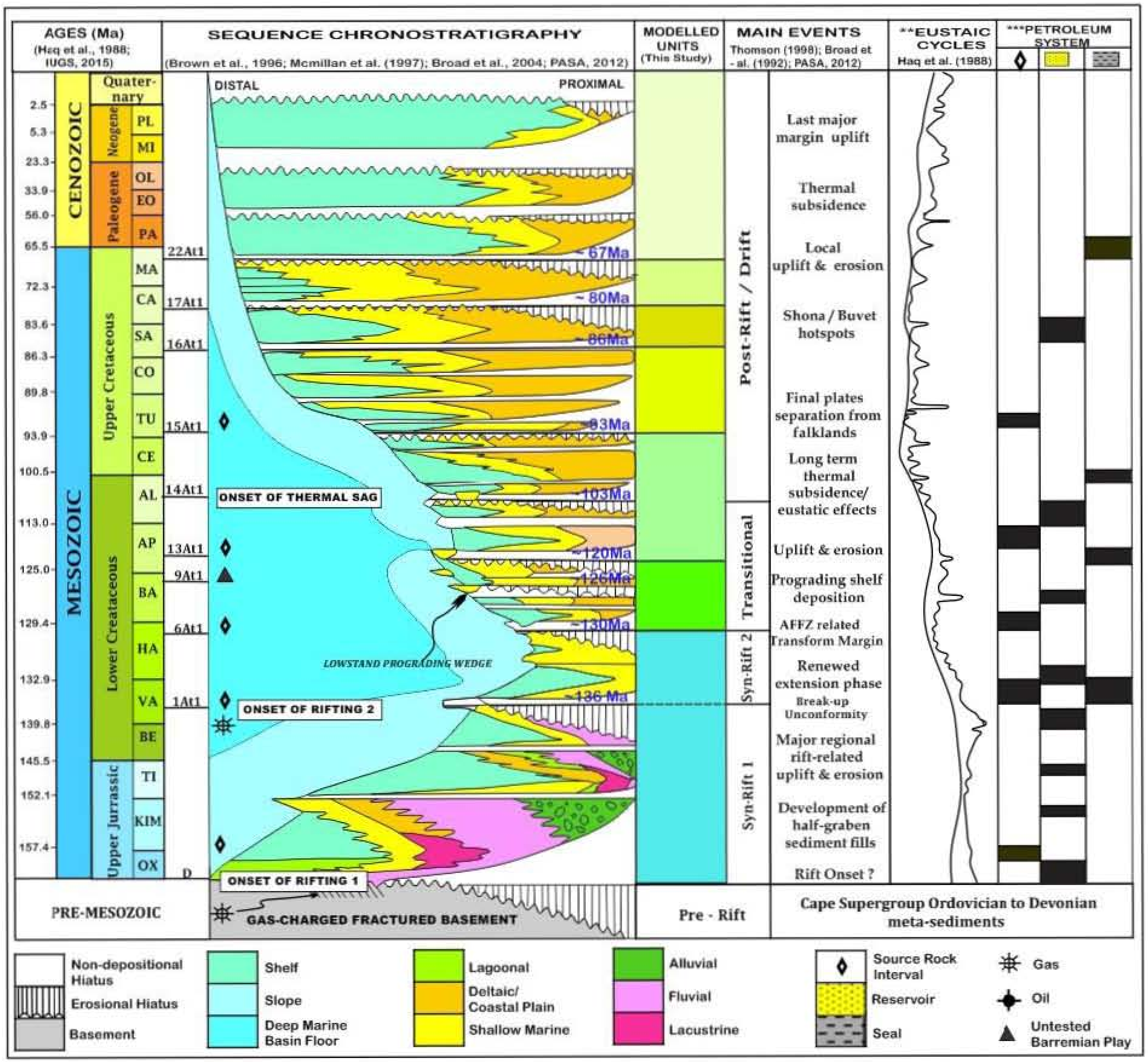

Figure 2. Generalised chronostratigraphic and sequence column detailing the stratigraphic ranges, ages and petroleum system elements within the Pletmos Basin, incorporated into the numerical models.

