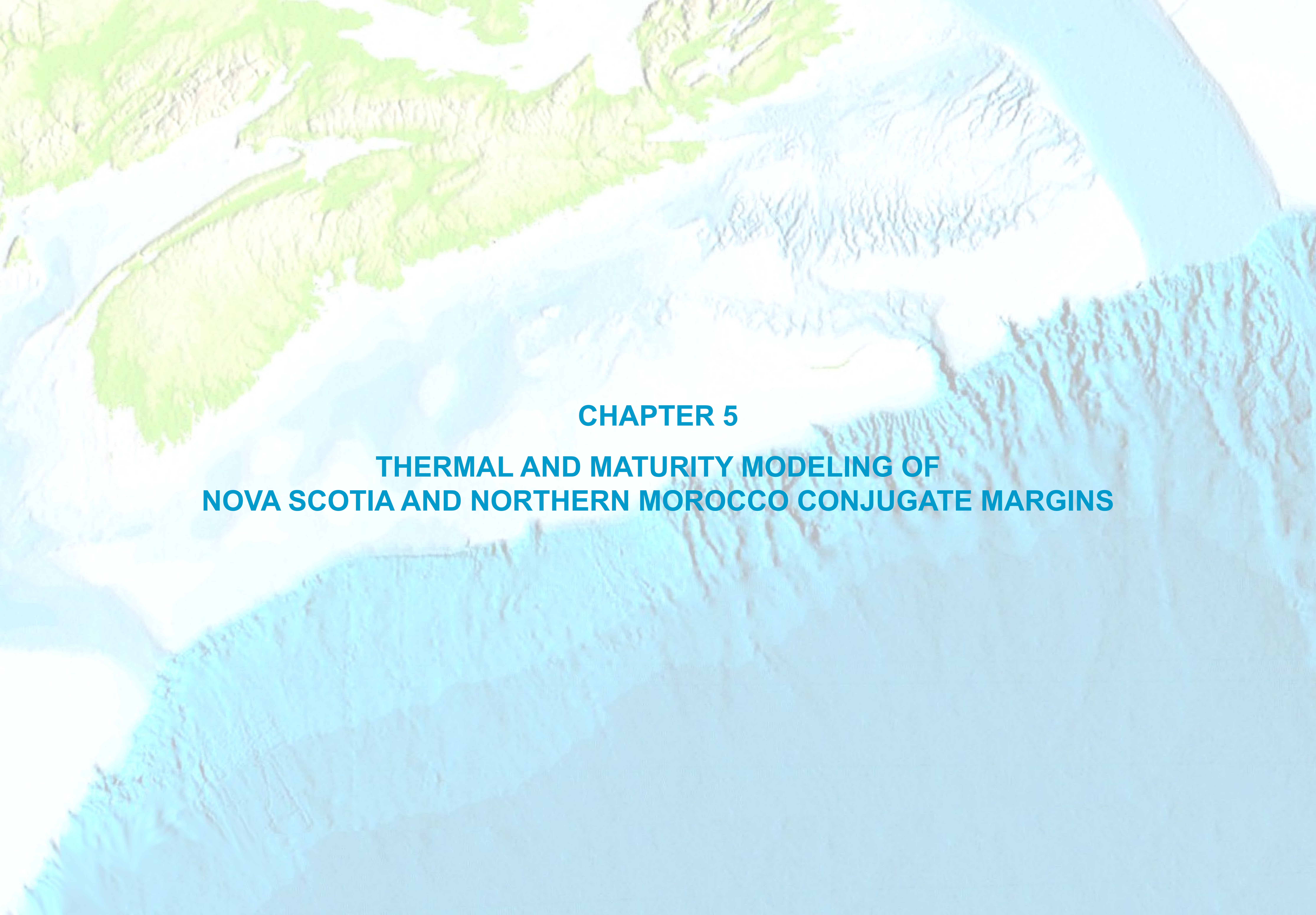


CHAPTER 5

THERMAL AND MATURITY MODELING OF NOVA SCOTIA AND NORTHERN MOROCCO CONJUGATE MARGINS

5.1 Objectives and Methodology

Objectives

The primary aim of the basin modeling phase was to investigate and compare the regional thermal and maturity regimes for all transects.

In order to achieve a consistent and meaningful assessment of the transects' thermal regime (individually or one versus another), similar base working hypotheses were used for all transects, in terms of: stratigraphic layering, facies groups (and their attached petrophysical properties), crustal models, and thermal conditions (notwithstanding local geological/thermal features, such as hotspots),

All the 2D basin models presented in the following plates were run using the IFPEN Group proprietary TemisFlow software (Fig. 5.1.1).

Workflow

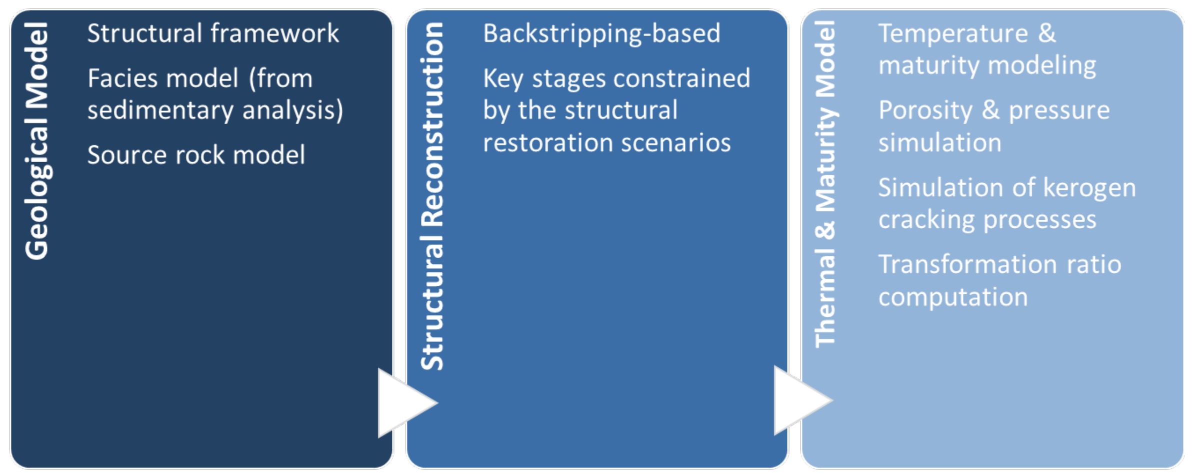


Figure 5.1.1: Basin modeling workflow

Facies model

The present-day facies model was created from the lithology interpretation from the sedimentology & stratigraphy task (Chapter 2). An example of such a section is shown in Fig. 5.1.2.

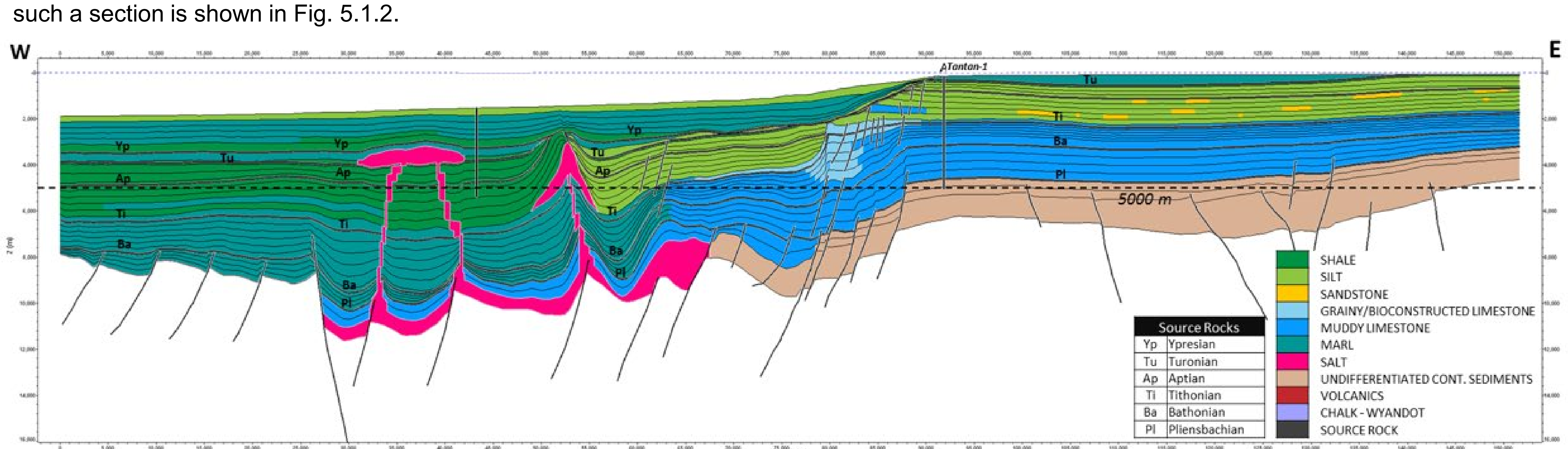


Figure 5.1.2: Facies model of Transect 3 (Morocco)

Crustal model & thermal events

A consistent thermal basement framework was built for all transects, relying primarily on the world-scale Crust 1.0 model from IGGP and in accordance with the hypotheses formulated during the structural restoration phase (Fig. 5.1.3). Additionally, the following thermal events were simulated:

- *An initial rifting period* (followed by thermal subsidence) associated with the Break-Up Unconformity (BKU),
- *The Canary hotspot activity* whose related magmatism tentatively impacts the thermal regime of Transects 3 and 4 (Morocco),
- *An Early Cretaceous thermal event* impacting Transect T4 (Canada). This event is discussed in the literature (*Bowman et al., 2012; Campbell, 2005*) and is related to a widespread regional volcanic activity.

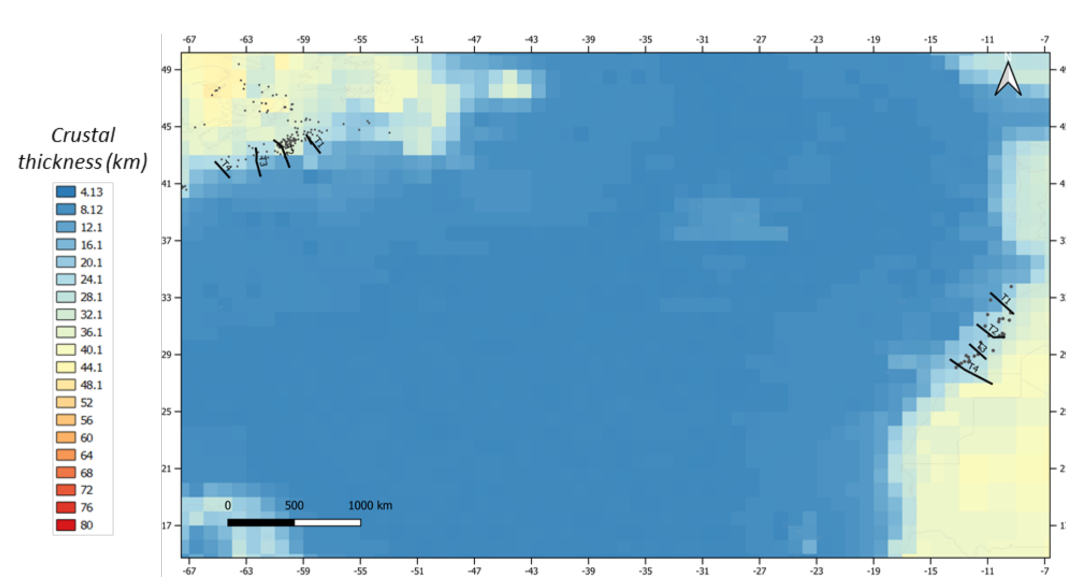


Figure 5.1.3: Crust 1.0 model grid.

Base map

A total of eight transects were modeled, four on each margin (Fig. 5.1.4). The transects are the ones used for structural restoration.

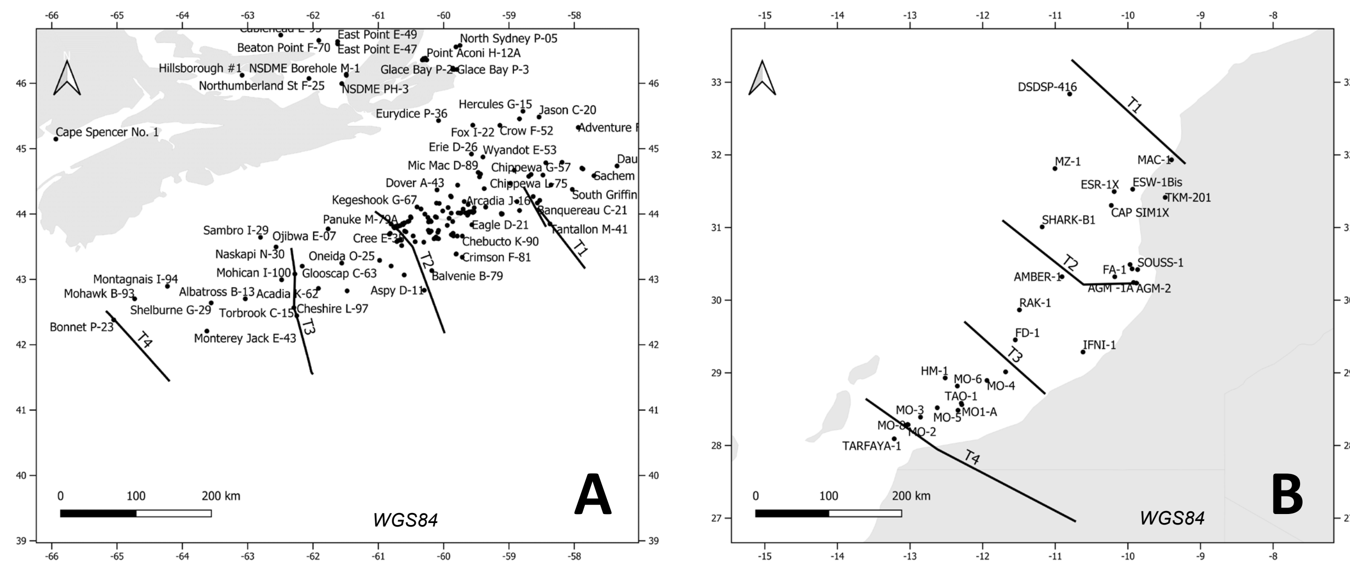


Figure 5.1.4: Location map of the modeled transects. (A) Nova Scotia margin, (B) northern Morocco margin.

Source rock model

The source rock model used for basin modeling relies on a geochemical synthesis performed under separate cover as input to this study (Fowler, 2018). Source rock parameters used in simulations are provided in Table 5.1.1. Since the main aim of this modeling work was the investigation of maturity regimes at regional scales, the lateral distribution of individual source rock units extended to cover the whole expanse of the transects (Fig. 5.1.5). While this is an extrapolation of the actual extension of source rock units, this working hypothesis allows « what if » scenarios for investigating the presence of possible kitchen areas through the modeled transects even if the presence of source rocks is locally unlikely or unproven.

Furthermore, an arbitrary 50 m effective thickness has been assigned to each source rock layer in order to allow visualization of the source intervals on the model cross sections. The effective thickness value used for modeling differs from the actual effective thickness of the organic cycles inferred in the geochemistry task, but this has no impact on the modeling results presented in the following plates which illustrate mostly maturity & transformation ratio profiles. In the same way TOC and HI in the Table are indicative values not used in the model interpretation.

Finally six (6) conceptual source rock layers from the Lower Jurassic to the Paleogene have been implemented in the models. This represents the whole range of possibilities along both margins. The stage at which the source rock potential has been implemented is also indicative. For example, the Lower Jurassic potential source rock is attributed to the Pliensbachian layer, however it might be as well Toarcian or Sinemurian locally.

Serie	***Stage*** *(tentative)*	***Age***	***Thickness (m)*** *(for graphical purpose only)*	***TOC (%)*** *(indicative)*	***HI (mg/g)*** *(indicative)*	***Kerogen Type***
Paleogene	Ypresian	56-54	50	2	550	Type II
Upper Cretaceous	Turonian	89-87	50	3	600	Type II
Lower Cretaceous	Aptian	115-112	50	2	300	Type II/III
Upper Jurassic	Tithonian	150-148	50	3	500	Type II
Middle Jurassic	Bathonian	168-166	50	3	600	Type II
Lower Jurassic	Pliensbachian	184-183	50	3	450	Type II/III

Table 5.1.1: Summary table of the source rock parameters used for modeling purposes.

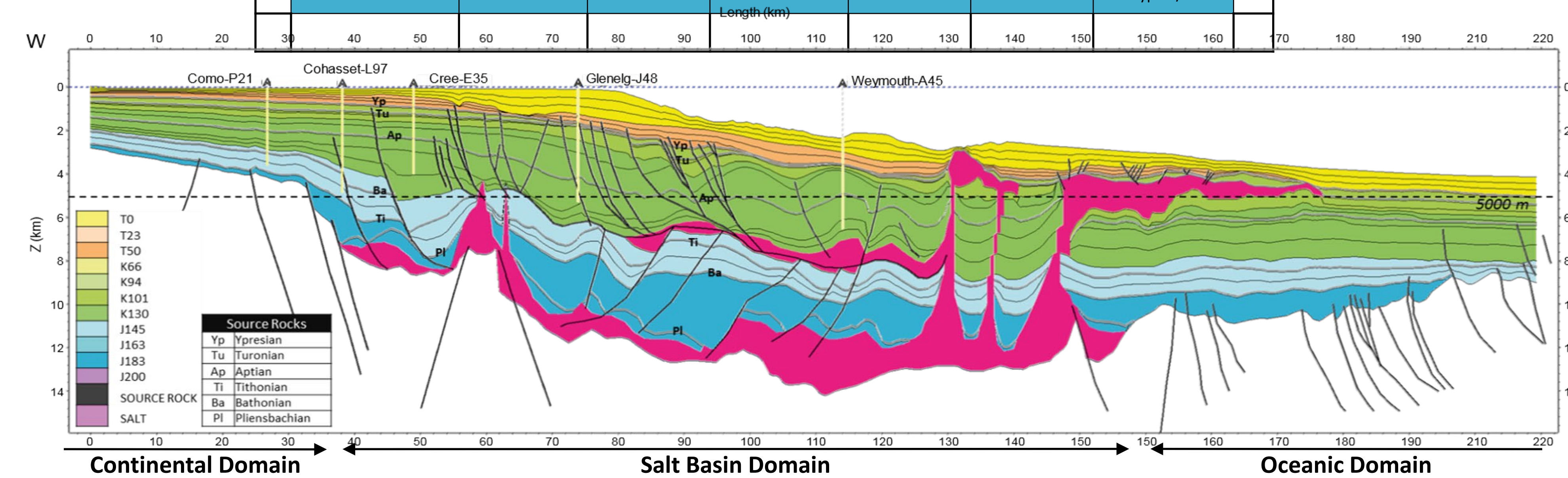


*Figure 5.1.5: Source rock model illustrated onto Transect 3 (**Nova Scotia**).*

5.2 Results

Transect T1 northern Morocco : Geological setting & calibration

Transect T1 (Morocco) is the northeasternmost transect simulated over the Morocco margin (Fig. 5.2.1). Located over the Safi basin which is a known salt province, it features an extended salt basin almost 100km wide. Salt features are complex and include well-developed canopies leading the formation of local sub-basins. Maximum burial reaches almost 7km in the deepest part of the salt basin.

In terms of facies Transect T1 is dominated by muddy carbonates on the shelf transitioning to marl and shale dominated depositional environments over the salt basins and in the distal domain (Fig. 5.2.2 and Fig. 5.2.3).

Calibration data is readily available for Transect T1 with some wells located as far as 80km which were used as proxies for constraining the thermal regime (Fig. 5.2.4). The calibration plates highlight a good match between the simulated thermal regime in terms of maturity & temperature trends at well location and the actual well data.

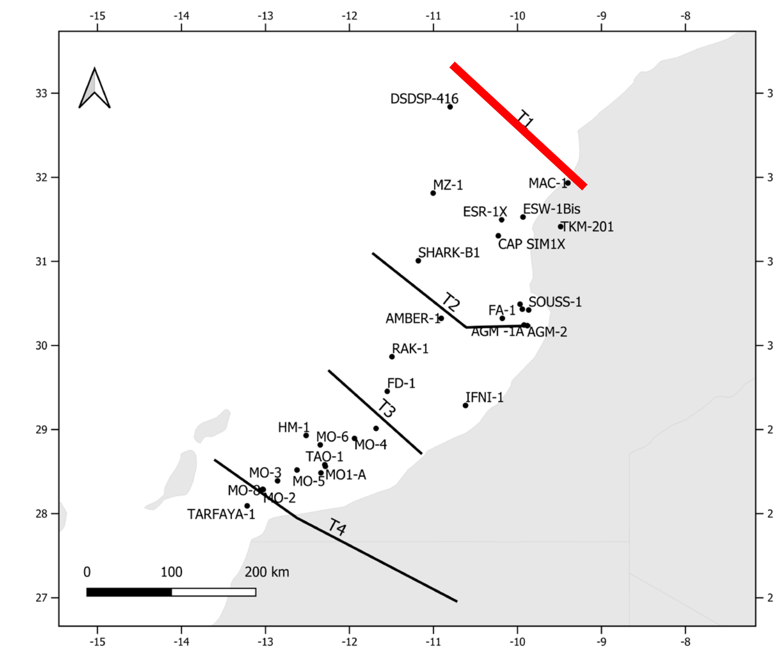


Figure 5.2.1: Location of T1 Morocco.

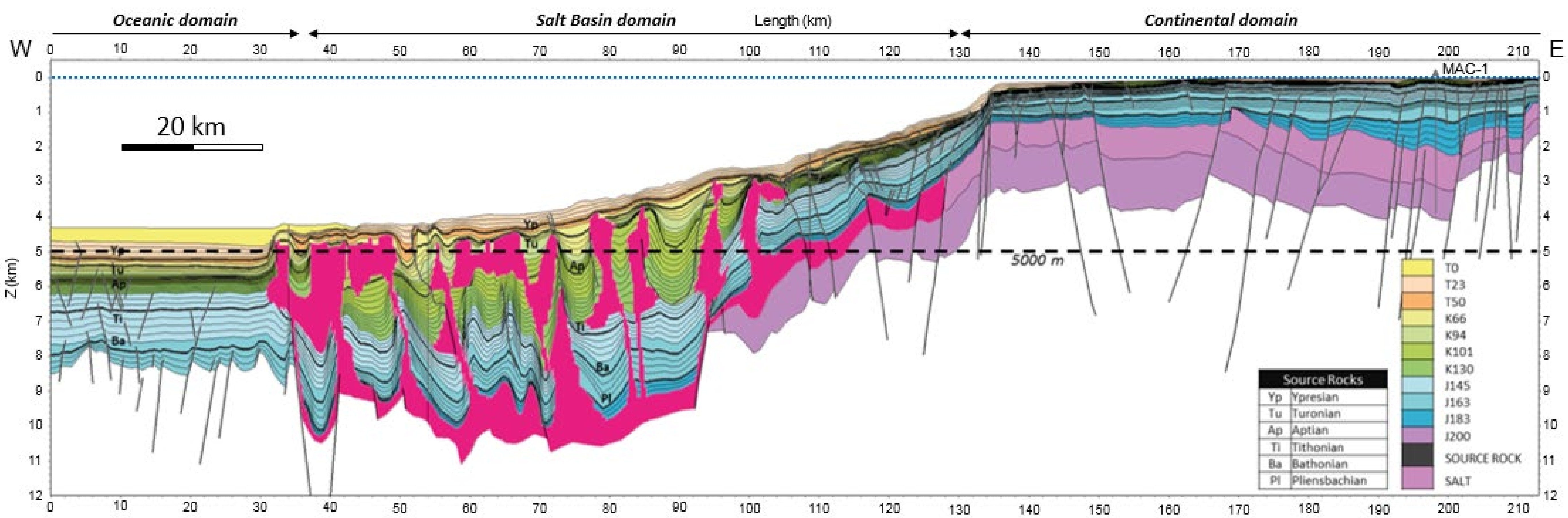


Figure 5.2.2: Stratigraphic framework of Transect T1 (Morocco).

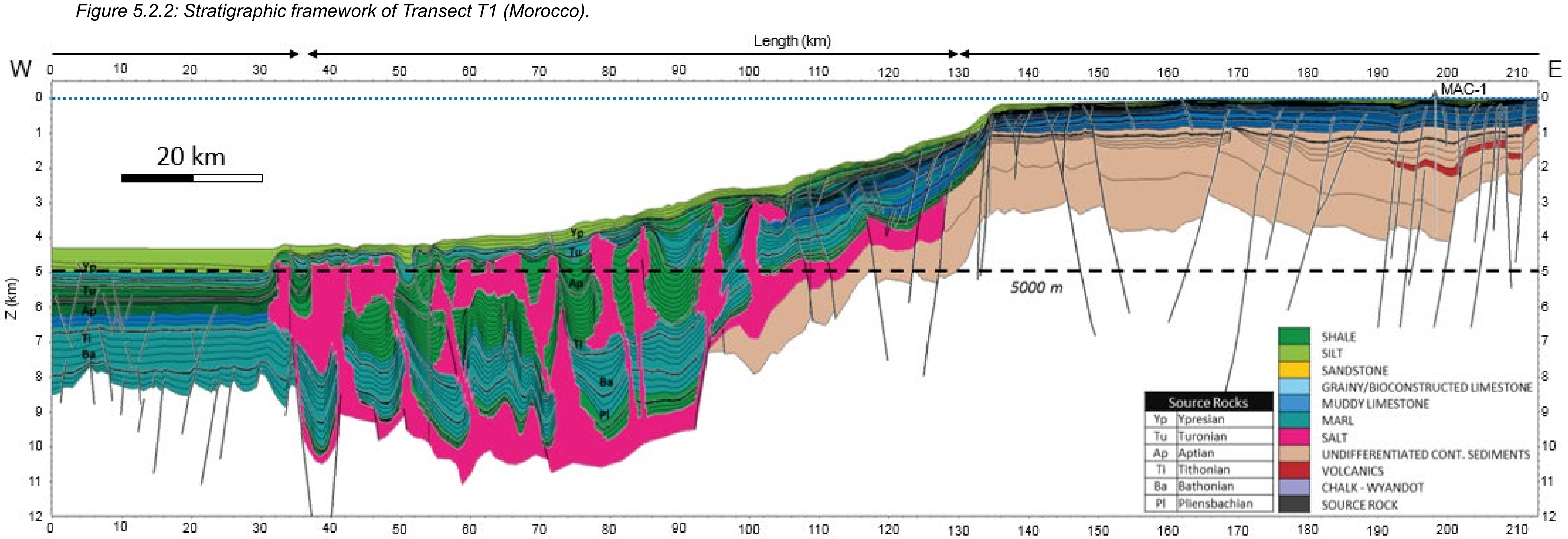


Figure 5.2.3: Facies model of Transect T1 (Morocco).

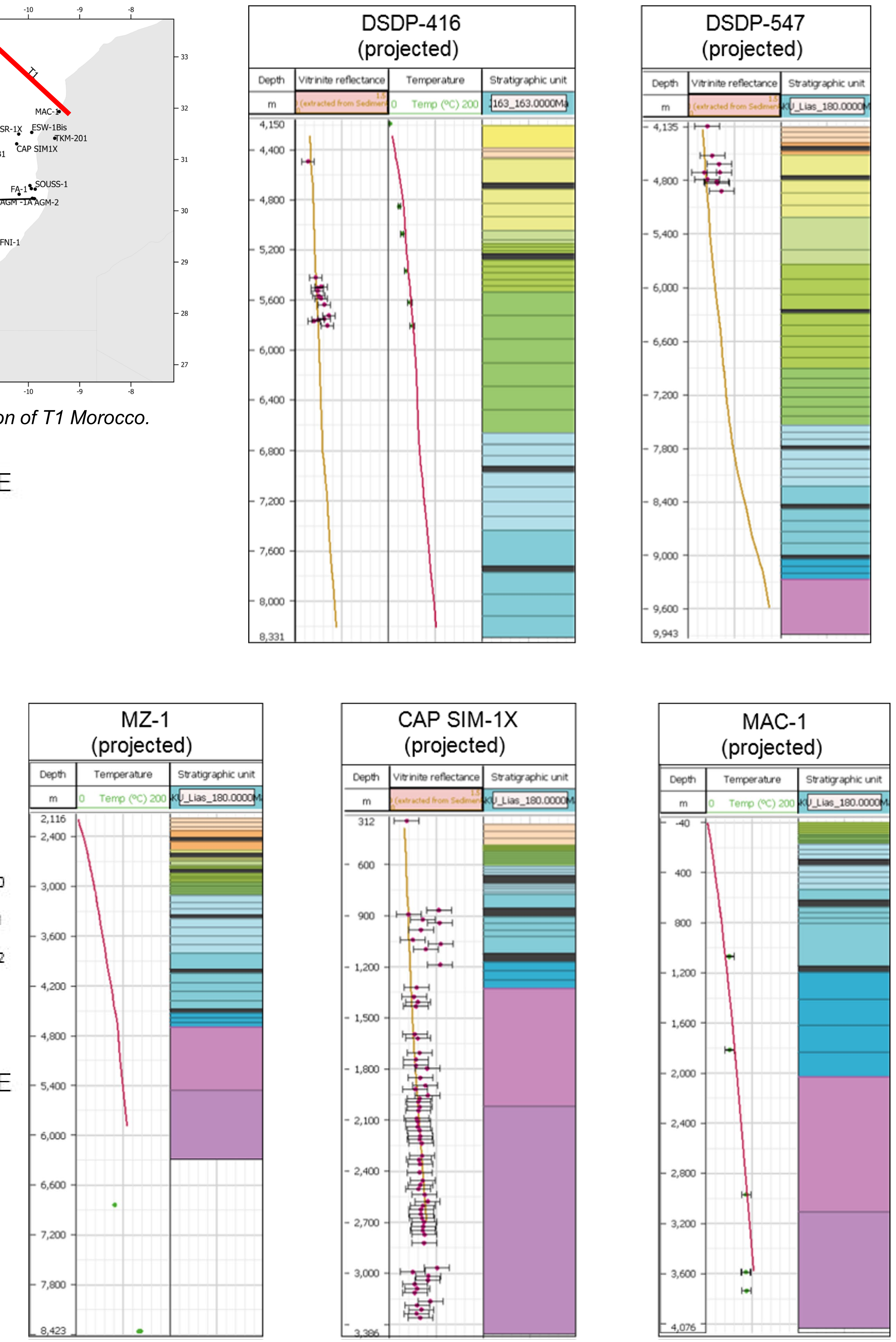


Figure 5.2.4: Thermal and maturity (vitrinite reflectance) of wells DSDP-416, DSDP-547, MZ-1, CAP SIM-1X and Mac-1.

Maturity & cathagenesis simulation results

The Cretaceous and Cenozoic source rocks remain immature all along the transect extension (Fig. 5.2.5).

The deep Pliensbachian & Bathonian source rocks are mature over the salt basin where thermal conditions are favorable (combined effect of significant burial, the presence of transitional crust and the heat-focusing effect of the salt bodies); here they lay respectively in the wet gas and condensates windows. These two source rock members would have cracked all their HC potential in the deepest kitchen areas where they reached their expulsion peak respectively circa 90 and 60Ma (Fig. 5.2.6).

