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Burial and Exhumation History of the Labrador-Newfoundland Margin and Implications for Hydrocarbon Exploration on the Grand Banks and on the Labrador Shelf*

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Abstract

The stratigraphic record along the continental margin of Labrador and Newfoundland provides ample evidence for vertical movements both prior to and after break-up that could have importance for hydrocarbon exploration in the region. Publically available vitrinite reflectance datasets from a well in the Jeanne d'Arc Basin indicate that the Cenozoic and deeper sections has been hotter in the past, presumably due to deeper burial prior to Late Cenozoic cooling. Furthermore, one of the datasets shows evidence of a major degree of deeper burial on the base-Tertiary unconformity, but additional data are required to investigate the reality of the base-Tertiary episode of burial and exhumation. Over much of the Labrador shelf, Miocene deposits are absent, and we show evidence based on vitrinite reflectance and sonic data that indicate that Miocene deposits of significant thickness may have been present prior to uplift and exhumation. Onshore Labrador, the presence of a Cretaceous outlier on Precambrian basement adds to the evidence of one or more events of exhumation that has removed pre-Cretaceous sediments on a regional scale, similar to the offshore Labrador where Cretaceous rocks rest on Precambrian basement over most of the shelf.

We also present results from a pilot study comprising apatite fission-track analysis (AFTA) data that reveals a Phanerozoic history involving a series of burial and exhumation episodes. The pilot study is a forerunner for a study of the onshore and offshore domain with three components: (1) A thermochronological study based on samples from outcrops and from onshore and offshore boreholes, (2) A stratigraphic landform analysis of the onshore study area based on mapping of erosion surfaces that will provide evidence of the vertical motion onshore and a relative denudation chronology, and (3) An integrated interpretation of the geological, geomorphological and thermochronological data to provide a

coherent model of the timing and magnitude of the vertical movements along the margin both prior to and after break-up. Failure to account for the effects of uplift and erosion, such as greater depths of burial prior to exhumation, may lead to serious underestimation of the petroleum resource maturity and to erroneous estimates of the timing of hydrocarbon generation, and not least to changes in migration routes and in the source-to-sink system of sediment input into offshore basins.

Introduction

The continental shelf of Labrador and Newfoundland has a long history of hydrocarbon exploration, and the accumulated oil production from the northern Grand Banks exceeds one billion barrels (Figure 1). The Canada-Newfoundland & Labrador Offshore Petroleum Board (www.cnlopb.ca) awarded new licenses on the Grand Banks in 2017. Vertical motion along passive continental margins such as the Atlantic margin of Canada plays an essential role in shaping these margins and their petroleum systems; in particular by removing and redepositing sedimentary strata (Japsen et al., 2012; Green et al., 2013). It is thus a fundamental question whether a hiatus in the stratigraphic record represents an episode of stability and non-deposition or an event involving deposition followed by removal of rocks. In this context, a hiatus represents not only a gap in the stratigraphic record, but also a gap in our understanding of the geological history. In terms of hydrocarbon systems, failure to account for greater depths of burial prior to exhumation can lead to serious underestimation of the maturity of petroleum resources. Similarly, the effects of exhumation on the timing of hydrocarbon generation, on changes in migration routes and on any reservoir hydrocarbons also require assessment (Dore et al., 2002). Insights into the uplift history of a margin are important for understanding the source-to-sink system of sediment input into offshore basins.

In broader terms of geological development, understanding the history of vertical movements along a passive continental margin is important for investigating whether the elevated regions along these margins, such as the Torngat Mountains in northern Labrador (Figure 1), are either (a) the eroded remnants of ancient orogens (McGregor et al., 2013), (b) rift shoulders related to processes during rifting and break-up (Weissel and Karner, 1989), or (c) the results of post-breakup episodes of burial and exhumation driven by plate tectonic forces (Japsen et al., 2006, 2012; Green et al., 2013).

Studies of the burial and exhumation history both onshore and offshore of Labrador and Newfoundland are, however, scarce, but several observations – that we review in the following – indicate that a number of uplift episodes followed by denudation, both pre- and post-breakup, shaped the present-day structure of the margin.

Evidence for Episodes of Burial and Exhumation of the Atlantic Margin of Canada

The Atlantic margin of Canada has many features in common with passive continental margins in other parts of the world (Japsen et al., 2012; Green et al., 2013), such as elevated plateaux (i.e. regional high-level landscapes of low, relative relief) at 1 to 2 km or more above sea level (a.s.l.) cut by deeply incised valleys and commonly separated from an adjacent coastal plain by one or more escarpments. The Torngat Mountains with peaks reaching 1.7 km a.s.l. in northern Labrador, slope much more steeply towards the Labrador Sea than they do towards the hinterland farther west in interior Labrador, and their overall shape is thus similar to that of the coastal mountains in Greenland (Figure 2). However, farther south (e.g. on Newfoundland) elevations do not reach 1 km a.s.l. As along other passive margins, Mesozoic-Cenozoic rift systems parallel the Labrador-Newfoundland margin with a transition from continental to oceanic crust farther offshore. Here, breakup occurred in the Early Cretaceous east of Newfoundland and in the Paleocene east of Labrador. The syn- and post-rift sediments at the landward margin of these rifts dip towards the rifts and are truncated by one or more shallow unconformities or by the seabed (Figure 3). In particular, the margin of Labrador shares the characteristics listed above with the conjugate margin of West Greenland where the geological record documents that the present-day high mountains are not remnants of the rifting process but the result of much later uplift which partially removed thick, post-rift deposits (Japsen et al., 2006).

