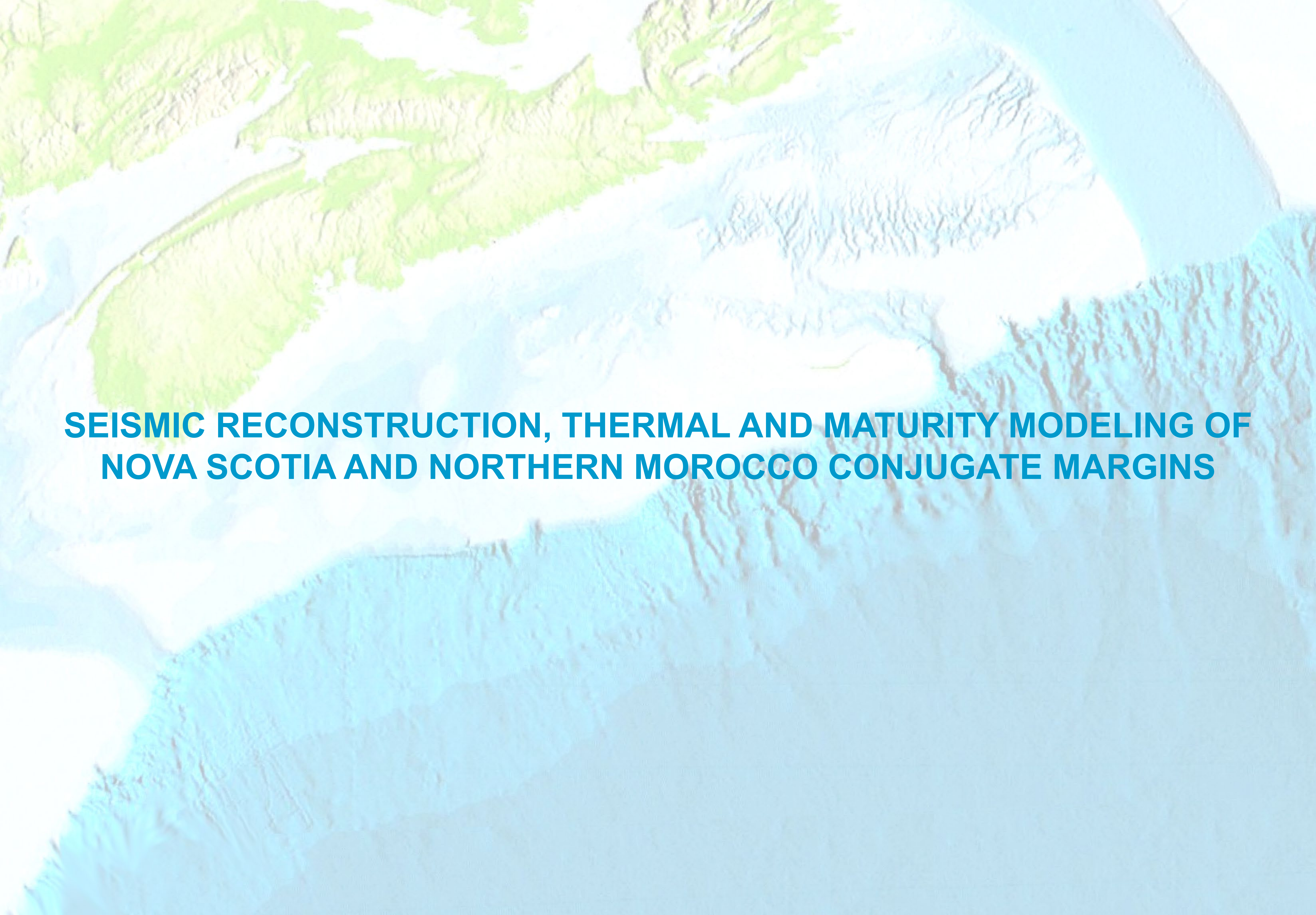


SEISMIC RECONSTRUCTION, THERMAL AND MATURITY MODELING OF NOVA SCOTIA AND NORTHERN MOROCCO CONJUGATE MARGINS

Objectives

The primary aim of the "Seismic Reconstruction, Thermal and Maturity Modeling of the Nova Scotia – Northern Morocco Conjugate Margins" Project is to compare and contrast the petroleum systems of the Central Atlantic conjugate margins.

To do this, the Project will develop two main Tasks, whose objectives are set out below:

1. Seismic Reconstruction

Using 2D seismic lines from offshore Nova Scotia and corresponding 2D lines from offshore northern Morocco, this work will assess and compare the various datasets that comprise the lines, then build four integrated, composite cross-sections that describe the main tectonic events including the early rifting history across the conjugate margin.

2. Thermal and Maturity Modeling

The aim of the basin modeling is to investigate the regional thermal and maturity regimes for the four conjugate transects and assess the expulsion history of the main source rocks proven or inferred over the zones of interest.

The Project integrates contributions from the academic and geoscience community in Halifax (Nova Scotia) as well as various contractors, and strongly benefited from the exchanges and discussion with the ONHYM (Office National des Hydrocarbures et des Mines) staff in Rabat, Morocco.