Moving from the deepest areas of the salt basin basinward & shelfward, the Bathonian maturity decreases while remaining in a favorable bracket (late oil window) with a transformation ratio bordering on 50-60%, close to the expulsion peak (Fig. 5.2.5 and Fig. 5.2.6).

The Tithonian source rock remains at best in the oil window in the deepest part of the transect. The Tithonian source rock expelled first oil circa 30Ma and has not yet reached the expulsion peak (Fig. 5.2.6).

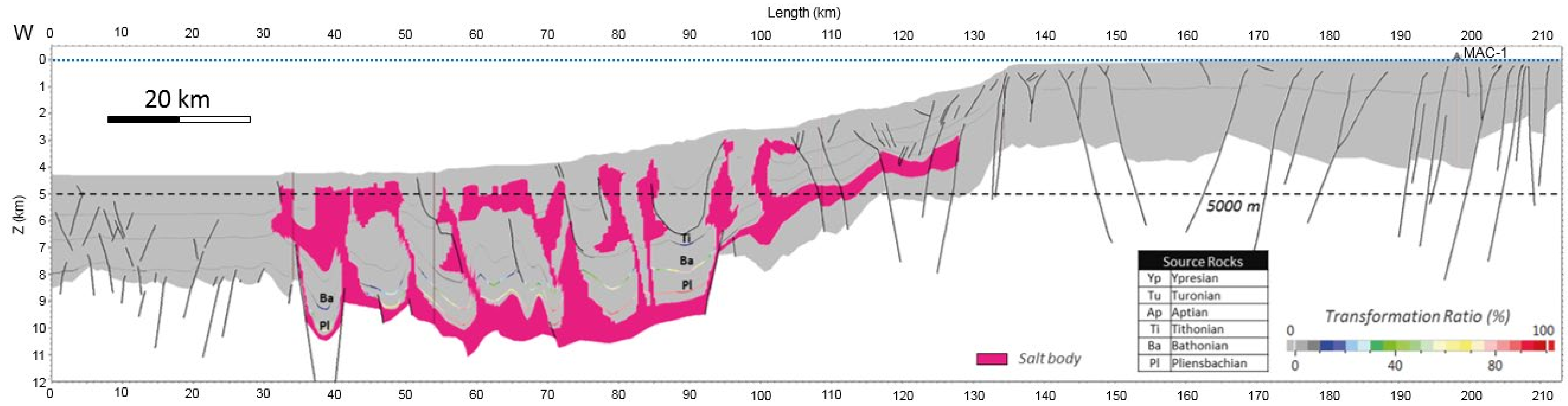


Figure 5.2.5: Simulated transformation ratio for Transect T1 (Morocco).

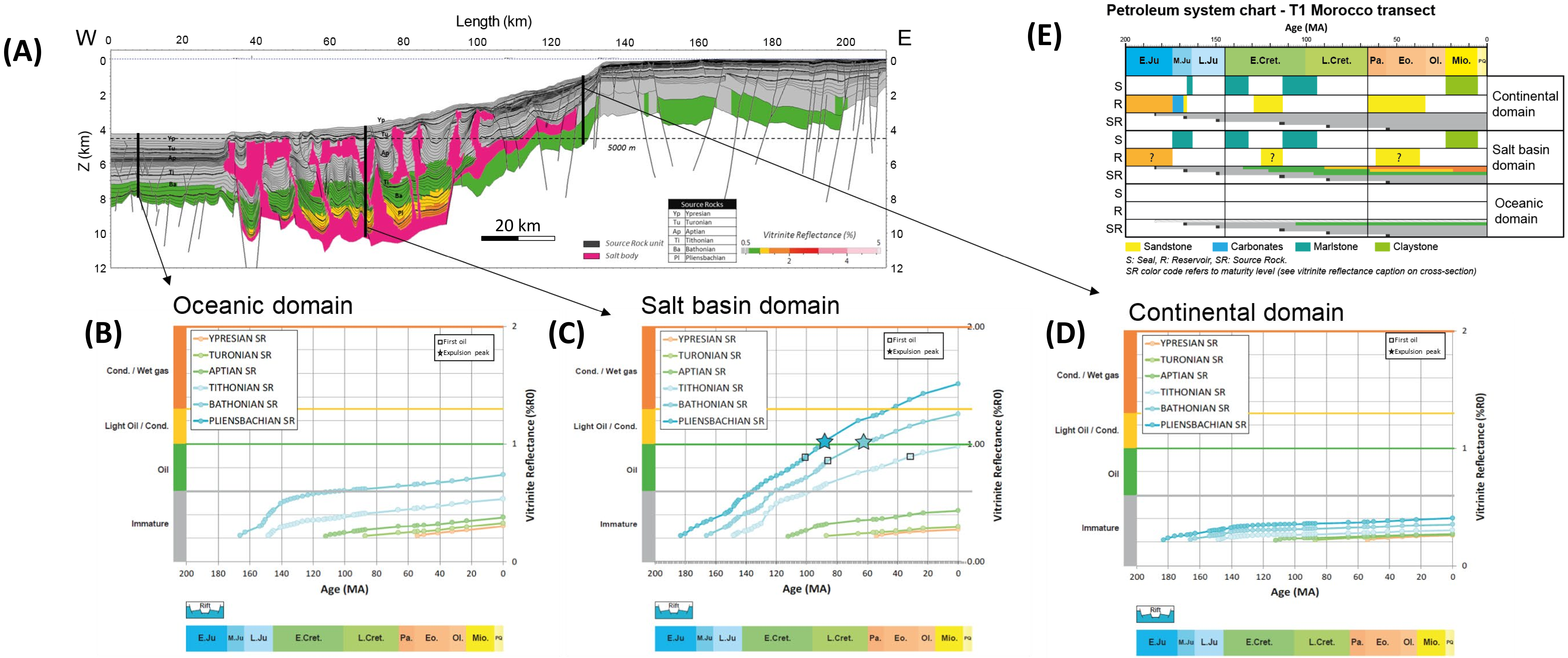


Figure 5.2.6: Maturity history at key locations along Transect T1. (A) Simulated maturity for Transect T1, (B) Simulated maturity profiles extracted from the model in the oceanic domain, (C) Simulated maturity profiles extracted from the model in the salt basin domain, and (D) Simulated maturity profiles extracted from the model close to the edge of the continental shelf, (E) Petroleum system chart along Transect T1.

Transect T2 northern Morocco: Geological setting & calibration

Transect T2 (Morocco) is in the Agadir Basin (Fig. 5.2.7) and crosses the salt basin, which is nearly 140 km wide at that location. Salt bodies mostly consist in diapirs. Most of diapirs reach the Late Cretaceous / Paleogene intervals, and some even reach the sea bottom (Fig. 5.2.8). The striking feature of T2 Morocco is the very thick aggradational sedimentary record which is up to 10 km in the present-day upper slope area (above salt basin).

In terms of facies, Transect T2 is believed to be dominated by muddy carbonates in the Jurassic interval, marls and claystones in the Lower Cretaceous and marls and siltstones in the Tertiary interval of the section (Fig. 5.2.9).

Calibration data is readily available for Transect T2 with four wells located at less than 20 km from the section. These wells were used as proxies for constraining the thermal regime (Fig. 5.2.10). The calibration plates illustrate a good match between observed and modeled present-day temperatures. Maturity calibration is also good at AGM-2.

The modeled maturity at FA-1 remains lower than the observed vitrinite reflectance data but the latter is questionable, as 1/ measurements do not show a consistent increase of the maturity range as a function of depth 2/ the thermal regime is calibrated at the neighboring AGM-2 well location, implying a discrepancy in the maturity datasets between both wells.

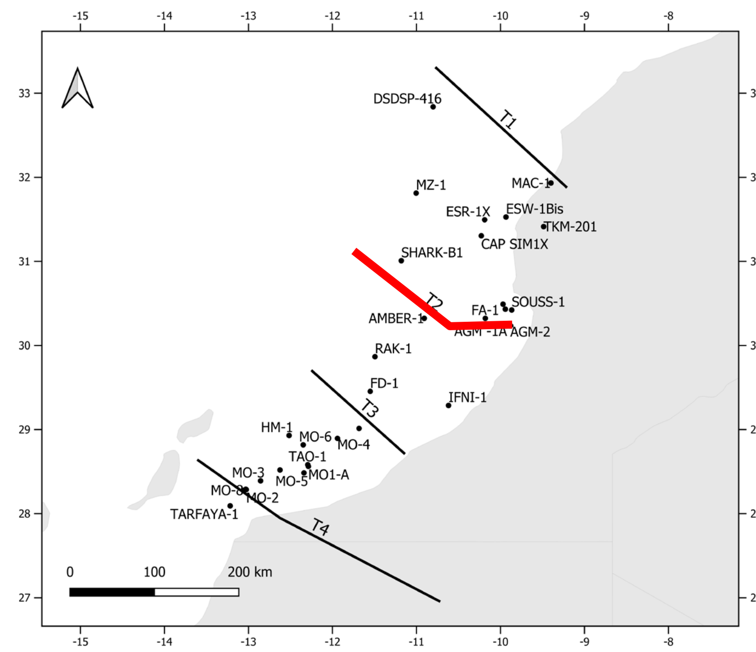
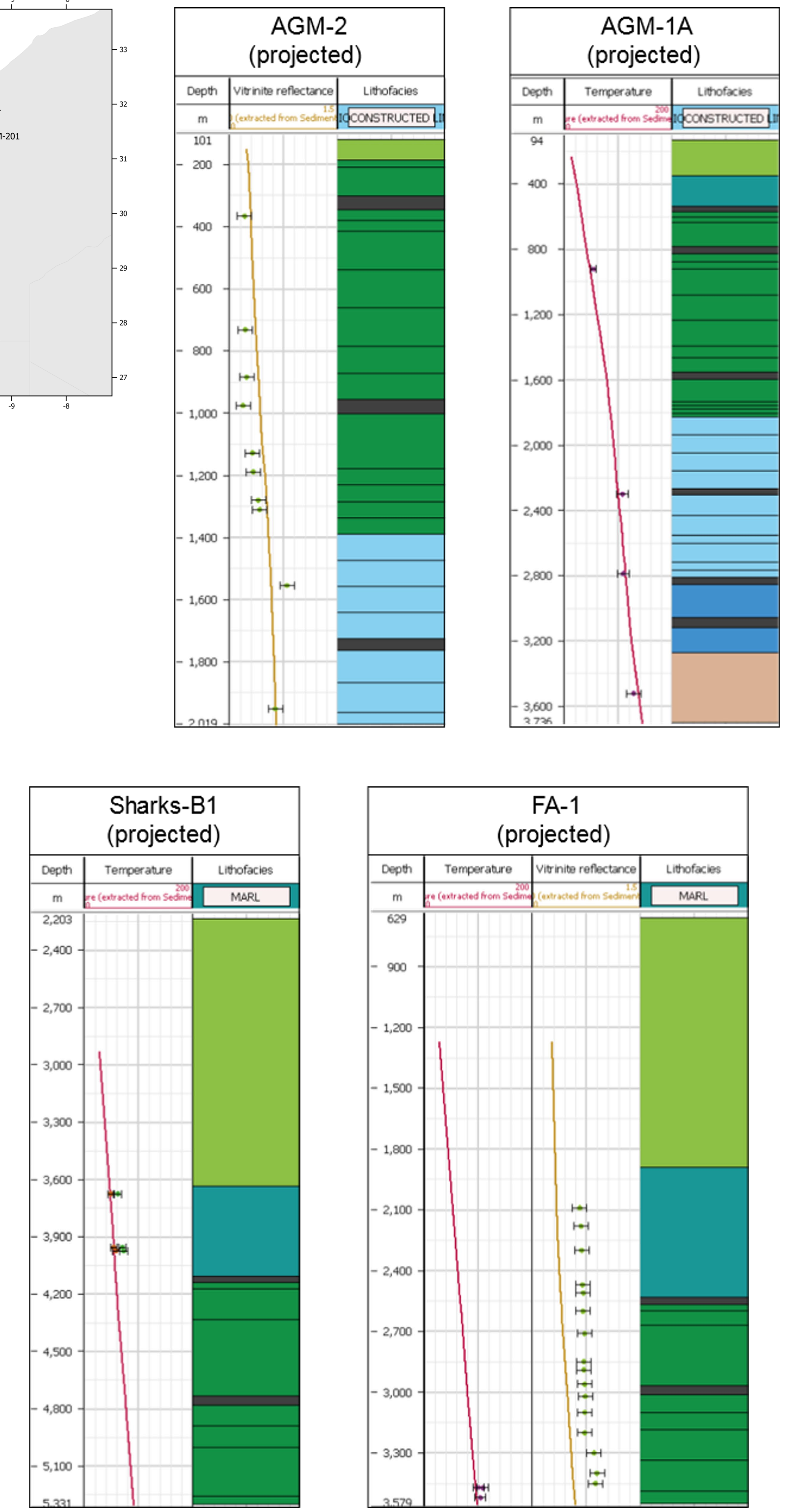


Figure 5.2.7: Location of T2 Morocco.



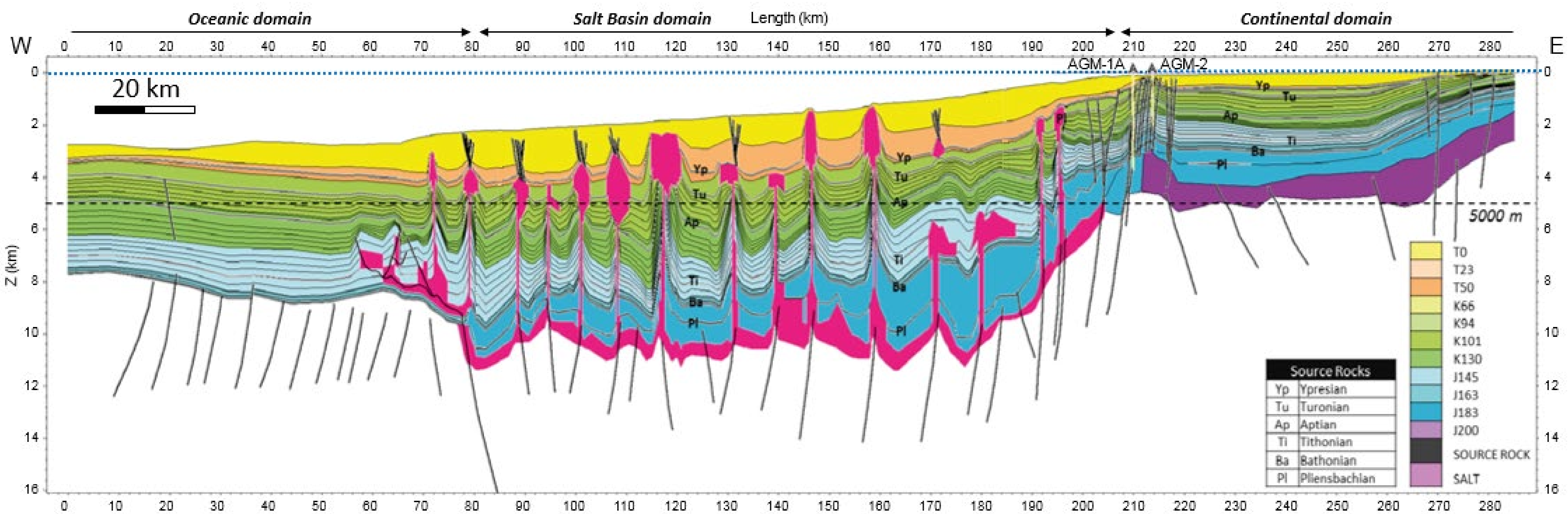


Figure 5.2.8: Stratigraphic framework of Transect T2 (Morocco).

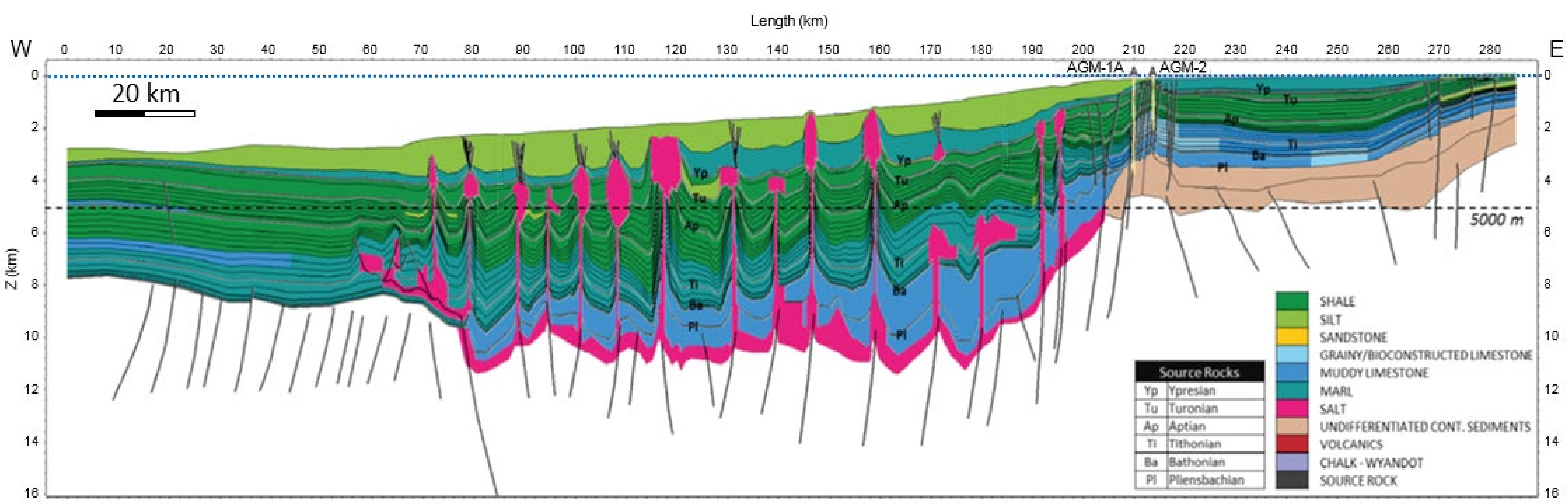


Figure 5.2.9: Facies model of Transect T2 (Morocco).

Figure 5.2.10: Thermal and maturity (vitrinite reflectance) of wells AGM-2 and AGM-1A, FA-1 and Shark-B1

Maturity & cathagenesis simulation results

The Cretaceous and Cenozoic source rocks are immature all along Transect T2 Morocco. Source rocks become mature below the Turonian source rock level (Fig. 5.2.11). In terms of maturity, three domains can be distinguished along the section: (1) the continental domain, (2) the salt basin domain, and (3) the oceanic domain (Fig. 5.2.12).

The salt basin domain displays the highest maturity levels especially for the Jurassic Pliensbachian, Bathonian and Tithonian source rocks. Highest maturity levels are found in the Jurassic section of the salt basin. The three Jurassic source rocks are very mature to even overmature. This thermal conditions is likely due to the combined effect of significant burial (up to 9 km for the Pliensbachian source rock), the presence of transitional crust underneath the salt basin (elevated heat flow) and the thermal conductivity of salt bodies. The Jurassic source rocks lay in the wet gas (Tithonian source rock) and the dry gas (Pliensbachian) windows. The Jurassic source rocks have cracked nearly all their potential and they reached their expulsion peak between 130 and 90Ma.

Toward the continental domain, maturity level decreases for all source rocks and even the Jurassic ones remain in the oil window. Expulsion peak is not yet reached and only the Pliensbachian source started expelling HC 55 Ma ago. In the oceanic domain maturity level is the lowest (due to low heat flow generated by the oceanic crust); the Jurassic source rocks are in the oil window.

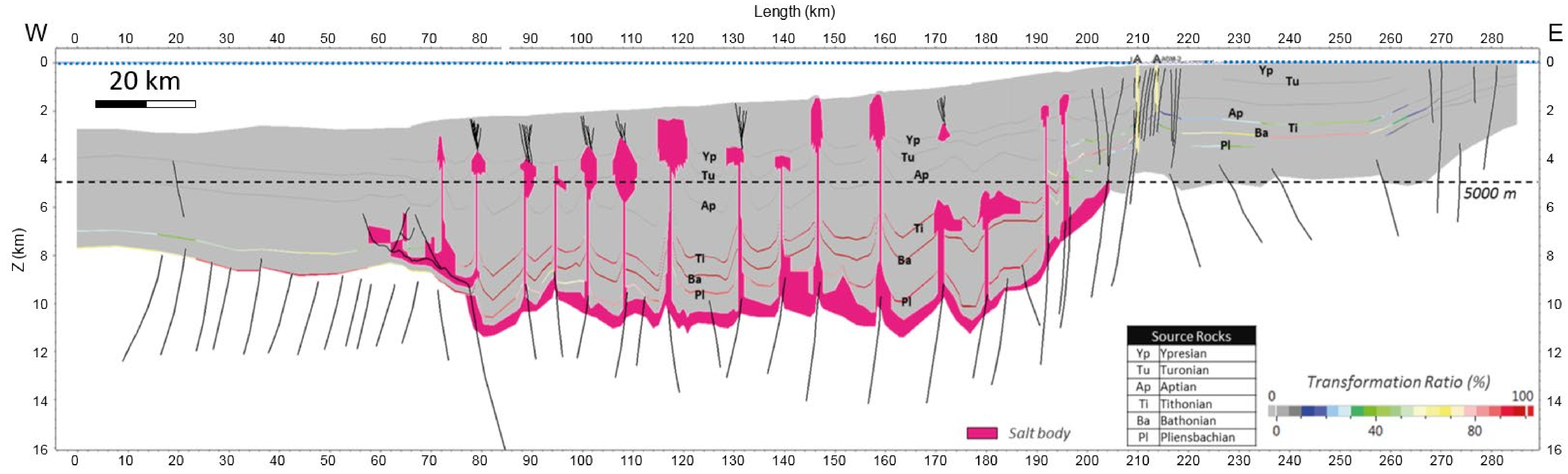


Figure 5.2.11: Simulated transformation ratio for Transect T2 (Morocco).

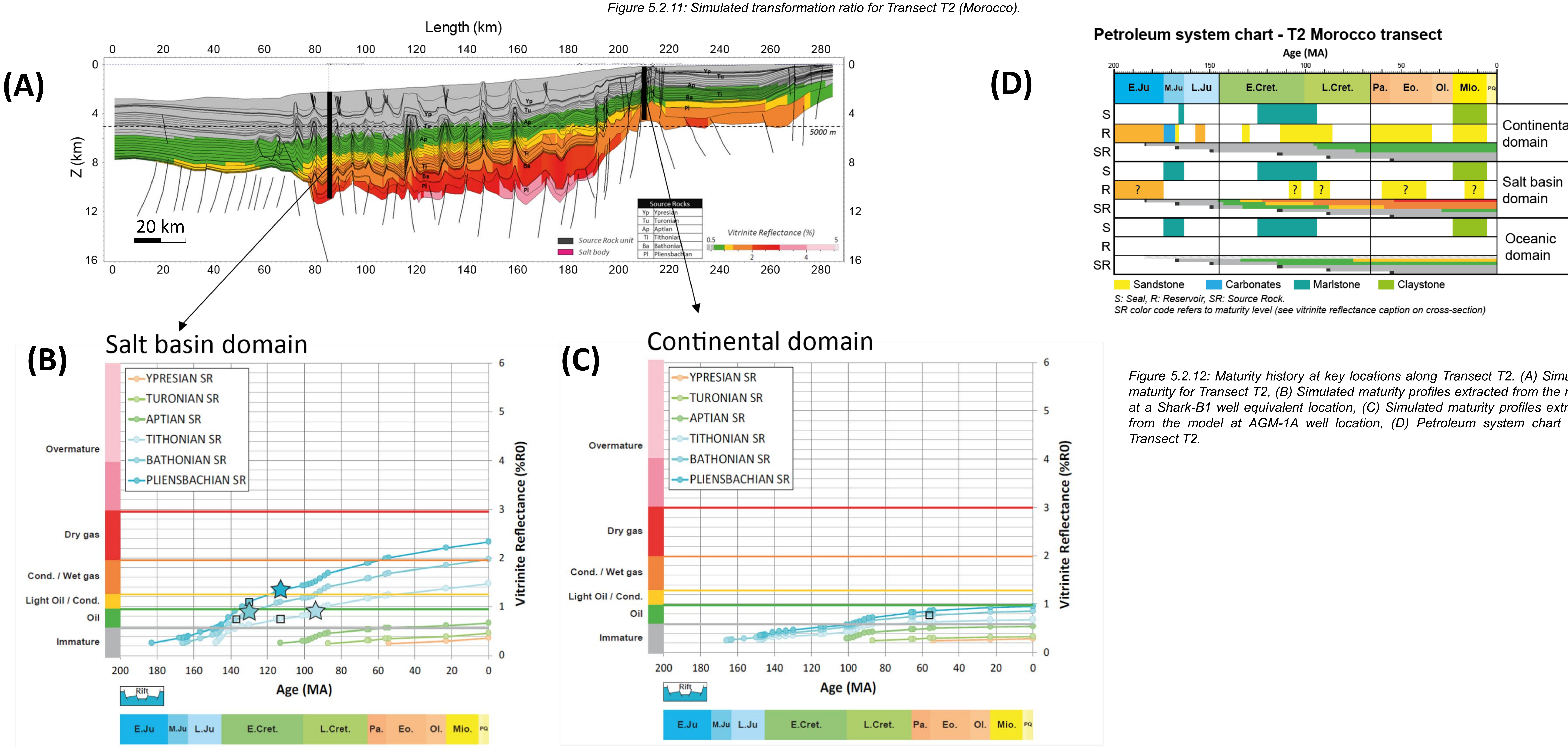


Figure 5.2.12: Maturity history at key locations along Transect T2. (A) Simulated maturity for Transect T2, (B) Simulated maturity profiles extracted from the model at a Shark-B1 well equivalent location, (C) Simulated maturity profiles extracted from the model at AGM-1A well location, (D) Petroleum system chart along Transect T2.

Transect T3 northern Morocco: Geological setting & calibration

Transect T3 (Morocco) is in the Tarfaya Basin (Fig. 5.2.13). At this location, autochthonous salt deposits are restricted to a narrow 40km trough intercalated between the continental crust domain (continental shelf) and the oceanic crust domain. Salt deposits rest on top of transitional continental crust. Like Transect T2 the overburden is thick on Transect T3: approximately 5 km constant thickness on the continental shelf, up to 10 km over the salt basin and 7 km on the oceanic crust domain (Fig. 5.2.14).

The facies dress-up of Transect T3 Morocco (Fig. 5.2.15) was mainly based on well Tantan-1 which penetrated Lower Jurassic at the present-day shelf edge. Seismic geomorphology also helped to interpret the conceptual facies distribution beyond the shelf edge. The Jurassic interval is dominated by carbonate deposits. Based on seismic geometries, an Upper Jurassic carbonate reef facies is interpreted at the edge of the continental shelf (rimmed carbonate platform). This reefal facies belt separated the shallow-marine platform interior (open lagoon facies) from the deep-water ones deposited on the reef foreslope and beyond. The Cretaceous deposits (from J145 to K94 units) display a nearly constant thickness of nearly 2 km and most consist of siliciclastics. The continental shelf was likely dominated by fine-grained clastics (siltstones) with possibly subordinate shallow-marine sandstones. From the outer shelf (Tantan-1 location) to the continental slope, deposits are interpreted as fine-grained clastics while further offshore (distal slope) sediments are believed to be mostly claystones (see FD-1 well). The Cenozoic interval and particularly the Paleogene series are poorly developed across the Transect. A major unconformity cutting down into Lower Cretaceous deposits is well defined on the present-day shelf edge. Observed elsewhere offshore, this major erosional unconformity bounds the Cretaceous series in the Tarfaya basin and was triggered by continental margin collapse (*Sequence stratigraphy and evolution of the Tarfaya Basin, Morocco, Wenke et al, 2011*).

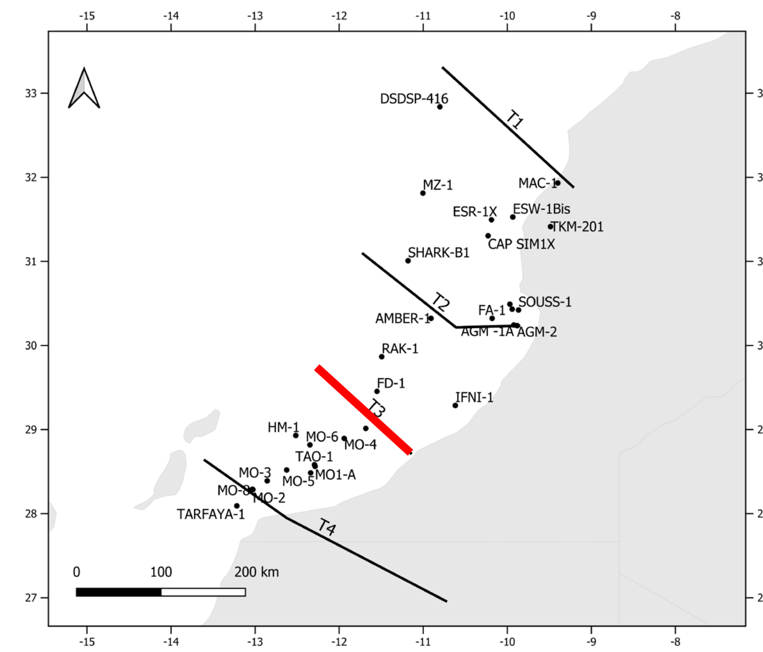


Figure 5.2.13: Location of T3 Morocco.

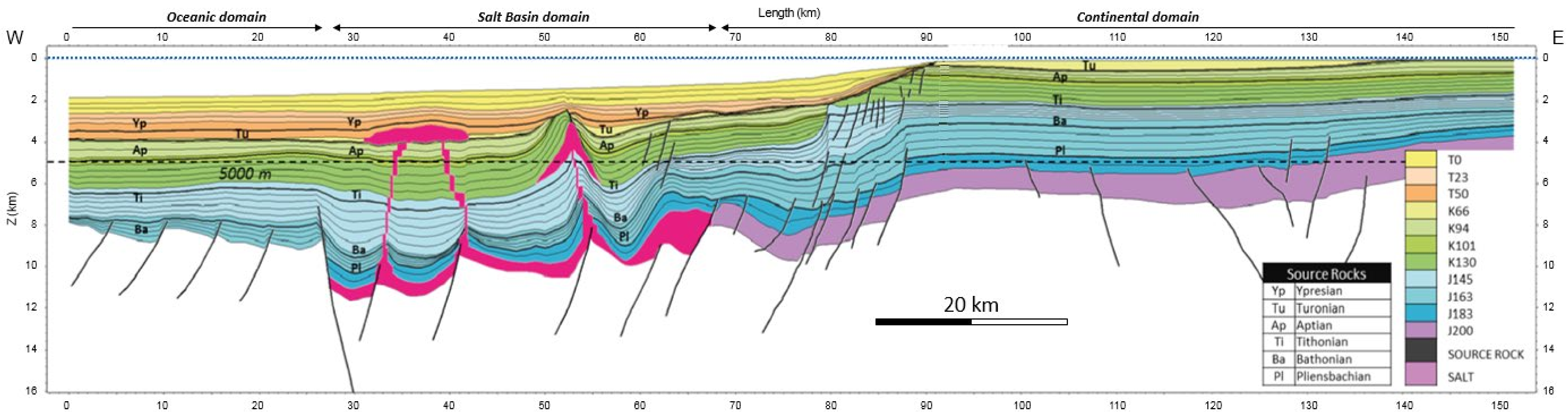


Figure 5.2.14: Stratigraphic framework of Transect T3 (Morocco).

