Seismic stratigraphy of the post-breakup succession offshore Northeast Greenland: Links to margin uplift

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Abstract: The timing of the continental breakup between Norway and Greenland and the subsequent plate tectonic motions are well understood. However, due to the remote location of the Northeast Greenland shelf, relatively few details about the tectonosedimentary response to the tectonism following the breakup have previously been published. This article gives new insights into the structural and sedimentary history of the Northeast Greenland shelf, with an emphasis on the post-breakup tectonics, using state of the art 2D seismic data. The results of this study clearly shows a highly dynamic post-breakup tectonic setting with pronounced, kilometre-scale fault offsets, tilting of the Danmarkshavn Basin and pronounced progradational events. The tectonosedimentary events are linked with the passage of the Icelandic mantle plume south of the Northeast Greenland shelf. Based on tectonostratigraphic interpretations and integration of data from ODP 913, this study constructs a temporally robust model for the post-breakup succession. Significant post-breakup uplift and tectonism related to thermal uplift is present on the margin. It is observed that the Icelandic hot spot passes relatively close by the Northeast Greenland shelf (<500 Km) during the Cenozoic. Its passage south of the shelf supports the observation of the northwards tilt of the shelf and associated northwards shift of the prograding clinoforms due to a combination of thermal uplift and possibly dynamic topography.

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
The data that has been used is confidential

Detailed response

This resubmission does not contain any major revisions of the manuscript. The resubmission is purely done so that all figures are contained in the revision. Please note that an outline of the salt affected area is included in figure 2, as a response to previous reviewer comments.

Best regards

Thomas Guldborg Petersen

Assistant Professor

***Highlights (for review)**

- Significant vertical motions along faults after the continental break-up
- Seismic interpretations reveal northward moving progradational units
- Passage of Iceland plume responsible for post-breakup tectonics

Seismic stratigraphy of the post-breakup succession offshore Northeast Greenland: Links to margin uplift

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Abstract

The timing of the continental breakup between Norway and Greenland and the subsequent plate tectonic motions are well understood. However, due to the remote location of the Northeast Greenland shelf, relatively few details about the tectonosedimentary response to the tectonism following the breakup have previously been published. This article gives new insights into the structural and sedimentary history of the Northeast Greenland shelf, with an emphasis on the post-breakup tectonics, using state of the art 2D seismic data. The results of this study clearly shows a highly dynamic post-breakup tectonic setting with pronounced, kilometre-scale fault offsets, tilting of the Danmarkshavn Basin and pronounced progradational events. The tectonosedimentary events are linked with the passage of the Icelandic mantle plume south of the Northeast Greenland shelf. Based on tectonostratigraphic interpretations and integration of data from ODP 913, this study constructs a temporally robust model for the post-breakup succession. Significant post-breakup uplift and tectonism related to thermal uplift is present on the margin. It is observed that the Icelandic hot spot passes relatively close by the Northeast Greenland shelf (<500 Km) during the Cenozoic. Its passage south of the shelf supports the observation of the northwards tilt of the shelf and associated northwards shift of the prograding clinoforms due to a combination of thermal uplift and possibly dynamic topography.

1 INTRODUCTION

Passive margin tectonism is widely debated, especially in the North Atlantic realm. Conventional models for continental breakup only predict thermally induced subsidence following the heating caused by upwelling mantle (e.g. McKenzie, 1978). However, observations around the margins of the North Atlantic suggest that significant tectonics and vertical motion occurred after the breakup (Lundin and Doré, 2002; Tsikalas et al., 2012). The term breakup, or continental breakup is here understood as the phase of separation between continental lithospheric plates, following the rift phase, *sensu* Cloetingh et al. (2013).

Although the Northeast Greenland shelf has been studied previously (e.g. Funck et al., 2017; Hamann et al., 2005; Petersen et al., 2015), very little is known about the tectonostratigraphic development of the shelf after the continental breakup. Based on a comprehensive seismic database consisting of the latest available data, this study yields new insights into the structural history and its influence on sedimentation. By conducting a thorough seismic stratigraphic study of the Northeast Greenland shelf, several seismic units significant to the understanding of the post-breakup development of Northeast Greenland are interpreted concerning depositional environment, tectonostratigraphy and relation to plate tectonics. A clear link between the passage of the Icelandic hotspot, uplift of the inner margin and a northward shift in prograding clinoforms is presented.

2 REGIONAL GEOLOGY

The North Atlantic plate tectonic history is described in multiple studies (e.g. Gaina et al., 2009; Matthews et al., 2016; Müller et al., 2016; Tsikalas et al., 2012). Evidence of rifting throughout the Paleozoic and Mesozoic along the margins of the North Atlantic is recorded as extensional tectonics both onshore (Stemmerik, 2000) and offshore (Tsikalas et al., 2012, 2005) as a part of the long-running opening of the Atlantic Ocean (Cloetingh et al., 2007). The rift to drift transition i.e. the continental breakup is dated by means of paleomagnetic anomalies to have occurred at 55.9 Ma (chron 24), at the Paleocene—Eocene transition (Gaina et al., 2009; Matthews et al., 2016; Ogg, 2012; Olesen et al., 2007). This is associated with pronounced volcanism, dated to the earliest Eocene (Larsen et al., 2014). The shelf south of *ca.* 78° N is the conjugate margin to the Vøring and Lofoten margin in Norway, and is associated with extension of the Mohns Ridge segment of the mid ocean ridge system of the North Atlantic (e.g. Gaina et al., 2009; Talwani and Eldholm, 1977; Ziegler, 1992). It is dominated by normal faulting prior to the continental breakup (Tsikalas et al., 2012). However, the shelf north of *ca.* 78° N is dominated by complex transpressional and transtensional deformation during the opening of the Greenland Sea, where transverse deformation initially occurred along the East Greenland Ridge, before shifting to the Knipovich Ridge during the Oligocene. A slowing of the plate tectonic motion (Gaina et al., 2009; Tegner et al., 2011), dated to *ca.* 49-47 Ma, coincides with the peak in the Eurekan Orogeny along the northernmost edge of Greenland. Absolute opposite plate motion, where Greenland drifts towards the Northwest and Norway towards the Southeast, was achieved during the earliest Oligocene (33.1 Ma), which implies that passive margin conditions were developed along the entire Northeast Greenland and North Greenland continental margin at this time (Gaina et al., 2009).

Pronounced progradation of clinoforms have been described previously, based on low density/low resolution seismic data, and attributed to a "Tertiary" age (Hamann et al., 2005). The pre-drift succession of the Northeast Greenland shelf have also been described in detail (Petersen et al., 2015), but very little has so far been published on the post-breakup seismic stratigraphy.

Sea level changes during the Cenozoic have been described previously (Miller et al., 2005) , and the effects of changing eustatic sea level obviously also had an impact on the sedimentation on the Northeast Greenland shelf. Even though this article focuses solely on the tectonic processes and on highlighting the vertical motions observed on the shelf during the post-breakup times, the author fully acknowledges the influence of eustatic sea level changes as well.

3 DATA AND METHODS

The database of this study is composed of the latest vintages of commercial 2D seismic data collected during a period from 2008-2014 by TGS, a commercial seismic data vendor, together with a scientific dataset collected by the Alfred Wegener Institute (AWI) during the early nineties (Berger and Jokat, 2009, 2008) (Fig.1). All seismic data are courtesy of TGS and Spectrum. The seismic data were supplied under the agreement that no shot points or navigational data are published. These data are supplemented by free air gravity data from the DTU10 global gravity field model (Andersen, 2010; Andersen et al., 2010). The locations of the North Atlantic hotspots are derived from Whittaker et al. (2013), and the locations of the magnetic anomalies are adopted from Müller et al. (2016). Plate tectonic reconstructions are based on Matthews et al. (2016). Reconstruction of the path of the hotspots was done using the open source software GPlates (www.gplates.org). The seismic interpretation was conducted using a seismic workstation (Petrel 2016). Standard seismic stratigraphic methods was applied as outlined by Emery and Myers (1996).