Evidence from the Labrador Shelf

Dickie et al. (2011) noted that the Tertiary sediments along Labrador are tilted seaward and truncated (Figure 3), and that Late Oligocene, as well as younger (possibly Miocene), unconformities may correspond to phases of uplift of the Labrador margin as proposed by McMillan (1973). According to Dickie et al. (2011), the sedimentary record along the Labrador margin is difficult to interpret because of the limited dating of the younger, post-Oligocene section, and the many phases of channeling and erosion that are exhibited. Subsequently, Ainsworth et al. (2014) studied the Cretaceous-Tertiary stratigraphy of the Labrador Shelf and provided improved constraints on several unconformities. In particular, they documented the presence of a regional Miocene hiatus. Vitrinite reflectance data from the Hopedale E-33 well (Figure 4) provide evidence that the pre-Pliocene sequences along Labrador have been more deeply buried in the past, most likely prior to the removal of Miocene strata.

Aspects of the Late Cenozoic uplift history of Labrador can be deduced from the stratigraphy of the Labrador Shelf. Balkwill et al. (1990) noted that whereas the lower (mainly Oligocene) Mokami Formation is shale dominated, the upper (mainly Miocene) Mokami Formation is the distal, shaly facies of a regional stratigraphic sequence that includes proximal coarse-grained sands assigned to the lower part of the Miocene-Pleistocene Saglek Formation. Balkwill et al. (1990), argued that the disconformity between the lower and the upper parts of the Mokami Formation marks a phase of regional emergence of the Labrador Shelf, and according to Ainsworth et al. (2014), Miocene deposits (corresponding to the upper part of the Mokami Formation) are absent in many wells along Labrador. Coarse grained quartz and igneous clasts, which first appears in the upper part of the Mokami Formation, are evidence of the first phase of the uplift of coastal Labrador in the Late Oligocene to Early Miocene (Balkwill et al., 1990; Ainsworth et al. 2014). This uplift accelerated throughout Miocene time and Balkwill et al. (1990) suggest that this produced the modern, incised topography of high relief of the Labrador and southern Baffin Island coasts. Offshore, this uplift produced a coarse-grained clastic wedge, the pre-glacial Saglek Formation, which forms the present-day outer shelf and slope.

Onset of progradation of coarse-grained proximal coastal facies of the Saglek Formation began in the Early Pliocene (Ainsworth et al., 2014). The Saglek Formation contains large numbers of metamorphic and igneous clasts which in association with the coarse, often arkosic nature of the sandstones, indicate a close-by high-relief source area (Balkwill et al., 1990; Ainsworth et al., 2014). The geometry of the Saglek deposits indicates that a broad system of coalescing fan deltas seen on seismic sections were probably alluvial fans, with their apical, updip positions contiguous to the source area, the Torngat Mountains (Balkwill et al., 1990).

From these observations it appears that a 3-stage uplift history along the Labrador margin seem likely: a first phase that began at the Oligocene-Miocene transition leading to progradation of the Lower Saglek Formation, a second phase in the Late Miocene corresponding to the intra-Saglek unconformity, and a final phase of Pliocene age leading to progradation of the Upper Saglek Formation.

Evidence from the Grand Banks

Grant and McAlpine (1990) discussed the geology of the continental margin of Newfoundland, including the Grand Banks. They focused their discussion of the unconformities in the region on the composite Kimmeridgian to Cenomanian Avalon unconformity, which they found to be related to a regional Late Mesozoic arch. They noted the presence of a generally thin cover of under-formed Upper Cretaceous and Tertiary sediments above the Avalon unconformity. They did not, however, discuss the nature of the regional base-Tertiary unconformity shown in their diagrams.

Our analysis of publically available maturity data from the West Flying Foam L-23 well in the Jeanne d'Arc Basin indicates major complexity in the thermal and burial history, with important implications for exploration, but inconsistencies in the data (Figure 5) suggest that a more detailed study is required before firm conclusions can be reached. The West Flying Foam L-23 well penetrated 4.5 km of Cenozoic-Mesozoic sediments in the Jeanne d'Arc Basin of the Grand Banks region. The section contains a prominent base-Tertiary unconformity representing most of the Upper Cretaceous (underlying Nautilus Fm is Albian) and a short 'Aptian' unconformity separating Ben Nevis and Avalon Fms (Aptian and Barremian, respectively) (Figure 5A). No breaks are reported within the Cenozoic section. The Default Burial History shown in Figure 5A is the starting point for thermal history reconstruction: If the VR data (Figure 5B) can be explained by the Default Thermal History derived from this burial history combined with the present-day thermal gradient, then all units are at maximum temperatures at the present day.

Almost all VR data (measured and equivalent values derived from Tmax) available from the NRC 'BASIN Database' in Figure 5B are higher than the trend predicted from the Default Thermal History, suggesting that units from the Banquereau Fm down, have been hotter in the past. At depths between 2000 and 2500 m, VR values from all four datasets are quite consistent. But at shallower and deeper levels, the three VR datasets show considerable differences, with very different implications for the underlying thermal history and the resulting history of hydrocarbon generation.

The break in the VR values from the GSC (Geological Survey of Canada) at a depth of around 2500 m occurs close to the base-Tertiary unconformity but lies within the Nautilus Fm. This offset may represent a problem with inconsistent depth datums or could be due to caving. This break suggests a major degree of deeper burial on the base-Tertiary unconformity. But the two Geochem datasets show no such break. None of the datasets suggests any effects due to the Aptian unconformity. All datasets above the base-Tertiary unconformity are higher than the profile, suggesting that this part of the section has also been hotter, presumably due to deeper burial prior to Late Cenozoic cooling.