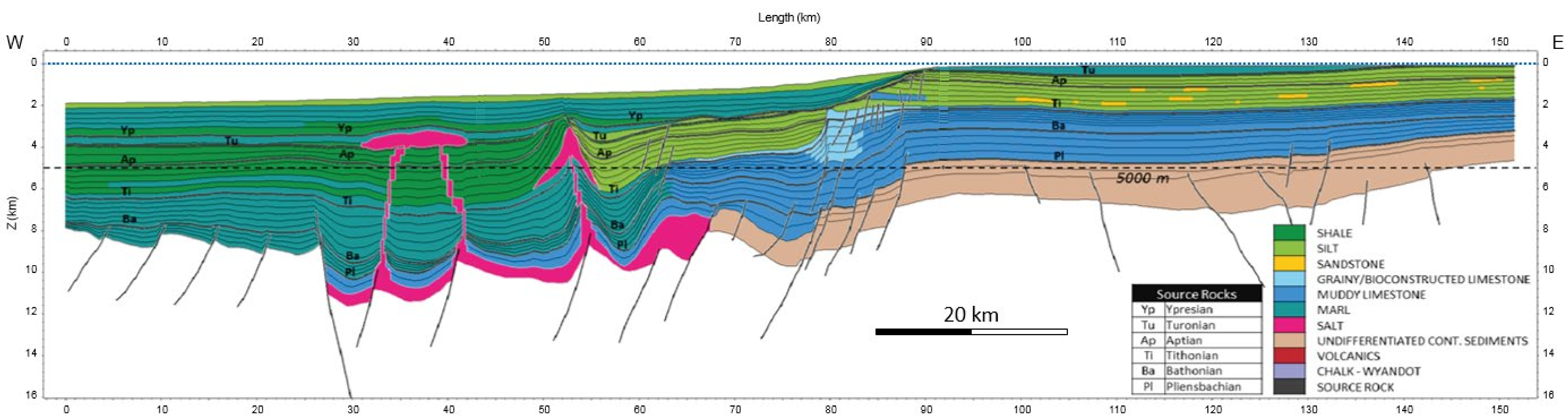


Figure 5.2.15: Facies model of Transect T3 (Morocco).

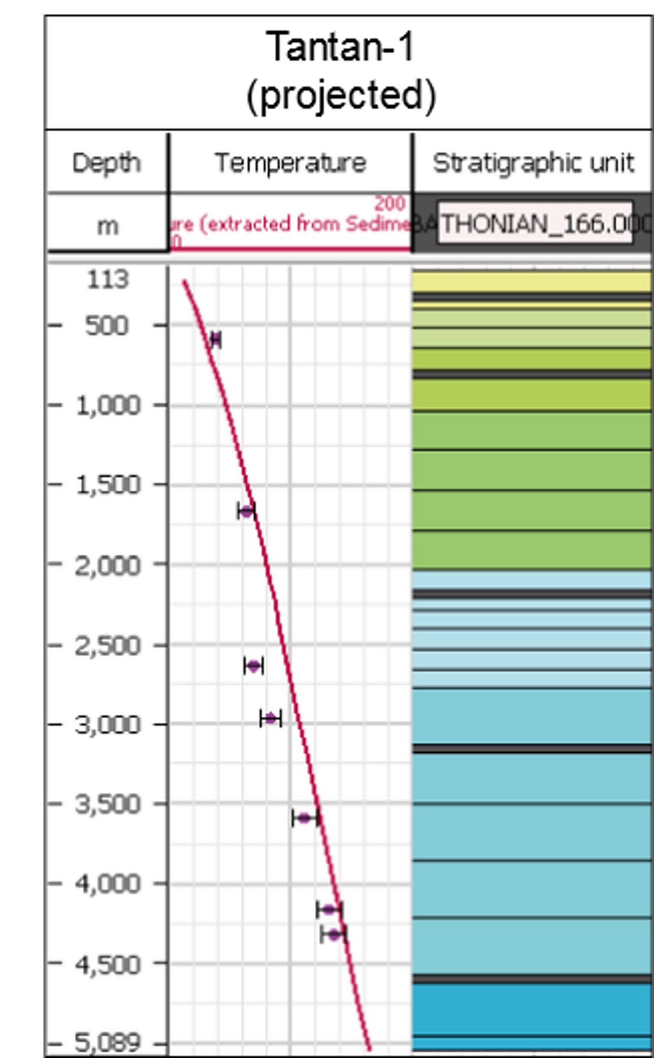


Figure 5.2.16: Thermal calibration (present-day temperature) of well Tantan-1.

Maturity results:

The Cretaceous and Cenozoic source rocks are immature all along Transect T3 Morocco (Fig. 5.2.17); only Jurassic source rocks are mature. Since Transect T3 Morocco is close to the Canary islands, two thermal hypotheses were considered to evaluate the impact of the mantle plume on the maturity profile of the different source rocks. The dashed lines displayed on the maturity profiles (Fig. 5.2.18) depict the potential thermal effect of the mantle plume on source rock maturity.

Except on the continental shelf and the upper slope where the Tithonian source rock is immature, Jurassic source rocks range from early mature to nearly overmature. In this transect two heat flow hypotheses were modeled and the thermal effect caused by the Canary mantle plume effect was considered (dashed line).

Maturity level is highest in the salt trough as a result of the combination of relatively high heat flow (transitional crust and heat-focusing effect of salt bodies) and the thick overburden (Fig. 5.2.18). In this area the Pliensbachian and the Bathonian source rocks are very mature (dry gas window). These source rocks started generating HC between 155 and 150Ma and reached their peak of expulsion as early as 150 and 135 Ma, respectively.

On the continental shelf, only the Pliensbachian source rock reached a significant maturity level (condensate to wet gas window). This source rock is the only one having reached its peak of expulsion, which occurred at around 130Ma. Other source rocks have not reached their peak of expulsion yet. The Bathonian source rock is the only one entering its HC generation window.

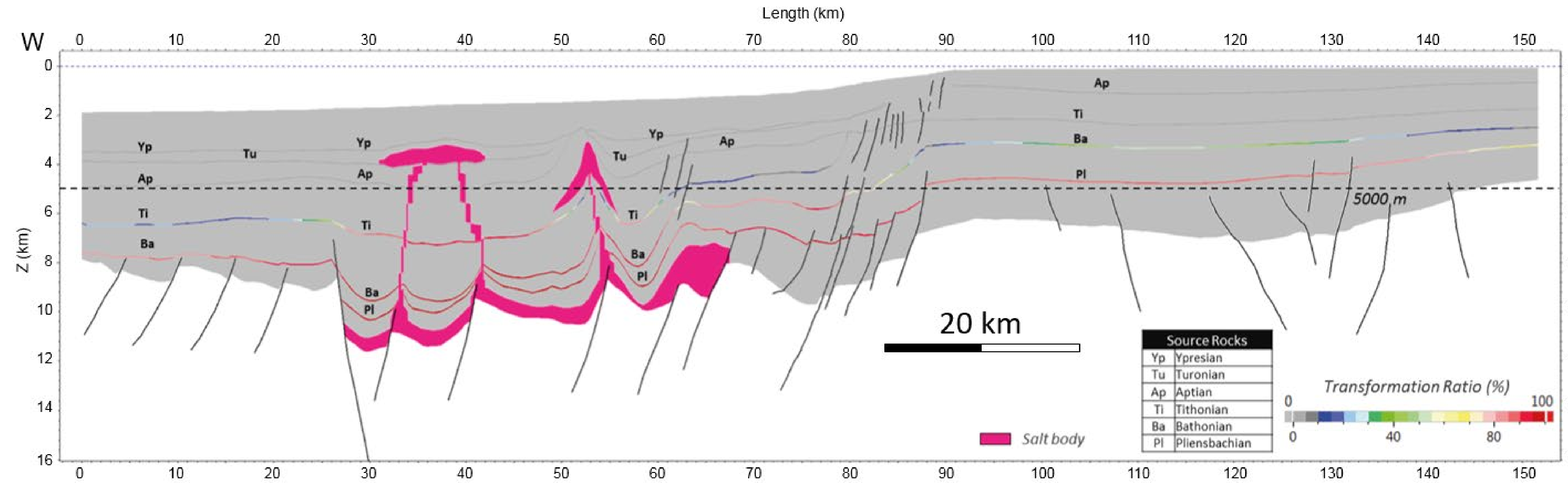


Figure 5.2.17: Simulated transformation ratio for Transect T3 (Morocco).

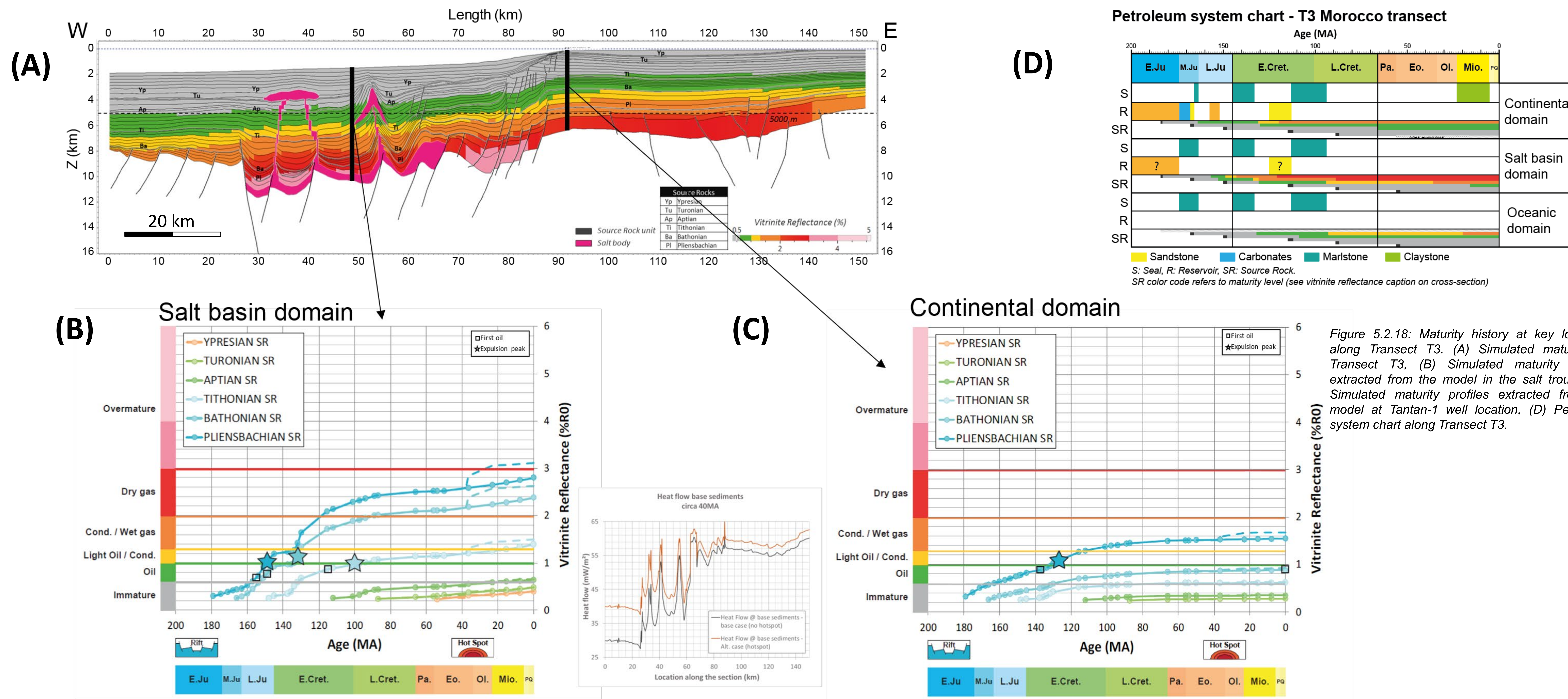


Figure 5.2.18: Maturity history at key locations along Transect T3. (A) Simulated maturity for Transect T3, (B) Simulated maturity profiles extracted from the model in the salt trough, (C) Simulated maturity profiles extracted from the model at Tantan-1 well location, (D) Petroleum system chart along Transect T3.

Transect T4 northern Morocco: Geological setting & calibration

Transect T4 (Morocco) is in the southern part of the Tarfaya Basin (Fig. 5.2.19). As the southwestern-most transect simulated, the section features limited salt diapirism because the salt basins in the area became restricted. Salt features are limited to thin & elongated vertical welds triggered by the thick sedimentary pile (exceeding 10 km total thickness in the deepest troughs) terminated by salt canopies of limited lateral extension. The overburden reaches up to 8 km thickness on the shelf and 11 km thickness over the salt basin (Fig. 5.2.20 and Fig. 5.2.21).

One geological highlight of Transect T4 is the Cape Juby structure, where positive oil findings were made. Several wells probed the area including Cape Juby-1, MO-2 and Maritime-1 for which oil columns were found, either in Upper Jurassic or Middle Jurassic carbonate reservoirs. Located close to the Canary Volcanic Province, Transect T4 is also impacted by the Canary hotspot thermal event primarily in its western half. The hotspot is believed to have reached T4 northwestern anchor circa 25-30 Ma. The impact of this event has been simulated by inserting a thermal anomaly at this age in the model.

Calibration data is readily available for Transect T4 with 2 wells located within a few km from the section (Fig. 5.2.22). The calibration plates illustrate a good match between observed and modeled present-day temperature & maturity profiles. The model successfully reproduces the pressure kick observed at 1700m (TVDSS) at MO-2 well projected location. The lack of vertical & horizontal resolution in terms of facies distribution within the Cretaceous & Jurassic series does not allow proper representation of the reservoir body itself at this location. This leads to a loosely accurate prediction of the pressure regime (i.e., a limited ability to model the fluid containment and the associated undercompaction/overpressure trends further down).

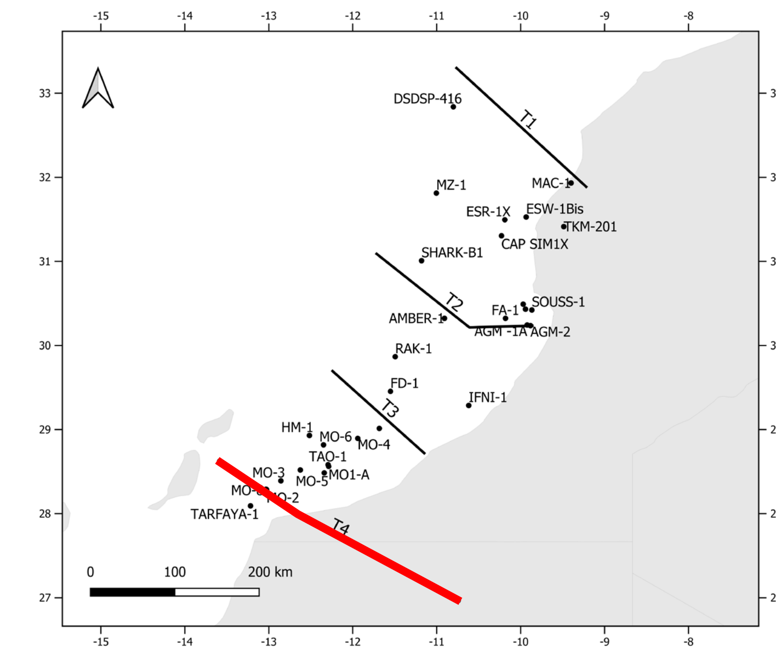


Figure 5.2.19: Location of T4 Morocco.

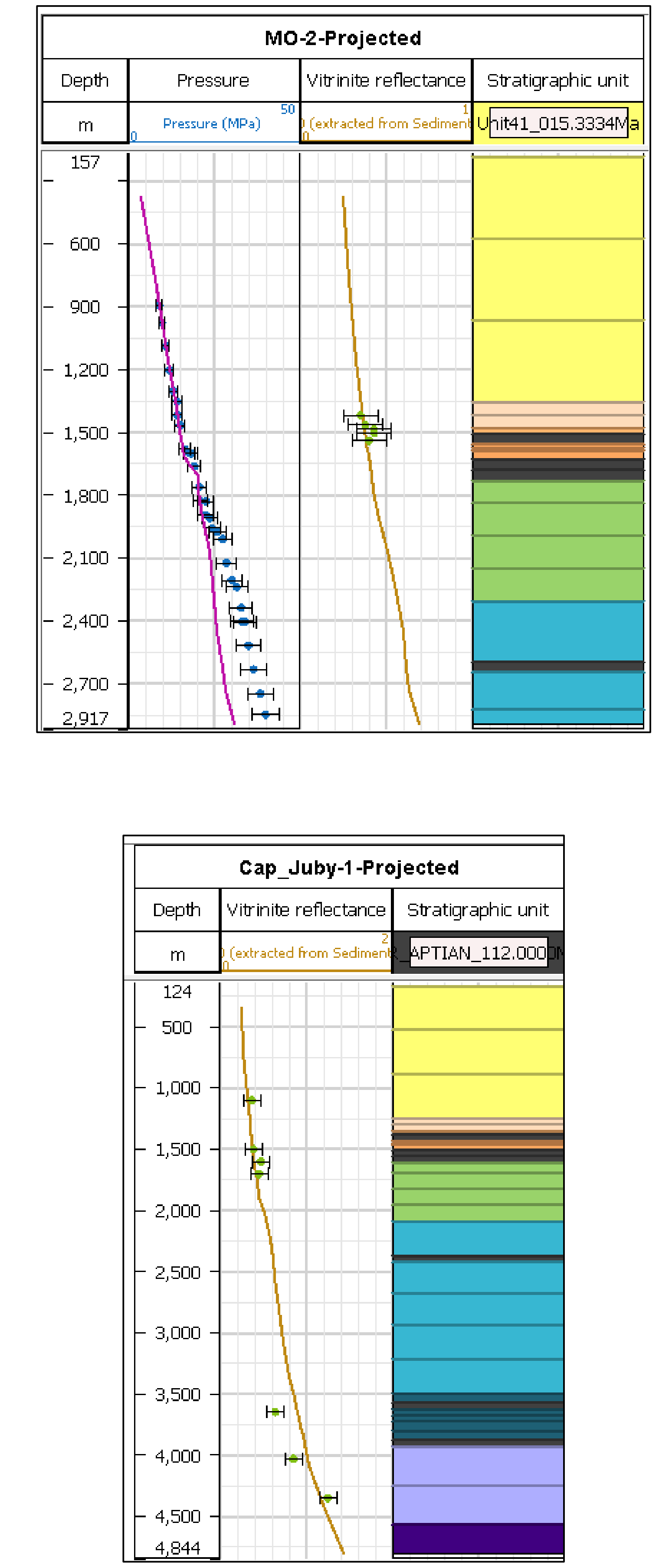


Figure 5.2.22: Thermal and maturity (vitrinite reflectance) of wells MO-2 and Cap Juby-1.

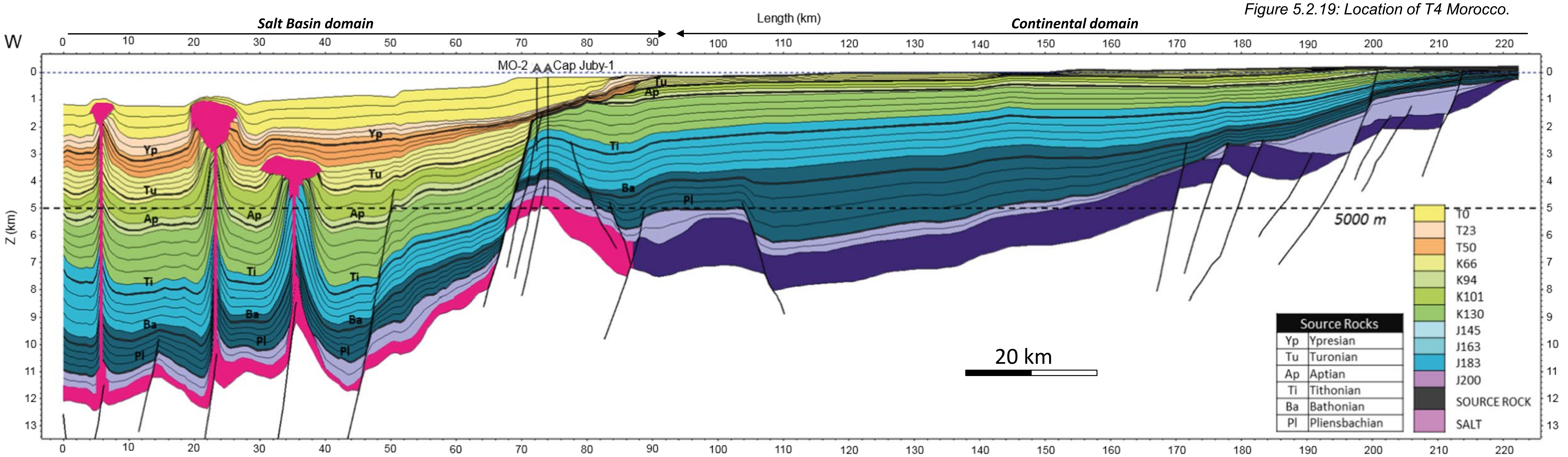


Figure 5.2.20: Stratigraphic framework of Transect T4 (Morocco).

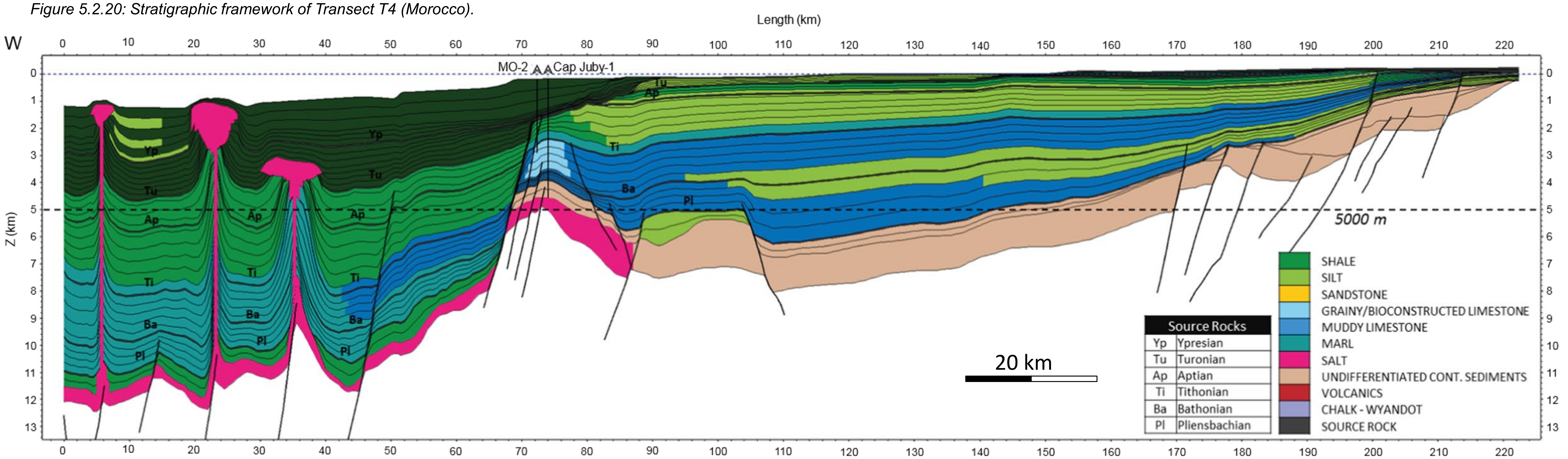


Figure 5.2.21: Facies model of Transect T4 (Morocco).

Maturity results:

The Cretaceous and Cenozoic source rocks are immature all along Transect T4 Morocco (Fig. 5.2.23), except for the Aptian member which is locally mature in mini-basins over the salt basin. Its maturity there remains within the oil window and the expulsion peak has not yet been reached. Jurassic source rocks are very mature (dry gas window) to overmature over the salt basins, where the combination of a relatively high heat flow (transitional crust and heat-focusing effect of salt bodies) and of the thick overburden induces a hot thermal regime. Source rock maturity decreases gradually upslope to the point where cathagenesis is no longer active over the continental domain (e.g., at the eastern edge of the transect).

In this transect two heat flow hypotheses were modeled in order to test the impact of the Canary mantle plume on the thermal regime (dashed lines) as illustrated in Figure 5.2.24.

Thermal modeling results support observations at the Cape Juby well location: maturity profiles extracted off-structure, landward in a tentative kitchen area possibly feeding the structure (km85), suggest that the expulsion peak occurred very early, circa 130MA for the deep Jurassic source rock members. At that time, the maturity regime was late oil window. At present day, the maturity range in the area remains close to the light oil/condensate window, indicating a limited sourcing of gas vs oil. This supports oil fluids found at wells. Furthermore, the temperature regime within the structure remains above the pasteurization temperature threshold for the Middle Jurassic series and below it for the Upper Jurassic, from the time of the Jurassic source rock expulsion peak (more than 100 Ma) and onward. This leaves ample time for the Upper Jurassic oils to be severely biodegraded as observed in the wells.

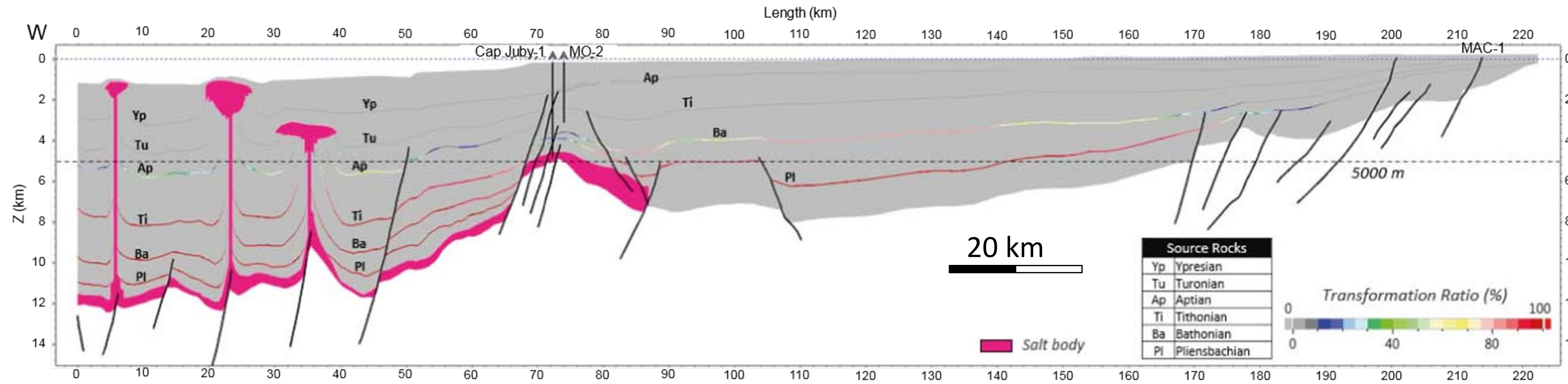
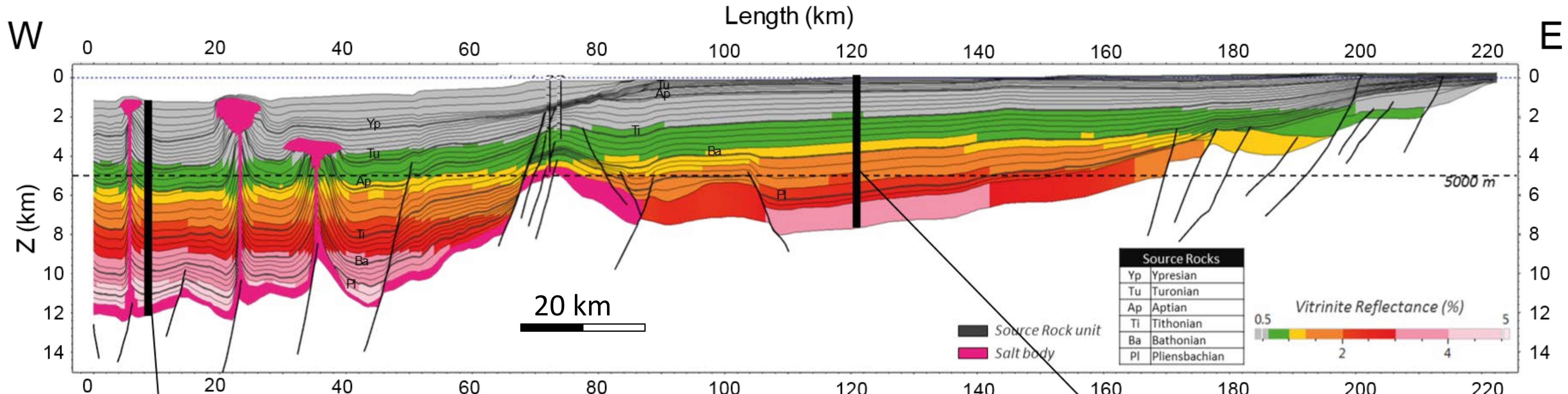
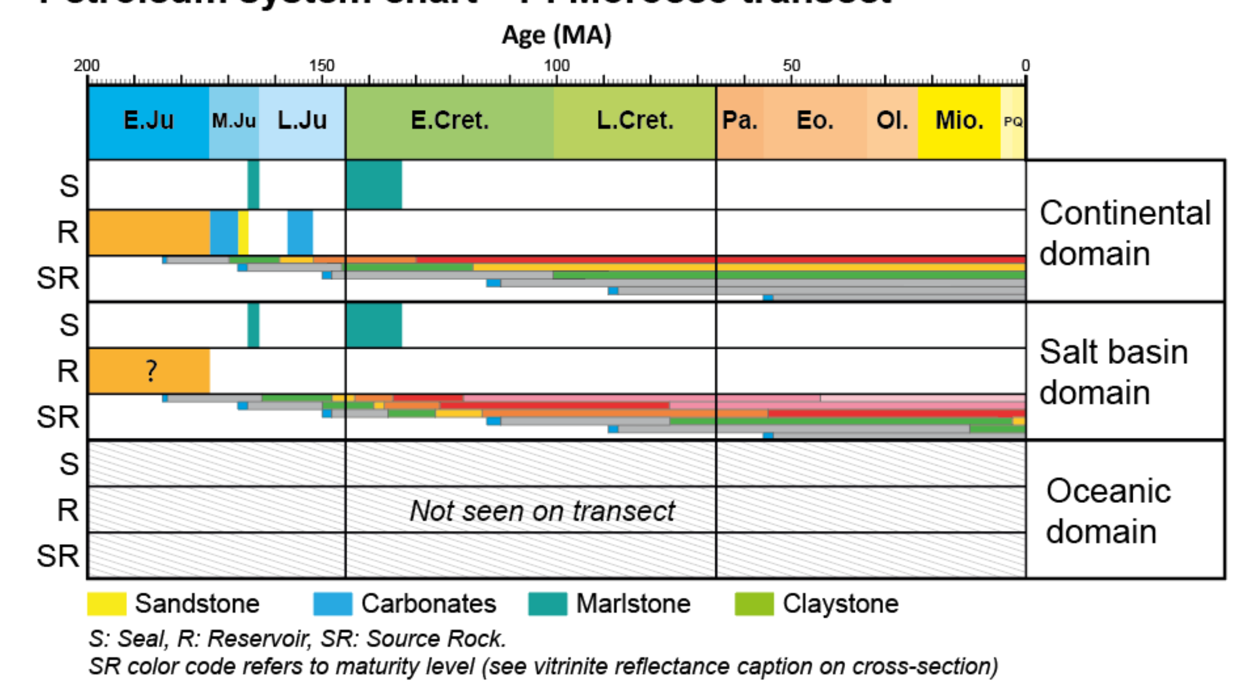


Figure 5.2.23: Simulated transformation ratio for Transect T4 (Morocco).