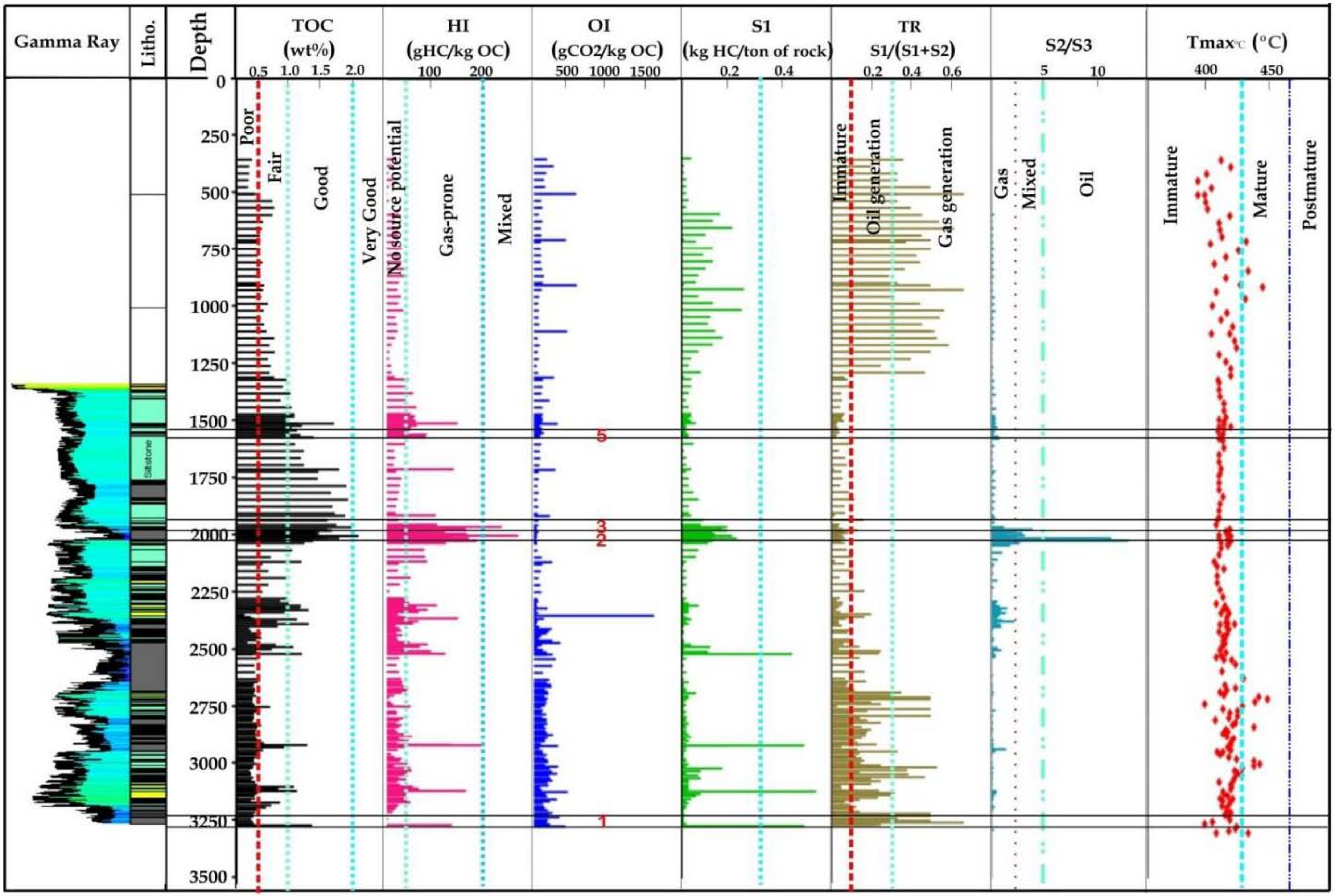

Figure 3. (a) Modified Van-Krevelen diagram (left) showing various kerogen types (quality) and (right) Hydrogen Index versus Tmax defining thermal maturity stages and distribution of analysed samples, and (b) Representative geochemical log, indicating the rock-eval parameters of modelled source rock intervals at present maturation levels, at the location of well Ga-Q1.