4 OBSERVATIONS

4.1 Potential field data

The use of free air gravity data gives excellent insights into the geometries of structural elements in the Northeast Greenland area (Fig. 2). The gravity data quite clearly show the location of the continental slope (Fig. 2), and the magnetic anomalies (Müller et al., 2016), shows the westward extent of the oceanic crust, as well as other key features of the Northeast Greenland shelf. The Danmarkshavn Basin stands out on the inner side of Northeast Greenland's continental shelf as a distinct low in the gravity field. In fact, the gravity low extends onshore Greenland, outlining the prominent sedimentary basins present there (Stemmerik, 2000). The Danmarkshavn Ridge is also outlined in detail as a positive gravity anomaly. The ridge is NE-SW striking and displays a noticeable right-lateral offset, separating the ridge into a north and a south segment (Fig. 2). It is also clear, that the deep faults observed on the shelf are parallel to the ridge, and that the faulting of the Cenozoic succession is focused at or near the ridge, with few exceptions (Fig. 2). Although a detailed description of the faults is given below, it is noted that faulting is also observed north of the Danmarkshavn Ridge gravity high. The Thetis Basin is seen as a relatively narrow, elongated gravity low parallel to the Danmarkshavn Ridge. This shape of the basin in the gravity data is controlled mostly by a very deep, narrow half graben created during the Mesozoic (Figs. 3a, b). The shape of the basin during the Cenozoic is wider however, and spans from the Danmarkshavn Ridge to the continental slope.

4.2 Seismic interpretation

Based on the observed seismic facies of the individual units, the sedimentary facies, depositional environment and tectonic evolution are evaluated. The methodology is briefly described in Emery and Meyers (1996), where they highlight the seismic expression of various depositional environments. Due to the lack of well control, the seismic facies interpretations in this study are associated with some uncertainty.

This study is based on the mapping of several seismic horizons across the Northeast Greenland shelf and onto the oceanic crust (Figs. 3-7). The shown seismic horizons all hold significant information about the tectono-sedimentary history during the Neogene of Northeast Greenland. By using conventional seismic interpretation techniques and seismic stratigraphic principles, it is possible to describe exhumation, subsidence and the relative timing of tectonic events. This study establishes a regional framework of tectonic events with good confidence due to the inclusion of the most comprehensive, high quality seismic database currently available (fig. 1). The seismic observations correlates well with the gravity data, confirming the control of deeper structures on the depositional pattern. (Fig. 2). Examples of both the seismic horizons and the interpreted faults are presented in seismic cross sections (Figs. 3-7), and in map form (Figs. 8, 9). Only one borehole is available for age correlation, namely the ODP 913 borehole (Thiede et al., 1995). The location of ODP 913 on the oceanic crust means that the pre-breakup succession is not penetrated. Due to the absence of any deep well bores on the Northeast Greenland shelf, all the ages of the pre-early Eocene seismic horizons are associated with some uncertainty. This study infers the ages of the seismic horizons from published regional studies (Engen et al., 2008; Hamann et al., 2005; Petersen et al., 2015; Tsikalas et al., 2012), and by correlating with plate tectonic events highlighted in this study.

Structure maps of key surfaces are also presented (Fig. 8a, b). These maps are all in Two Way Time (TWT) reported in seconds. All structure and thickness maps are interpolations of seismic data, within the extent of the interpreted horizon. This means that the outer boundary of a surface is defined by the absence of the seismic horizon due to either erosion or condensation, or due to the lack of resolution in the seismic data. The study also includes thickness maps used to highlight areas of deposition (Figs. 10-12).

The seismic units described below, subdivide the Paleogene and Neogene succession of the Northeast Greenland margin into three seismic units significant for the understanding of the tectonic evolution after the continental breakup. The interpretation and definition of the seismic units was based on their importance concerning structural evolution of the margin, especially during post-breakup times. Pronounced unconformities was the central focus, as they play a significant role in the identification of the location and timing of tectonic events on the Northeast Greenland shelf. Seismic facies in the respective units are also described in order to interpret the depositional mechanisms responsible for the deposited sediments and to constrain the structural evolution of the Northeast Greenland margin after the breakup.

4.3 Dating of the seismic units

All dating of the seismic units is done by correlation with the plate tectonic evolution as well as understanding of regional tectonic events in conjunction with the previously mentioned ODP 913 borehole. Previous studies have created a framework for the dating of the pre- and syn- breakup succession (Petersen et al., 2016, 2015). The current study further constrains the ages of the pre-breakup succession suggested in these studies by usage of better quality seismic data and closer correlation to the ODP 913 borehole. Furthermore, this study adds significant new knowledge about the post-breakup seismic units and their relative timing. The addition of reprocessed and recently acquired seismic data improves the reliability of these interpretations and adds additional information regarding the ages of the depositional events.

Prior to the onset of Paleocene deposition, a regional unconformity is observed in the Wandell Sea area, north of the current study area (Håkansson and Stemmerik, 1989). This and other observations are used by Hamann et al. (2005) to define the base of the Cenozoic succession in the Danmarkshavn Basin area. Furthermore, observations onshore Northeast Greenland in the Wollaston Foreland and Sabine Ø area (Fig. 2) confirms a hiatus between the Createaceous and the Paleogene (Nøhr-Hansen et al., 2011). A change from syn-tectonic halfgraben infill to parallel reflections mark the Mesozoic-Cenozoic transition in the Thetis Basin. The accuracy of the age of the unconformity is uncertain due to the lack of any means of direct dating. Furthermore, the interface is most likely diachronous across most of the study area, although early Cenozoic deposits appear relatively conformable at their base, with the exception of the south part of the study area, where Petersen et. al (2015) describe progadation from the southwest.

The Early Eocene Unconformity is relatively well dated due to its association with the breakup volcanism. Compelling evidence of deepening of the erosion towards the centre of the magmatic intrusions in the Danmarkshavn Basin, (Petersen et al., 2015), together with the coinciding gas vent structures from the intrusions (Reynolds et al., 2017) yields a relatively tight constraint on the age of this horizon (Fig. 5). This is achieved by utilizing the well-known absolute ages of the peak in magmatic intrusions onshore Northeast Greenland (Larsen et al., 2014). These observations are further corroborated by the availability of the high quality data for this study. Especially the northwards correlation of this event makes it possible to constrain the ages of the tectonosedimentary events in the north of the study area (Fig. 7b).

There are no direct means of constraining the age of the Erosional incision seismic horizon, so a relative dating of the horizon is suggested. The Erosional incision horizon clearly truncates the well-dated Early Eocene Unconformity (Figs. 4a-c), thus a post- Early Eocene age can be initially suggested. The erosional incision also truncates strata younger than early Eocene, so the incision must post-date the Early Eocene Unconformity by some margin. The upwards constraint of the age of the erosional incision is the Intra Miocene Unconformity, as this horizon is not truncated by the incision. However, a significant sedimentary succession is present between the two horizons, which hampers the possibility for a more accurate age for the Erosional incision horizon other than late Eocene—mid Miocene. An important observation in this context is that the Erosional incision horizon post-dates the continental breakup.

The Intra Miocene horizon is dated using the information from the ODP 913 borehole using the seismic tie from Berger and Jokat (2008). This is the only directly dated horizon in this study, but some uncertainty is still associated with the age of this horizon. Firstly, it is an unconformity, which is inherently a time-transgressive surface. Therefore significant lateral changes in the age of the horizon may occur. Secondly, the seismic correlation from the ODP 913 drill site and onto the Northeast Greenland shelf is associated with some uncertainty, due to sparse seismic data in the area and condensation across the continental slope. Still, this horizon remains possibly the most accurately dated seismic horizons of this study, and therefore it forms a significant anchor for the dating of the post-breakup events on the Northeast Greenland Shelf.

The youngest horizon interpreted in this study is the Top upper prograding unit seismic horizon. No direct methods for dating this horizon exists. It is clearly younger than the Intra Miocene unconformity horizon and it was affected by the uplift and rotation of the Danmarkshavn Basin and Ridge areas. This is evident from its location above a set of very steep clinoforms associated with the uplift (Fig. 3a). The only age constraint of this horizon is an age younger than mid Miocene, and predating the Quaternary glaciations of the shelf, since the shallow Quaternary erosion does not incise deeply into the unit (Fig. 4a).