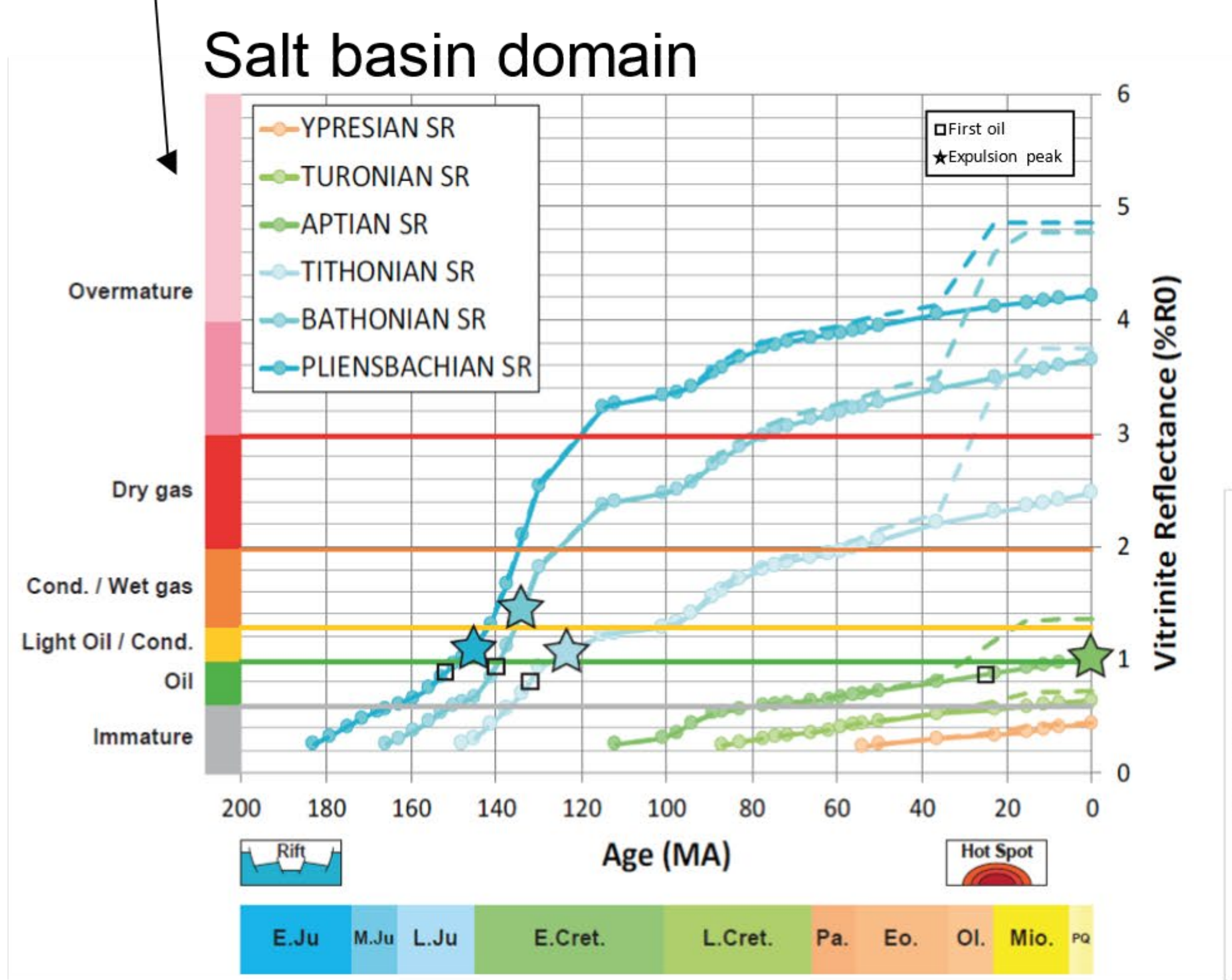
(A)

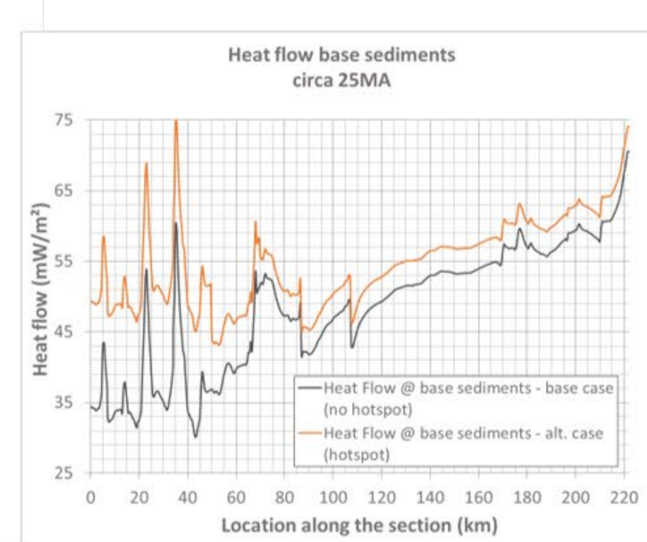


(D)



(B)





(C)

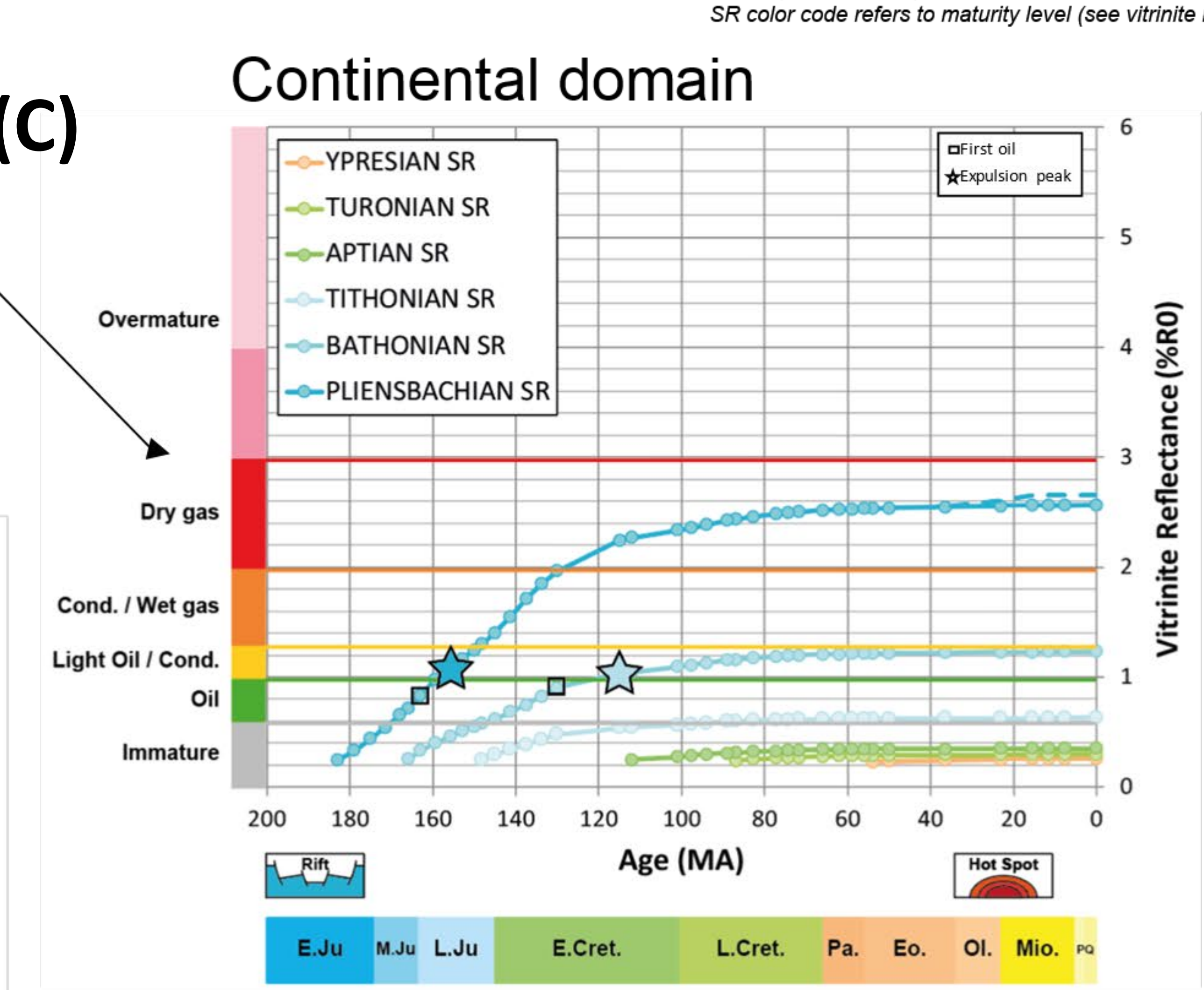


Figure 5.2.24: Maturity history at key locations along Transect T4. (A) Simulated maturity for Transect T4, (B) Simulated maturity profiles extracted from the model in the salt trough, (C) Simulated maturity profiles extracted from the model on the shelf, (D) Petroleum system chart along Transect T4.

Transect T1 Canada: Geological setting & calibration

Transect T1 (Canada) is located near the northern end of the Scotian Margin within the Sable Sub-basin (Fig. 5.2.25). The most striking feature depicted by Transect T1 is the geological complexity and the significant impact of salt tectonics leading to synkinematic sedimentation (Fig. 5.2.26). The so-called "Banquereau Synkinematic Wedge" (BSW) is a large salt-related structure comprising a thick Jurassic and Cretaceous sedimentary column characterized by extension in the upper part (depicted on Transect T1) and compression in the downward part. The BSW is interpreted as a roho system with autochthonous salt (underneath present-day continental shelf) feeding salt canopy (e.g. Kendell, 2012; Deptuck et al., 2014; Saint-Ange et al., 2017). The synkinematic wedge was active from Middle Jurassic onwards as demonstrated by the significant changes in thickness above the J183 interval. The synkinematic wedge was triggered by massive Jurassic deltaic sediment input from the northwest (see Saint-Ange et al., 2017).

Facies dress-up of Transect T1 was based on geological record at wells Louisbourg-J47, Southwest Banquereau-F34 and Tantallon-M41 (Fig. 5.2.27). Upper Jurassic deposits predominantly consist of marlstones on the continental shelf. Further offshore and downdip facies are tentatively interpreted as marlstones as well. Cretaceous deposits recorded at the three well locations are dominated by sandstones and claystones in the inner part of the section and grade to claystone toward the east. Upper Cretaceous carbonates (Petrel Member) cap the Cretaceous siliciclastics on the continental shelf. Finally the Mesozoic series is overlain by up to 1.5 km thick Cenozoic siltstones and claystones.

The thermal calibration of Transect T1 was checked at the three well locations (Fig. 5.2.28). Simulated present-day thermal conditions (temperature) and maturity (vitrinite reflectance) match the observed data. A slight discrepancy between simulated and observed pressures is observed at Louisbourg J-47 as the model does not reproduce exactly the minor overpressure kick measured in the Upper Jurassic series. The lack of detailed facies information is the reason, as the Upper Jurassic is considered as a homogeneous marly interval in the model for the sake of regional homogenization of the facies trends. This leads consequently to a loosely accurate prediction of the pressure regime in this interval. In any case overpressure remains limited (below 10 MPa) and has a negligible impact on the thermal regime, the prime objective of this work.

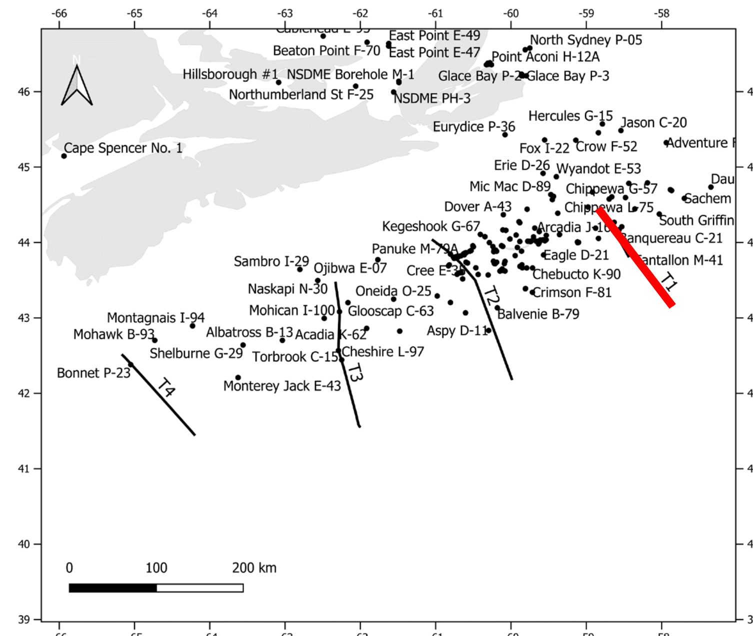


Figure 5.2.25: Location of T1 Canada.

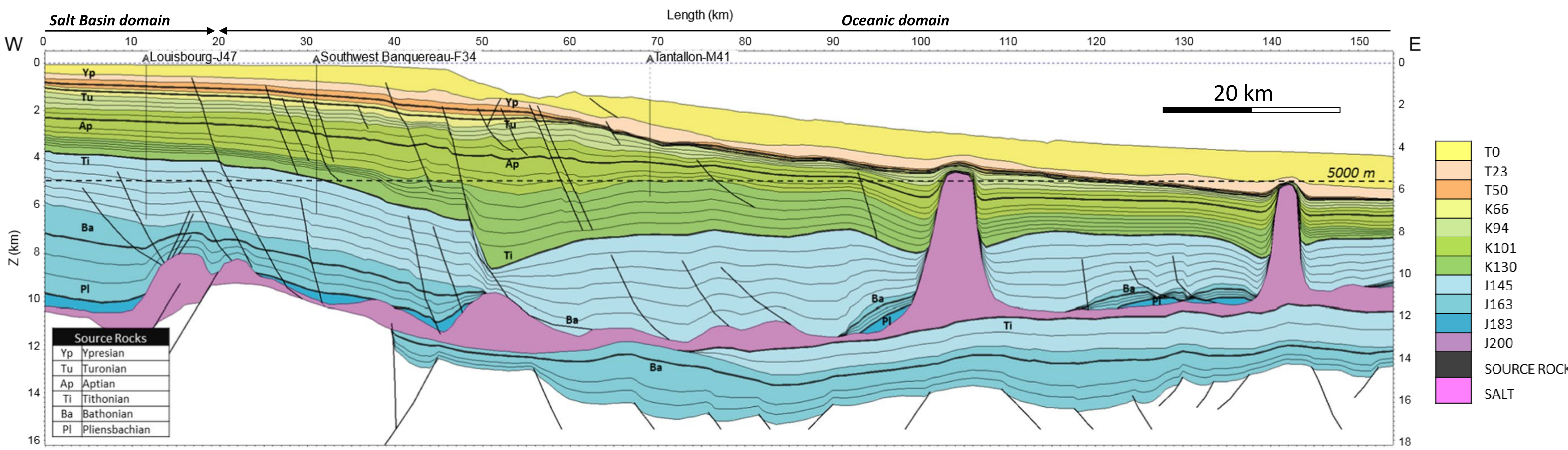
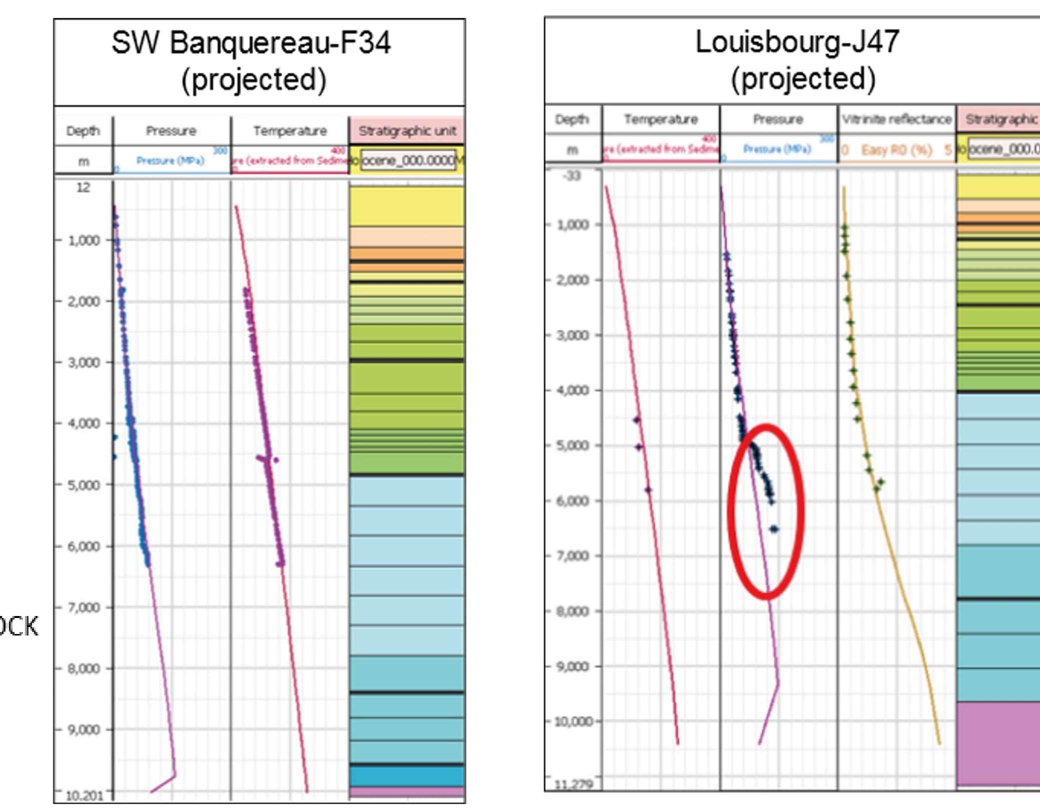


Figure 5.2.26: Stratigraphic framework of Transect T1 (Canada).



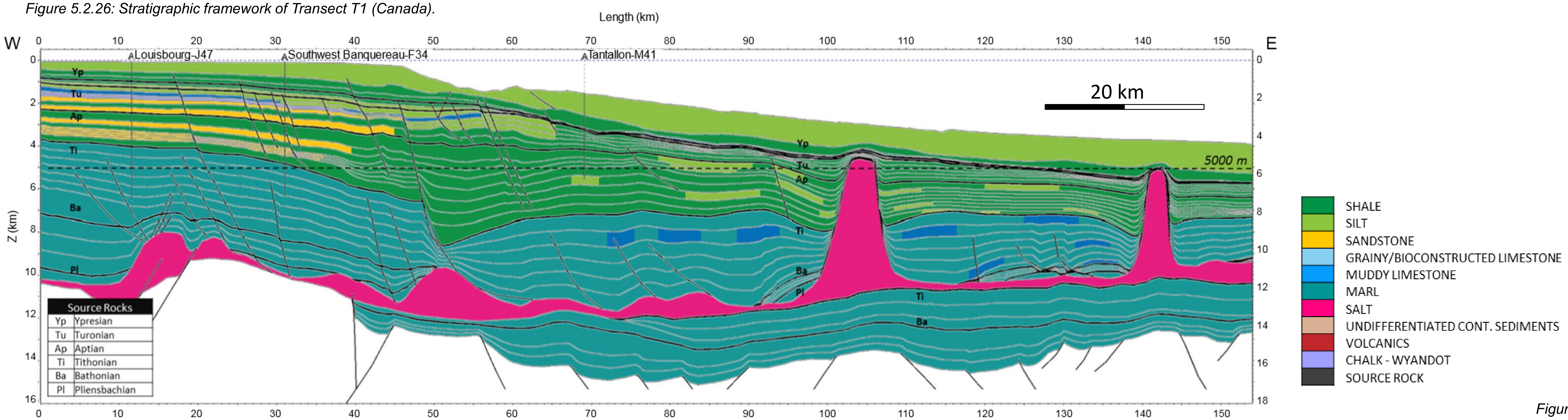


Figure 5.2.27: Facies model of Transect T1 (Canada).

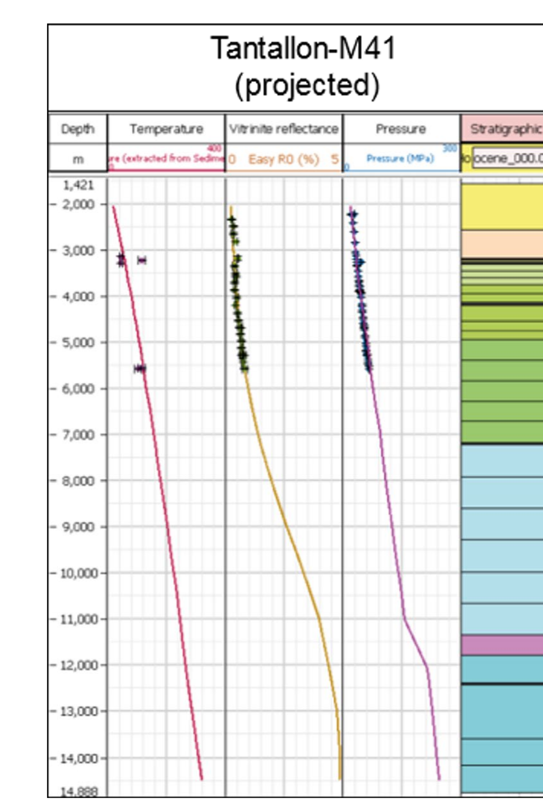


Figure 5.2.28: Thermal and maturity (vitrinite reflectance) of wells Louisbourg J-47, West Banquereau F-34 and Tantallon M-41.

Maturity results:

The Cretaceous and Cenozoic source rocks are immature across Transect T1 (Canada). Jurassic source rocks have maturity ranging from immature to overmature (Fig. 5.2.29).

Sub-salt source rocks (e.g., Bathonian and Tithonian ones) are in a very mature stage and lay in the condensate / wet gas to overmature windows (Fig. 5.2.30). These source rocks reached their peak of expulsion as early as the Lower Cretaceous from 145 to 105 Ma.

Above salt canopy, the maturity of the Pliensbachian and Bathonian source rocks is also high (dry gas to overmature at the western end of the transect above the salt basin) but gradually decreases seawards (condensate / wet gas window). The peak of expulsion of these source rocks was reached between the Upper Jurassic (ca 150Ma) and Upper Cretaceous (ca 90 Ma).

The Tithonian source rock remains in the oil window along most of the transect but has not reached its peak of expulsion at present day.

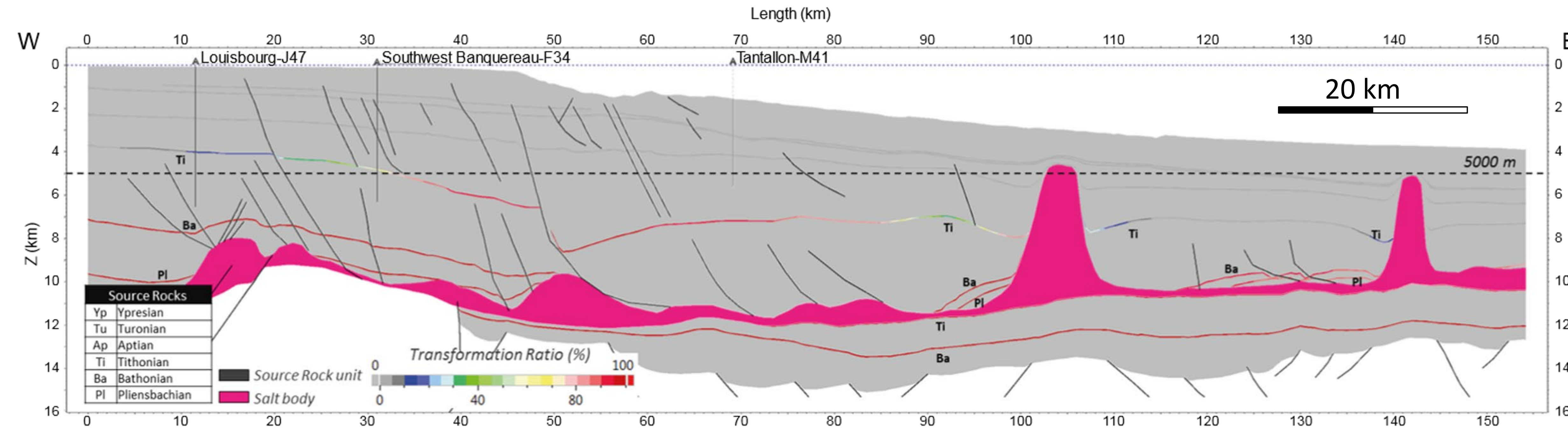


Figure 5.2.29: Simulated transformation ratio for Transect T1 (Canada).

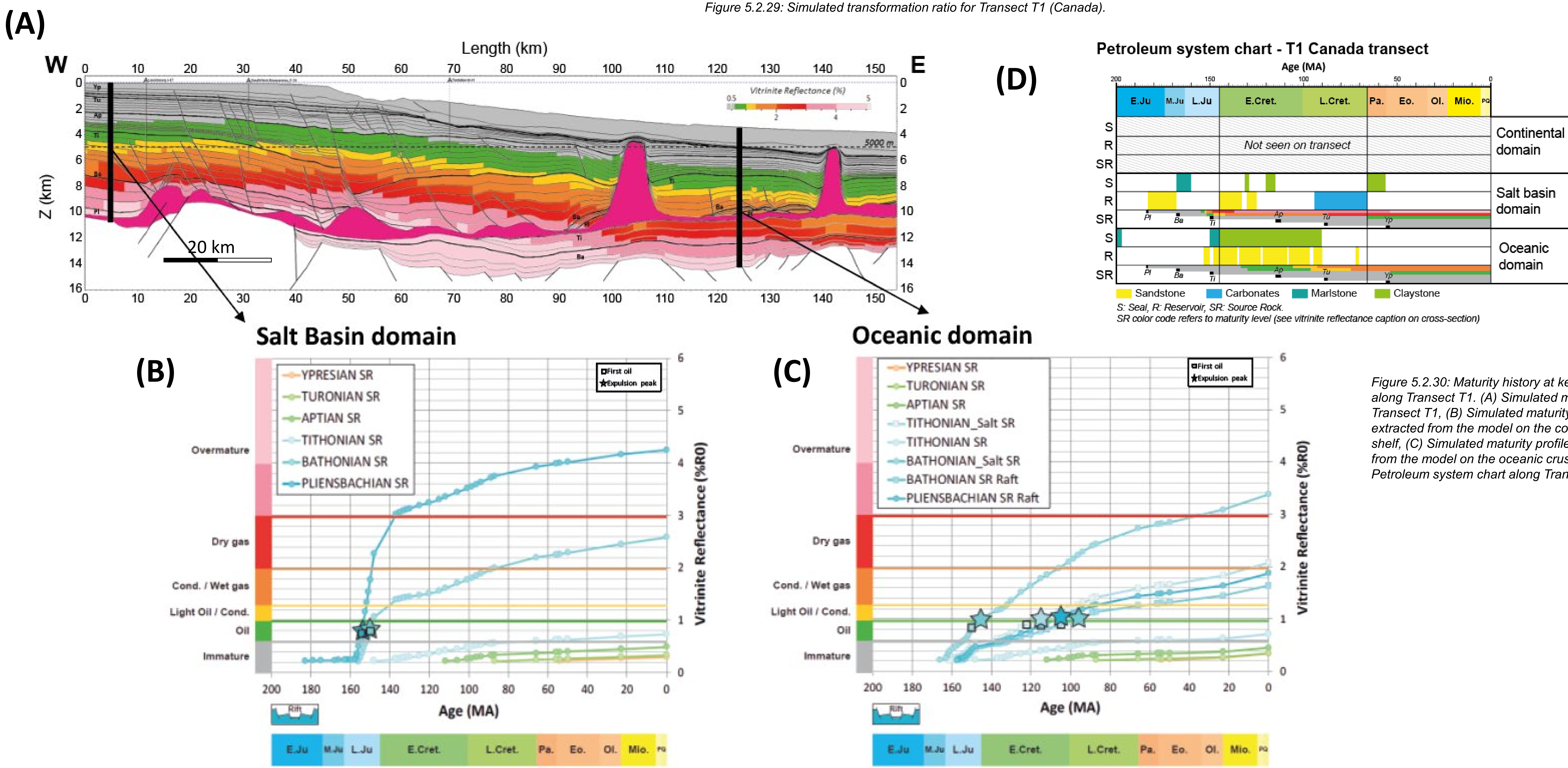


Figure 5.2.30: Maturity history at key locations along Transect T1. (A) Simulated maturity for Transect T1, (B) Simulated maturity profiles extracted from the model on the continental shelf, (C) Simulated maturity profiles extracted from the model on the oceanic crust. (D) Petroleum system chart along Transect T1.

Modeling of the T1 Canada transect – Maturity

Calibration of transect T2 Canada:

Transect T2 (Canada) is located the southern part of the Sable Sub-basin (Fig. 5.2.31). As noted for Transect T1 Canada, the main structural feature of Transect T2 is the complex salt geometries involving a roho system, salt diapirs and salt canopy. Salt kinematics was primarily triggered by clastic sediments supplied by the Lower Cretaceous Mississauga delta system. Due to the southward migration of the deltaic system, salt deformation was controlled by the Balvenie Synkinematic Wedge formed during Lower Cretaceous.

The facies dress-up of Transect T2 Canada was performed using available well data. The Jurassic interval is filled with platform to deep-marine carbonates. A reef system is interpreted at the edge of the shallow marine platform, separating micritic shallow-marine carbonates (shelfal lagoon) from deep-water marly facies. The Lower Cretaceous interval was interpreted as a prograding deltaic sequence with sandstones deposited up to the shelf edge and claystones in deeper waters. Above the Aptian interval the depositional system was dominated by claystones except in the Coniacian-Ypresian interval during which chalk deposition occurred.

Thermal and maturity calibration was achieved on four wells (Fig. 5.2.34) and a good match was found between simulated and observed temperature and vitrinite reflectance.

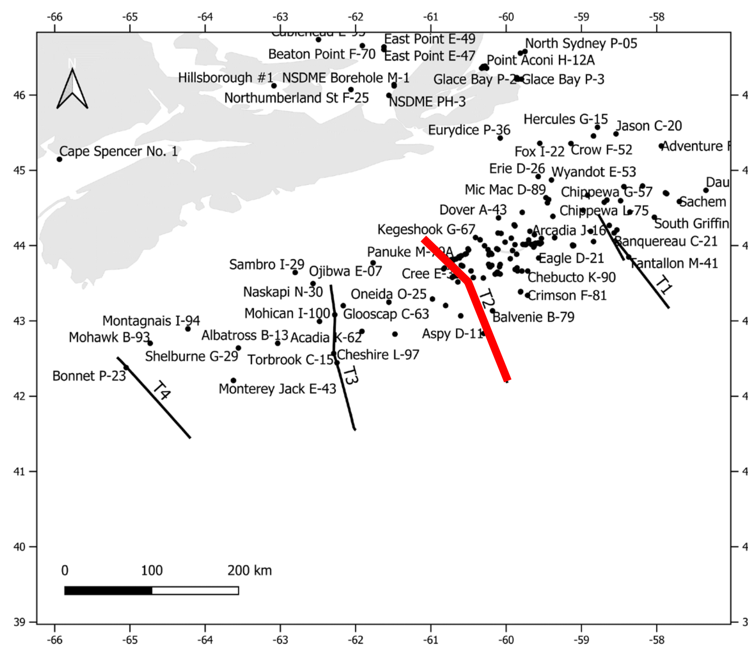


Figure 5.2.31: Location of T2 Canada.