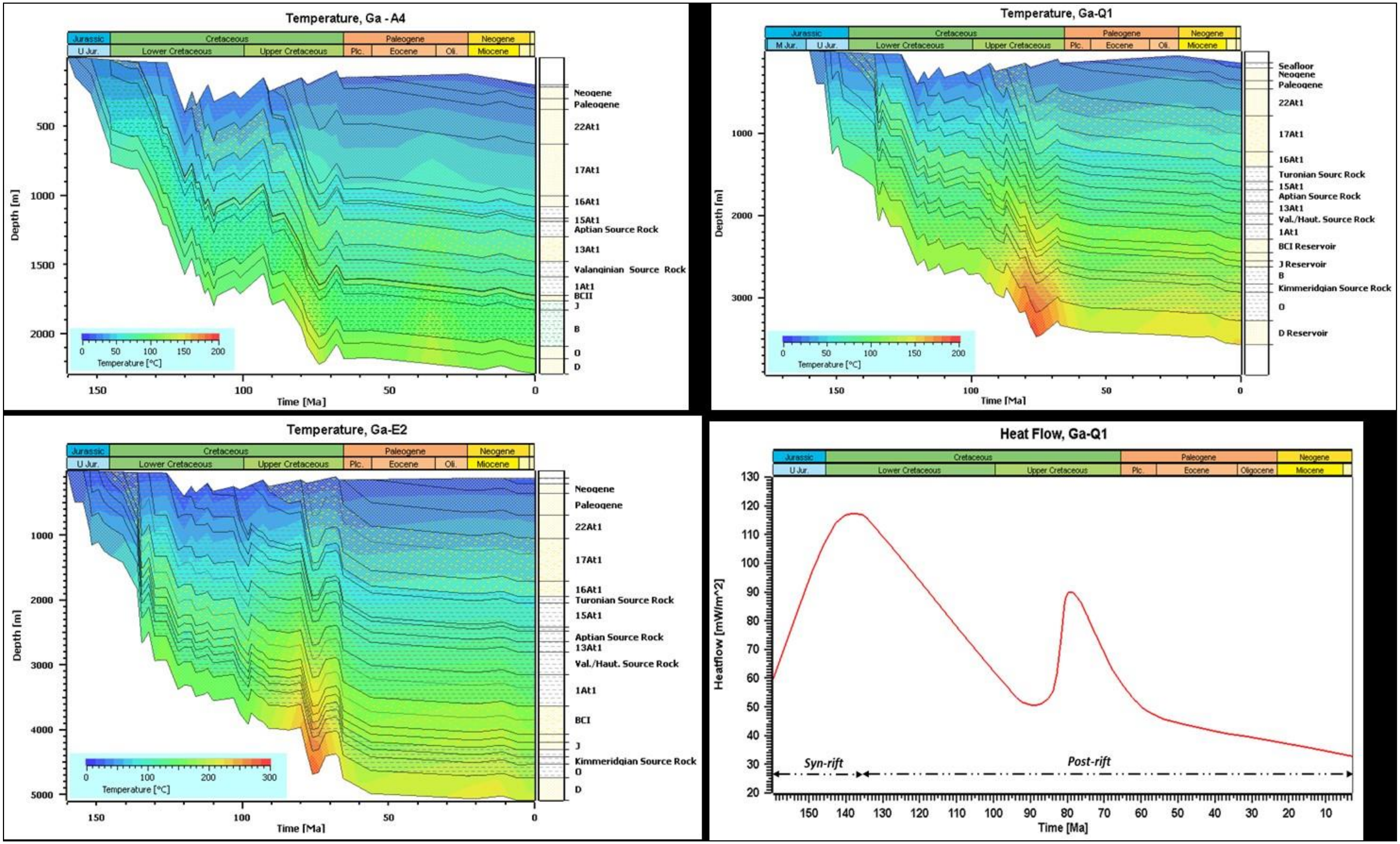

Figure 4. Burial and thermal histories at representative well locations from (a) the Northern - Ga-A4, (b) central - Ga-Q1 and (c) Southern - Ga-E2. Plus (d) the Mesozoic-Cenozoic basal heat flow evolution at the abovementioned wells. Note: basal heat fluxes are considerably higher for Northern domains.