4.4 Pre-Cenozoic units

It is beyond the scope of this study to conduct a detailed interpretation of the Palaeozoic and Mesozoic succession on the Northeast Greenland shelf. However, some general observations are of relevance to the further interpretation, and will be summarised here. For a more complete understanding of the pre-Cenozoic geology of the Northeast Greenland shelf, see e.g. Hamann et al. (2005). The Palaeozoic—Mesozoic Succession is largely conformable, but minor angular unconformities exist near the presumed Palaeozoic—Mesozoic transition (Figs. 3a, b). The succession is intersected and rotated by normal faults near the Danmarkshavn Ridge. The faults are all apparently deeply rooted (e.g. Fig. 5). The pre-Cenozoic succession of the Thetis Basin is largely deposited in a rotated half graben setting, with the controlling fault located along the east margin of the Danmarkshavn Ridge (Fig. 3b). The Cenozoic succession is thus underlain by several kilometres of Palaeozoic and Mesozoic sediments, intersected by faults mostly generated during Mesozoic rifting (Hamann et al., 2005).

4.5 Paleocene(?)—Early Eocene seismic unit

The unit is partially described in Petersen et al. (2015), in the southern part of the Danmarkshavn Basin. A more regionally cohesive interpretation is included in this study since it is important for understanding the structural framework, and it forms an important temporal constraint of the continental breakup. The Base Paleogene horizon is the base of this unit is and is regionally extensive and observed across most of the Northeast Greenland shelf area. It is primarily defined as an erosive unconformity, with a deepening incision towards the west in the Danmarkshavn Basin (Fig. 3a, b). A significant topographic break is observed at the transition from the Danmarkshavn Basin/Danmarkshavn Ridge and into the Thetis Basin (Figs. 3a, 8a), where the Base Paleogene lies significantly deeper. Towards the south, faulting offsets the Base Paleogene in the west part of the Thetis Basin (Figs. 3b, 4c). The Base Paleogene is delimited towards the west by erosion due to uplift and tilting of the Cenozoic succession. Towards the east, i.e. towards the continental slope, the Base Paleogene is truncated, since the continental rifting did not occur before the earliest Eocene (Gaina et al., 2009). The north and south extent of the unconformity is not resolved by the current data set.

In the Thetis Basin, east of the basin bounding fault system (Fig. 2), the Base Paleogene Horizon seems to be mostly conformable with the underlying Mesozoic sediments. There are however some evidence of faulting below the Base Paleogene, especially along the western margin of the Thetis Basin (Fig. 5). The Danmarkshavn Basin displays clear evidence of inversion following the Mesozoic rift phases, creating compressional structures such as folds and domes below the Base Paleogene (Fig. 5). These structures were subsequently eroded during a Late Cretaceous—Paleogene (?) and early Eocene erosional events (Figs. 3b, 4a). This compressional event is focused in the Danmarkshavn Basin and Ridge areas, in comparison with the more conformable nature of the Base Paleogene in the Thetis Basin. The seismic facies below the Base Paleogene show frequent examples of high amplitude, discontinuous reflections, often intersecting the bedding. These structures have previously been described as magmatic intrusions (Fig. 7b), (Petersen et al., 2015; Reynolds et al., 2017). Towards the eastern margin of the Thetis Basin, the seismic data show a rise of the Base Paleogene (Fig. 8a). This rise coincides with the shelf to continental slope transition, which is also coinciding with a gravity high (Fig. 2). The high-amplitude, discontinuous reflectors are also very prominent below the rise.

The unit mostly consists of parallel, medium to high amplitude reflections, with the high amplitudes focused mainly in the Danmarkshavn Basin and the Danmarkshavn Ridge areas. The unit is thinning across the eastern margin of the Danmarkshavn Ridge, and there is evidence of internal erosion along the ridge margin, especially to the north (Fig. 3a).

The thickness map (Fig. 10) show a southerly-located depo-centre in the Thetis Basin, with a distinct thinning across the Danmarkshavn Ridge, and smaller depo-centres in the Danmarkshavn Basin, consistent with previous observations (Petersen et al., 2015). Diverging internal reflections towards the faults separating the Danmarkshavn Ridge from the Danmarkshavn Basin indicate syn-tectonic deposition related to normal faulting (Fig. 5). The truncation of the seismic unit that deepens towards the south is mostly controlled by structural rotation and uplift (Fig. 5). The horizon is heavily disturbed in some places, where deep (100-200ms TWT, *ca.* 100-200 m) and laterally extensive (<2 km) depressions or pockmarks are observed specifically at this level (Fig. 5). These features have been mapped previously and been interpreted as gas escape structures related to the earliest Eocene volcanism (Reynolds et al., 2017).

4.6 Early Eocene Unconformity

The Early Eocene Unconformity is a very prominent angular unconformity in the southern area of the Danmarkshavn Basin (Fig. 5), whereas it is mostly conformable across the Danmarkshavn Ridge and in the northern part of the Danmarkshavn Basin (Fig. 3a, b). It forms the upper boundary of the Paleocene(?)—Early Eocene seismic unit described above. Some indications of an angular unconformity below the horizon is also observed on the southern part of the Danmarkshavn Ridge (Fig. 4c). The Early Eocene Unconformity is truncated by the same tilt-induced incision along the western margin of the Danmarkshavn Basin as the underlying Base Paleogene horizon. The truncation occurs further east compared to the Base Paleogene, which inhibits interpretation of the Early Eocene Unconformity in most of the Danmarkshavn Basin (Fig. 3a).

The horizon is offset by deep-rooted, reactivated faults on both the west and east sides of the Danmarkshavn Ridge (Fig. 5). The angular unconformity in the Danmarkshavn Basin deepens towards the southwest. Towards the south, the Early Eocene Unconformity is erosionally truncated by the Erosional Incision horizon observed along the boundary between the Danmarkshavn Ridge and the Thetis Basin (Fig. 3b). Faulting of the Early Eocene Unconformity is also observed along the Intra Danmarkshavn Basin Fault (Fig. 6).

4.7 Erosional incision

This seismic horizon is a very distinct feature along the south segment of the Danmarkshavn Ridge, where it truncates the Early Eocene Unconformity and overlying strata (Fig. 3b). The incision is concave down towards the west and becomes subparallel to the bedding towards the Thetis Basin (Figs. 4a-c). The incision is clearly associated with the westwards bounding fault system of the Thetis Basin. Uplift of the Danmarkshavn Basin and Ridge created a dip along the eastern edge of the ridge (Figs 8a) above the angle of repose of the strata on the Danmarkshavn Ridge, which caused extensive mass wasting of material from the elevated Danmarkshavn Ridge and into the Thetis Basin (Fig. 5). The westward extent of the horizon is defined by the onset of the incision, and the eastward extent of the incision is defined by the transition to conformity (Fig. 3b). The incision is located further east of the Danmarkshavn Ridge and into the Thetis Basin towards the south. In the north, the incision is located on the eastern margin of the Danmarkshavn Ridge (Fig. 4a), whereas the incision is located about 10 km east of the ridge in the south (Fig. 4c). Furthermore, the mass wasting event seems more related to the Intra Thetis Basin Fault observed in the south Thetis Basin (Fig. 4c). The incision is a noticeable unconformity below the horizon, with very pronounced downlaps across the horizon (Figs. 4a-c). The steep incision is not observed north of the central part of the study area (Fig. 7a). However, other local erosional incisions are found along the north segment of the Danmarkshavn Ridge, and although they cannot be correlated with the incision seen in the south, this study indicates they are of similar age as the Erosional incision horizon and related to faulting between the Danmarkshavn Ridge and the Thetis Basin.