Inconsistencies between the various VR datasets preclude any firm conclusions. Focusing on the GSC dataset, which define consistent trends in Figure 5D, two major paleo-thermal episodes are needed to explain these data (Figure 5C). (1) An earlier event, in which pre-Cenozoic units reached their maximum paleotemperatures, is associated with deeper burial on the base-Tertiary unconformity, and (2) A later event, in which most of the Cenozoic and all of the Mesozoic section was more deeply buried prior to a late phase of exhumation in which the additional cover was eroded (this requires a major stratigraphic break at a shallow level within the Cenozoic section). This reconstruction involves burial by 4500 m of additional Upper Cretaceous-Paleogene section on the base-Tertiary unconformity as well as 900 m of additional section deposited on an unconformity at the present-day sea bed.

Figure 5D shows the maturity profile (red lines) predicted by the burial history reconstruction in Figure 5C. Most of the measured and equivalent VR values above the base-Tertiary unconformity agree with the predicted maturity profile, but only the GSC VR data agree below this horizon.

The impact of this possible base-Tertiary paleo-thermal event, involving major burial and exhumation, is of key importance to exploration for hydrocarbons. Any source rocks within the Lower Cretaceous and older section would have generated hydrocarbons prior to the onset of cooling from the paleo-thermal maximum. The nature of the Cenozoic paleo-thermal event implied by the relatively high VR data for the Cenozoic section may be similar to that implied for the Labrador Shelf (Figure 4). It is clear from the scattered maturity data in Figure 5B, that additional data are required to investigate the reality of the base-Tertiary episode of burial and exhumation. Data from other techniques such as apatite fission-track analysis (AFTA) would also be useful in providing improved definition of the thermal history. Sonic velocity data may also provide important constraints on the burial and exhumation history, in similar fashion to the results from the Hopedale E-33 well shown in Figure 4B.

Evidence from the Onshore Domain

Precambrian rocks dominate Labrador and Newfoundland, but Phanerozoic cover rocks are present across the region, for example in the Palaeozoic basins of western Newfoundland (Cooper et al., 2001). Hendriks et al. (1993) interpreted apatite fission-track data from western Newfoundland to indicate major episodes of Late Carboniferous and Jurassic exhumation. This agrees with evidence from thermal maturity of Palaeozoic rocks that they had been more deeply buried below a cover up to 3 km thick (Williams et al., 1998). An outlier of Cretaceous sediments on central Labrador around Schefferville (Dorf, 1967) constrains the construction of a model of the burial and exhumation history of the region by documenting when basement rocks were exhumed to the surface. Grist and Zentilli (2003) reported evidence for post-Jurassic exhumation with as much as 30° C of post-Paleocene cooling of the southern portion of the Canadian Atlantic margin, based on fission-track data, e.g. from Nova Scotia. They also reported high vitrinite reflectance values for Jurassic strata in the Fundy Basin, offshore Nova Scotia, in agreement with 2 km of post-Jurassic erosion inferred from seismic data.

Integrated Investigation of the Vertical Movements along the Margin

The observations reviewed above demonstrate that episodes of burial and exhumation have affected the Atlantic margin of Canada both prior to and after break-up. The available evidence does not, however, allow further definition of the timing and magnitude of the vertical movements that shaped the present-day margin. In particular, it is not possible to define neither when the mountains along the margin reached their present elevation, nor when Cretaceous-Paleogene units offshore reached their maximum burial.

We have therefore initiated a research project aimed at defining the main events of burial and exhumation along the margin onshore and offshore Labrador and Newfoundland (Japsen et al., 2016). The study has three components: (1) A thermochronological study based on samples from outcrops and from onshore and offshore boreholes with associated thermal history interpretations (Green et al., 2013). A pilot study comprising AFTA data in 12 samples (Figure 1) revealed a long history of Phanerozoic cooling and exhumation episodes, (2) A stratigraphic landscape analysis of the study area aimed at mapping exposed denudation surfaces. This analysis provides evidence of both uplift and subsidence using cross-cutting relationships between palaeosurfaces and stratigraphic constraints and thus to construct a relative chronology for surface formation and tectonic events (Green et al., 2013), and (3) An integrated interpretation of the geological, geomorphological and thermochronological data in order to estimate the timing and magnitude of uplift and exhumation along the margins of Labrador and Newfoundland.

Figure 6 illustrates the integration of the AFTA data in the pilot study from the northernmost part of Labrador with constraints from the geological record. These observations imply that the bedrock outcropping on the coast today was buried below a km-thick rock column (possibly including sedimentary rocks) prior to Triassic and Jurassic exhumation and also that the bedrock subsequently was reburied below a somewhat thinner cover (but still of kilometre thickness) of Cretaceous to Paleogene volcanic rocks and sediments prior to late Cenozoic exhumation. For reference, a 2-km thick rock column of that age was penetrated by the Karlsefni A-13 well, 60 km off the coast.