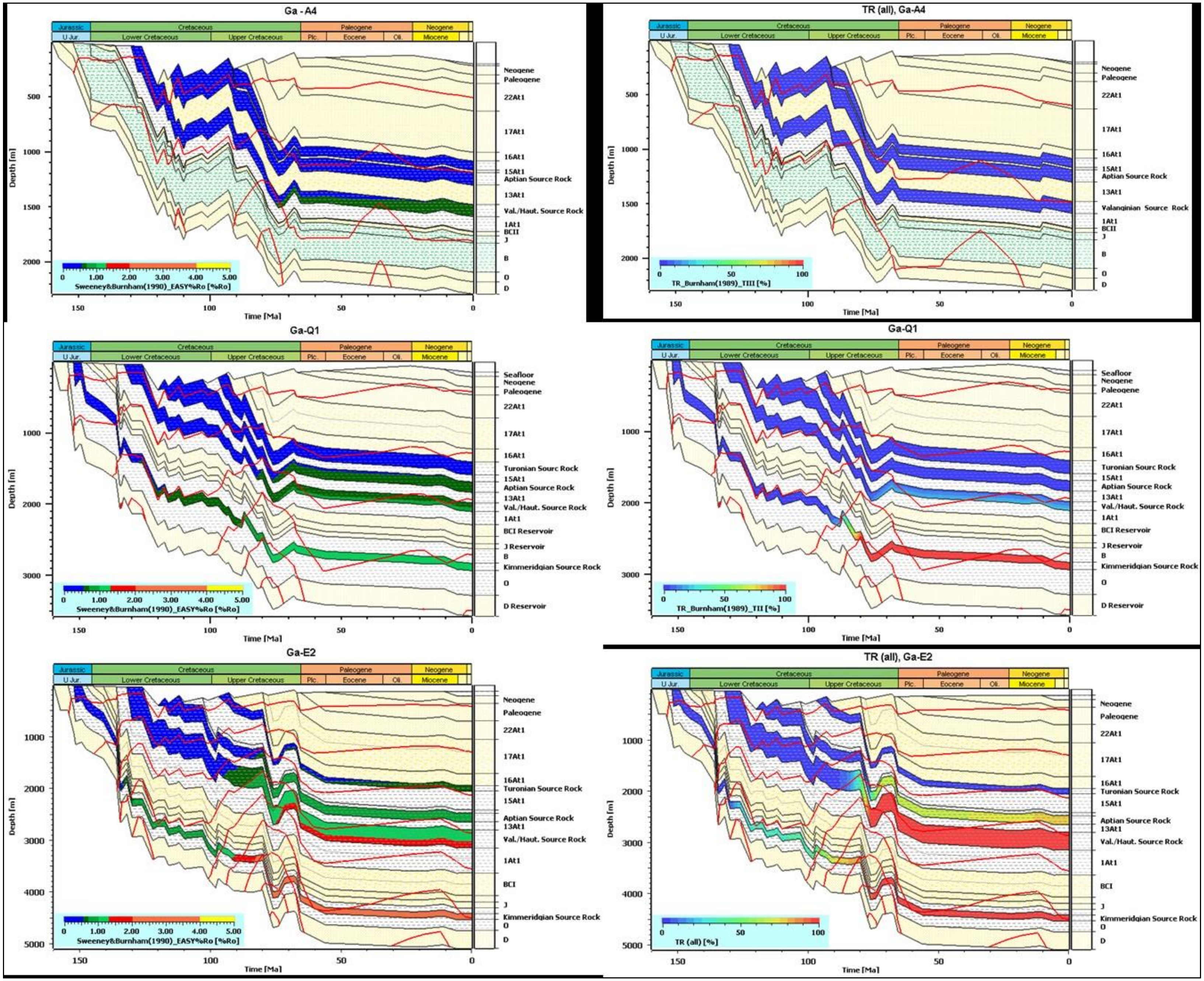

Figure 5. 1D Modelled maturity (left) and transformation ratio (right) distribution plots, detailing the evolutions of the source rock units, at the three well locations of the representative regions.

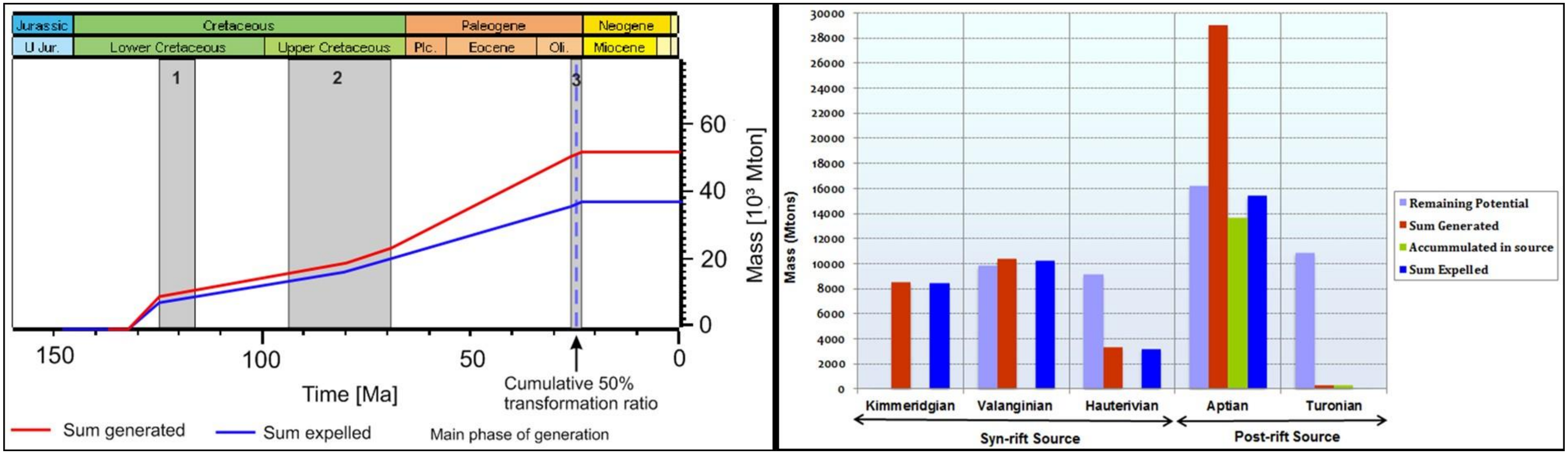

Figure 6. (a) Present-day average maturity (Ro) and transformation ratio (TR) distribution maps of the modelled source rocks, and (b) cumulative transformation ratio over time indicating the critical moment (left) with estimated hydrocarbons mass and the remaining potential (right).