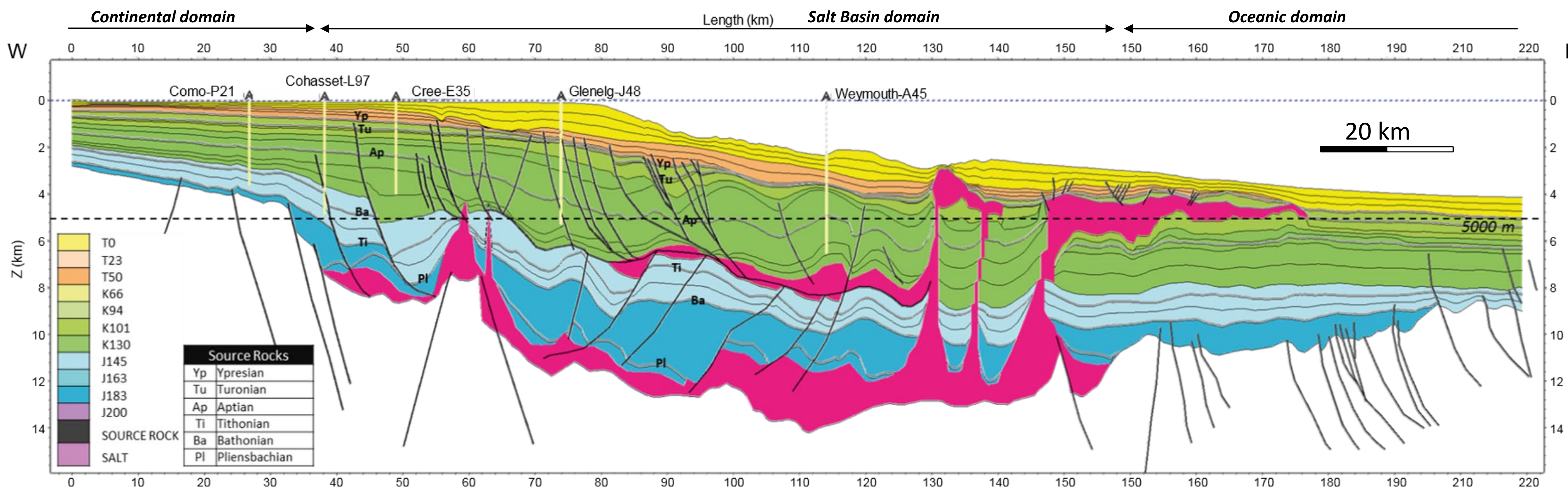


Figure 5.2.32: Stratigraphic framework of Transect T2 (Canada).

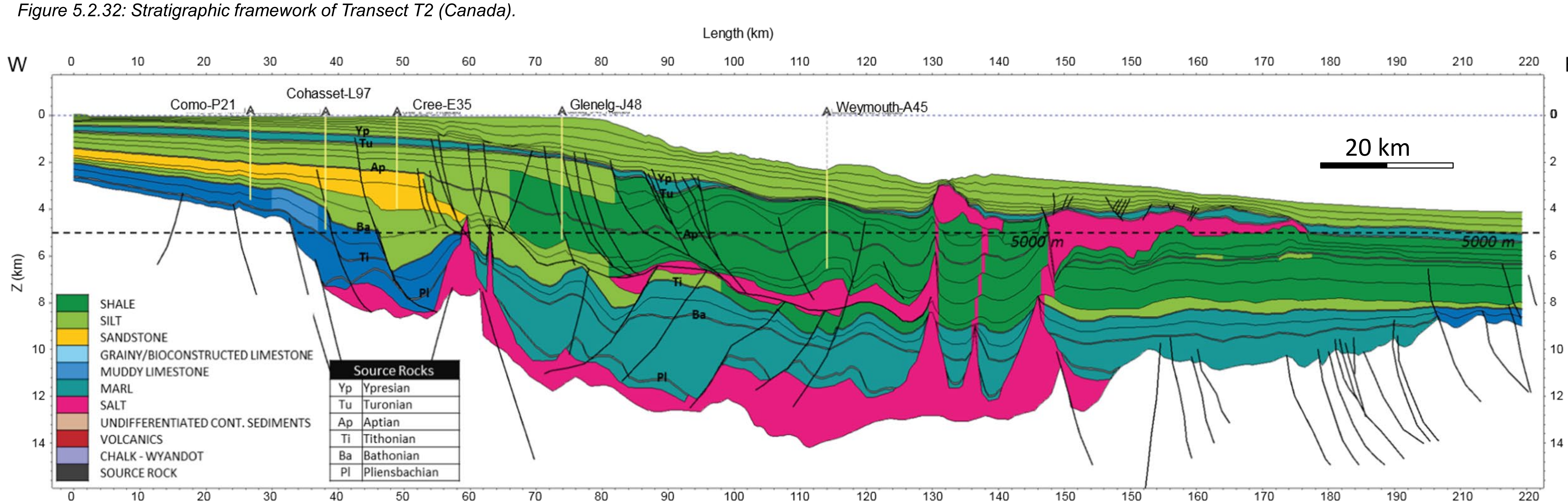


Figure 5.2.33: Facies model of Transect T2 (Canada).

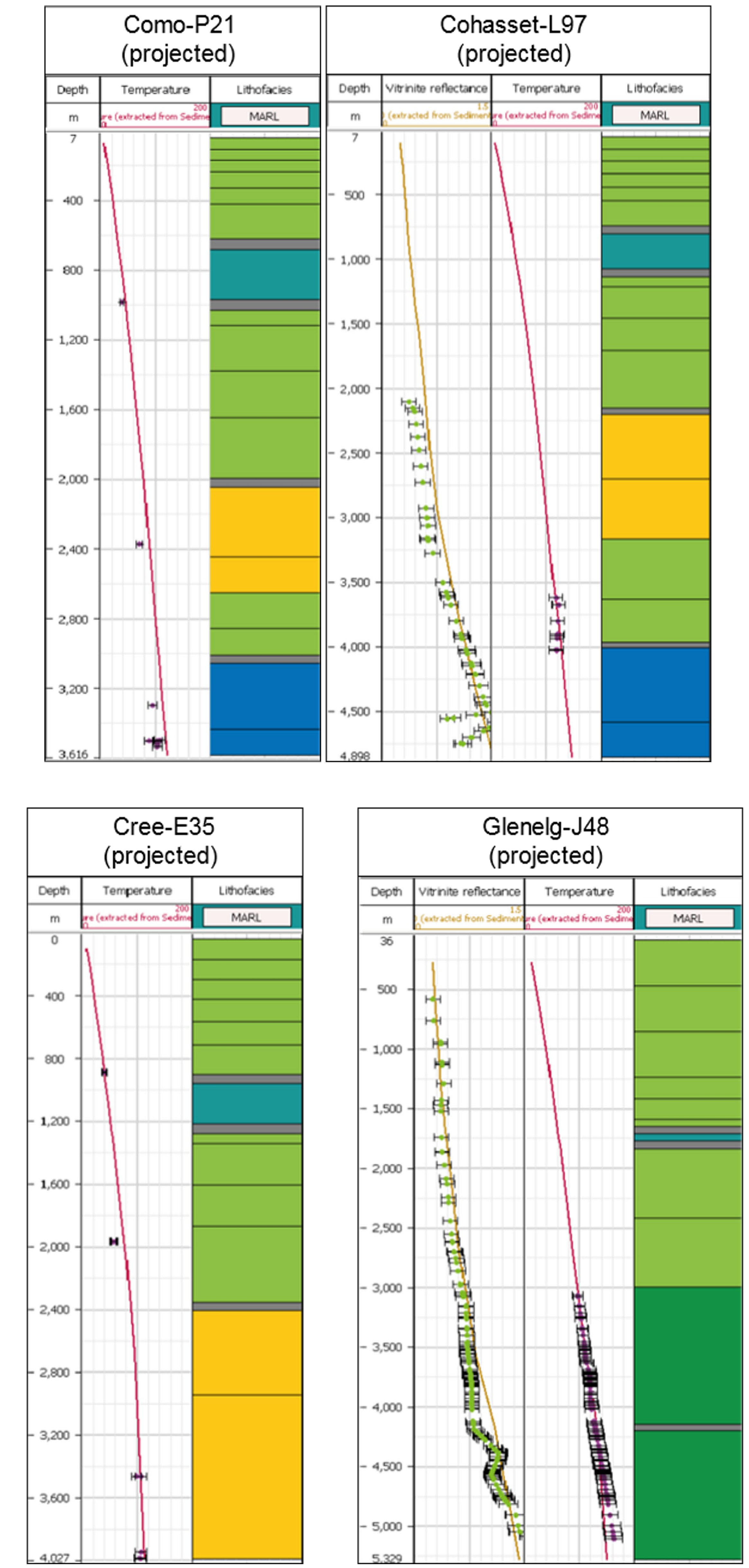


Figure 5.2.34: Thermal and maturity (vitrinite reflectance) of wells Como P-21, Cohasset L-97, Cree E-35 and Glenelg J-48.

Maturity results:

Cenozoic and Upper Cretaceous potential source rocks are immature along this section.

The maturity of older formations depends on the structural location: relatively low maturity level in the shallow continental domain (light oil window at best), much higher maturity in the very thick salt basin domain (up to 14km of sediments), intermediate maturity level (decreasing to the east) in the oceanic domain. This section is characterized by a very high sedimentation rate during the Jurassic and Cretaceous related to development of the Mississauga delta.

Both Lower and Middle Jurassic potential source rocks are overmature in the core of the salt basin domain, since the Lower Cretaceous. Due to this extreme maturity level acquired a long time ago the probability of finding gas related to these source rocks (if any) is low except toward the margin of the salt basin.

The Tithonian SR which is proven on the shelf in the area is often within the gas window at present day, locally within the light oil-condensate window at the edge of the continental domain and possibly in the oceanic domain (deep offshore). It is usually assumed to be the main source of Sable Sub-basin gas and oil fields. Potential Lower Cretaceous source rock associated with the same deltaic system would be within the oil window, almost reaching the light oil window in the deepest areas.

In the core of the salt basin peak hydrocarbon generation occurred before the end of the Early Cretaceous; the maturity level has remained almost stable since that time. However a slight increase in maturity is observed at the transition between the continental domain and the salt basin where the petroleum systems might continue to show some activity until today (for example around Cohasset and Cree).

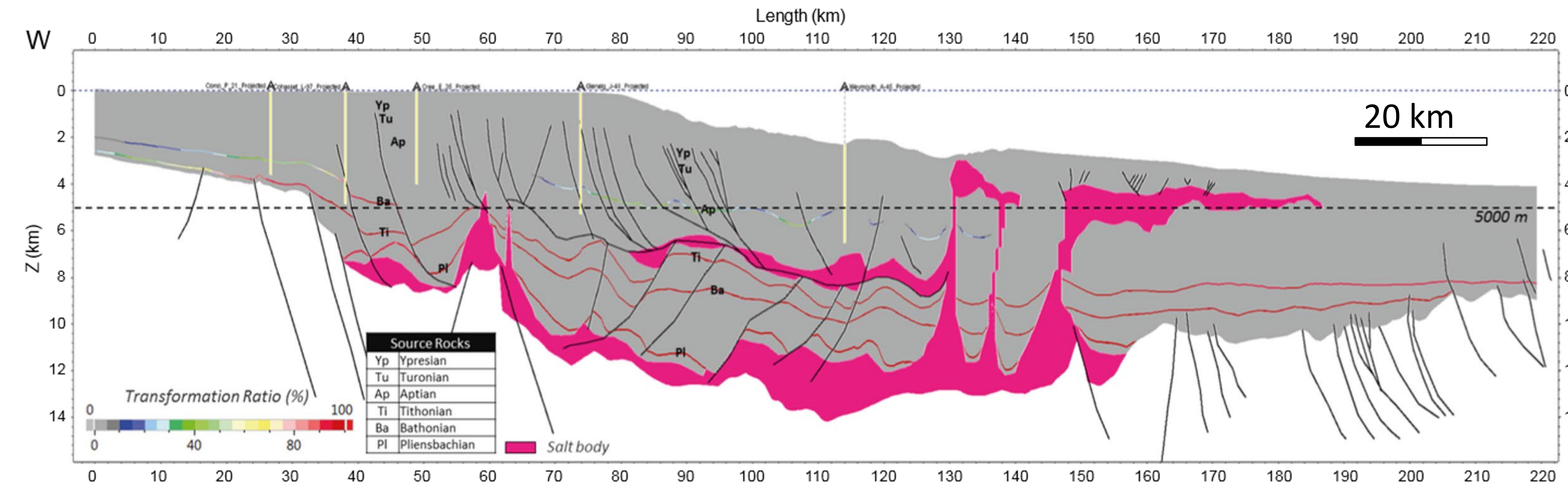
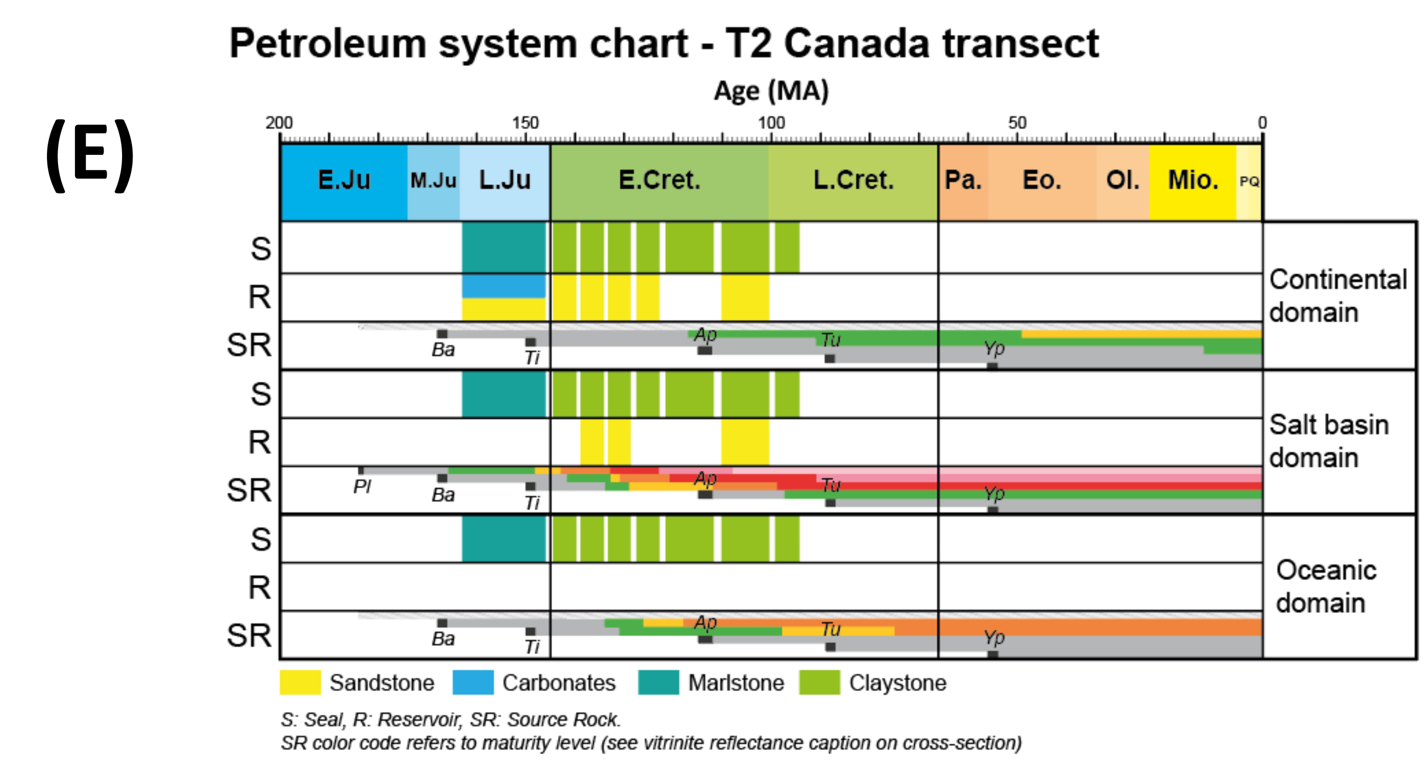
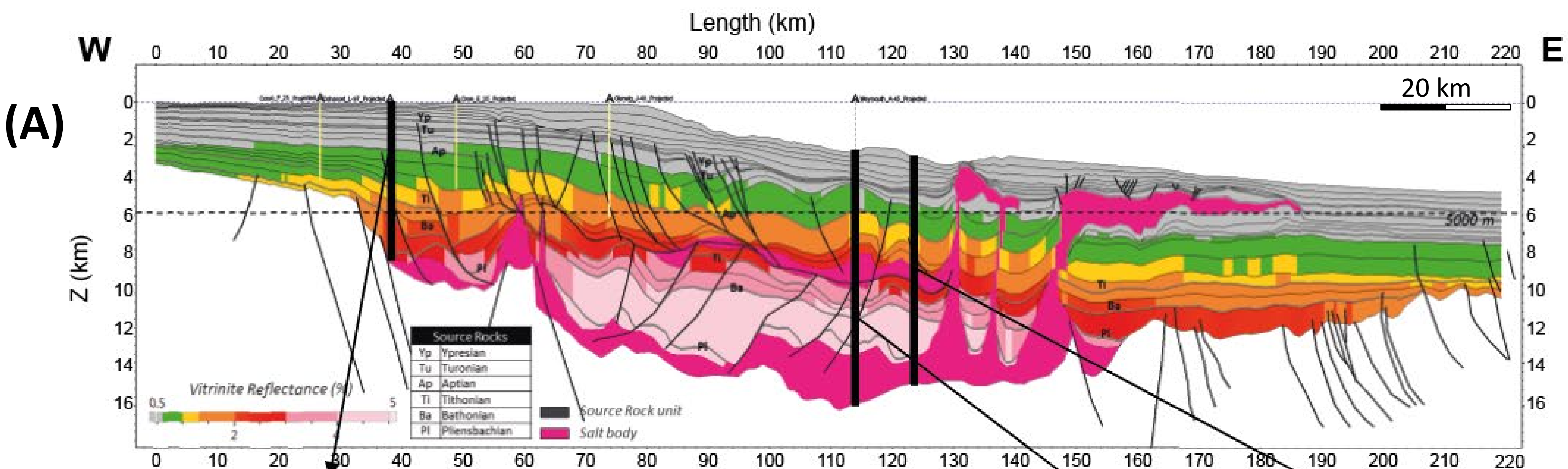


Figure 5.2.35: Simulated transformation ratio for Transect T2 (Canada).





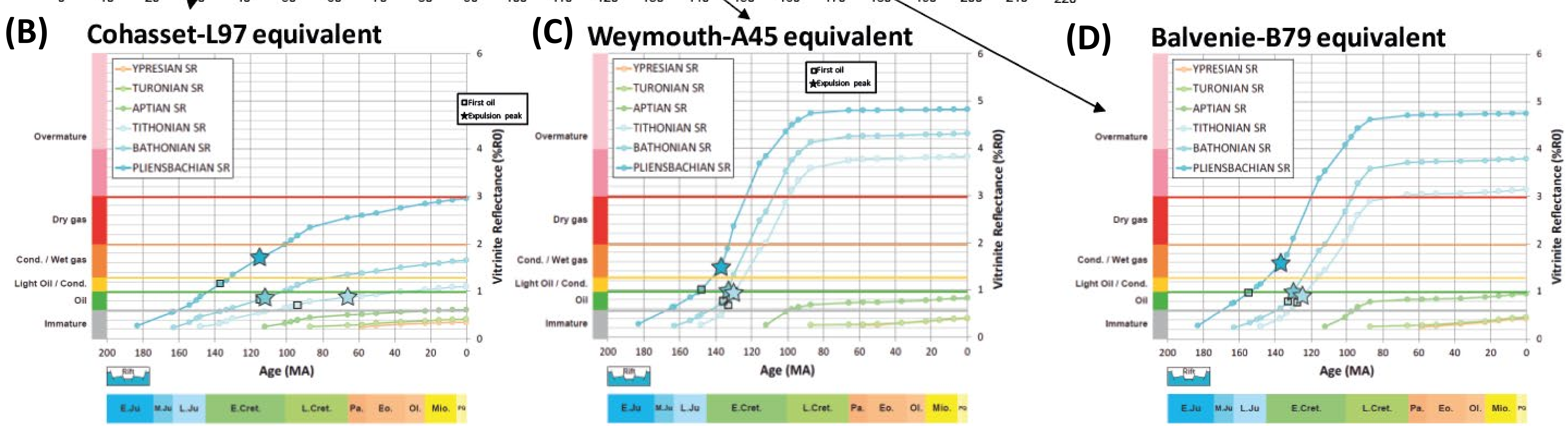


Figure 5.2.36: Maturity history at key locations along Transect T2. (A) Simulated maturity for Transect T2, (B) Simulated maturity profiles extracted from the model on the inner border of the salt basin, at Cohasset-L97 well location, (C) Simulated maturity profiles extracted from the model in the salt basin at Weymouth-A45 well location, (D) Simulated maturity profiles extracted in the salt basin near Balvenie-B79 well location, (E) Petroleum system chart along Transect T2.

Transect T3 Canada: Geological setting & calibration

Transect T3 (Canada) is in the Shelburne Sub-Basin (Fig. 5.3.37). The salt basin is nearly 90 km wide and deformation mainly consists in diapirs. Seaward the salt basin is terminated by a salt canopy of limited extension on top of the Continent Ocean Boundary. In the deep offshore beyond the present-day slope overburden reaches 7 km over the salt basin and less than 5 km on the shelf.

The facies dress-up highlights four main lithostratigraphic megasequences. The Jurassic interval was dominated by carbonates. Recently drilled deep-offshore Monterey Jack E-43 and Cheshire L-97 wells indicated that shallow-marine carbonates extended far over the salt basin. Two episodes of shallow-marine carbonate sedimentation are interpreted in the lowermost Jurassic and the Middle Jurassic. The Upper Jurassic interval marked the onset of a reef system (Baccaro Member of the Abenaki Formation) which set-up at the inner edge of the salt basin domain. Lower to Upper Cretaceous sedimentation was clastic-dominated (mostly claystones). Chalk was deposited during the Uppermost Cretaceous and Lowermost Cenozoic. Oligocene and Miocene sediments consist mostly in claystones and siltstones.

Thermal and maturity calibration was achieved on five wells (Fig. 5.2.40) and a good match was found between simulated and observed temperature, pressure and vitrinite reflectance.

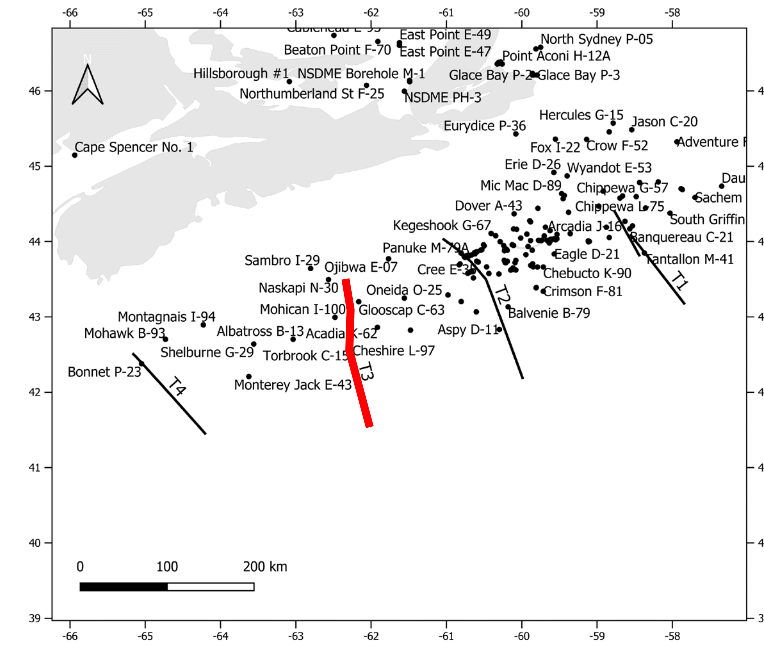


Figure 5.2.37: Location of T3 Canada.

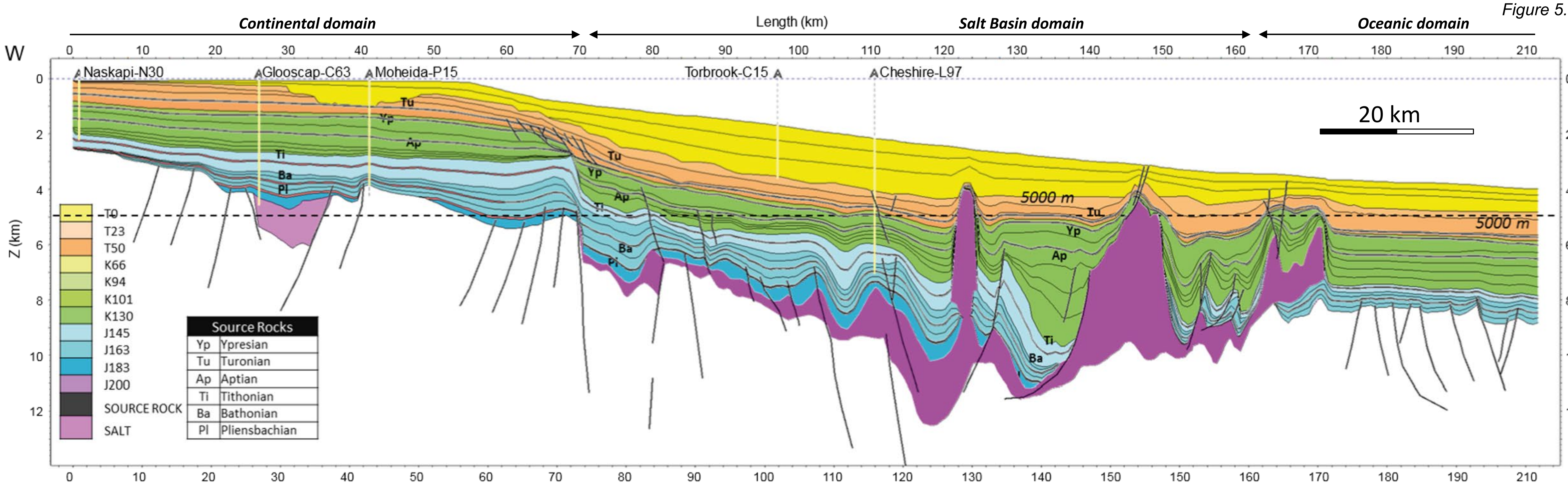


Figure 5.2.38: Stratigraphic framework of Transect T3 (Canada).

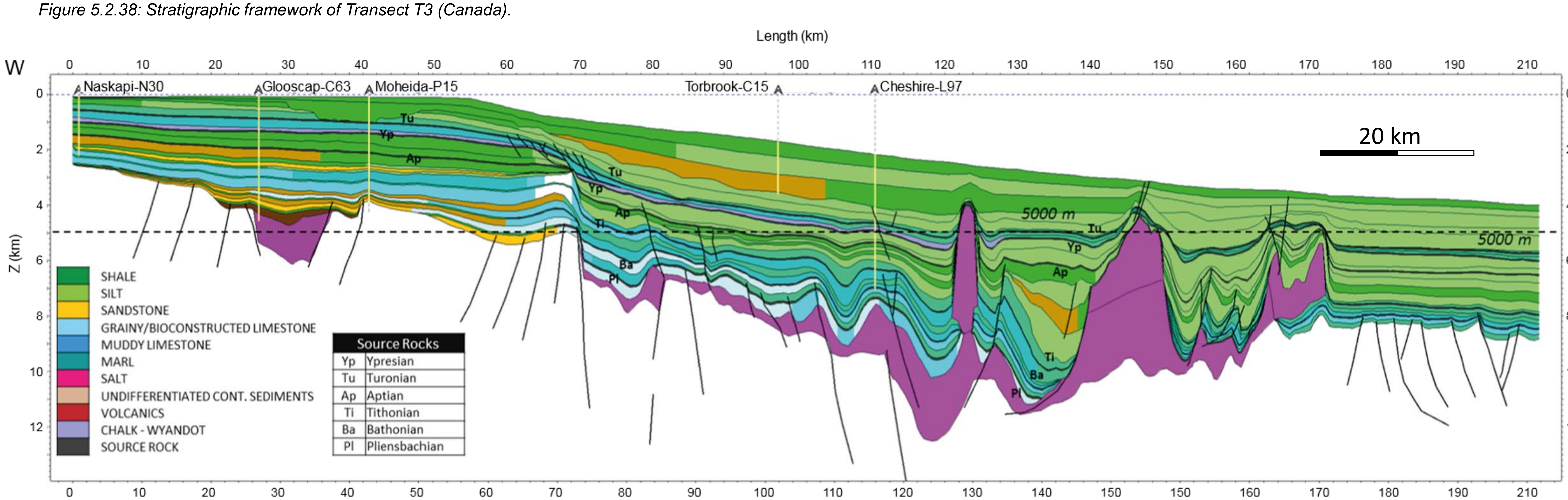


Figure 5.2.39: Facies model of Transect T3 (Canada).