Implications for Hydrocarbon Exploration

Understanding the magnitude and extent of vertical motions in hydrocarbon prospective basins is crucial in minimizing exploration risk. Failure to account for greater depths of burial prior to exhumation in offshore basins may lead to serious underestimation of the maturity of petroleum resources and to erroneous estimates of the timing of hydrocarbon generation. Furthermore, uplift may lead to tilting of reservoirs and loss of charge, or changes in migration routes. Exhumation can also lead to loss of charge due to seal breach resulting from the pressure reduction as overburden is reduced, resulting in loss hydrocarbon charge from reservoirs. For further discussion of the effects of exhumation on hydrocarbon prospectivity see Doré et al. (2002). Insights into the uplift history of continental margins are also important for understanding the source-to-sink system of sediment input into offshore basins. The complex history of vertical movements along the Labrador-Newfoundland margin underlines the importance of establishing a framework for anticipating the possible effects from uplift on the petroleum system along the margin.

Conclusions

The stratigraphic record along the continental margin of Labrador and Newfoundland provides ample evidence for vertical movements both prior to and after break-up. In the offshore domain, major hiatuses punctuate the stratigraphic record. On the Labrador Shelf, Lower Cretaceous volcanics rest on Palaeozoic sediments, and Miocene sediments are absent across a wide area. In the Grand Banks area, Upper Triassic sediments rest on Paleozoic basement, the composite Avalon unconformity truncates Mid-Cretaceous and older strata, and a low-angular, base-Tertiary unconformity is present over much of the area. The preliminary analysis of public-domain data presented here indicates that Mesozoic strata along parts of the margin may have been more deeply buried prior to phases of exhumation, but the analysis also highlights that new data are needed to investigate the reality of these episodes. It is our ambition to combine the evidence from the stratigraphic record with results from stratigraphic landscape analysis and thermochronology onshore and offshore to provide a coherent model of the timing and magnitude of the vertical movements along the margin both prior to and after break-up.

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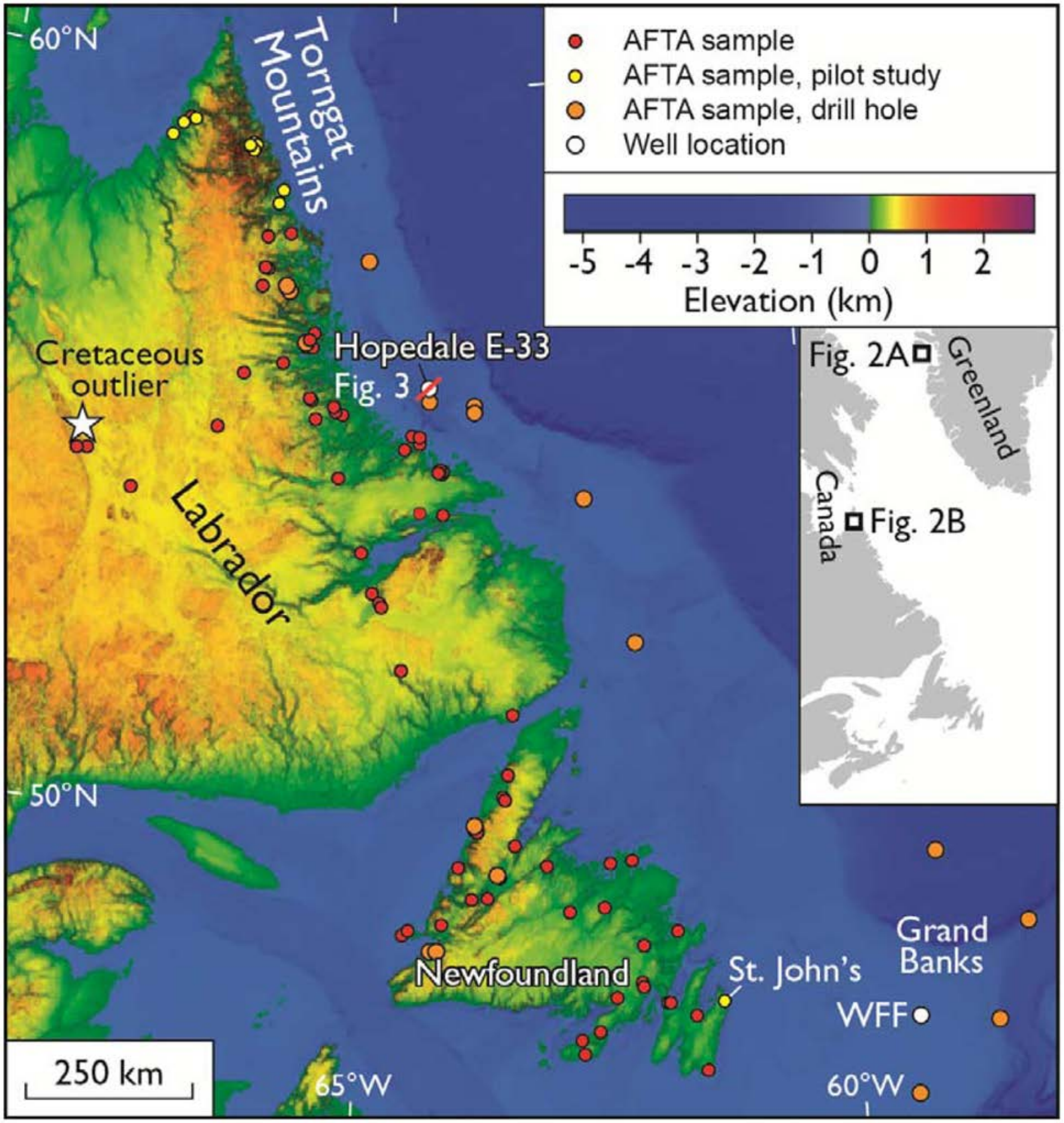

Figure 1. Outline of the study area, c. 1500 km along the Labrador-Newfoundland margin between 46 and 60.5° N. Yellow star: Cretaceous outlier at Schefferville (Dorf, 1967). AFTA: Apatite fission-track analysis. WFF: Well West Flying Foam L-23.