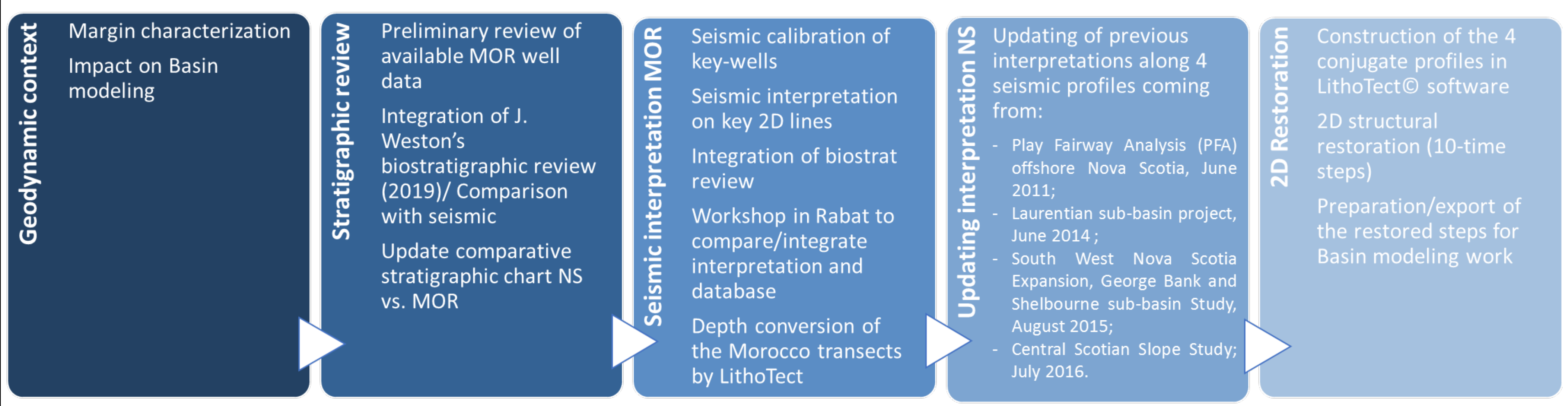
The Project integrated the results of a number of linked sub-projects. These included:

- Geodynamic Review
- Seismic Database Preparation and Interpretation
- Salt Structural Interpretation
- Biostratigraphy (J. Weston)
- Geochemistry (M. Fowler)
- Structural Restoration
- Petroleum Systems Modeling

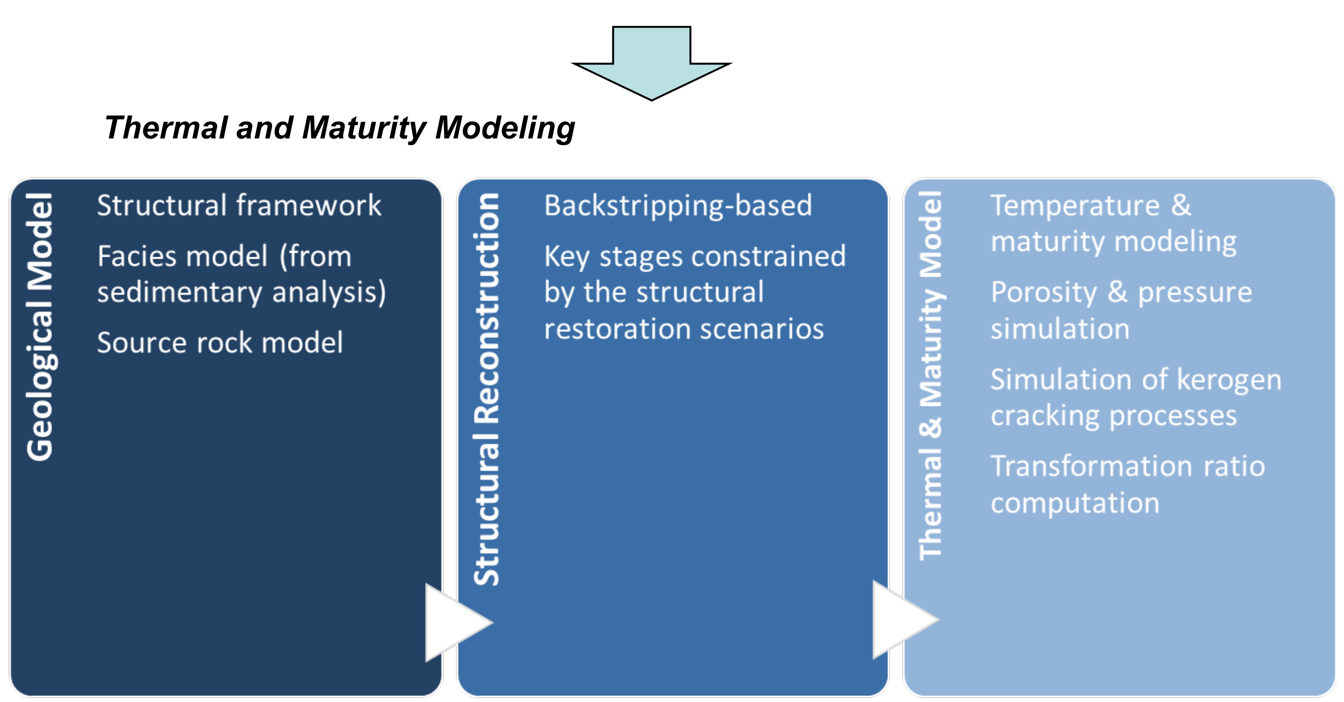
(MOR = Morocco; NS= Nova Scotia)