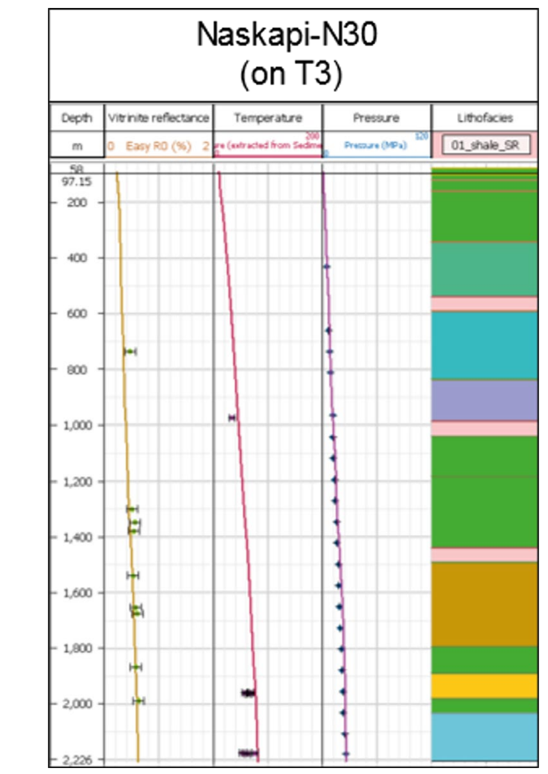
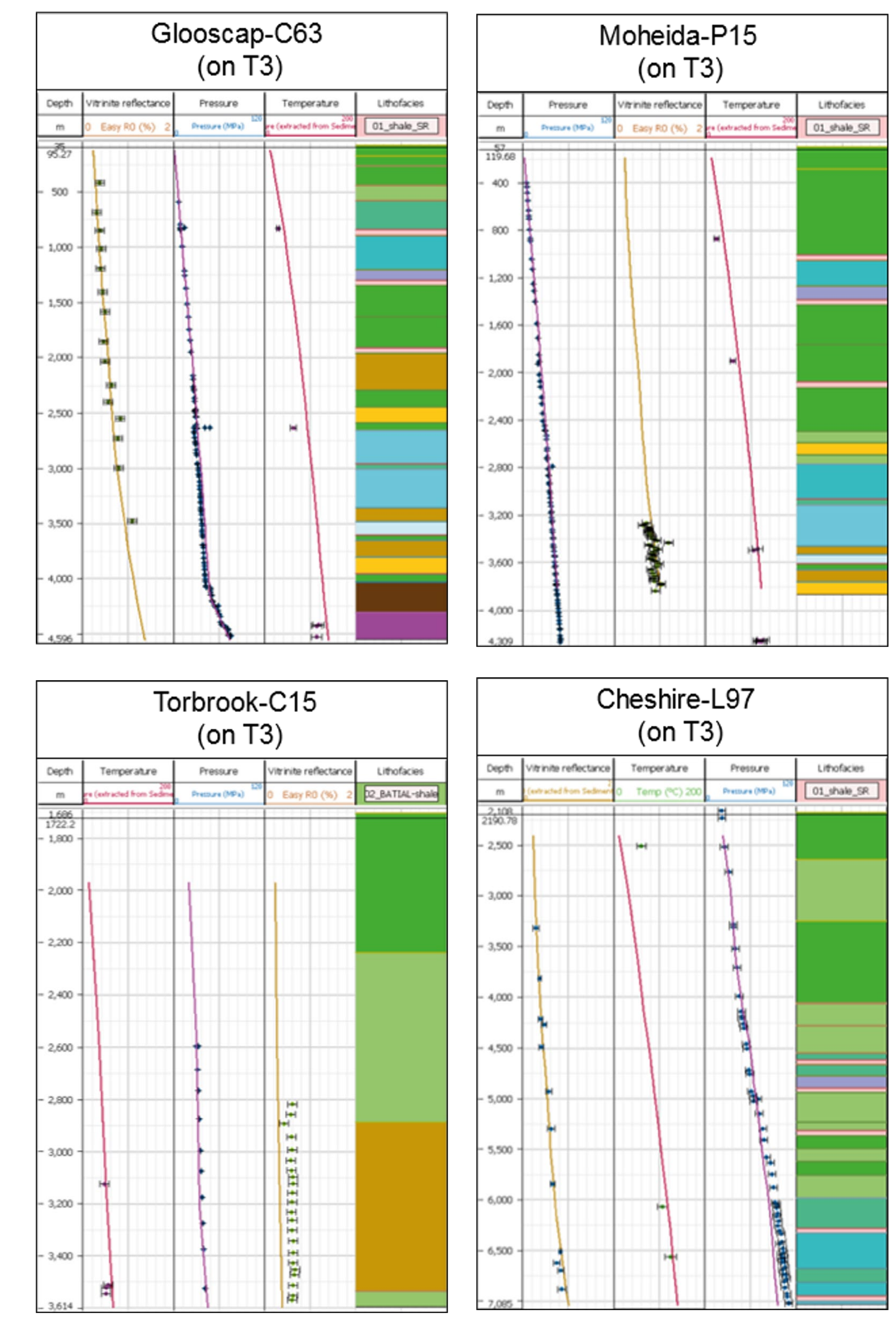



Figure 5.2.40: Thermal and maturity (vitrinite reflectance) of wells Naskapi-N30, Glooscap-C63, Moheida-P15, Torbrook-C15 and Cheshire-L97.

Maturity results:

At a given stratigraphic layer the maturity level is quite homogeneous along this section, just a bit higher in the “Salt Basin domain” at least within salt mini-basins.

- Cenozoic and Cretaceous potential source rocks are immature.
- The Tithonian would be within the oil window except in the deepest salt mini-basins where it could reach the wet gas window.
- Middle Jurassic units are often within the light oil / condensate window locally, in the wet gas window within the salt mini-basins and the oil window in the continental domain.
- Potential Lower Jurassic source rocks would be at present day within the light oil / condensate or the wet gas window.

The maturity level is generally lower than along other studied sections mainly due to the lower burial depths (relatively “starved” margin between Mississauga and Shelburne deltas). A striking element is the progressive increase of the maturity level since the Cretaceous until present day both in the continental domain and in the salt basin domain. In the salt basin domain there is even a sharp increase of the maturity level during the Neogene, which is quite specific to this part of the Shelburne basin. Although the oil window was reached early during the Cretaceous, it means that potential Lower Jurassic petroleum systems (if any) would be still active at present day.

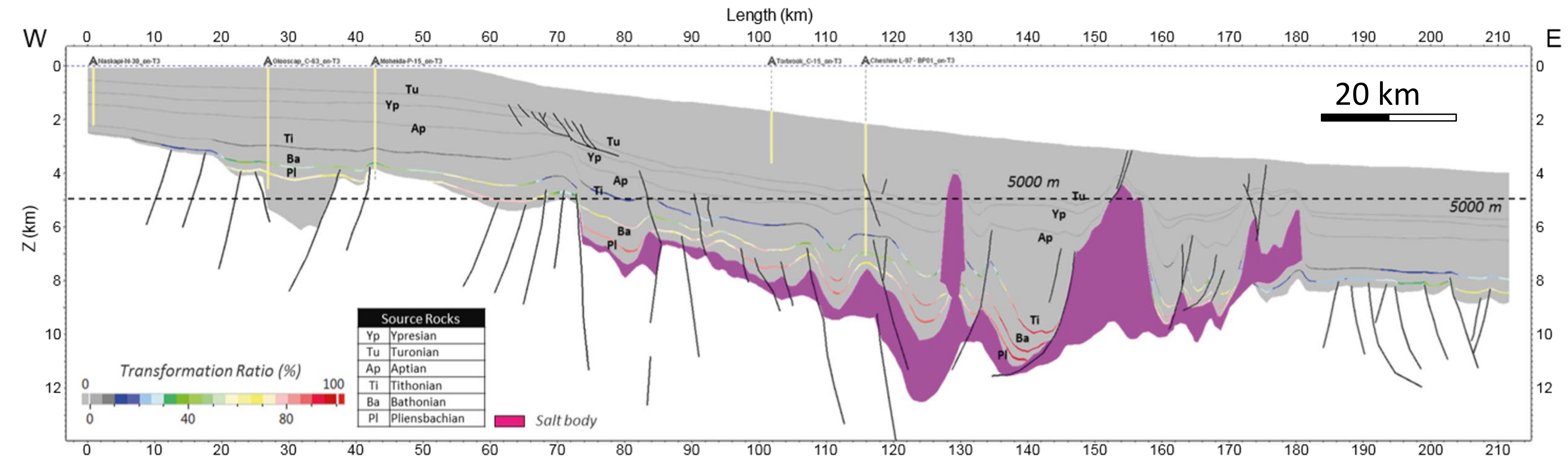
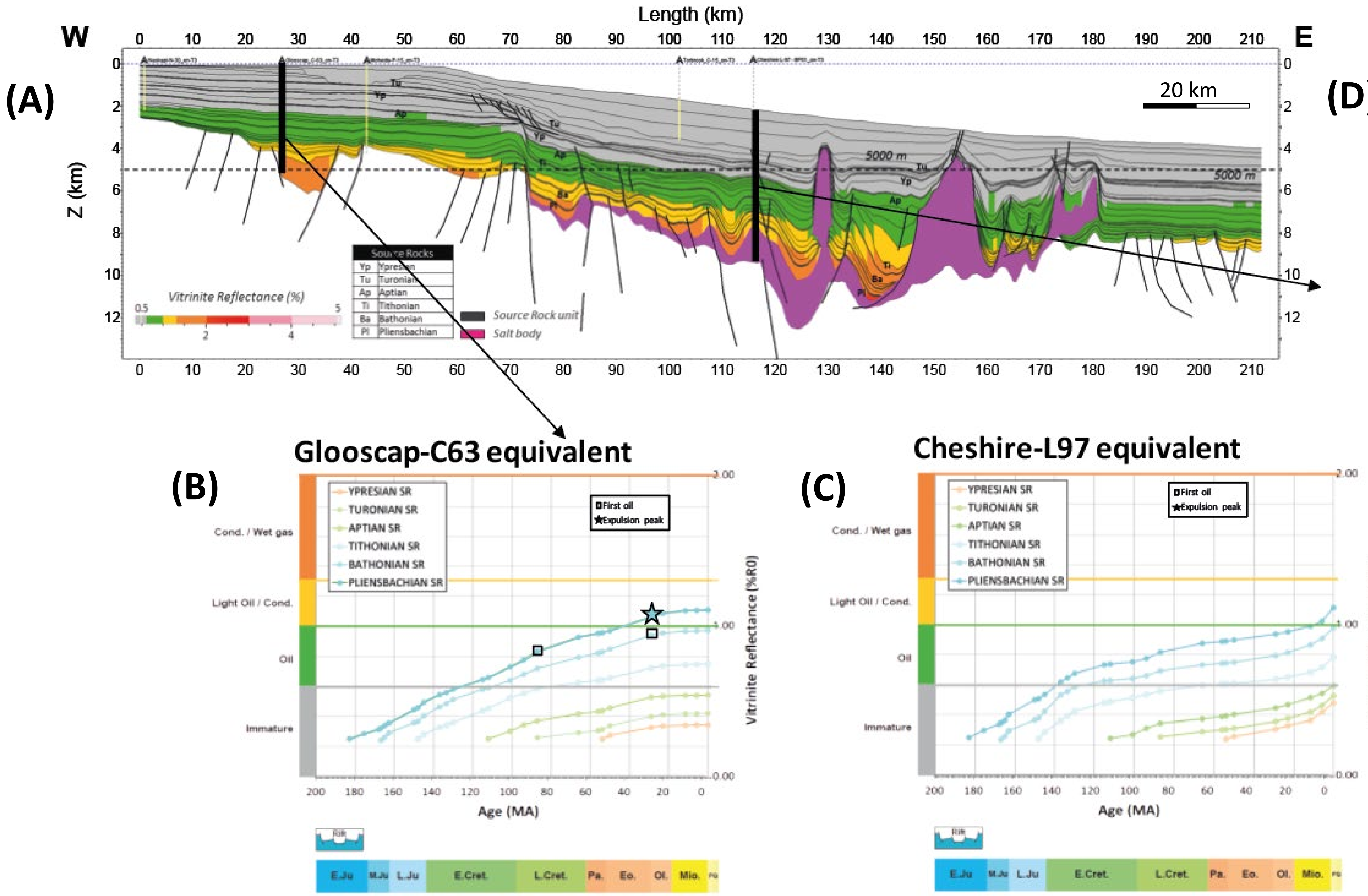


Figure 5.2.41: Simulated transformation ratio for Transect T3 (Canada).



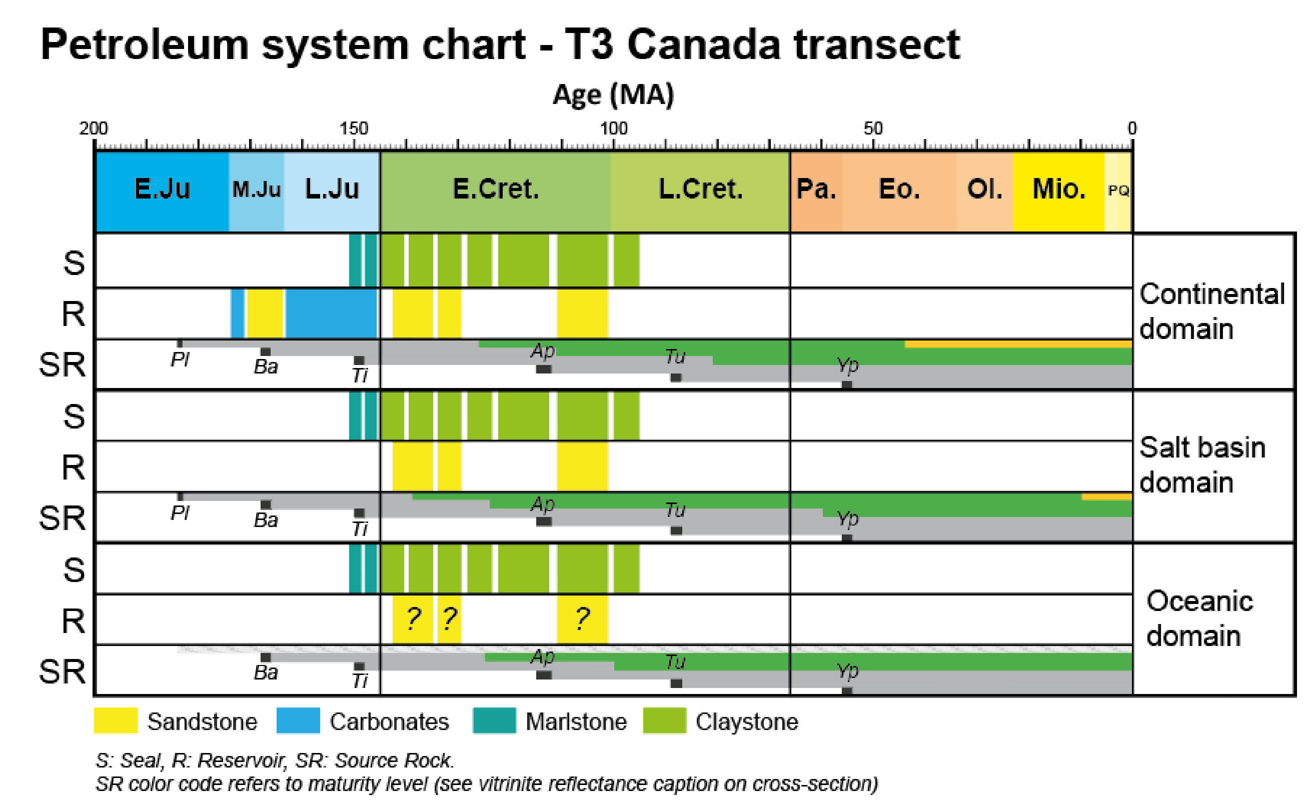


Figure 5.2.42: Maturity history at key locations along Transect T3. (A) Simulated maturity for Transect T3, (B) Simulated maturity profiles extracted from the model on the rifted continental crust, at Glooscap-C63 (projected), (C) Simulated maturity profiles extracted from the model in the salt basin in a position equivalent to Cheshire-L97 well, (D) Petroleum system chart along Transect T3.

Transect T4 Canada: Geological setting & calibration

Transect T4 (Canada) is located near the southern end of the Scotian Margin at the limit between Georges Bank and the Shelburne Sub-Basin (Fig. 5.2.43). The three structural domains (continental, salt basin and oceanic) are depicted along the 140 km long transect. Salt geometries consist in diapirs reaching Neogene strata and a salt canopy extending above the terminal horst at the Continent Ocean Boundary (Fig. 5.2.44). The main stratigraphic feature recorded along Transect T4 is the major Eocene regional unconformity which cuts down into the Cretaceous series at the continental shelf edge. This major erosional surface is interpreted as the mass failure that resulted from the Montagnais bolide impact dated 50.5 MA (Jansa and Pe-Piper, 1987). The Cretaceous shelf edge collapsed upon impact and the Cenozoic continental shelf gradually rebuilt on top of the unconformity from the Oligocene.

The post-Lower Jurassic facies dress-up was based on well Bonnet-P23 which is located on the Transect. Lower Jurassic series were tentatively interpreted from deep-water wells Cheshire-L97 and Monterrey Jack-E43 drilled further east in the Shelburne Sub-Basin (see Shelburne Sub-basin postmortem analysis 2019 report). In this scheme Lower Jurassic platform carbonates were expected to extend over the salt basin domain beyond the Upper Jurassic rimmed platform. Two episodes of shallow-marine carbonate sedimentation (Lowermost Jurassic and Middle Jurassic) are tentatively interpreted considering the regional sedimentary record particularly on the Moroccan margin. The Upper Jurassic sedimentary record is characterized by the development of a reef system (well Bonnet-P23) which lasted until Aptian times. In the deep-water domain sedimentation became clastic-dominated during the Lower Cretaceous with some possible turbidite fans trapped in minibasins isolated by salt diapirs. Upper Cretaceous and Cenozoic deposits mostly comprise claystones and minor siltstones.

Thermal regime was calibrated on well Bonnet-P23 data (Fig. 5.2.46). Simulated pressure, vitrinite reflectance and temperature could be satisfyingly calibrated on observed data. However a Lower Cretaceous thermal event had to be simulated in order to match vitrinite reflectance measured in the Middle Jurassic interval of Bonnet-P23. This event corresponds to an increase of the regional heat flow caused by the Montegerian hotspot (see South West Nova Scotia Expansion, Beicip, 2015 report).

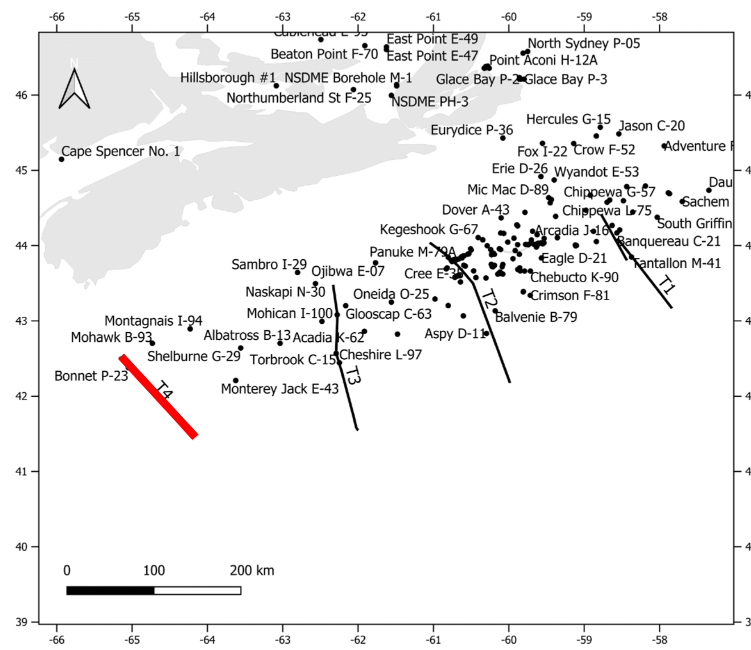


Figure 5.2.43: Location of T4 Canada.

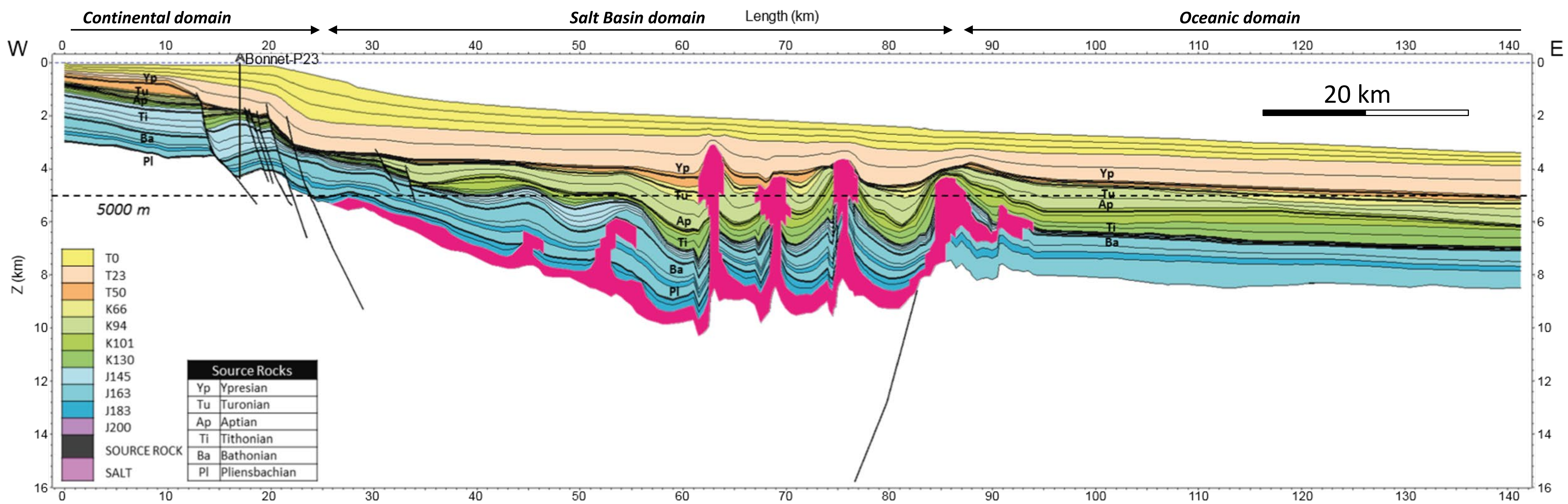
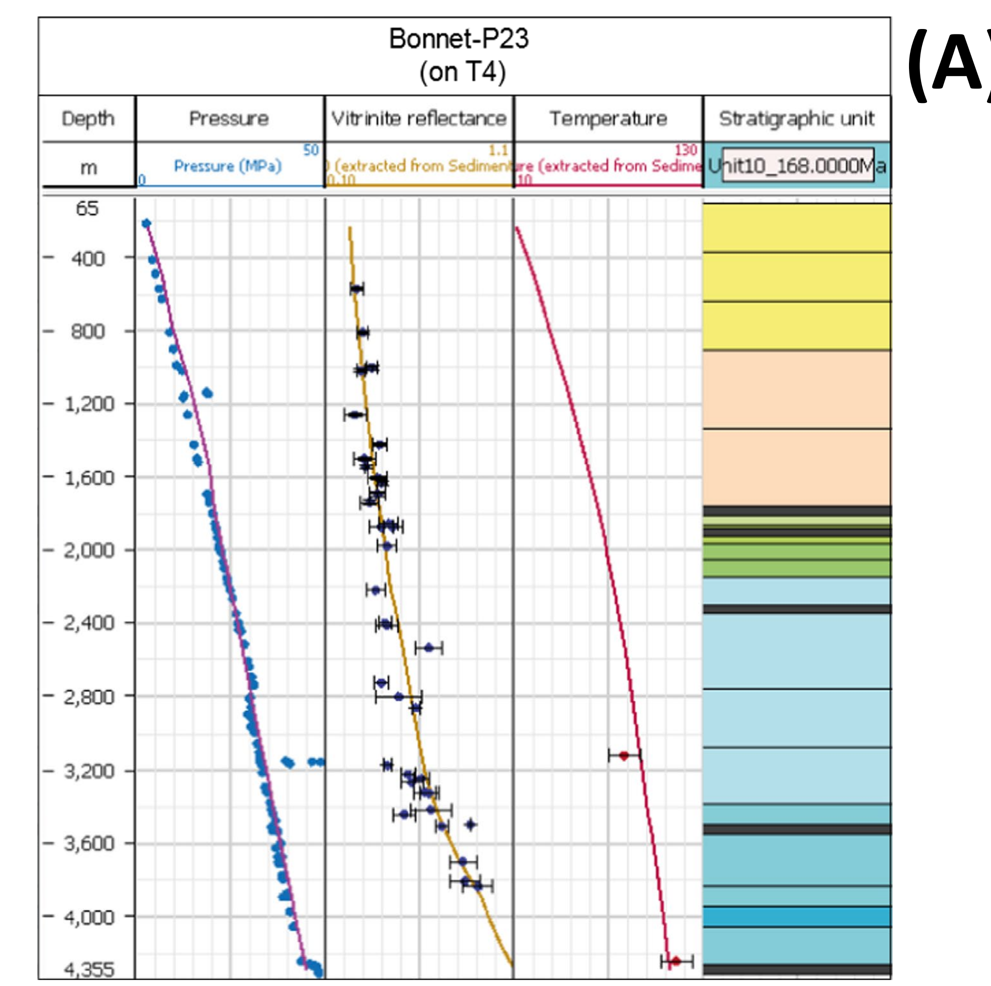


Figure 5.2.44: Stratigraphic framework of Transect T4 (Canada).



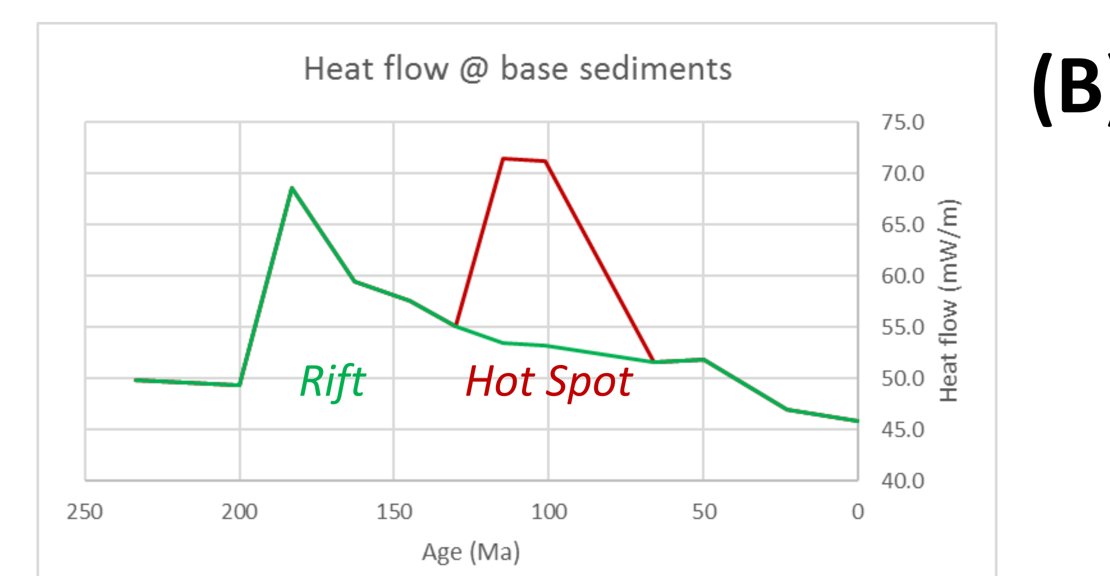


Figure 5.2.46: (A) Thermal and maturity (vitrinite reflectance) of well Bonnet P-23; (B) Heat flow model used to calibrate on observed vitrinite reflectance data at well Bonnet P-23.

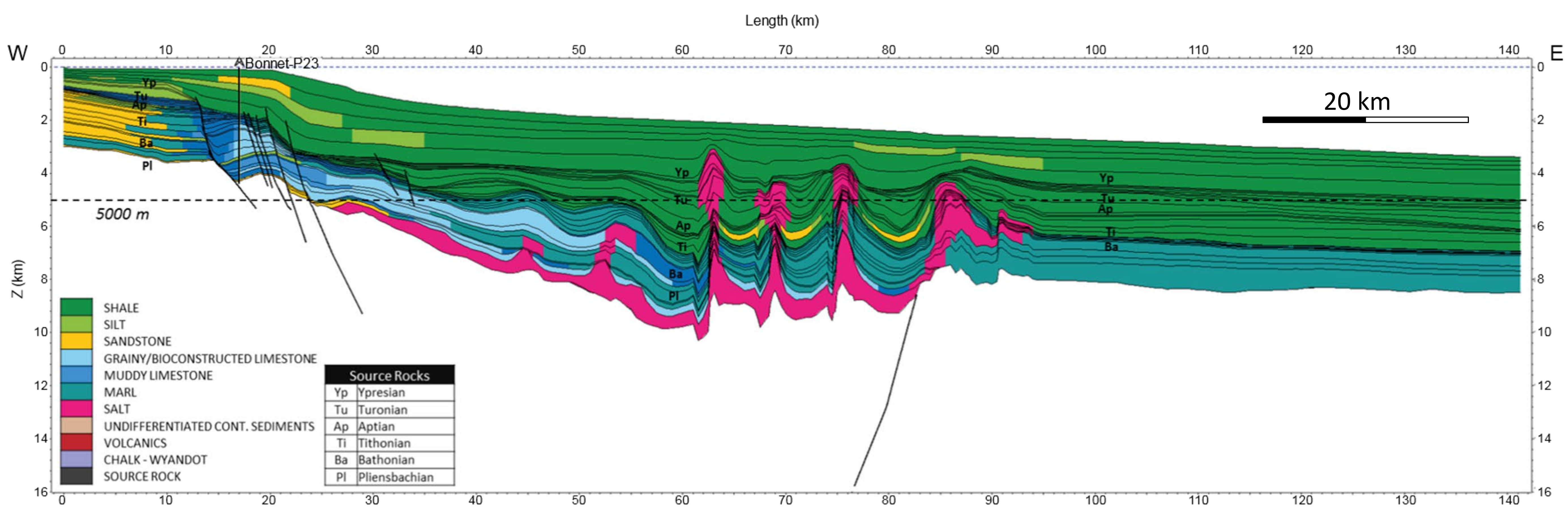


Figure 5.2.45: Facies model of Transect T4 (Canada).

Maturity results:

The Cretaceous and Cenozoic source rocks are immature all along transect T4 Canada, except for the Aptian member which is locally early mature to mature within salt-related mini-basins. At those locations, the Aptian source rock has gone past the expulsion peak (Fig. 5.2.47).

Jurassic source rocks remain immature overall in the oceanic domain due to the low radiogenic nature of the crust and over the shelf where sediment thickness is limited (Fig. 5.2.48). Yet the deepest Jurassic source rock members over the shelf (Pliensbachian) and in the distal domain (Bathonian) are predicted to be have acquired some maturity and may source some oil if some initial potential is in fact attached to those levels.

In the salt basin area east of Bonnet-P23 well both the Pliensbachian and Bathonian source rocks are mature due to favorable thermal conditions there (a combined effect of a significant burial, the presence of a transitional crust and thermal conductivity of salt deposits). The two source rocks lay in the light oil to wet gas window (Fig. 5.2.48).