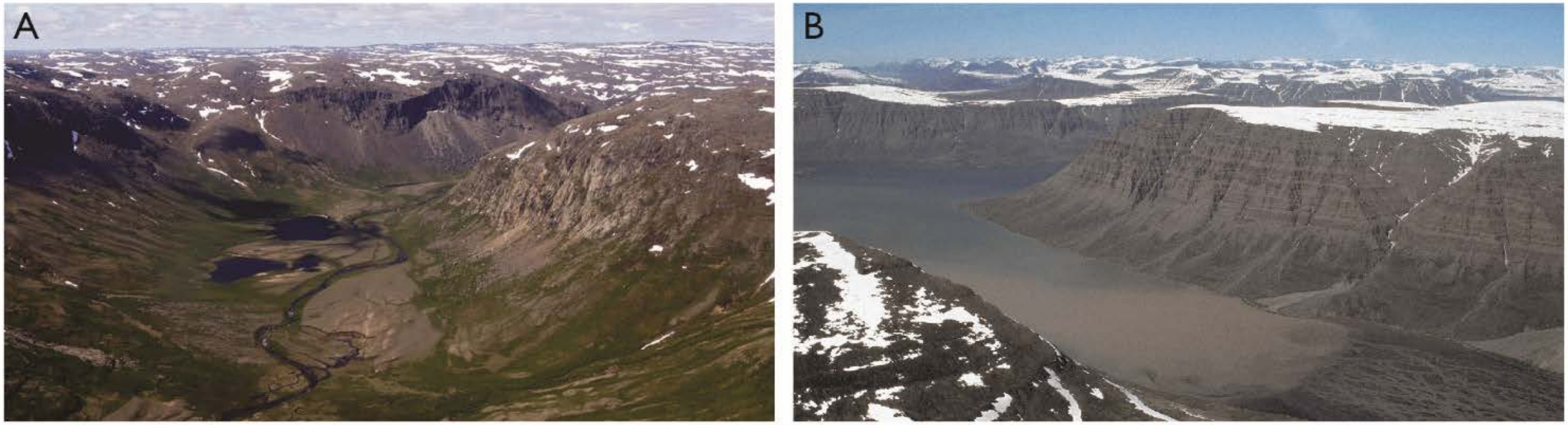

Figure 2. Similar landscapes on the conjugate margins across the Labrador Sea. (A) Elevated plain (c. 800 m a.s.l.) across Precambrian basement cut by a deep valley, Torngat Mountains, Labrador. (B) Elevated plain (c. 900 m a.s.l.) across Paleocene basalts cut by a deep valley, Disko Island, West Greenland. The study will investigate whether the elevated plain is a Cenozoic erosion surface, as is the case for the conjugate margin in West Greenland (Bonow et al., 2006; Japsen et al., 2006). Photo locations in Figure 1.