4.8 Eocene—Middle Miocene

The Eocene—Middle Miocene seismic unit directly overlies the Paleogene—Early Eocene unit, and is therefore bounded at its base by the Early Eocene Unconformity. The top of the unit is defined by the Intra Miocene Unconformity. The seismic facies in the Danmarkshavn Basin area are very similar to the underlying unit, with high amplitude, parallel reflectors (Figs. 3b, 4a). The Erosional incision horizon across the Danmarkshavn Ridge to Thetis basin transition is associated with steep, prograding clinoforms, extending out into the central part of the Thetis Basin (Figs. 4a-b). The clinoforms are most pronounced in the south of the study area, whereas they are absent in the north (Fig. 3a). The clinoforms are very specifically linked to the erosional incision horizon described above (Fig. 3b). The earliest clinoforms show very little accretion in the topsets, indication of a very rapid initial progradation. The later clinoforms are associated with more topset aggradation and less progradation. The eastern part of the Thetis Basin is dominated by the sub-parallel reflections of the toesets associated with the clinoforms, with a gradual condensation and thinning towards the continental slope (Fig. 3b). A very well defined depo-center along the south margin of the Danmarkshavn Ridge (Fig. 11) correlates with the location of the clinoforms. The thinning towards the shelf edge is also noticeable in the thickness map, as well as the fault control. Minor east-dipping normal faults with a relatively small offset (ca. 100 ms TWT, *ca.* 100 m) and no deep roots are present in several location above the steep prograding clinoforms (Figs. 4c-b). These faults appear to terminate in the Eocene—Middle Miocene seismic unit, and are thus not related to deep-rooted tectonics.

The upper boundary of this unit is the Intra Middle Miocene Unconformity, and is primarily defined based on correlation with the ODP 913 borehole, located on the oceanic crust (Fig. 1), and is thus temporally relatively well constrained based on an unconformity observed in the cores (Berger and Jokat, 2008; Døssing et al., 2016; Thiede et al., 1995). The incision caused by the structural tilt mentioned previously also truncates the Intra Miocene Unconformity along the centre of the Danmarkshavn Ridge. The horizon extends beyond the continental slope to the east, and mimics the same general topographic trends as the underlying horizons, with a steep, fault related slope along the Danmarkshavn/Thetis Basin interface, a deepening in the central Thetis Basin, and a topographic rise towards the shelf edge. The Intra Miocene Unconformity is a prominent downlap surface in the north of the study area. (Fig. 3a). In the south however, the horizon is located at the top of a prograding interval, and is largely conformable both below and above (Fig. 3b). The horizon is often intersected by minor faults, with offsets around 50-250 ms (or *ca.* 50-250 m). The faults are all located where the underlying clinoforms display the strongest progradation, and on a relatively steep slope (Figs. 4b-c, Fig. 5). In the northern part, where the Intra Miocene Unconformity is mainly overlying gently dipping strata, no evidence of faulting of the horizon is observed in the Thetis Basin (Fig. 3a, 4a).

4.9 Middle Miocene—Top Prograding Unit

The Top Prograding Unit seismic horizon defines the upper boundary of the upper prograding seismic unit, the Middle Miocene—Top Progading Unit. When comparing the horizon north to south, it is evident that very steep clinforms are present immediately below the horizon in the north (Fig. 3a), but the seismic unit is approaching subparallel reflections to the south (Fig. 3b). In the southernmost part of the study area, evidence of most likely Quaternary erosional truncation of the Top upper prograding unit horizon is observed at the sea floor as well (Fig. 4c). The horizon is only observed in the Thetis Basin and along the eastern margin of the Danmarkshavn Basin (Fig. 8b). A combination of either erosional incision or condensation defines the westwards extent of the horizon (Fig. 4a-c). Onlap of the Top Prograding Unit horizon onto the shelf edge high defines the eastwards extent, effectively constraining the top of this upper prograding unit to the Thetis Basin.

Towards the south, the seismic facies show a more or less continuous and conformable deposition with slight progradation and aggradation (Fig. 4c, b). The toesets thin considerably over the marginal high, where the unit condenses beyond seismic resolution. Towards the north, the unit is dominated by steep, rapidly prograding clinoforms, with very little topset accommodation (Fig. 3a, 7b). The upper part of the clinoforms show very high amplitudes, with a noticeable drop in amplitudes below the offlap break, indicative of either a facies change or simply scattering of seismic energy due to the steep geometry of the clinoforms (Fig. 7b). This unit displays a close correlation between the locations of the clinoforms and the depocentre, similar to that of the underlying unit. It is clear that the main progradation is located along the northern part of the Danmarkshavn Ridge (Fig. 12) as opposed to the underlying unit, where a more southerly depocentre is observed (Fig. 11).

4.10 Faulting and structures

This study maps a significant number of faults active during the post-breakup phase of the Northeast Greenland shelf. The fault pattern is used to constrain the timing, location and mechanisms related to the post-breakup tectonism and vertical motions observed. The faulting observed on the

Northeast Greenland shelf is mostly extensional, with some indication of transverse movement in the Danmarkshavn Basin (Fig. 6, 9). This is consistent with the tectonic setting of the North Atlantic since the Carboniferous, where rifting and continental spreading dominated (Ziegler and Cloetingh, 2004).

A prominent structural break is observed between the Danmarkshavn Ridge and the Thetis Basin, which affects the geometry of the seismic units described above significantly (Figs. 3a-b, 8a-b). West of this break, the Cenozoic succession in the Danmarkshavn Basin is dominated by a significant structural tilt and uplift towards the west (Fig. 3b), whereas the Thetis Basin remains mostly sub-horizontal. This in turn is associated with a westwards deepening erosional truncation of the Cenozoic succession. Cenozoic deposits are thus only preserved in the westernmost part of the Danmarkshavn Basin (Fig. 9). Seismic horizons up to and including the Top Upper prograding unit are affected by the tilt, although it is not possible to constrain it further due to the erosional incision.

The Danmarkshavn Ridge is a relatively complex structure. It is primarily a horst structure (Fig. 5) extending about 200 km across the Northeast Greenland shelf (Fig. 2). The Danmarkshavn Ridge also defines the orientation and dip of the main, basin bounding faults (Type 1 on Fig. 9). Towards the North, the ridge is dominated by inverted Palaeozoic—Mesozoic sedimentary basins overlying an uplifted crystalline basement (Fig. 3a), whereas the south segment of the ridge consists mostly of crystalline basement (Fig. 3b). The faults east of the ridge dips to the east to southeast, thus forming the border faults to the Mesozoic half graben Thetis Basin (Fig. 3b, 9). The faults separating the Thetis Basin and the Danmarkshavn Ridge show larger offsets in the seismic data towards the south, although seismic reflection patterns suggest that similar faults also exist to the north. The base Cenozoic reflector is clearly downthrown from the Danmarkshavn Ridge (Fig. 5), although the structural style varies across the fault zone. The central section of the ridge show a complex transition with several listric faults constituting the border fault system (Fig. 7b). To the north, the vertical movement between the Thetis Basin and the Danmarkshavn Ridge is mostly accommodated by folding of Paleogene—middle Miocene strata across the transition from the Danmarkshavn Ridge and into the Thetis Basin (Fig. 3a). The Intra Thetis Basin fault parallel to the southern segment of the Danmarkshavn Ridge is located about 25 km east of the Danmarkshavn Ridge (Figs. 3b, 4c). The Intra Thetis Basin fault is aligned with the main fault system east of the northern segment of the Danmarkshavn Ridge (Fig. 9). It shows that the southern segment of the Danmarkshavn Ridge was not involved in the reactivation of the faulting along the east margin of the Thetis Basin during the Cenozoic.

The faults on the west side of the Danmarkshavn Ridge are all west dipping normal faults (Fig. 9), with the exception of a few antithetic faults (Fig. 3a). The faults clearly define the transition from the Danmarkshavn Ridge and into the deep Danmarkshavn Basin (Fig. 3b) in the south, whereas the northern segment is more ambiguous (Fig. 3a). The observation of faulting of the Cenozoic succession in the Danmarkshavn Basin is limited due to thinning and erosion. However, a fault on-trend with the south segment of the Danmarkshavn Ridge is observed in the Danmarkshavn Basin (Type 2, Fig. 9). It is tentatively suggested to be transpressional due to the localised, but intense compressional deformation in combination with a limited vertical offset of the deformed succession (Fig. 6). The fault is part of a zone that accommodates some shortening of the Danmarkshavn Basin, where the footwall block show strong eastwards tilting of Cenozoic strata close to the fault (Fig. 6). It is also observed that the Danmarkshavn Basin fault is associated with basin inversion of the Paleozoic—Mesozoic succession as well as a basement high (Fig. 3b).