Workflow

Seismic reconstruction



Thermal and Maturity Modeling



Base maps

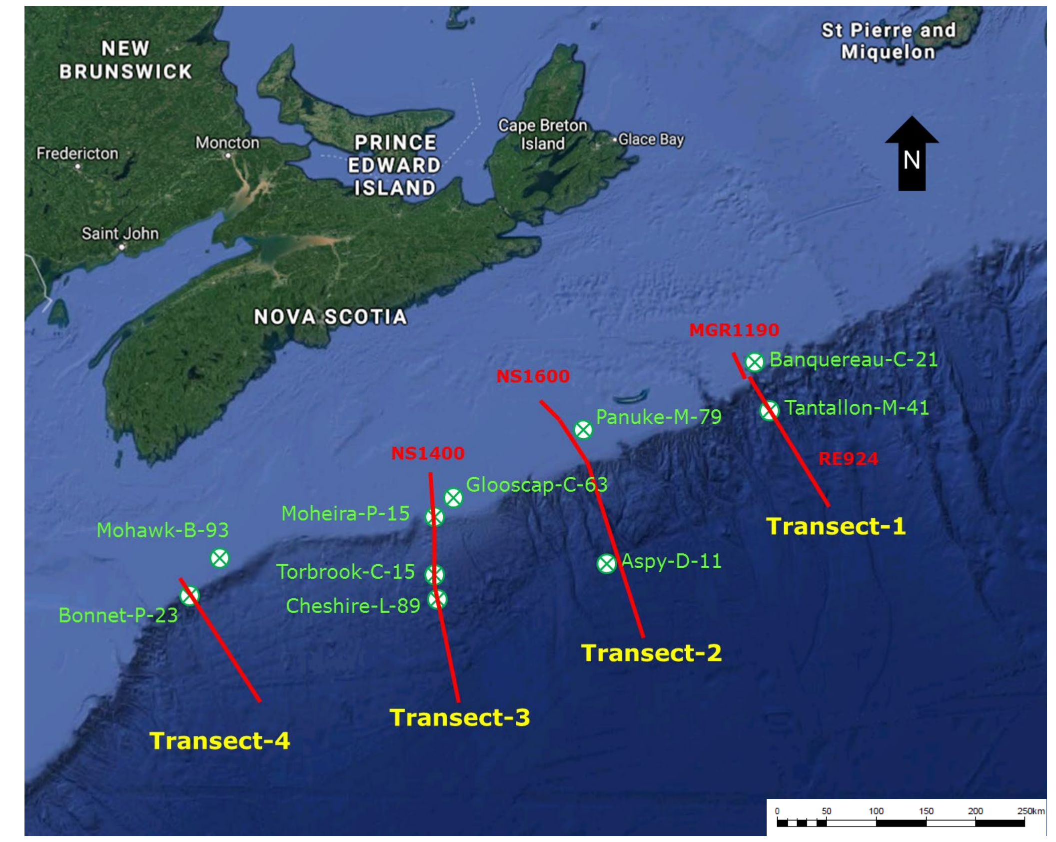


Figure A Location map of the structural transects and wells on the Nova Scotia margin.

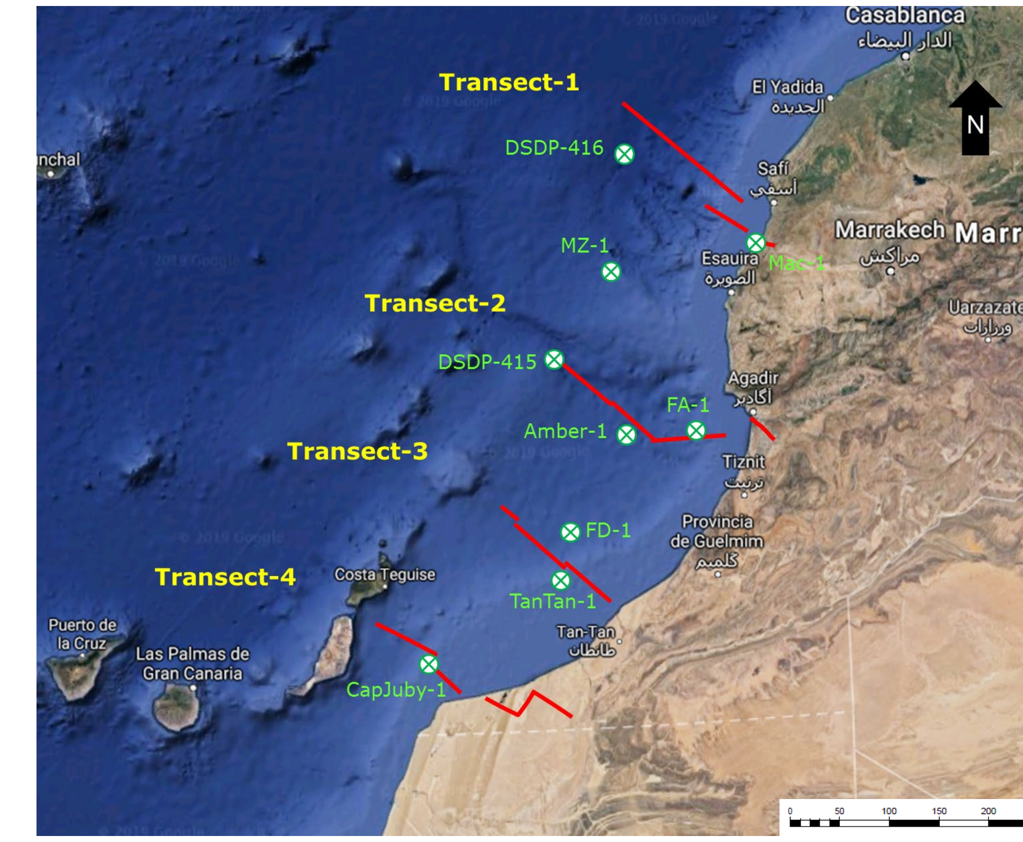


Figure B: Location map of the structural transects and wells on the northern Morocco margin.