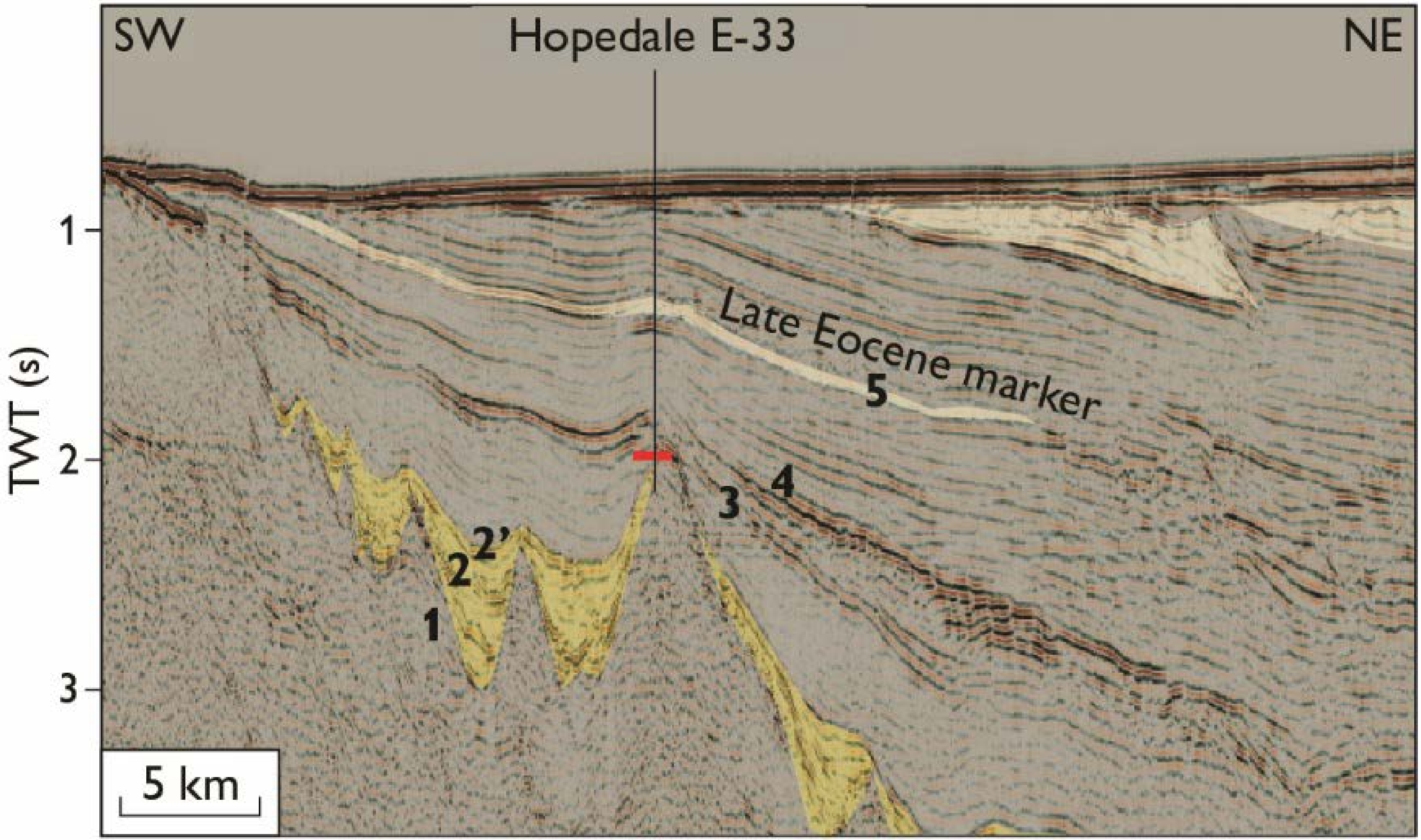

Figure 3. Seismic profile off Labrador illustrating post-Eocene tilting and truncation of the sedimentary sequences (after Dickie et al., 2011). Unconformities: (5) Late Eocene. (4) base Eocene. (3) Mid-Paleocene. (2') Late Cretaceous. (2) Mid-Cretaceous. (1) top basement. Sand-prone units: Gold and yellow colours. Location on Figure 1. TWT: two-way travel time.