The northwards termination of the Danmarkshavn Ridge is marked by increasing depth to the basement north of the ridge. This is also observed in the gravity field as a reduced positive gravity anomaly north of the Danmarkshavn Ridge (Fig. 9). Numerous faults intersect the Cenozoic succession north of the Danmarkshavn Ridge (Fig. 2, Fig. 9, Fault type 5), but show lower lateral extent and less organised orientations, although an easterly dip is prevailing. The less organised nature of the faults in the north of the study area is largely attributed to the presence of salt in this area (Figs. 7a-b). Diapirism is frequently observed, with salt diapirs rising close to the sea floor in many occasions. The faulting appear to be thin-skinned with a sole-out in the salt of most of the faults (Fig. 7a). The salt tectonics appear to have initiated during either Palaeozoic or Mesozoic times, which is confirmed by previous studies (Rowan and Lindsø, 2017). It is beyond the scope of the current study to give a detailed interpretation of the salt tectonics, but it would appear as if the Paleogene—earliest Eocene succession does not display any signs of salt-related thickness changes towards the salt diapirs (Fig. 7b, far left). Furthermore, the salt related faulting (Fig. 7a) shows little to no syn-tectonic deposition during this time. This indicates that the salt may have been activated during the post-breakup phase.

5 DISCUSSION

The results of this study of recent seismic data clearly shows a highly dynamic post-breakup tectonic setting with pronounced, kilometre-scale fault offsets, uplift and tilting of the Danmarkshavn Basin and pronounced progradational events. The large-scale structures and pre-breakup tectonostratigraphy have previously been described (Hamann et al., 2005; Petersen et al., 2015; Tsikalas et al., 2005). This study however presents new details on the causes and timing of the post-breakup tectonics. Based on tectonostratigraphic interpretations and integration of data from the ODP 913 borehole, this study constructs a temporally robust model for the tectonosedimentary evolution during the late Palaogene—Early Neogene period.

5.1 Seismic facies

The plane-parallel, high amplitude seismic facies of the Paleocene—early Eocene succession indicates deposition of well-bedded, laterally cohesive sediments in a quiet setting, such as a marine setting below wave base. However, previous studies find small-scale, prograding clinoforms in the southwest of the study area (Petersen et al., 2016, 2015). This is confirmed in the current study both in map view (Fig. 10), where the clinoforms correlate with depo-centres, and in seismic section (Fig. 6). Such clinoforms indicate that initial infill of the Danmarkshavn basin was controlled by a channelized system, most likely in a shallow water setting. Such clinoforms are likely to be sand prone, whereas the plane parallel seismic facies present elsewhere is more consistent with a clay prone sedimentary facies.

Cenozoic deposits are very scarce onshore East and Northeast Greenland, but Nøhr-Hansen et al. (2011) describes early Paleocene fluvial deposits in the Wollaston Forland and Sabine Ø Area, south-west of the study area (Fig. 2). A sediment fairway from the south-west during the Paleocene is consistent with the prograding clinoforms observed in the seismic data in the southwest part of the study area.

The Eocene—mid Miocene succession is comprised of two main seismic facies types. In the Danmarkshavn Basin and Ridge, the facies strongly resemble that of the underlying unit, suggesting a continued deposition in a marine, sub-wave base, clay-rich environment. In the Thetis Basin however, the seismic facies are dominated by the steep, prograding clinoforms (*e.g.* Figs. 5, 7) associated with the uplift and tilting of the Danmarkshavn Basin and the faulting that intersects the Cenozoic deposits across the east margin of the Danmarkshavn Ridge. Evidence of one or several mass wasting events following rapid motion on the fault system east of the Danmarkshavn Ridge is observed (Fig. 5).

The prograding clinoforms are indicative of more coarse-grained material, most likely sand prone in the proximal part, and fining in the distal direction, i.e. towards the centre of the Thetis Basin. The topsets of the prograding succession (Fig. 4b) may be composed of either typical delta top deposits such as overbank fines and fluvial deposits, or alternatively a form of sub-marine fine-grained top-set deposit.

The focus of the prograding clinoforms during the Eocene—mid Miocene is located in the south part of the Thetis Basin, along the edge of the Danmarkshavn Ridge (Fig. 11). This implies that the south Danmarkshavn Ridge, Danmarkshavn Basin and the area onshore Northeast Greenland south of

Store Koldewey most likely acted as the source area for this progradational event. The presence of fluvial deposits of an latest Paleocene—earliest Eocene age in the Wollastand Forland and Sabine Ø area (Nøhr-Hansen et al., 2011), highlights the presence of a fluvial system southwest of the study area during the time of deposition of the clinoforms. It seems highly likely that this fluvial system transported the sediment forming the Eocene—mid Miocene clinoforms to the margin.

The interpretation of whether the erosional incision of the uplifted footwall of the Danmarkshavn Ridge occurred in a marine or terrigenous environment have obvious implications for the understanding of the depositional evolution of the Northeast Greenland margin. If the erosional incision was terrigenous, it would imply a very dramatic change in depositional environment, from below (storm) wave base to subaerial exposure due to fault related uplift of the Danmarkshavn Ridge. However, erosional incision and prograding clinoforms may as well occur in a marine setting, and the continuous, uniform nature of the topsets and the overlying strata seems to be more consistent with deposition in a marine environment. This does not however imply that there was no tectonic motion. In fact, the steepness of the incision, in combination with the chaotic nature of the material transported into the Thetis Basin resulting from the mass wasting event, indicates a rapid and significant tectonic movement (Fig. 5).

The post-mid Miocene, upper prograding unit, displays very similar facies patterns as the underlying unit. However, as described above, the location of the clinoforms are shifted further north in the Thetis Basin (Fig. 12). The seismic facies of the clinoform-dominated northern part of the unit show a very distinct proximal to distal facies change (Figs. 3a, 7b). The high amplitudes of the topsets indicate a highly heterogenic depositional environment, with interbedded sand and shale. The foresets are most likely dominated by lateral sand-on-sand contacts, as the amplitudes show a marked dimming, resulting from relatively homogenous sediments. The chaotic to moderately well bedded toesets are consistent with basin floor fan deposition dominated by various mass wasting deposition such as slides, slumps and turbidites. The northwards shift of the clinoforms indicates a change in the drainage pattern of the Northeast Greenland shelf, and possibly also onshore Northeast Greenland, from mainly focused south of Store Koldewey for the lower prograding unit to north of Store Koldewey for the upper.

5.2 Structural evolution

The seismic data offshore Northeast Greenland clearly demonstrate that tectonics play a prominent role in the sedimentation pattern after the continental breakup. The post-breakup faulting observed mainly around the Danmarkshavn Ridge is extensional in nature, as all faults have some degree of a normal motion on them. However, the total extension of the shelf after the continental breakup is interpreted to be relatively modest due to the steep dips of the fault planes and low amount of heave on the individual faults.

The two main tectonic events are the tilting and uplift of the strata in the Danmarkshavn Basin, and the 1-2 s TWT throw on the western boundary fault system in the Thetis Basin. Both events clearly post-date the Early Eocene Unconformity, as this horizon is involved in both the structural tilt and intersected by the faulting. The relative timing between these two events indicates that the western boundary fault of the Thetis Basin was reactivated prior to any significant tilting in the Danmarkshavn Ridge or Danmarkshavn Basin area. Tilting might however have initiated west of the Danmarkshavn Basin at an earlier stage.

The intra-Thetis Basin fault (Fig. 4c) display normal faulting of the entire Cenozoic succession in the southern area of the basin. Although the fault throw is relatively modest, the initiation of the fault is significant, as it controls the location of the footwall erosional escarpment, and seems to be aligned with the northern segment of the Danmarkshavn Ridge. It also indicates that the southern segment of the Danmarkshavn Ridge was not tectonically active after the breakup.