Four cross-sections to be restored and modelled were chosen along each of the Nova Scotia and northern Morocco margins at a separation of around 200 km, to best represent the variety of structures encountered in the study areas. The geodynamic reconstructions at 190-170 Ma (approximate age of the Central Atlantic continental breakup; Schettino and Turco, 2009; see Figures 1.22 and 1.23 in PL.1.7) allowed the team to define the respective paleo-locations of each of the four conjugate transects.

The seismic and well databases for the Nova Scotia margin come from previous studies undertaken in the area, whereas the selected database (2D seismic lines and wells) for the Morocco margin was provided by ONHYM. Figures A and B show the location of the transects and the main wells used for seismic ties and interpretation. Details regarding the well database used for thermal modeling are presented in subsequent Chapters.

Chapters of the present ATLAS

The main elements of the study are described in the following Chapters of this ATLAS:

- Chapter 1: Geodynamic Context

An overview of the main geodynamic models impacting the structural geometries and the petroleum system main parameters

- Chapter 2: Sedimentology and Stratigraphy Review

Update of the stratigraphic framework of the Moroccan shelf in order to refine potential links with the Nova Scotia margin

- Chapter 3: Seismic Interpretation

Seismic interpretation of the selected northern Morocco seismic lines. Updating of the seismic interpretation from previous studies on the Nova Scotia margin, in particular the PFA 2011. Construction of the four conjugate transects.

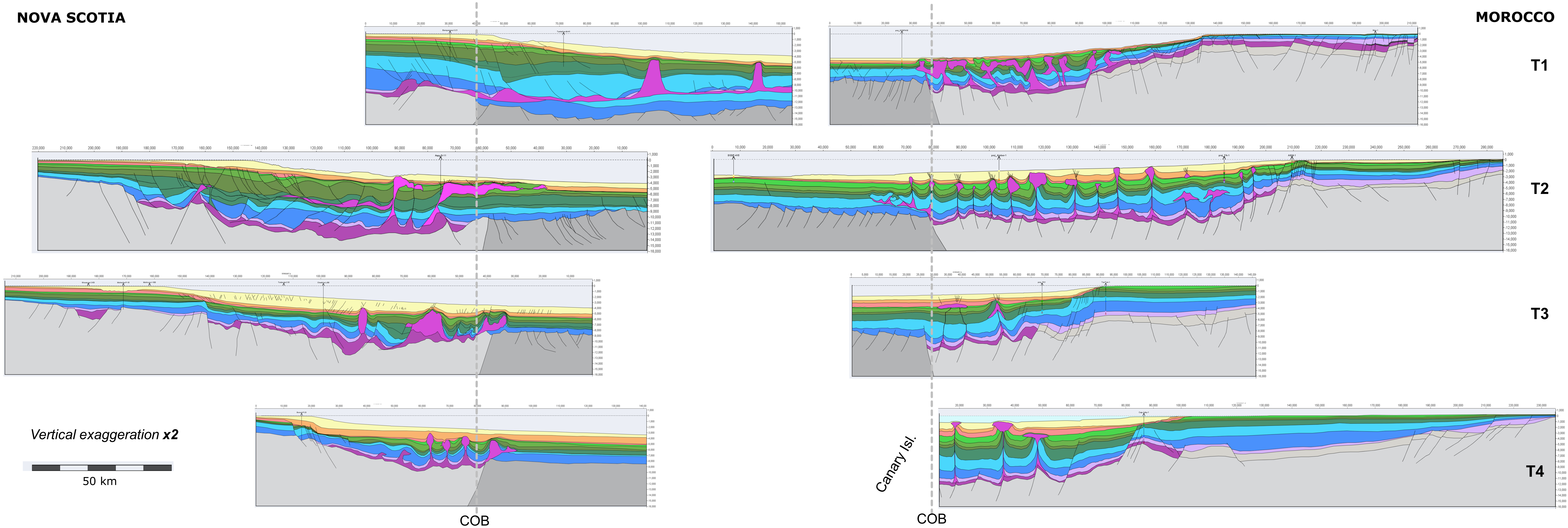
- Chapter 4: Structural Restoration

2D sequential restoration of the four conjugate transects at selected geological times. This work provides inputs for the Thermal and Maturity modeling tasks.

- Chapter 5: Thermal and Maturity Modeling

Investigation of the regional thermal and maturity regimes for all transects and assessment of the related state of the main source rocks proven or inferred over the zones of interest

Executive Summary



Nova Scotia margin

Following the sub-divisions proposed by Shimeld, 2004; Albertz et al., 2010; and PFA 2011, the four cross-sections restored in the present study are located in various sub-provinces and show examples of the different structural styles and salt geometries characterizing the slope domain of the Nova Scotia margin.

Transect 1 is located in the Banquerau Syn-kinematic Wedge province, described in detail by Ings and Shimeld, 2006. It is characterized by a major gravity gliding allochthonous wedge active mainly during Jurassic to Early Cretaceous times. This wedge is detached on top of a large early-created salt tongue. Late vertical diapirs stake the SW boundaries of this major wedge.