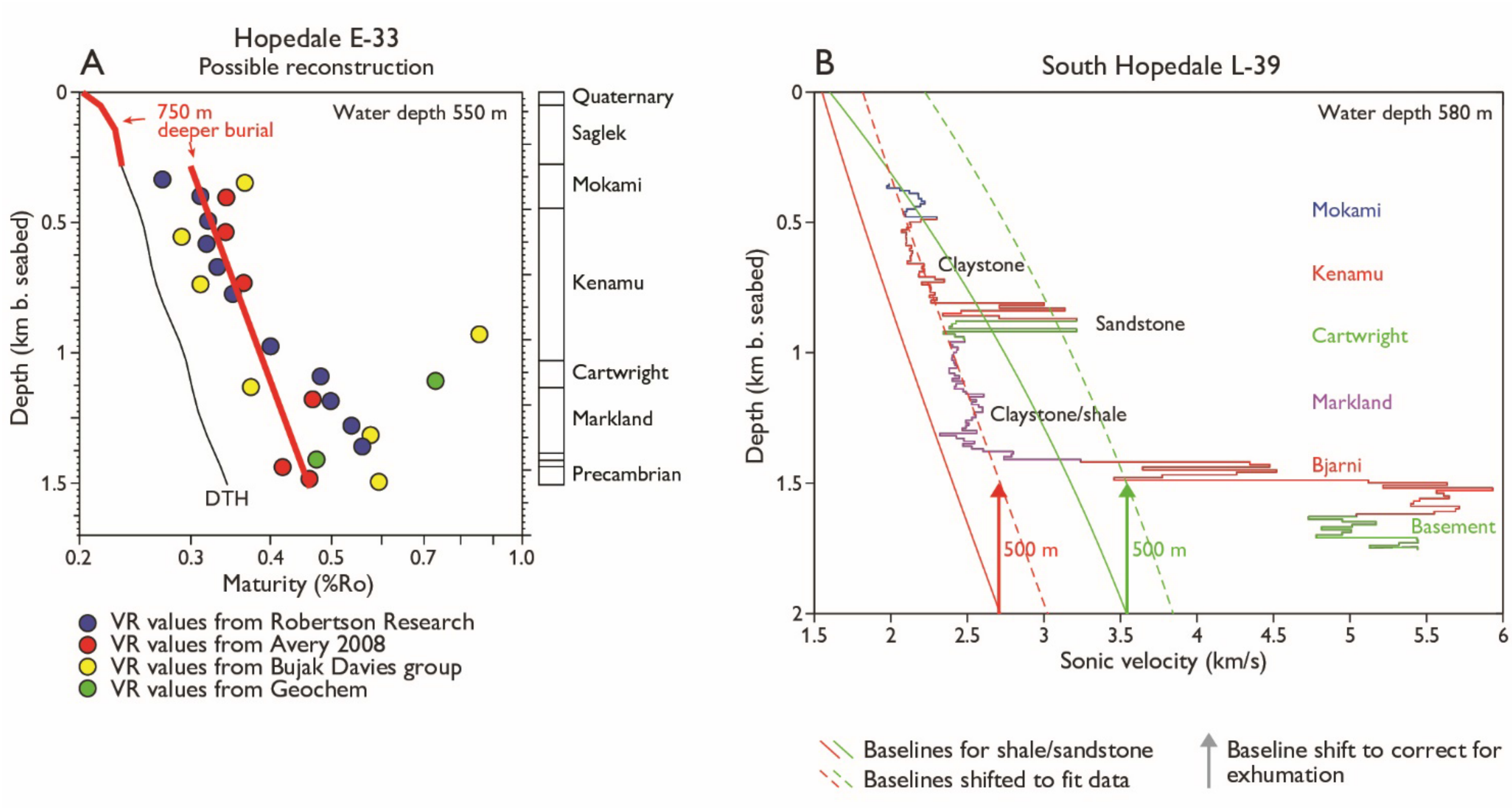

Figure 4. (A) Scattered vitrinite reflectance (VR) data from various labs for the Hopedale E-33 well (source: Canada Basin Database; http://basin. gdr.nrcan.gc.ca/index_e.php; location in Figure 1 and Figure 3). The solid black line shows the profile predicted if all units in the well are currently at their maximum post-depositional temperatures (default thermal history, DTH). All values plot consistently above the black line, suggesting that units below the Plio-Pleistocene Saglek Formation have been hotter in the past, although a detailed interpretation of these data is not possible because of the scatter in the data and differences between datasets. The red profile shows the prediction from a history in which the pre-Saglek section has been buried more deeply by 750 m prior to exhumation. (B) Sonic log data for the South Hopedale L-39 well (located 6 km south of the Hopedale E-33 well). Comparison of the sonic velocities for the shales and a normal velocity-depth trend for shale (Japsen et al., 2007) indicates that the drilled sequences have been more deeply buried by about 500 m after the deposition of the Eocene Kenamu Formation. Adding this burial anomaly to the post-exhumational burial of 180 m (= the thickness of the Saglek Fm) yields a missing section of about 700 m. Ainsworth et al. (2014) found a regional Miocene hiatus below the Early Pliocene - Pleistocene Saglek Formation on the Labrador Shelf, and it is thus likely that the Palaeogene and older sequences drilled in these wells were buried below a significant cover of Miocene sediments prior to Late Neogene exhumation.

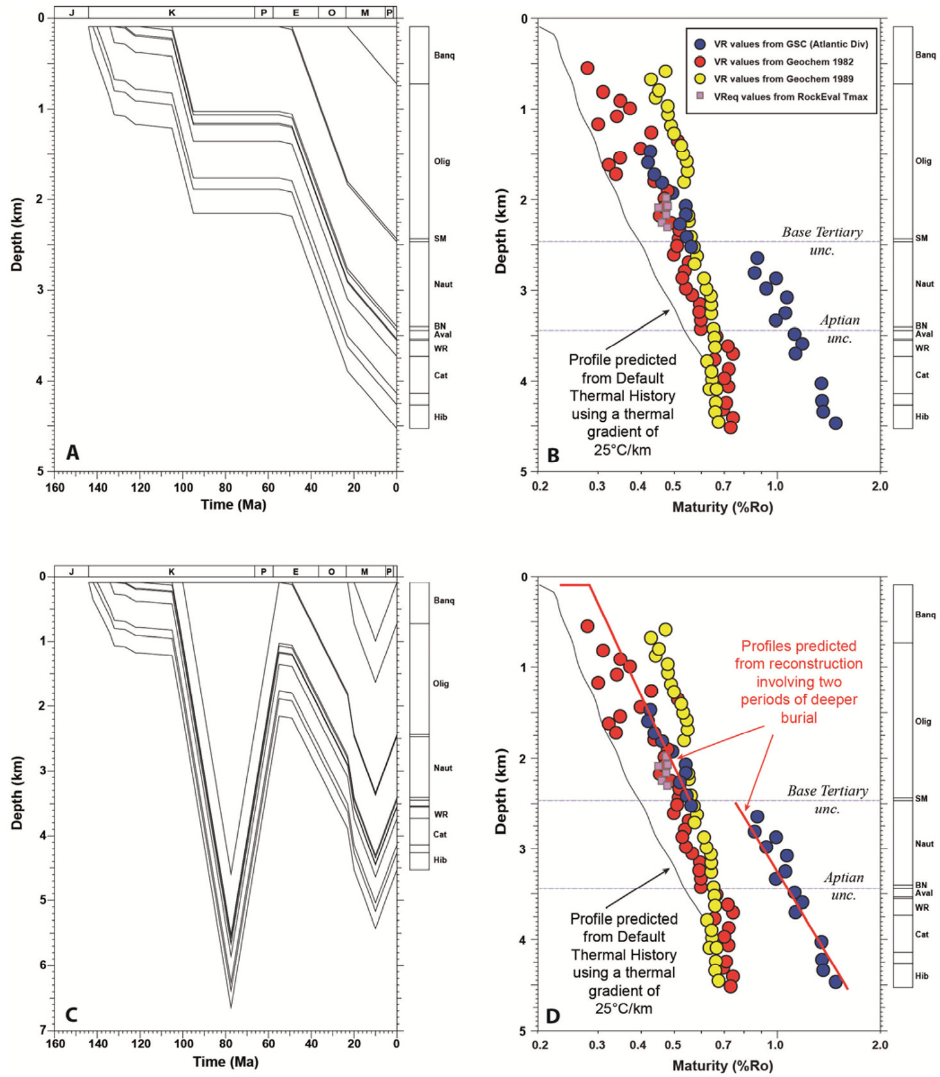

Figure 5. Burial histories and VR data for the West Flying Foam L-23 well. (A) Burial history produced from the lithostratigraphic breakdown obtained from the NRC 'BASIN Database'. (B) Measured VR values and equivalent VR data derived from Tmax data plotted against depth. Based on three sets of VR data available in the NRC 'BASIN Database', plus one set of RockEval Tmax values. (C) Burial History Reconstruction required to explain the GSC VR data (Figure 5B), involving two major paleo-thermal episodes. The thermal gradient is kept constant through the history. (D) Maturity profile (red line) predicted by the burial history reconstruction in C. Most of the measured and equivalent VR values above the base-Tertiary unconformity agree with the profile, but only the GSC VR data agree below this horizon. Banq: Banquereau Fm. Olig: Oligocene sandstone. SM: South Mara Mb. Naut: Nautilus Fm. BN: Ben Nevis Fm. Aval: Avalon Fm. WR: White Rose Fm. Cat: Catalina Fm. Hib: Hibernia Fm.