A significant amount of vertical offset has accumulated between the Thetis Basin and the Danmarkshavn Ridge during the Eocene—Miocene(?) period, amounting to 1-2 s TWT. By assuming an average seismic velocity of 2000 m/s (Berger and Jokat, 2008) this equates to 1-2km of vertical offset. As mentioned above, extension appear to be limited during the Cenozoic. Therefore, it seems likely that the vertical offset was created by a steep, listric fault with a sole-out at the base of the crust. This is consistent with the seismic observations in this study and with other geophysical observations (Tsikalas et al., 2005). Some of the post-breakup subsidence may be caused by differential compaction between the Danmarkshavn Ridge and the Thetis Basin. However, the abrupt nature of the subsidence, causing slope failure on the footwall, seems in contrast to relatively slow and continuous compaction-related subsidence.

In a regional perspective, it is apparent that the extensional faulting observed around the Danmarkshavn Ridge and in the Thetis basin is oriented sub-parallel to the main extensional axis created during continental breakup (Fig. 2), even though some of the faulting post-dates the breakup by >40 Ma. This is clear evidence that the structural grain created during the Mesozoic rifting (Tsikalas et al., 2012) was reactivated during the post-breakup extensional tectonics.

The timing of the salt movement can in the context of the current study yield important information about tectonic events. Remobilised salt is observed throughout the northern part of the study area (Fig. 2), and is associated with a complex fault pattern (Fig. 9). Salt diapirs frequently rise to or close to the sea floor, indicating that salt mobilisation has been occurring close to present time, although presumed Quaternary erosion truncates the crests of the diapirs, hampering a more accurate constraint on the timing (Figs. 7a, b). Since there is no evidence of Paleocene—Eocene rim synclines, no pre-breakup salt mobilisation is interpreted. Since the salt was not activated during the continental breakup, it seems likely that most of the tectonic deformation during the breakup (at *ca.* 55 Ma) was focused along the margin of the shelf, away from the Danmarkshavn Basin. The lack of pre-breakup tectonism on the shelf, apart from the thermally induced uplift in the earliest Eocene, further confirms this observation. It then seems more likely that the salt mobilisation is linked to the same post-breakup tectonics seen in the data as movement of the Thetis Basin boundary fault and tilting of the Danmarkshavn Basin.

5.3 Uplift and erosion

The Northeast Greenland shelf displays a series of uplift events from the Late Cretaceous through the Neogene (Hamann et al., 2005; Petersen et al., 2016, 2015). The unconformity below the Cenozoic succession is a surface of regional significance, also observed onshore Northeast Greenland (Nøhr-Hansen et al., 2011). In the current study, the unconformity is mostly observed in the Danmarkshavn Basin and on the Danmarkshavn Ridge, and is particularly well developed in the south of the study area. This trend is seen in subsequent uplift events as well, where uplift events are most pronounced towards the south. The uplift and related intrusions of hot magma, peaking around *ca.* 55 Ma (Larsen et al., 2014) reported previously (Petersen et al., 2015; Reynolds et al., 2017), also display a deepening incision in the south part of the Danmarkshavn Basin, associated with progradation of clinoforms into the Danmarkshavn Basin (Petersen et al., 2016, 2015). Some minor basin inversion is also observed at the earliest Eocene times (Fig. 5), although this is in contrast to the generally extensional tectonic regime of the shelf during the Cenozoic. However, compression may be caused by counter-clockwise rotation of Greenland during the Palaeocene, which may have caused minor NE-SW compressional stresses to be transmitted onto the Northeast Greenland shelf (Guarnieri, 2015). However, this mechanism seems unable to account for neither the geometry nor the amount of uplift observed on the Northeast Greenland shelf.

The gradual uplift and associated denudation of the Cenozoic deposits of the Danmarkshavn Basin and Ridge area most likely post-dates the intra Miocene unconformity. The exhumation of the inner part of the shelf and its association with steep, prograding clinoforms with downlaps onto the Intra Miocene Unconformity (Fig. 3a), points to a post-mid Miocene age for the cessation of the uplift of the inner Northeast Greenland shelf. The vertical motions seems to stop or slow significantly around the time of the Top upper prograding unit seismic horizon (Fig. 7b). The end of the main denudation phase is therefore poorly constrained, since the age of the Top upper prograding unit can only be attributed to a post-mid Miocene age. It is suggested in this study, that the main cause of uplift and tectonics following the continental breakup is caused by thermal uplift and dynamic topographic effects associated with the Icelandic mantle plume. (Fig. 13)

A central feature of the post-breakup denudation of the inner Northeast Greenland shelf is the time transgressive nature of the uplift, as indicated by the prograding units and their migration northwards over time. This is evident when comparing the thickness maps of the two uppermost late Paleogene—Neogene units (Figs. 11 and 12), but in fact, the north to south migration of clinoforms seems to start potentially as early as the Palaeocene (Petersen et al., 2015). This northwards move of the main depocentre indicates that the uplift and exhumation of the Northeast Greenland shelf must have been focused east, southeast or south of the current study area. This initially created a structural tilt of the Danmarkshavn Basin towards the west, but with a minor northwards component as well. The earliest observations of clinoforms in the south is dated as Paleocene, and the youngest clinoforms are post mid-Miocene, a period of about 45 Ma. This implies a slow northwards tilting of the Northeast Greenland shelf. Alternatively, it is possible that the northwards tilting occurred much faster, but that the sedimentation occurred in pulses related to hinterland uplift.

5.4 Effect of mantle plume path on deposition

The Icelandic hotspot and its effect in the North Atlantic realm, in particular in relation to the continental breakup, has been the source of much debate (Campbell, 2007; Clift et al., 1998; Storey et al., 2007). In the current study, it is suggested that the mantle plume system at present day located beneath Iceland and Jan Mayen (Rickers et al., 2013), was instrumental in the uplift of the inner Northeast Greenland shelf, and that it was responsible for a gradual, northwards shift of the main sediment fairway. The central argument for this interpretation is that the Icelandic plume system moved along a trajectory south of the study area during the Cenozoic, which is in good agreement with the time-transgressive northward movement of the prograding units observed in this study.

The plume activity, its trajectory and its morphology are all influencing the depositional patterns observed during the Cenozoic on the Northeast Greenland shelf. The plume underneath the North Atlantic show a significant lateral extent, with an origin observed down to the lower mantle (Rickers et al., 2013). Døssing et al (2016) concludes that the thermal perturbation at 2-15 Ma (mid Miocene--Pilocene) is linked to the IMU (Intra Miocene Unconformity) observed around the East Greenland Ridge, indicating a clear link between the thermal pertubations of the passing hotspot and tectonism in the region.

The coupling between the Atlantic mantle plume system and the North Atlantic Igneous Province is well established (e.g. Ganerød et al., 2010; Hansen et al., 2009; Larsen et al., 2014; Storey et al., 2007). Onshore Northeast Greenland, the accurately dated igneous rocks show a distinct trend of younger igneous rocks towards the north (Larsen et al., 2014). The youngest igneous rocks (40-20 Ma) observed according to Larsen et al.(2014) are all found north of 67° N (Fig. 13), further indicating a south to north time transgressive impact of the passing Icelandic mantle plume system. The location of the Icelandic and Jan Mayen hotspots directly south of the study area during mid Miocene times (Fig. 13), is in very good agreement with uplift in the south and tiliting of the margin towards the north during the mid Miocene—Quaternary.

6 CONCLUSIONS

This study utilizes a vast database of the most recent seismic data and presents a series of novel observations on the tectonosedimentary development of the Northeast Greenland shelf following the continental breakup. A summary of the tectonic and sedimentary events described in the current study is presented in Fig. 15.

It is demonstrated that significant vertical motion and associated extensional faulting are observed after the continental breakup at *ca.* 55 Ma. Differential subsidence, some of which may be attributed to deep-rooted faults, in the order of 1-2 km is observed along the west boundary of the Thetis Basin, during the Eocene to post-Miocene times. The faulting occurred simultaneously with a pronounced uplift and eastward tilt of the inner Northeast Greenland shelf.