Transect 2 goes through the Canopy province, described in detail by Deptuck et al; 2009; Deptuck, 2010; Deptuck et al., 2015. It is characterized by large allochthonous salt tongues (canopies) fed by one or several deep salt stems that may be of allochthonous or autochthonous origin. These canopies can be completely disconnected from their feeding zones, the stems corresponding to steeply dipping weld zones.

Transect 3 lies between the Canopy and Diapir provinces (PFA, 2011). Transect 4 is located in the Diapir province characterized by mainly vertically raised diapirs on top of the autochthonous salt basin with local salt tongues of relatively reduced extent (compared to structures of the Canopy province) at the southwestern limit of the autochthonous salt basin (Deptuck et al. 2010).

General observations

There is a significant variation in sediment thicknesses from the NE to the SW (i.e. from T1 to T4). This variation is not the same in the two margins: overall sediment thickness increases from the NE to the SW on the northern Morocco side whereas it decreases on the Nova Scotia side. This difference may be related to different geological causes, for example the strong sediment supply of the Laurentian River in the north of the Nova Scotia margin and the presence of the Canary Island Arc capturing sediments since Early Paleogene in the south of the Morocco margin.

Different structural styles and salt geometries are also noted in the two margins (for example the presence of the Banquereau Syn-kinematic Wedge and the "roho" system in the Canadian margin), which are likely to be mainly related to the initial salt thickness and the sediment supply through time.

In both margins, the salt basin termination to the south has been sampled at level of Transect 4, as described in literature. Both margins are characterized in their conjugate southern parts (Transects 3 and 4) by the presence of Upper Jurassic carbonate platforms.

Northern Morocco margin

Based on the Morocco salt basin sub-division proposed by Tari et al., 2003; Tari and Molnar, 2005; and Tari et al., 2013 the four cross-sections restored in the present study are located in various sub-provinces and show examples of the different structural styles and salt geometries characterizing the slope domain of the northern Morocco margin.

Transect 1 is located in the Safi sub-basin (Essaouira Basin). It shows the characteristic halokinetic elements of a passive margin such as extensional salt structures beneath the shelf and the upperslope and compressional features downdip on the lower slope (Tari and Jabour, 2013).

Transect 2 is located in the Agadir Basin characterized by simple, mostly vertical diapirism driven dominantly by the load of supra-salt, mostly Cenozoic age sediments (Tari et al. 2003). Gravity-driven compressional features such as toe-thrust are present on the salt basin western boundary.

Transect 3 and Transect 4 are located in the Tarfaya Basin and Cap Juby area, respectively, where there are only a few salt pillows and diapiric salt walls outboard of the prominent Jurassic shelf margin (Hafid et al., 2008). The Cap Juby area is bounded to the west by Canary Island volcanism (starting from Paleocene-Eocene time).

Implication for petroleum systems

Relative distribution of the gas and oil provinces, related to the burial during geological times, should not be comparable between the two margins and even reversed in a N-S direction, as the sediment thicknesses show significant variations.

The Early Jurassic series deposition (including a possible Early Jurassic source rock) is related to mini-basin development controlled by early salt movements. Therefore mini-basin evolution can locally control the distribution and characteristics of Liassic source rocks.

Clastic reservoir presence and distribution can be related to sediment supply and are therefore reversed in the Nova Scotia and northern Morocco margins.

On the other hand, potential Jurassic carbonate reservoirs appear to be similar in the southern parts of both margins (T3-T4 areas).

T1 mega-regional transect (Fig. 1 & Fig. 2):

Comparing T1 maturity regimes at present day on both sides of the margin allows the consistency of the thermal modeling results at both distal ends of the section to be highlighted. A striking feature is the hotter thermal regime simulated over transect T1 Canada, because of the thick sedimentary pile observed there (which is even further increased by the action 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 northern Morocco where, outboard the salt, being over the oceanic domain or upslope towards the shelf, the maturity trend drops significantly to a point where even the deepest petroleum systems become inefficient. Cenozoic and Cretaceous source rocks remain immature on both sides of the Atlantic. Jurassic source rocks are proficient and the deepest are even overcooked on the Canadian side while they remain in the oil up to wet gas window over the salt basin, Moroccan side.

T2 mega-regional transect (Fig. 1 & Fig. 3):

Opposite trends in terms of overall overburden thicknesses are observed when comparing Transects T1 & T2: overall burial decreases slightly following a north to south trend on Canadian side, moving from T1 to T2, as the sediment supply from the St Lawrence River begins to drop. On the other hand burial increases on Moroccan side, moving north to south from T1 to T2 and transitioning from the Essaouira to the Agadir Basin. The impact on the thermal regime is significant on Moroccan side: the maturity regime increases regionally. There, the deepest Jurassic source rocks sit now in the condensates to wet gas window over the shelf and reach the dry gas window over the salt basin. Regarding Cretaceous source rocks the Aptian unit sits 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 & Ypresian source rock members remain immature through Transect T1 Canada, the Aptian unit is locally mature over the salt basin, transitioning from the early oil window to the condensate & wet gas window where burial is greatest.