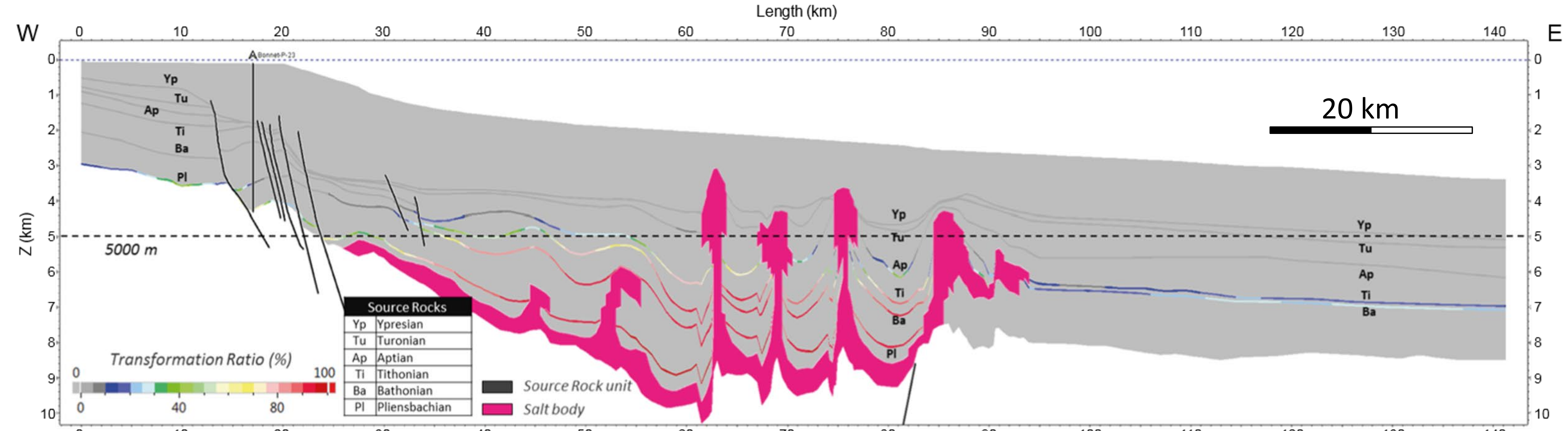
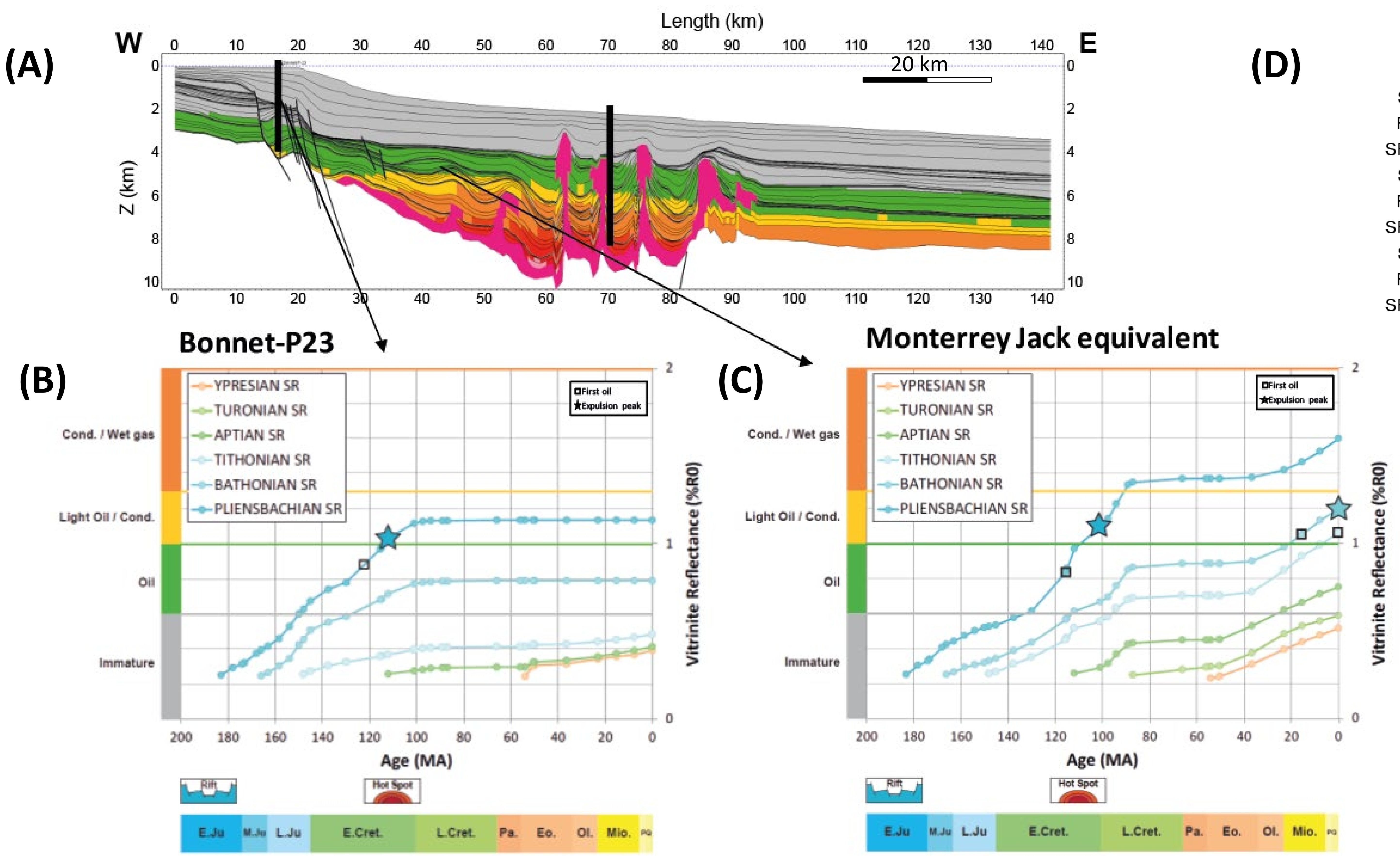


Figure 5.2.47: Simulated transformation ratio for Transect T4 (Canada).



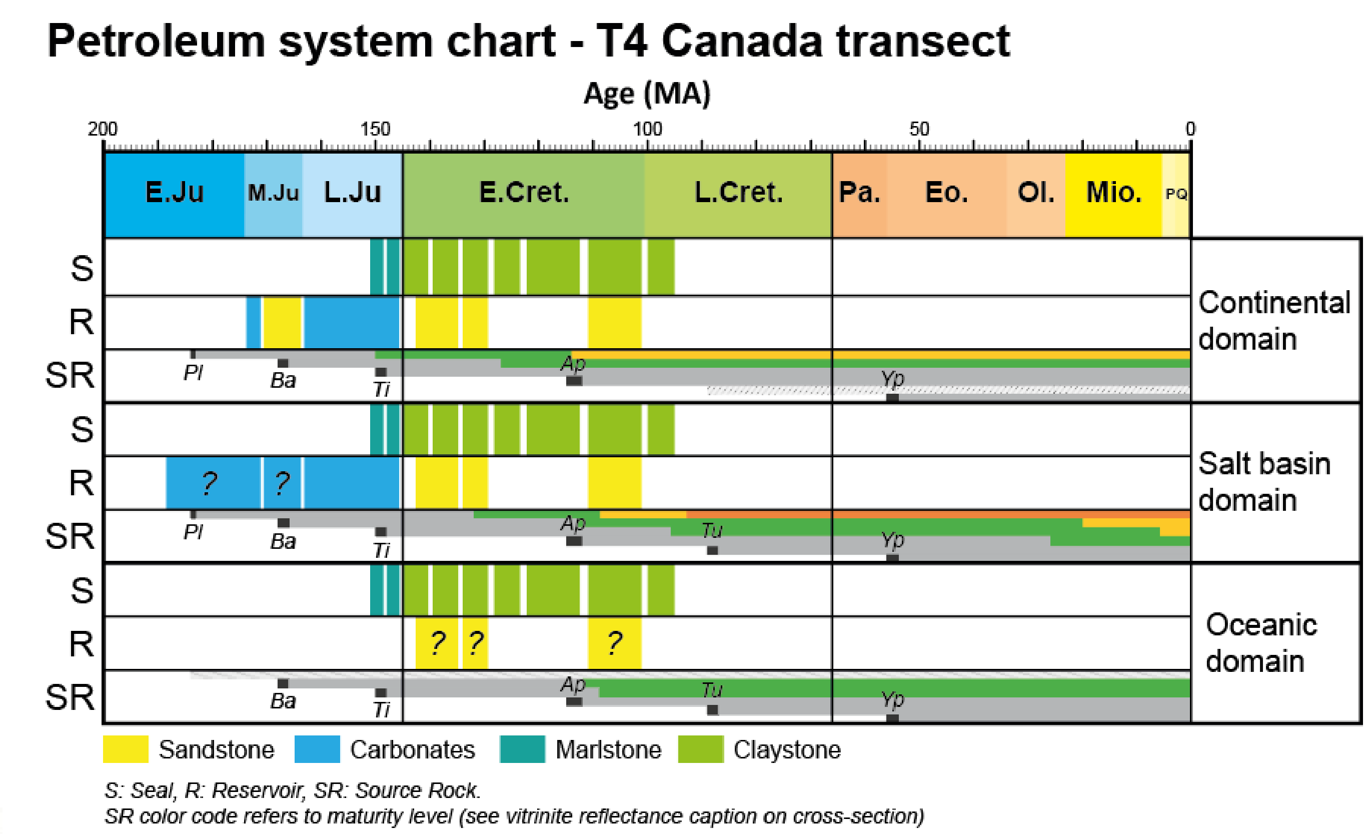
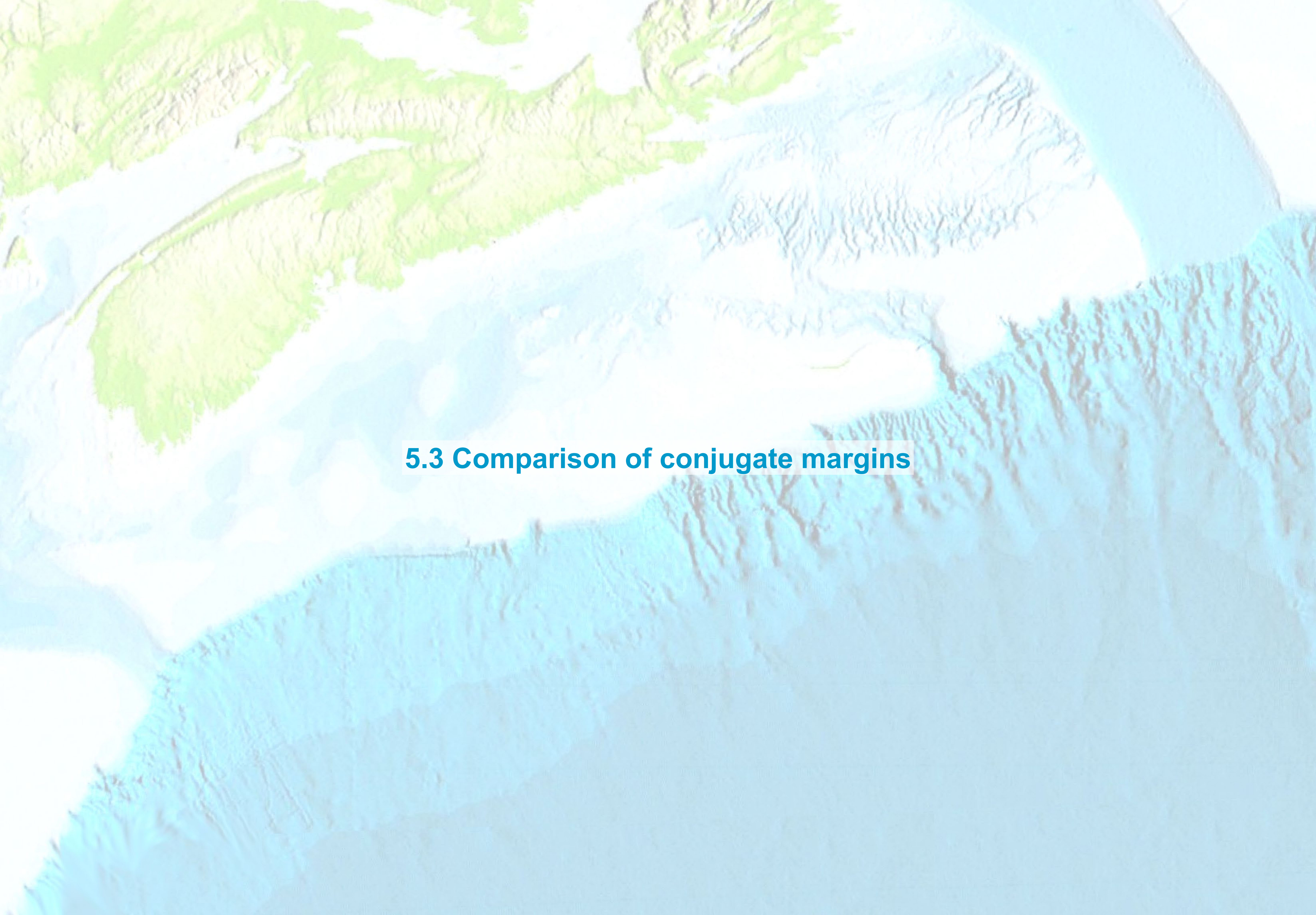


Figure 5.2.48: Maturity history at key locations along Transect T4. (A) Simulated maturity for Transect T4, (B) Simulated maturity profiles extracted from the model at the faulted edge of the continental crust domain, at Bonnet-P23 well location, (C) Simulated maturity profiles extracted from the model in the salt basin in a position equivalent to Monterrey Jack-E43 well, (D) Petroleum system chart of Transect T4.



5.3 Comparison of conjugate margins

T1 mega-regional transect (Fig. 5.3.1 & Fig. 5.3.2):

Comparing T1 maturity regimes at present day on both sides of the margins allows the consistency of the thermal modeling results to be highlighted at both distal ends of the section. A striking feature is the hotter thermal regime simulated over Transect T1 Canada due to the thick sedimentary pile which is further increased by the presence of the Banquereau Synkinematic Wedge and of a salt basin developed all along the transect. The impact of the salt basin and of the related increase in burial on the maturity regime is clearly visible on Transect T1 Morocco where, outboard the salt, being over the oceanic domain or upslope towards the shelf, the maturity trend drops significantly up to a point where even the deepest petroleum systems become inefficient. Cenozoic and Cretaceous source rocks remain immature on both sides of the Atlantic. On the Canadian side Jurassic source rocks are proficient and even overcooked for the deepest of them, while they remain in the oil up to wet gas window over the salt basin on the Moroccan side.

T2 mega-regional transect (Fig. 5.3.1 & Fig. 5.3.3):

Opposite trends in overall overburden thickness are observed when comparing Transects T1 & T2: overall burial decreases slightly from north to south on the Canadian side moving from T1 to T2 as the sedimentary supply from the St Lawrence River starts to drop. On the other hand burial increases on Moroccan side, moving north to south from T1 to T2 and transitioning form the Essaouira to the Agadir basin. The impact on the thermal regime is significant on the Moroccan side as the maturity regime increases regionally. There, the deepest Jurassic source rocks lay now in the condensates to wet gas window over the shelf and reach the dry gas window over the salt basin. Cretaceous source rocks the Aptian unit lay in the oil window in the salt basin. Cathagenesis is, as for Transect T1, predicted to be very active on the big picture for Transect T2 Canada with the deepest Jurassic source rocks being overcooked in the salt basin, in the dry gas to condensate window in the bathyal domain and in the wet gas to early oil window on the shelf. While the Turonian and Ypresian source rock members remain immature trough Transect T1 Canada, the Aptian unit is locally mature over the salt basin, transitioning from the early oil window up to the condensate & wet gas window where its burial is maximized.

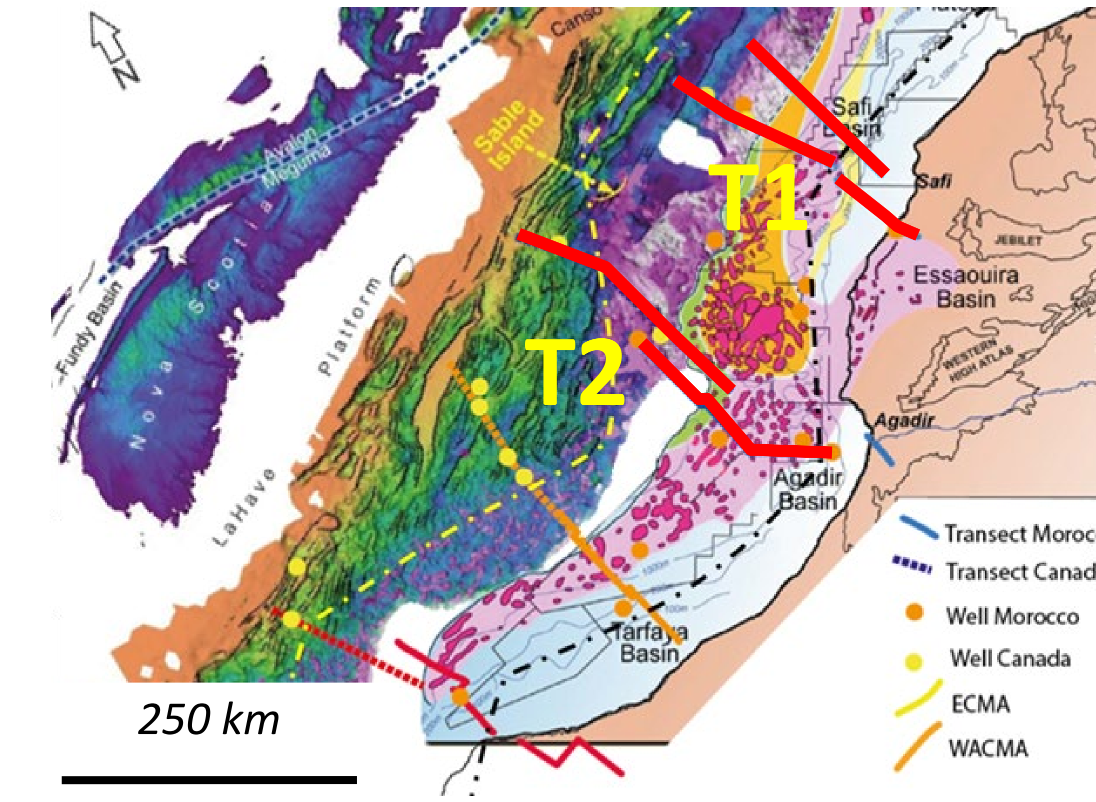


Figure 5.3.1: Position of conjugate transects. Plate reconstruction at 190 Ma (Deptuck and Altheim, 2018; Tari and Jabour, 2008).

Transect 1 Canada

Transect 1 Morocco

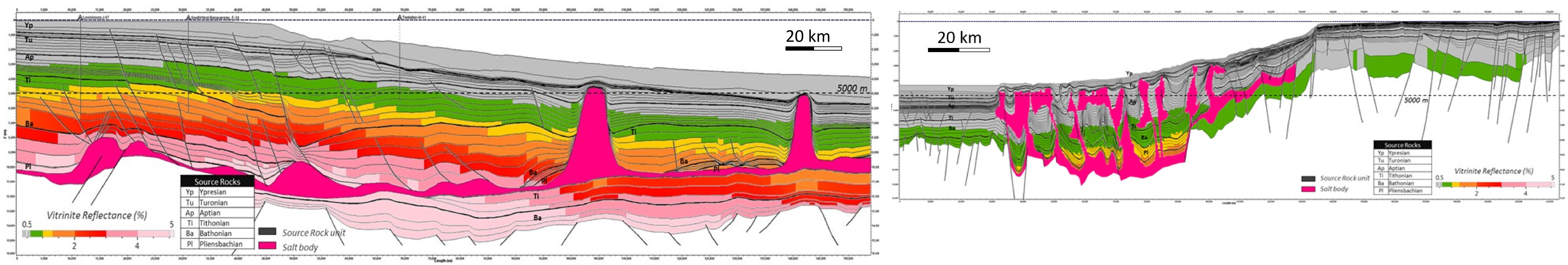


Figure 5.3.2: Source rock maturity windows on conjugate Transects 1.

Transect 2 Canada

Transect 2 Morocco

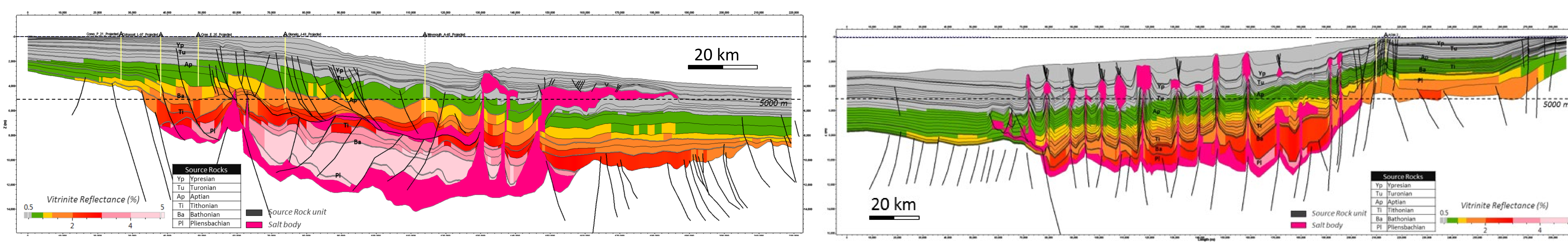


Figure 5.3.3: Source rock maturity windows on conjugate Transects 2.

T3 mega-regional transect (Fig. 5.3.4 & Fig. 5.3.5):

The global maturity trend continues to decrease on the Canadian side compared to Transects T1 & T2 as the sedimentary pile is thinner, overall. A reverse observation is made for Transect T3 where the thermal regime gets hotter as overburden increases. Located nearby the Tarfaya basin, Transect T3 Morocco highlights a restricted salt basin with limited diapirism & salt structure growth. Transect T3 Morocco experienced the thermal effect of the Canary hotspot which was more substantial on its western edge; the impact of this geological event is recorded in the maturity profile displayed below. The Cretaceous and Cenozoic source rocks remains immature across both transects. The Tithonian source rock lays in the oils window over the salt basin Canadian side, locally reaching the wet gas window where burial is maximized. It remains within the oil window Moroccan side except over the salt basin where it enters the wet gas bracket. The Bathonian and Pliensbachian source rocks remain in the condensates to wet gas window over the salt basin Canadian side while they achieve the dry gas window (even overcooked) in the salt province, Moroccan side, due to a maximum burial exceeding 10km. On the shelf and in the distal domain, Moroccan side, the deep Jurassic source rock remain in a more favorable maturity range (wet gas to condensates).

T4 mega-regional transect (Fig. 5.3.4 & Fig. 5.3.6):

The thermal regime of Transect T4 Canada follows a similar trend to Transect T3 except that it encompasses more of the oceanic domain and features an overall increase in burial, leading to a slight thermal stress rise over the salt province. Its western edge laying so close to the Canary islands, Transect T4, of all Moroccan transects, experiences the most severe thermal impact of the Canary province magmatism. Coupled to the dramatic thickness of the sedimentary pile (in excess of 11km at its deepest), this results in an excessively hot thermal regime on the western half of the salt basin. While the Ypresian and Turonian source rocks remain immature across both transects, the Tithonian is mature (early oil to late oil/condensates window) and may be proficient locally, on both sides of the Atlantic. The Tithonian is in the condensates / wet gas window on Canadian side while it progresses from being immature on the shelf to entering the dry gas window in the deepest parts of the salt basin, Moroccan side. The Pliensbachian and Bathonian are overcooked there; their maturity decreases gradually moving upslope and shelfward but they remain in the gas ranges. On Canadian side the deepest Jurassic source rocks remain in the wet to dry gas maturity ranges.

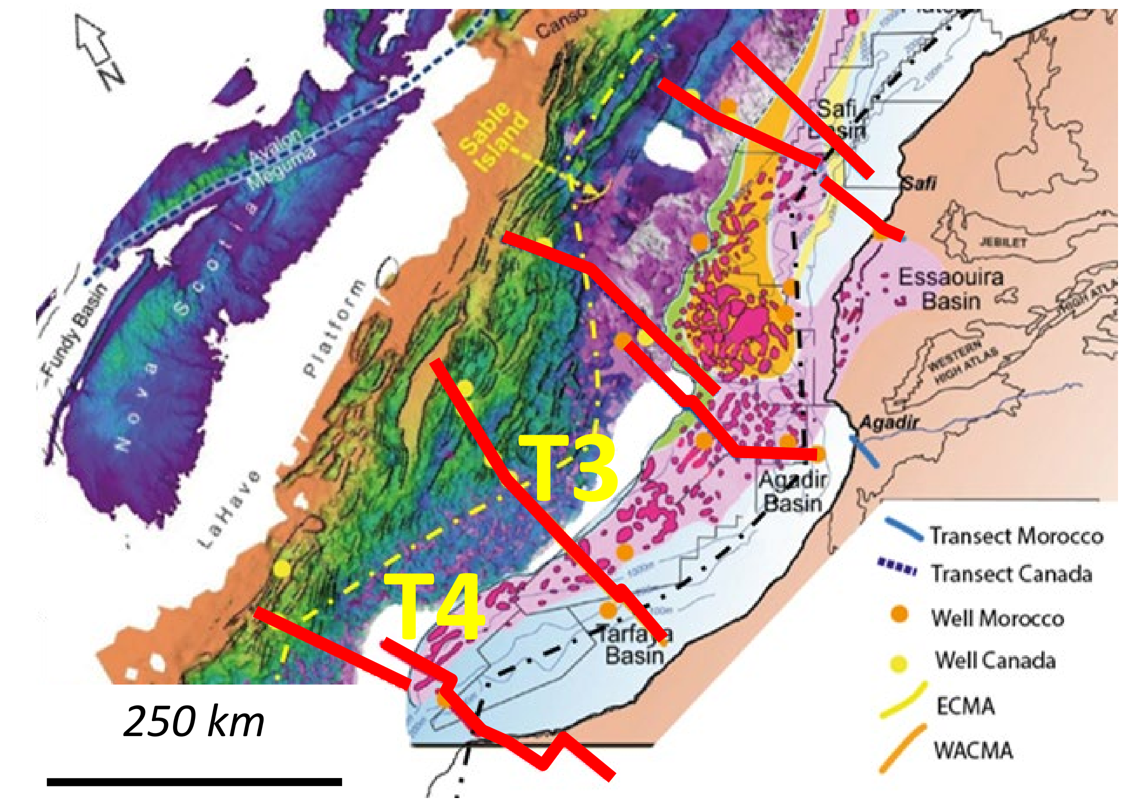
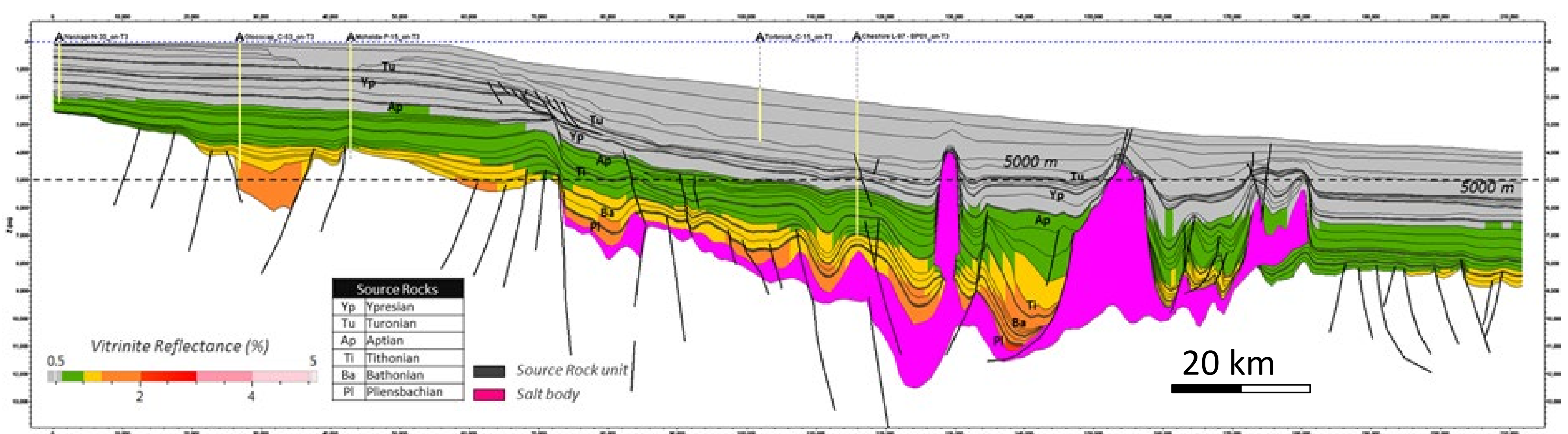


Figure 5.3.4: Position of conjugate transects. Plate reconstruction at 190 Ma (Deptuck and Altheim, 2018; Tari and Jabour, 2008).

Transect 3 Canada



Transect 3 Morocco

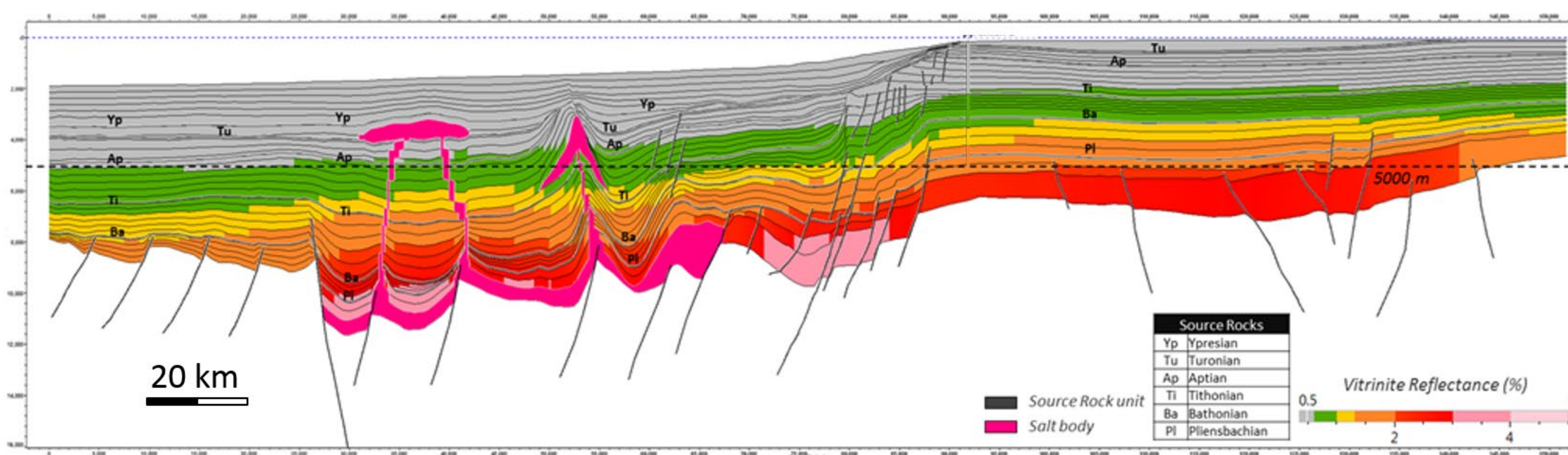
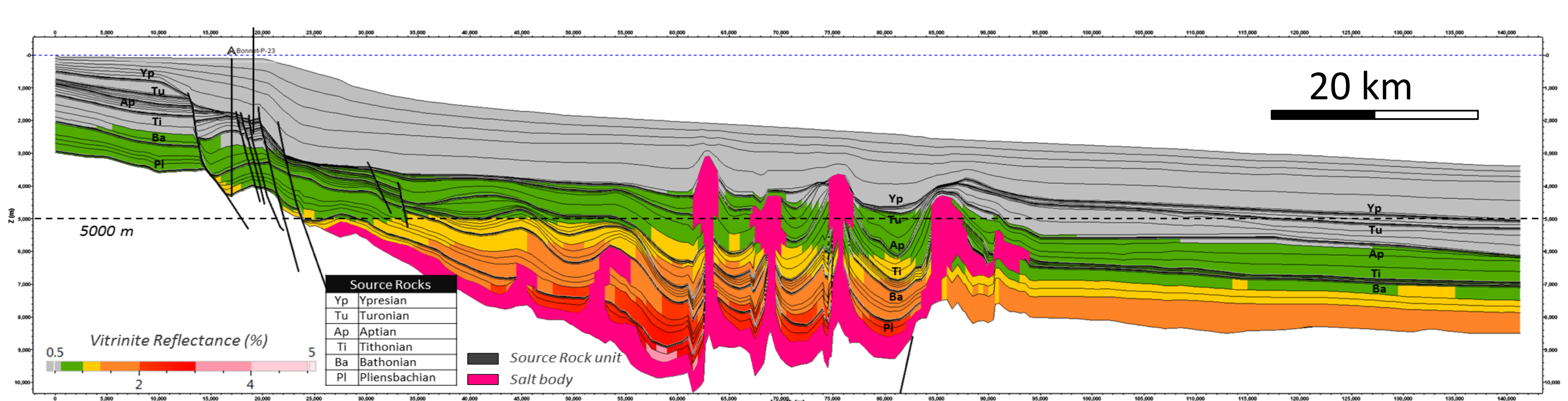


Figure 5.3.5: Source rock maturity windows on conjugate Transects 3.