Several progradational events are interpreted based on the seismic data. The earliest clinoforms are of a pre-breakup age, and located in the south Danmarkshavn Basin. The clinoforms are however more pronounced after the earliest Eocene breakup, where steep, rapidly prograding clinoforms oversteps the Danmarkshavn Ridge and progrades into the Thetis Basin. These clinoforms display a northward migration over time, with a significant clinoform succession formed in the north of the Thetis Basin sometime after the mid Miocene.

The Icelandic hot spot is suggested as the main cause of uplift, rotation and extensional faulting of the shelf. The trajectory of the Icelandic hot spot south of the Northeast Greenland shelf during the Neogene fits very well with a gradual, northwards shift of progradation due to thermally induced uplift and dynamic topography. This is observed in the seismic data as northwards tilting of the shelf during post-breakup times. Lastly, the reactivation of the fault system separating the Danmarkshavn Ridge and the Thetis Basin is also attributed to the thermal uplift caused by the passage of the Icelandic hotspot.

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Captions

Fig. 1. Overview of the study area and the seismic database. The data are composed of two vintages. The AWI seismic data, collected during the nineties, and the TGS data collected 2008-2014. The TGS data are of both better quality and much higher density, as shown on the map. The AWI data covers the important transition from continental to oceanic crust however. All data are courtesy of TGS and Spectrum. Approximate locations of the seismic cross sections are also highlighted.

Fig. 2. Map of the main structural elements, traces of the interpreted faults, free air gravity anomalies, as well as magnetic isochrons. The map shows the NNE-SSW elongated Danmarkshavn Basin (DKHB), the Danmarkshavn Ridge (DKHR), right-lateral transfer zone (TS) and the Thetis Basin located on the easternmost side of the shelf. The East Greenland Ridge (EGR), Store Koldewey (SKW) and Wollaston Forland (WSF) are also shown. Gravity data are courtesy of DTU Space DNSC08GRA and DTU10 data sets (Andersen 2010 and Andersen et al 2010).

Fig. 3. (a) Regional west to east oriented seismic profile through the northern part of the study area. The section shows a thick Palaeozoic and Mesozoic succession that overlies the northernmost extent of the Danmarkshavn Ridge basement high. The section shows a distinct step down of the Base Paleogene horizon from the Danmarkshavn Ridge and into the Thetis basin caused by ductile accommodation of normal reactivation of faults at the Danmarkshavn Ridge to Thetis Basin transition. To the west, in the Danmarkshavn Basin, the Cenozoic succession shows evidence of tilting and erosional incision, associated with pronounced progradation in the Thetis Basin, above the Intra Middle Miocene reflection. (b) Regional west to east oriented seismic profile through the southern part of the study area. The Cenozoic succession displays a significant uplift and tilt to the east across the Danmarkshavn Basin and Danmarkshavn Ridge. Faulting is present in the Danmarkshavn Basin, where it offsets the Cenozoic succession (IDBF: Intra Danmarkshavn Basin Fault). Faulting is also present between the Danmarkshavn Ridge and Thetis Basin, as well as in the Thetis Basin, with the faults downfaulting the Cenozoic succession towards the East along the Intra

Thetis Basin Fault (ITBF). Evidence of a steep erosional scar infilled with prograding clinoforms is present across the Danmarkshavn Ridge. Seismic data are courtesy of TGS and Spectrum.

Fig. 4. Seismic examples of the Danmarkshavn Ridge to Thetis Basin transition at the southern segment of the Danmarkshavn Ridge. (a) The Palaeocene to Miocene(?) seismic facies across the Danmarkshavn Ridge is dominated by parallel, high amplitude reflections unconformably overlying the Danmarkshavn Ridge. A concave erosional truncation of the Palaeocene to Miocene(?) marks the transition from the Danmarkshavn Ridge to the Thetis Basin, where two east dipping normal faults off sets the Paleogene succession by >1 s TWT down into the Thetis Basin. Steep, prograding clinoforms fills out the accommodation space created by the erosional incision and extends out into the Thetis Basin. (b) Seismic section further south compared to (a). The two faults still mark the transition from the Danmarkshavn Ridge to the Thetis Basin. The prograding clinoforms persist, reaching far out into the Thetis Basin. Small-scale faults intersect the succession between the Early Eocene Unconformity and the Top upper prograding unit. (c) Seismic example from the southernmost Danmarkshavn Ridge. Note the increase in distance between the Danmarkshavn Ridge and the Intra Thetis Basin Fault (ITBF). The erosional incision is located east of the Danmarkshavn Ridge, indicating that the ITBF triggered the incision. Note the pronounced angular unconformity below the Early Eocene Unconformity to the far west. Seismic data are courtesy of TGS and Spectrum.

Fig. 5. Seismic section through the central study area covering the Danmarkshavn Basin, the Danmarkshavn Ridge and the Thetis Basin. The seismic section clearly show domal uplift and truncation below the Early Eocene Unconformity in the Danmarkshavn Basin, with some indications of minor compression and inversion are observed along the west margin of the Danmarkshavn Ridge. To the far NW of the profile, disturbances in the reflections below the Early Eocene Unconformity indicates gas venting and a pockmark associated with volcanic activity. The bounding fault between the Danmarkshavn Ridge and the Thetis Basin offsets the entire succession above the

Base Paleogene, but the Erosional incision seismic horizon and prograding clinoforms are confined to the Thetis Basin. Chaotic seismic facies indicate mass deposited sediments below the Erosional incision reflection. Seismic data are courtesy of TGS and Spectrum.

Fig. 6. Seismic profile across the largest fault in the Danmarkshavn Basin, the Intra Danmarkshavn Basin Fault (IDBF). There is a distinct offset of the Palaeogene succession along the fault, and several minor associated faults are present. Also, notice the prograding clinoforms west of the fault. Seismic data are courtesy of TGS and Spectrum.

Fig. 7. (a) Seismic example north of the Danmarkshavn Ridge. The structural style here is heavily affected by the salt, which forms a detachment plane at the base of the faults. Salt diapirism is also observed. (b) Seismic section showing the structural complexity of the Danmarkshavn Ridge in the central part of the study area. Several eastwards dipping, listric faults comprise the Danmarkshavn Ridge to Thetis Basin transition. At the westernmost edge of the profile, a salt diapir rises close to the seafloor. Note how the main progradational event is now above the Intra Miocene Unconformity. For comparison, see fig. 4. Seismic data are courtesy of TGS and Spectrum.

Fig. 8. (a) Structure map of the Base Palaeogene horizon in TWT with fault traces of the main faults that outline the Danmarkshavn Ridge overlain. The map clearly shows the steep transition from the relatively elevated Danmarkshavn Basin/Ridge area and lower lying Thetis Basin. Also, note the coincidence between the faulting and the steep transition zone. (b) Structure map of the Upper prograding unit horizon in TWT with fault traces of the main faults that outline the Danmarkshavn Ridge trace overlain. The steep slope along the northern Danmarkshavn Ridge is due to steep, prograding clinoforms rather than structural deformation. Note the eastwards movement of the western limit of the unit.

Fig. 9. Overview and classification of the faults interpreted in this study overlain the free air gravity data. Faults are subdivided into five categories: Main, ridge-delineating faults (type 1, black), Intra-

Danmarkshavn Basin faults (type 2, green), pre-Cenozoic faults that are not reactivated (type 3, grey), Intra-Thetis Basin faults (type 4, blue), and salt related faults (type 5, magenta). The white fault is a hybrid between the ridge delineating fault and the salt related fault types. The ridge delineating faults are all located on the margins of the NE-SW oriented positive gravity anomaly associated with the Danmarkshavn Ridge. A right-lateral transfer zone between the north and south segments of the Danmarkshavn Ridge is highlighted. Note that all the salt related faults are located in the northern part of the study area, where the gravity anomaly is relatively low. The westwards erosional truncation of the Cenozoic deposits is also highlighted (grey line).