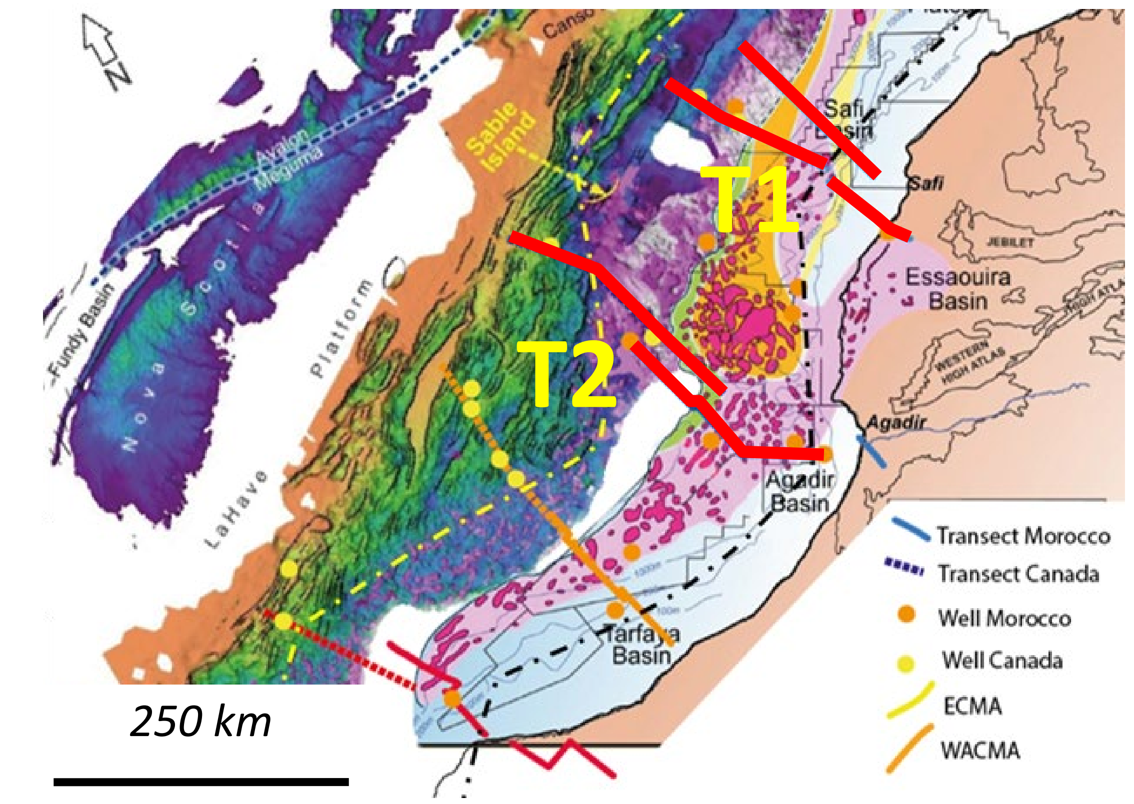


Figure 1: Position of conjugate transects. Plate reconstruction at 190 Ma (Deptuck and Altheim, 2018; Tari and Jabour, 2008).

Transect 1 Canada

Transect 1 Northern Morocco

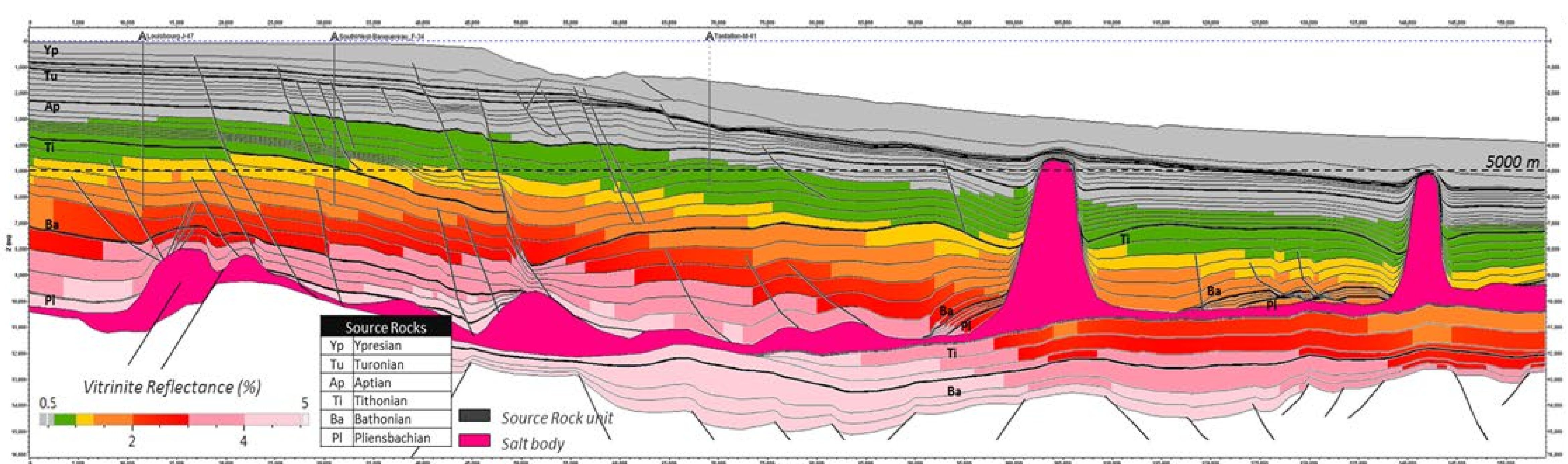


Figure 2: Source rock maturity windows on conjugate Transects 1.