Transect 4 Canada



Transect 4 Morocco

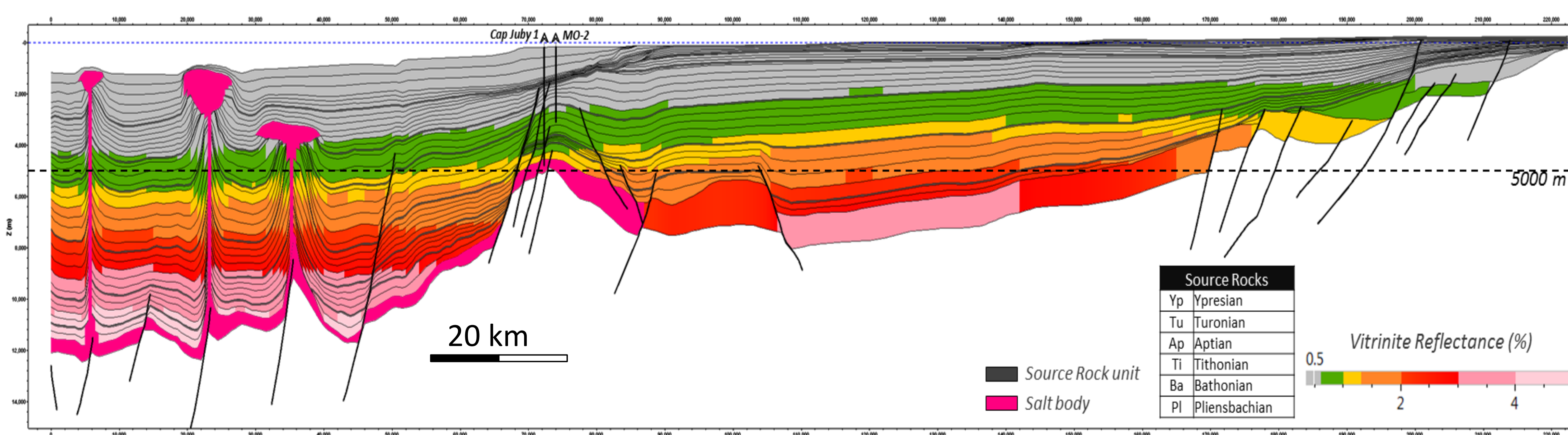
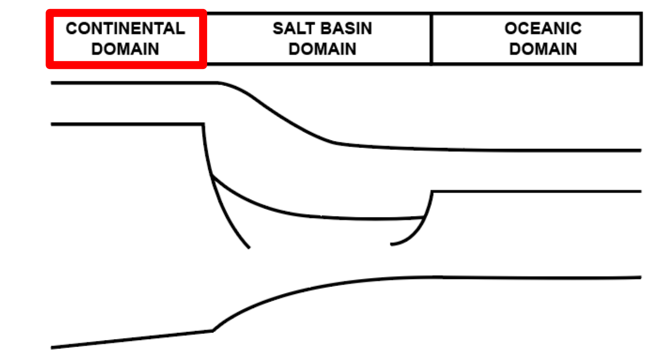


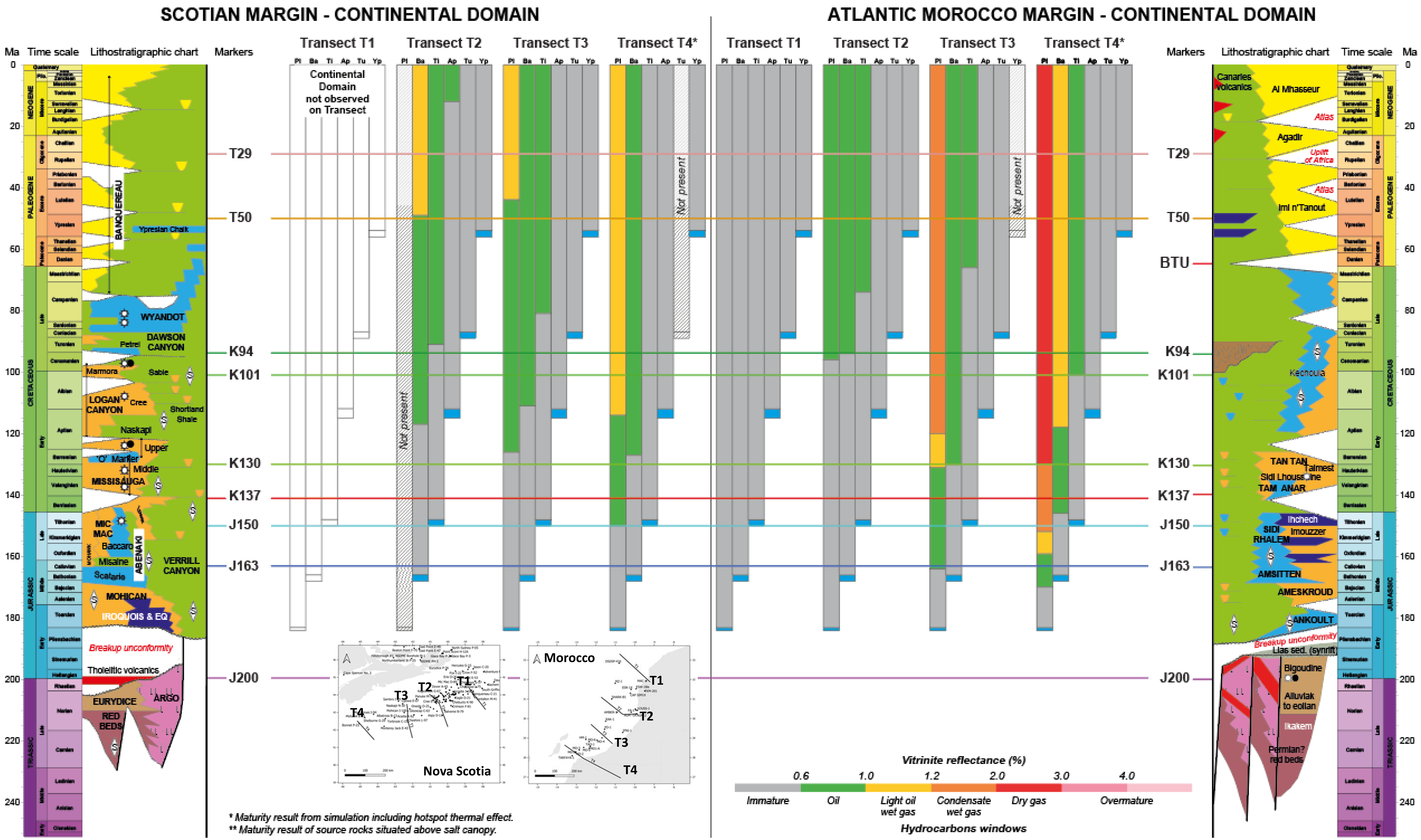
Figure 5.3.6: Source rock maturity windows on Transects 4.

Thermal and Maturity Modeling of Nova Scotia and Northern Morocco Conjugate Margins

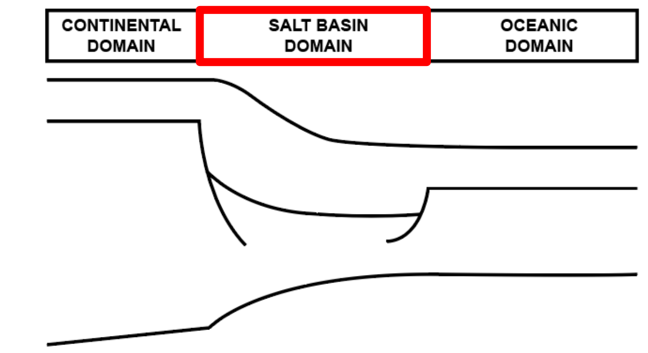


Regional comparison of source rocks maturity in the continental domain of the conjugate margins:

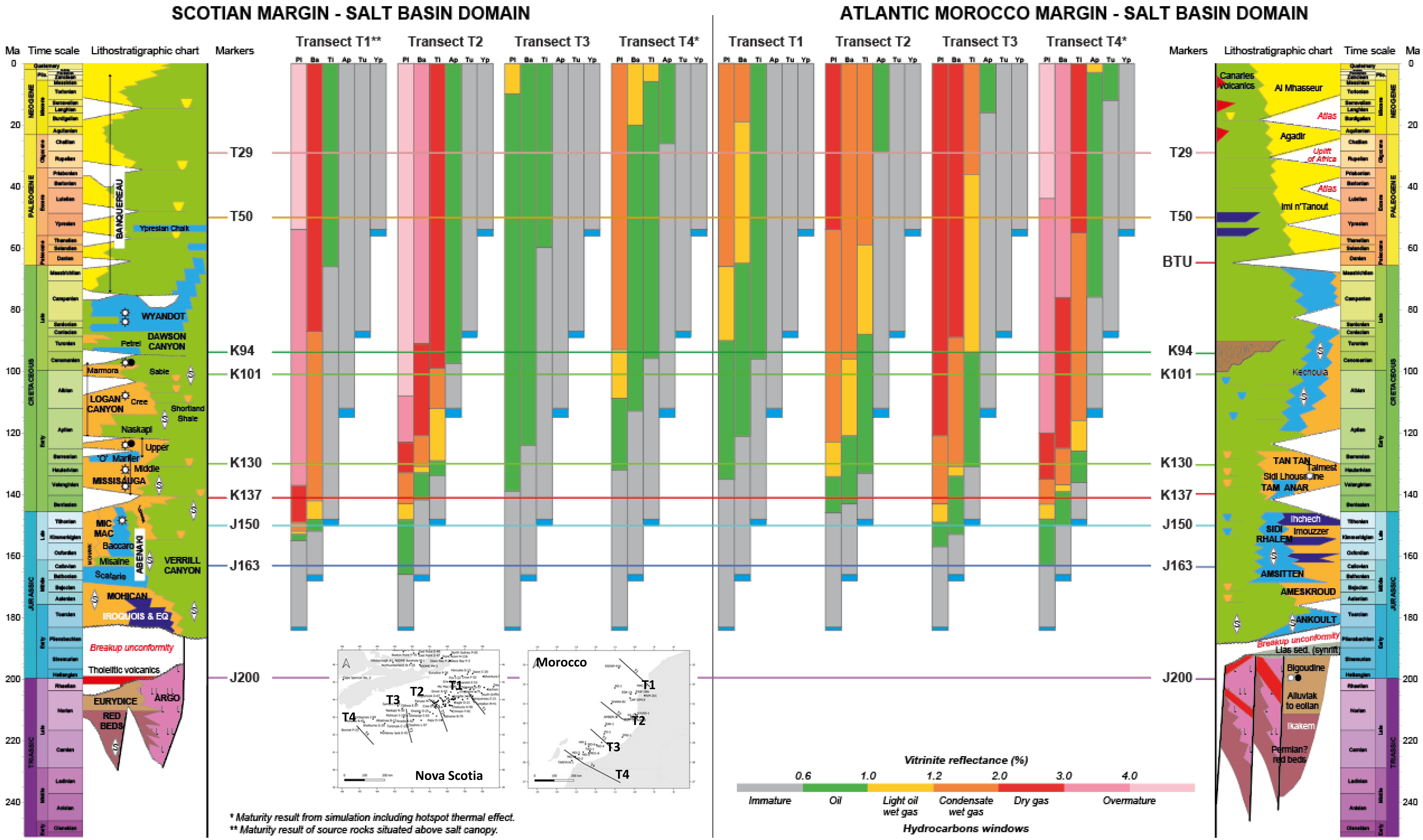
Comparison of maturity profiles of all simulated source rocks across the conjugate margins reveals that Upper Cretaceous and Cenozoic source rocks are systematically in an immature stage (vitrinite reflectance less than 0,6%). The Aptian and Tithonian source rocks are locally mature (oil window). Bathonian and Pliensbachian source rocks are mature to very mature and lay at present day in the oil to dry gas windows. The Atlantic Morocco margin displays a well-defined maturity trend from north (T1) to south (T4). This trend is interpreted as the result of overburden which nearly doubles between the Safi Basin (Transect T1) and the Tarfaya Basin (Transect T4). In The Safi Basin, no source rock reached the oil window while in the Tarfaya Basin the Jurassic source rocks are in the oil to dry gas windows. The trend also results from the increased heat flow caused by the Canaries hotspot located south of Transect T4. The Nova Scotia Margin displays a less pronounced maturity trend although overall maturity tends to increase toward the south as well. Similarly, the trend likely results from the combination of the increasing overburden and the effect of the Montegerian hotspot.



Regional comparison of source rocks maturity in the salt basin domain of the conjugate margins:

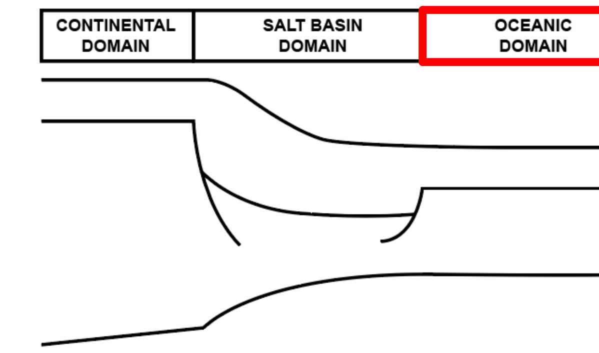


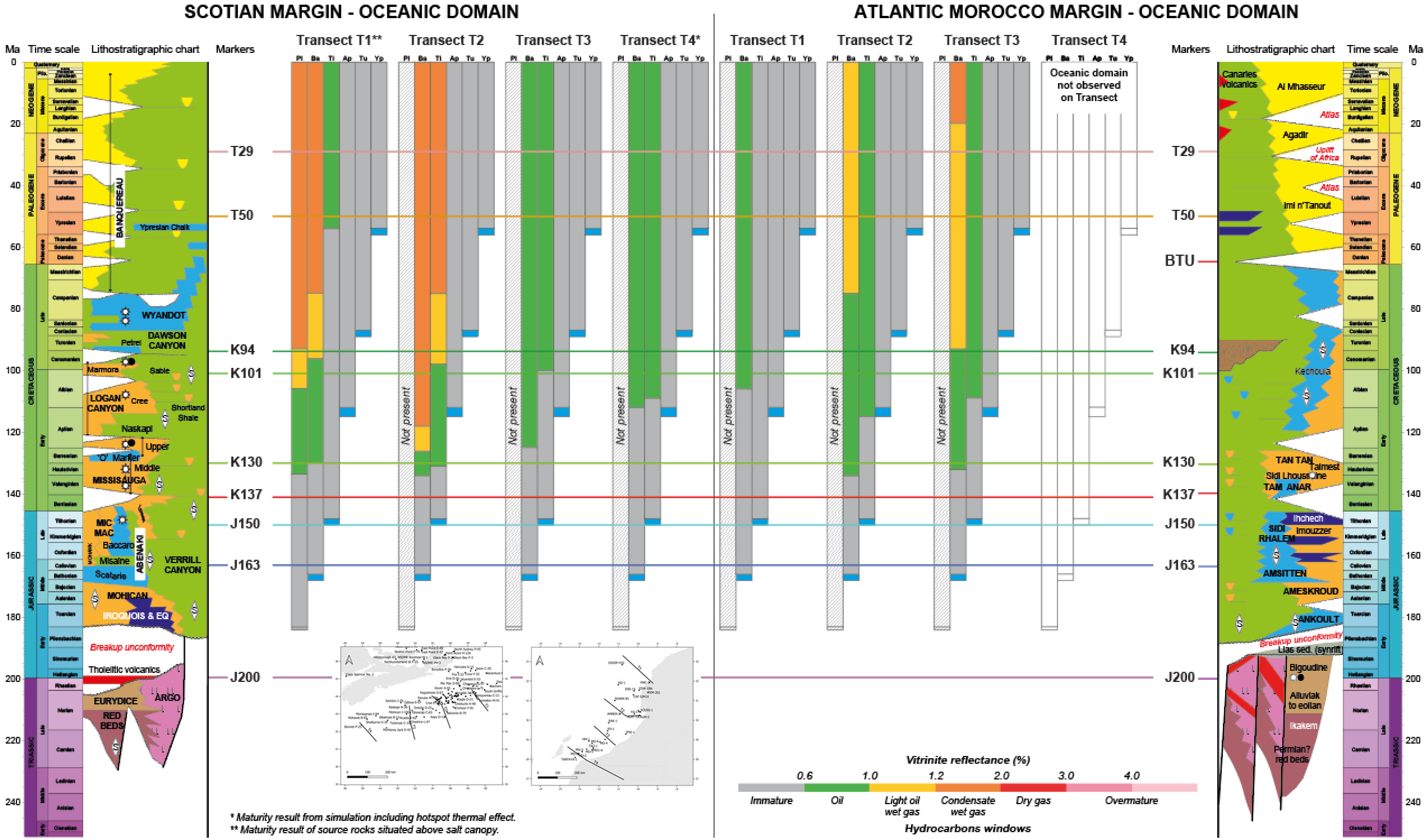
The salt basin domain recorded the highest maturity level simulated among the three domains on both conjugates. This overall high maturity level is believed to result from the combination of overburden, elevated heat flow associated with the transitional crust and the thermal conductivity of salt deposits. Lower Cretaceous and Jurassic source rocks have maturity ranging from early mature (oil window) to overmature (especially from Pliensbachian and Bathonian source rocks). The Upper Cretaceous and Cenozoic source rocks remain immature on both margins except on Transect T4 Morocco where the Turonian source rock recently reached the oil window. As discussed in the continental domain (previous plate), regional trends in maturity are well defined across both margins. On the Morocco Margin source rock maturity significantly increases toward the south, from the Safin Basin to the Tarfaya Basin due to the increasing overburden and the thermal effect of the Canaries hotspot. On the Scotian Margin the northern transects have very high maturity levels caused by the burial effect of the Banquereau Synkinematic Wedge on Transects T1 and T2. At scale of the conjugates, the best hydrocarbon window is in the Shelburne Sub-basin (southern Scotian Margin). In Transects T3 and T4 Canada the Jurassic source rocks are predominantly in the oil window.



Regional comparison of source rocks maturity in the oceanic domain of the conjugate margins:

The oceanic domain is the one which displays the lowest maturity levels on both margins. Cretaceous and Cenozoic source rocks are systematically immature as a response to low oceanic crust heat flow and limited burial. Jurassic source rocks are in a mature stage and lay at present day in the oil to wet gas windows. The Pliensbachian source rock is not present in the oceanic domain except on Transect T1 Canada where Lower Jurassic sediments were rafted on top of salt canopies. The already documented along-strike maturity trends are still visible on both conjugates: southward-increase in maturity on the Morocco Margin (increasing overburden and thermal effect of Canaries hotspot) and opposite trend on the Scotian Margin (Banquereau Synkinematic Wedge). Except in the northern part of the Scotian Margin, Jurassic source rocks are in a mature stage and lay in the oil window in most of the transects.





* Maturity result from simulation including hotspot thermal effect.
** Maturity result of source rocks situated above salt canopy.

Comments on the source rock distribution

It is noteworthy that all the source rock layers implemented in the model are not necessarily effective along all the studied sections. The Table 5.3.1 presented by Dr Martin Fowler (APT Canada Ltd.) gives some hints for better interpreting basin modelling results, particularly present-day maturity levels calculated along studied sections and synthetized in Table 5.3.2. Several elements can be pointed out:

Age	Nova Scotia	Morocco	Comments
Upper Cretaceous	not significant	**very important**	Morocco SRs deposited in an upwelling zone
Lower Cretaceous	not significant	minor	
Upper Jurassic	**very important on Shelf**	not significant	Nova Scotia SRs deposited in a deltaic system
Middle Jurassic	not significant/present?	significant	Morocco SRs in Essaouira Basin is a restricted carbonate
Lower Jurassic	potentially present	**very important?**	Morocco SRs are mostly restricted carbonates

Table 5.3.1: Source rock potential comparison between Nova Scotia and Morocco (Dr Martin Fowler)

- **"Ypresian SR"** is poorly documented. In any case it is never mature along studied 2D sections
- **Upper Cretaceous "Turonian SR"** is not significant along the Nova Scotia margin but has a high potential in offshore Morocco (source rocks related to upwellings are deposited along the shelf break – neither in the abyssal plain, nor at very shallow depth – rather along the eastern coast of the oceans). However it may reach the oil window only locally, rather in southern Morocco and not necessarily along the shelf break. If the source rock was locally more buried than along studied sections, there would be a potential for heavy-medium oil (possible type II-IIS kerogen). Along studied sections only bitumen and traces of heavy oil / early methane are expected.
- **Lower Cretaceous "Aptian SR"** is not significant along the Nova Scotia margin although scattered terrestrial organic matter (coaly type III kerogen) is expected in the Mississauga complex in the northern shelf and slope (sections T1 and T2 Canada). It would be in the oil or locally in the wet gas window in the "salt basin domain" (e.g. in the Sable sub-basin). The Aptian SR has potential in Morocco and is expected to be in the oil window mainly in the salt basin as shown in Table 5.3.2.
- **Upper Jurassic "Tithonian SR"** is classically assumed to be the main source of hydrocarbons in producing fields on the Nova Scotia shelf. This source rock contains type III or II-III kerogen directly related to early stages of the massive Mississauga delta development (sections T1 and T2 Canada). New data indicates this source rock is not developed along T3 and T4 (Cheshire & Monterey Jack wells respectively), in the more distal deltaic and deepwater areas of the Scotian Margin. The source rock deposits are likely related to an increase of the primary productivity at the delta mouth with a contribution of terrestrial organic matter. The kerogen is usually within the dry gas window in the northern "salt basin domain" (where the main discoveries are), locally in the oil window along the margin of the basin. Gas, condensate, and locally light oil are related to this petroleum system in Canada. The low potential would discount this hydrocarbon source in Morocco.
- **Middle Jurassic "Bathonian (to L. Oxfordian) SR"** is locally significant in Morocco (e.g., Callovian-L. Oxfordian in the Essaouira Basin, onshore T1 Morocco). Organic-rich layers have been identified elsewhere in offshore Morocco but so far it usually corresponds to relatively thin and scattered intervals. The source rock is clearly missing in some sections (T2 Morocco, Ifni-1 well between T2 and T3 Morocco, continental domain). Restricted carbonate source rocks are often spatially discontinuous and are rather expected in the upper part of the shelf (lagoon setting), spatially in the "continental domain" at this age. In Nova Scotia, including in deep recent wells in the Shelburne basin, there is no evidence of significant organic-rich layers although TOC about 1% are often seen in Misaine / Scatarie Formations. Such a source rock would be mature almost everywhere, usually in the oil or wet gas window in the continental domain, in the gas window in the salt basin domain.
- **Lower Jurassic "Pliensbachian SR"** is not yet proven offshore even if several clues support its existence: outcrops and wells onshore Morocco, several oil and gas shows in Morocco (e.g. in the Cape Juby area), numerous seeps identified offshore Nova Scotia, in the deep Shelburne Basin, etc. However, like the Middle Jurassic source rock, it is certainly missing in many areas (T2 Morocco continental domain, Ifni-1 well, T4 Morocco at the top of structural highs such as Cape Juby). Finally this source rock would exist in isolated deep mini-basins throughout the salt basin domain (relatively shallow carbonate platform developed at that time). It would not exist in the continental domain of the Nova Scotia margin, at least in the south (sections T3 and T4 Canada), although it has been locally identified onshore Morocco. At present day it is likely within the gas window or overmature in the areas where its presence is more likely, locally within the late oil / wet gas window.

Note: Paleozoic source rocks, not studied here, are locally proven onshore (especially in Morocco) and could be efficient in the continental domain of studied sections.

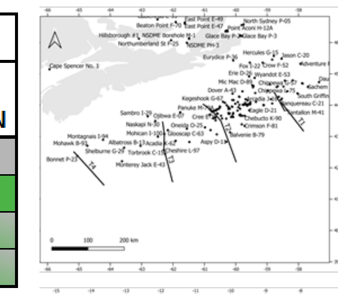
Computed maturity level vs. petroleum results:

The comparison between well results and computed maturity levels is interesting keeping in mind that: the present day maturity level may be not representative of hydrocarbon composition at the time of the trap charge; hydrocarbon charge can be polyphasic with various origins or with long vertical and horizontal pathways which renders difficult a hydrocarbon-source correlation without biomarker analysis; there are reservoir processes that can change hydrocarbon composition (dis-migration and fractioning, biodegradation, secondary cracking, etc.); shows corresponding to small amounts of hydrocarbons are not necessarily representative of active petroleum systems; and gas can have a low-maturity origin (biogenic methane). The following observations can be made:

- The maturity level of the Tithonian SR in the Mississauga paleo-delta area (T2 Canada, salt basin domain, edge of the continental domain) is fully consistent with the presence of gas and gas-oil fields in the Sable Sub-basin, the occurrence of liquid hydrocarbon increasing toward the continental domain and at the margin of the deltaic system (e.g. Cohasset).
- The lack of hydrocarbon shows on the southern Nova Scotia platform (T3 and T4 Canada, continental domain) is not explained by an insufficient maturity level (Jurassic units in oil to wet gas window in general) but by a lack of efficient source rock down to the basement in the continental domain. Nevertheless it cannot be excluded that isolated pods of Lower Jurassic source rocks exist locally in undrilled deeps.
- The maturity level in the deep Shelburne Basin (T3 Canada, salt basin domain) is relatively low compared to other sections, the Lower Jurassic source rock being in the wet gas windows in salt mini-basins at present day. Condensate and wet gas are more likely to be found than heavy oil and dry gas (apart from potential biogenic gas). It is mostly due to a smaller burial. Contrarily to other areas, the source rock crossed the oil window recently during the Tertiary, often during the Neogene. The active Lower Jurassic petroleum system at present day could explain observed seeps at the surface and suggest that shallower targets (Lower Cretaceous and even Tertiary turbidites) could be efficiently charged. It is a special case along studied margins where deep Jurassic sources (probable but not yet proven) could directly feed shallow targets. The situation is somehow similar along the section T1 Morocco where the maturity level is even lower than in the Shelburne Basin but where the hydrocarbon generation would have been less intense during the Neogene due to a lower sedimentation rate.
- Several significant oil shows in "Middle" Cretaceous units around the T2 Morocco, at the edge of the continental domain (34 API oil in BTS-1, Souss-1, AGM-1, AGM-2) suggest the existence of a Cretaceous SR with a limited potential, certainly within the "Albian-Cenomanian shale". Well results in the area indicate that relatively good Jurassic reservoirs are water bearing (absence of Jurassic source rock). The model indicates that the conceptual "Aptian source rock" has potential in Morocco and is expected to be in the oil window, mainly in the salt basin, as shown in Table 5.3.2.
- At first glance the maturity level of Middle and Lower Jurassic source rocks at present day in Cape Juby area (T4 Morocco, continental domain) seems quite high for explaining the occurrence of oil accumulations in Middle Jurassic (oil 38 API in MO-8) and Upper Jurassic units (biodegraded oil in Cape Juby, MO-2), as well as bitumen in Cretaceous units. However the thermal modeling shows that hydrocarbon generation and peak expulsion precociously occurred during the Early Cretaceous. Hydrocarbon accumulations have been certainly charged at that time. While Upper Jurassic accumulations remained under the pasteurization temperature (60-80°C) for more than 100 Ma and have been biodegraded, Middle Jurassic accumulations have been preserved from the biodegradation the temperature remaining stable around 100-120°C (under the onset temperature of the secondary cracking). Gas could have been expected in those reservoirs (either as a by product of biodegradation or as a product of primary cracking, even in minor proportion). Gas may have diffused out of the structure due to low gas sealing capacity and the long residence time of the hydrocarbon within the trap. Early charge and subsequent leakage is frequently put forward in the area for explaining the presence of dead oil in water-bearing reservoirs (e.g. Tarfaya-1).

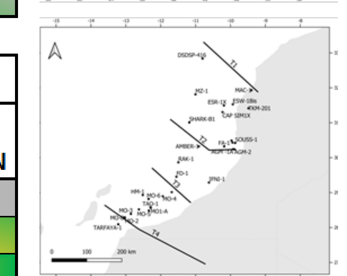
YPRESIAN SOURCE ROCK	CANADA			MOROCCO		
	CONT. DOMAIN	SALT BASIN	OCEANIC DOMAIN	OCEANIC DOMAIN	SALT BASIN	CONT. DOMAIN
T1						
T2						
T3						
T4						

TITHONIAN SOURCE ROCK	CANADA			MOROCCO		
	CONT. DOMAIN	SALT BASIN	OCEANIC DOMAIN	OCEANIC DOMAIN	SALT BASIN	CONT. DOMAIN
T1						
T2						
T3						
T4						



TURONIAN SOURCE ROCK	CANADA			MOROCCO		
	CONT. DOMAIN	SALT BASIN	OCEANIC DOMAIN	OCEANIC DOMAIN	SALT BASIN	CONT. DOMAIN
T1						
T2						
T3						
T4						

BATHONIAN SOURCE ROCK	CANADA			MOROCCO		
	CONT. DOMAIN	SALT BASIN	OCEANIC DOMAIN	OCEANIC DOMAIN	SALT BASIN	CONT. DOMAIN
T1						
T2						
T3						
T4						



APTIAN SOURCE ROCK	CANADA			MOROCCO		
	CONT. DOMAIN	SALT BASIN	OCEANIC DOMAIN	OCEANIC DOMAIN	SALT BASIN	CONT. DOMAIN
T1						
T2						
T3						
T4						

PLIENSBACHIAN SOURCE ROCK	CANADA			MOROCCO		
	CONT. DOMAIN	SALT BASIN	OCEANIC DOMAIN	OCEANIC DOMAIN	SALT BASIN	CONT. DOMAIN
T1			Rafts			
T2						
T3						
T4						

Maturity Window
Immature
Oil
Light Oil / Cond.
Cond. / Wet Gas
Dry Gas
Overmature
Not Deposited
Out of the Model

Table 5.3.2: Source rock maturity on both conjugates based on results of 2D petroleum system models.

Continental domain = sediments on top of relatively thick, stretched continental crust, with locally marginal evaporite basins
Salt Basin Domain = sediments on top of thinned and hyperextended continental crust with thick Triassic salt deposits
Oceanic Domain = sediments on top of oceanic crust (Breakup Unconformity J183, oldest oceanic crust younger than potential Pliensbachian Source Rock)
This subdivision refers to structural domains and is not related to present day geomorphic features (Onshore, continental shelf, slope, abyssal plain).