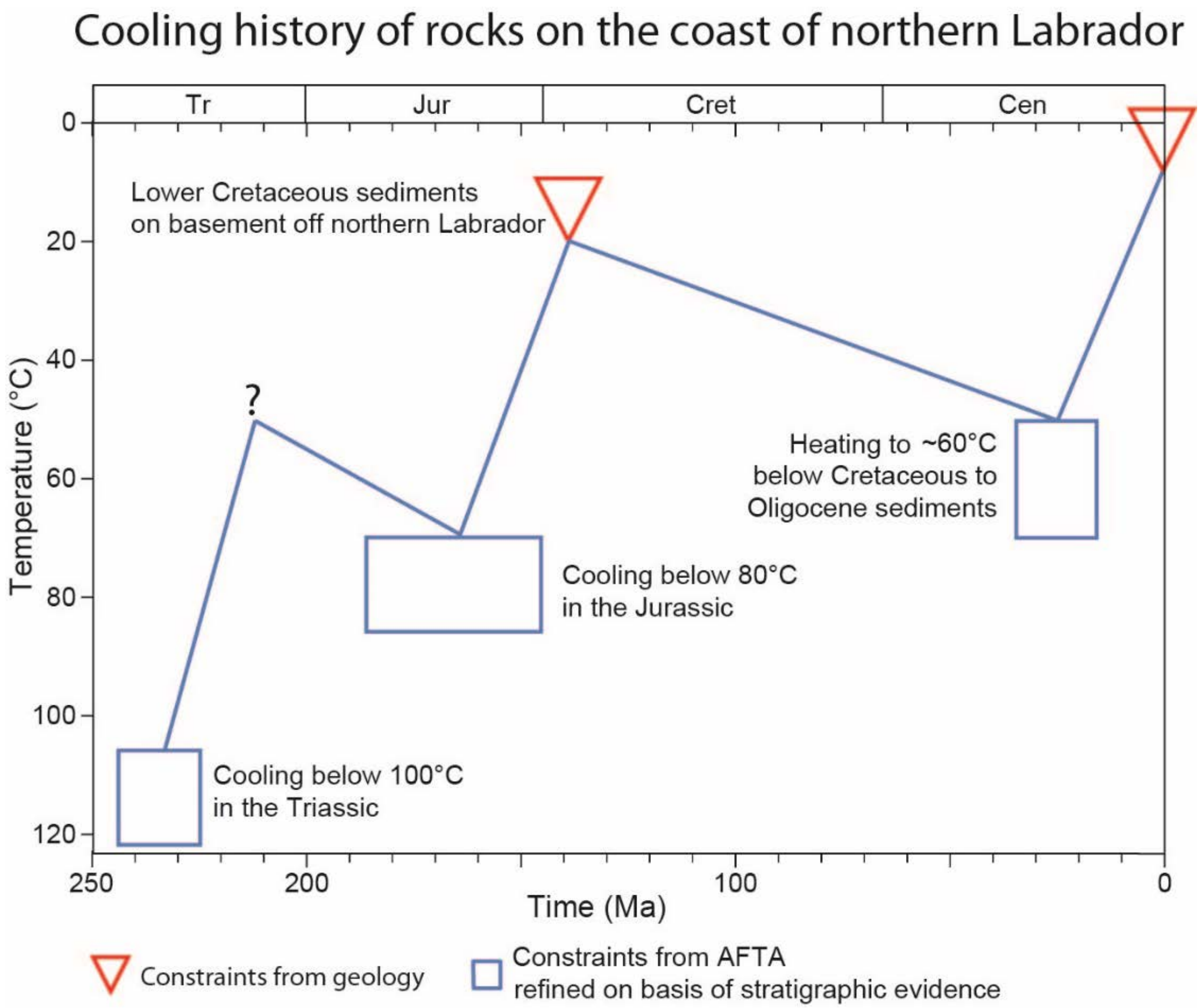

Figure 6. Diagram illustrating the burial and exhumation history along the Atlantic coast of northernmost Labrador. Apatite fission track analysis (AFTA) data from the area show that the basement there cooled below 100° C (blue rectangle) in the Triassic (beginning between 244 and 225 Ma) and from about 80° C (blue rectangle) sometime in the Jurassic - Early Cretaceous (beginning in the interval 189-100 Ma). But the cooling from such paleotemperatures must have happened before the Cretaceous (and thus in the interval 189-145 Ma) because lowermost Cretaceous rocks rest on basement off the coast; e.g. in the Karlsefni A-13 well (www.cnlopb.ca). The bedrock on the coast must therefore have been close to the surface in the earliest Cretaceous (red triangle). Furthermore, the AFTA data show that the bedrock was heated to about 60° C (blue rectangle) in latest Cretaceous - Tertiary, but according to Balkwill et al. (1990), uplift and exhumation of Labrador began at the Oligocene-Miocene transition, and that implies that maximum Cenozoic palaeotemperatures happened around that time. Final exposure of the basement happened sometime in the Late Neogene (red triangle).