Transect 2 Canada

Transect 2 Northern Morocco

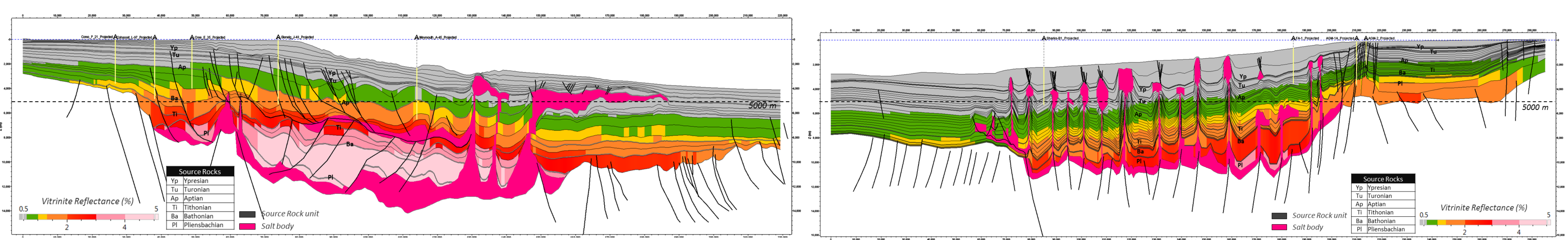


Figure 3: Source rock maturity windows on conjugate Transects 2.

T3 mega-regional transect (Fig. 4 & Fig. 5):

The global maturity trend of T3 continues to decrease on Canadian side compared to Transects T1 & T2, as the sedimentary pile is thinner, overall. A reverse observation can made for Moroccan 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 and 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 remain immature across both transects. The Tithonian source rock sits in the oil window over the salt basin Canadian side, locally reaching the wet gas window where burial is greatest. It remains within the oil window on the Moroccan side except over the salt basin where it enters the wet gas bracket. The Bathonian & Pliensbachian source rocks remain in the condensates to wet gas window over the salt basin Canadian side while they reach the dry gas window (even overcooked) in the salt province, Moroccan side, due to a maximum burial in excess of 10km. On the shelf and in the distal domain, Moroccan side, the deep Jurassic source rock remains in a more favorable maturity range (wet gas to condensates).

T4 mega-regional transect (Fig. 4 & Fig. 6):

The thermal regime of Transect T4 Canada follows a similar trend compared to Transect T3, except that it encompasses more of the oceanic domain and that it 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 & Turonian source rocks remains immature across both transects, the Tithonian is mature (early oil to late oil/condensates window) and may be proficient locally, on both side 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 state decreases gradually moving upslope and shelfward but remain in the gas ranges. On Canadian side the deepest Jurassic source rocks remains in the wet to dry gas maturity ranges.

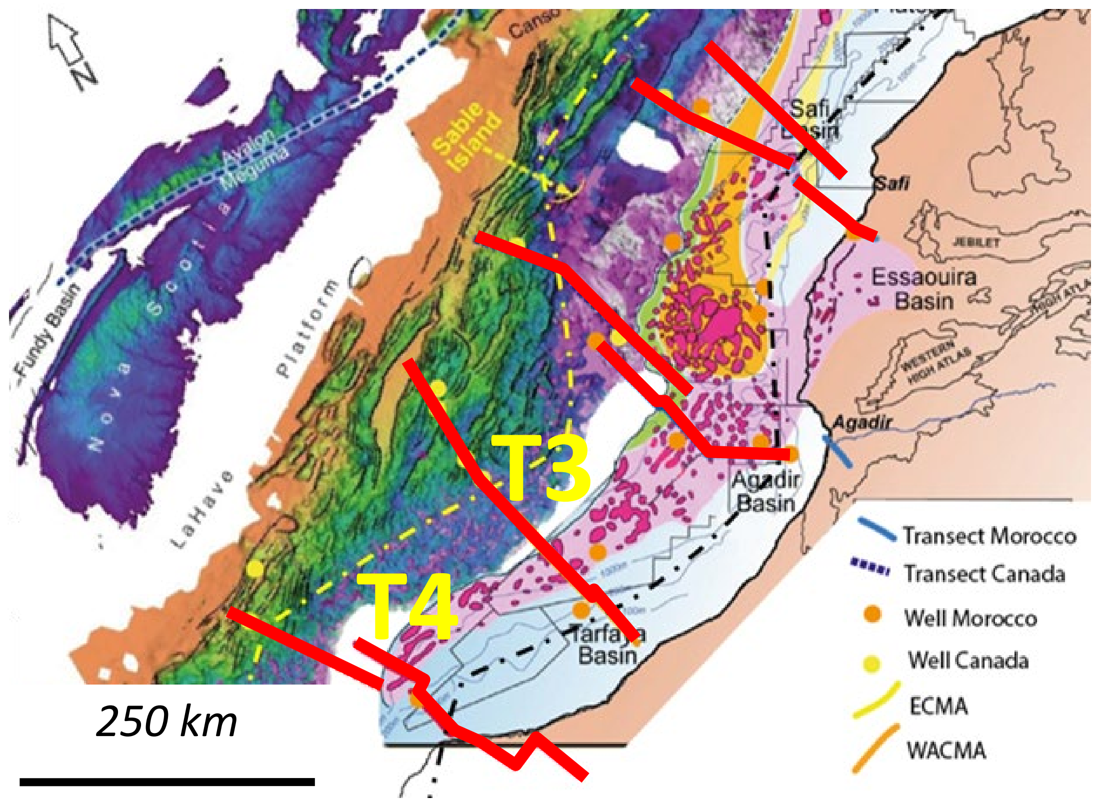


Figure 4: Position of conjugate transects. Plate reconstruction at 190 Ma (Deptuck and Altheim, 2018; Tari and Jabour, 2008).

Transect 3 Canada

Transect 3 Northern Morocco

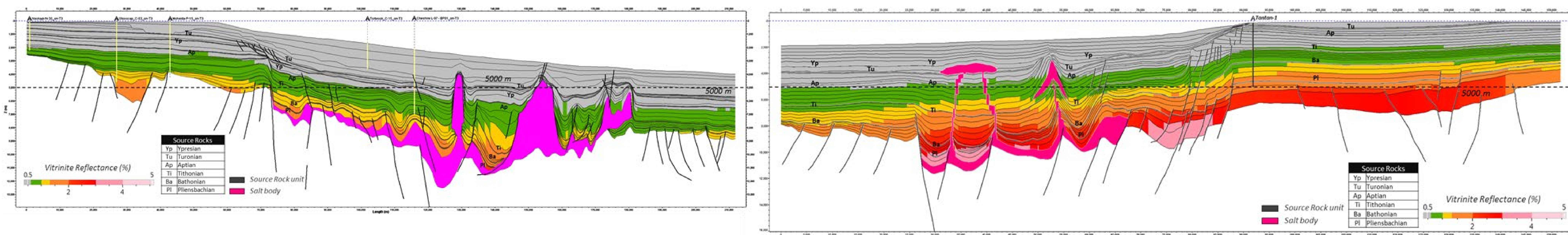


Figure 5: Source rock maturity windows on conjugate Transects 3.

Transect 4 Canada

Transect 4 Northern Morocco

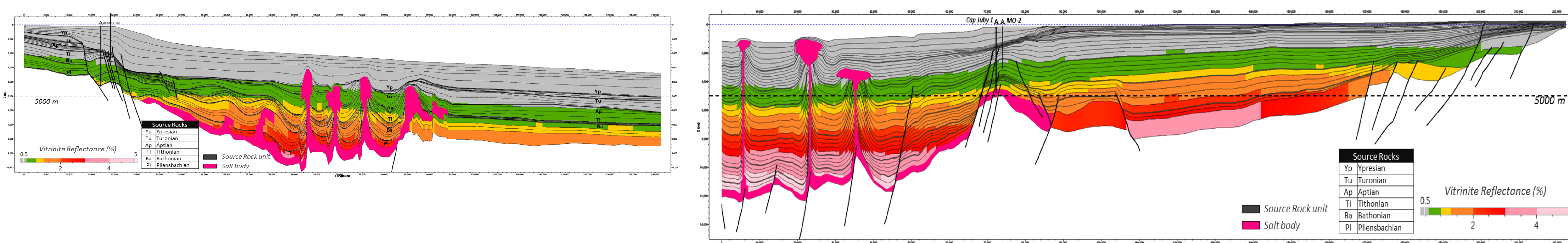


Figure 6: Source rock maturity windows on Transects 4.

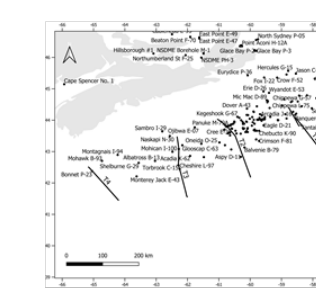
Computed maturity level vs. petroleum results:

Comparison between well results and computed maturity levels is useful keeping in mind that: the present day maturity may not be representative of hydrocarbon composition at the time of trap charge; hydrocarbon charge can be polyphasic with various origins or with long vertical and horizontal pathways (which makes hydrocarbon-source correlation difficult without biomarker analysis); there are processes occurring in the reservoir that can change the hydrocarbon composition (e.g., dis-migration and fractioning, biodegradation, secondary cracking, etc.); shows correspond to small amounts of hydrocarbons not necessarily representative of active petroleum systems; and gas can have a low-maturity origin (e.g., 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, as well as 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 are generally within the oil to wet gas window) 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 is 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 lesser burial. In contrast to other areas, the source rock crossed the oil window recently during the Tertiary, often during the Neogene. An 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 Aptian SR has potential in Morocco and is expected to be in the oil window, mainly in the salt basin, as shown in Table 1.
- 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 were 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 biodegradation - the temperature has remained stable around 100-120°C (under the onset temperature of 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 hydrocarbons 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).

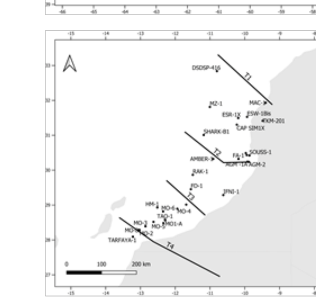
YPRESIAN SOURCE ROCK	CANADA			MOROCCO		
	CONT. DOMAIN	SALT BASIN	OCEANIC DOMAIN	OCEANIC DOMAIN	SALT BASIN	CONT. DOMAIN
T1						
T2						
T3						
T4						

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						

PLIENSBASCHIAN 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
- Missing

Table 1: 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
Salt Basin Domain = sediments on top of thinned and hyperextended continental crust with Triassic salt deposits
Oceanic Domain = sediments on top of oceanic crust
This subdivision refers to structural domains and is not related to present day geomorphic features (Onshore, continental shelf, slope, abyssal plain).