Fig. 10. Thickness map (in TWT) of the succession between the Early Eocene and the Base Paleogene, corresponding to the Palaeocene—lowermost Eocene. The main depo-center is located in the southernmost part of the Thetis Basin, and thins substantially on the Danmarkshavn Ridge. A potential northerly depo-center is also tentatively interpreted from the data. The Location of the Danmarkshavn Ridge and the right-lateral transfer zone are shown for reference together with the main, basin delineating faults.

Fig. 11. Thickness map (in TWT) of the succession between the Early Eocene and the Intra middle Miocene horizons, corresponding to the Eocene—lower Miocene interval dominated by early prograding clinoforms. The main depo-center is prominently located immediately west of the southern segment of the Danmarkshavn Ridge. The Location of the Danmarkshavn Ridge and the right-lateral transfer zone are shown for reference together with the main, basin delineating faults.

Fig. 12. Thickness map (in TWT) of the succession between the Intra middle Miocene and Upper prograding unit horizons, dominated by the late prograding event. The upper age of this interval is poorly constrained to a post-Miocene age. The depo-centre is located NE of the Danmarkshavn Ridge. Compared to fig. 11, it is evident that the depo-center shifts further north and further into the Thetis Basin. The Location of the Danmarkshavn Ridge and the right-lateral transfer zone are shown for reference together with the main, basin delineating faults.

Fig. 13. Overview map showing the path and estimated extent of the Jan Mayen-Iceland hotspot system after Rickers et al. 2013, shown together with free air gravity anomalies. Ages of the observed, onshore volcanics (Larsen et al. 2014) show a trend of younger magmatic rocks towards the north (italics, stars and horizontal lines). A relatively good correlation between the passage of the hot spots and the ages of the intrusions are seen, with the Jan Mayen plume branch a likely candidate for the northern (and younger intrusions). The observed northwards shift in prograding clinoforms, southwards deepening erosion during the latest Eocene and the area with seismic observations of volcanics are shown as reference.

Fig. 14. Summary of tectonostratigraphic events during the early-mid Cenozoic period of the Northeast Greenland shelf. Red arrows show uplift, blue arrows show normal faulting/subsidence. Note how the clinoforms shift northwards during Eocene—Miocene period. The Thetis Basin is dominated by varying degrees of subsidence (blue minus), but the Danmarkshavn Ridge and Danmarkshavn Basin show a more complicated history of uplift (red plus) and erosion (grey hatched).

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Seismic stratigraphy of the post-breakup succession offshore Northeast Greenland: Links to margin uplift

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Abstract

The timing of the continental breakup between Norway and Greenland and the subsequent plate tectonic motions are well understood. However, due to the remote location of the Northeast Greenland shelf, relatively few details about the tectonosedimentary response to the tectonism following the breakup have previously been published. This article gives new insights into the structural and sedimentary history of the Northeast Greenland shelf, with an emphasis on the post-breakup tectonics, using state of the art 2D seismic data. The results of this study clearly shows a highly dynamic post-breakup tectonic setting with pronounced, kilometre-scale fault offsets, tilting of the Danmarkshavn Basin and pronounced progradational events. The tectonosedimentary events are linked with the passage of the Icelandic mantle plume south of the Northeast Greenland shelf. Based on tectonostratigraphic interpretations and integration of data from ODP 913, this study constructs a temporally robust model for the post-breakup succession. Significant post-breakup uplift and tectonism related to thermal uplift is present on the margin. It is observed that the Icelandic hot spot passes relatively close by the Northeast Greenland shelf (<500 Km) during the Cenozoic. Its passage south of the shelf supports the observation of the northwards tilt of the shelf and associated northwards shift of the prograding clinoforms due to a combination of thermal uplift and possibly dynamic topography.

1 INTRODUCTION

Passive margin tectonism is widely debated, especially in the North Atlantic realm. Conventional models for continental breakup only predict thermally induced subsidence following the heating caused by upwelling mantle (e.g. McKenzie, 1978). However, observations around the margins of the North Atlantic suggest that significant tectonics and vertical motion occurred after the breakup (Lundin and Doré, 2002; Tsikalas et al., 2012). The term breakup, or continental breakup is here understood as the phase of separation between continental lithospheric plates, following the rift phase, *sensu* Cloetingh et al. (2013).

Although the Northeast Greenland shelf has been studied previously (e.g. Funck et al., 2017; Hamann et al., 2005; Petersen et al., 2015), very little is known about the tectonostratigraphic development of the shelf after the continental breakup. Based on a comprehensive seismic database consisting of the latest available data, this study yields new insights into the structural history and its influence on sedimentation. By conducting a thorough seismic stratigraphic study of the Northeast Greenland shelf, several seismic units significant to the understanding of the post-breakup development of Northeast Greenland are interpreted concerning depositional environment, tectonostratigraphy and relation to plate tectonics. A clear link between the passage of the Icelandic hotspot, uplift of the inner margin and a northward shift in prograding clinoforms is presented.

2 REGIONAL GEOLOGY

The North Atlantic plate tectonic history is described in multiple studies (e.g. Gaina et al., 2009; Matthews et al., 2016; Müller et al., 2016; Tsikalas et al., 2012). Evidence of rifting throughout the Paleozoic and Mesozoic along the margins of the North Atlantic is recorded as extensional tectonics both onshore (Stemmerik, 2000) and offshore (Tsikalas et al., 2012, 2005) as a part of the long-running opening of the Atlantic Ocean (Cloetingh et al., 2007). The rift to drift transition i.e. the continental breakup is dated by means of paleomagnetic anomalies to have occurred at 55.9 Ma (chron 24), at the Paleocene—Eocene transition (Gaina et al., 2009; Matthews et al., 2016; Ogg, 2012; Olesen et al., 2007). This is associated with pronounced volcanism, dated to the earliest Eocene (Larsen et al., 2014). The shelf south of *ca.* 78° N is the conjugate margin to the Vøring and Lofoten margin in Norway, and is associated with extension of the Mohns Ridge segment of the mid ocean ridge system of the North Atlantic (e.g. Gaina et al., 2009; Talwani and Eldholm, 1977; Ziegler, 1992). It is dominated by normal faulting prior to the continental breakup (Tsikalas et al., 2012). However, the shelf north of *ca.* 78° N is dominated by complex transpressional and transtensional

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deformation during the opening of the Greenland Sea, where transverse deformation initially occurred along the East Greenland Ridge, before shifting to the Knipovich Ridge during the Oligocene. A slowing of the plate tectonic motion (Gaina et al., 2009; Tegner et al., 2011), dated to *ca.* 49-47 Ma, coincides with the peak in the Eurekan Orogeny along the northernmost edge of Greenland. Absolute opposite plate motion, where Greenland drifts towards the Northwest and Norway towards the Southeast, was achieved during the earliest Oligocene (33.1 Ma), which implies that passive margin conditions were developed along the entire Northeast Greenland and North Greenland continental margin at this time (Gaina et al., 2009).

Pronounced progradation of clinoforms have been described previously, based on low density/low resolution seismic data, and attributed to a "Tertiary" age (Hamann et al., 2005). The pre-drift succession of the Northeast Greenland shelf have also been described in detail (Petersen et al., 2015)~~F~~, but very little has so far been published on the post-breakup seismic stratigraphy.

Sea level changes during the Cenozoic have been described previously (Miller et al., 2005), and the effects of changing eustatic sea level obviously also had an impact on the sedimentation on the Northeast Greenland shelf. Even though this article focuses solely on the tectonic processes and on highlighting the vertical motions observed on the shelf during the post-breakup times, the author fully acknowledges the influence of eustatic sea level changes as well.

3 DATA AND METHODS

The database of this study is composed of the latest vintages of commercial 2D seismic data collected during a period from 2008-2014 by TGS, a commercial seismic data vendor, together with a scientific dataset collected by the Alfred Wegener Institute (AWI) during the early nineties (Berger and Jokat, 2009, 2008) (Fig.1). All seismic data are courtesy of TGS and Spectrum. The seismic data were supplied under the agreement that no shot points or navigational data are published. These data are supplemented by free air gravity data from the DTU10 global gravity field model (Andersen, 2010; Andersen et al., 2010). The locations of the North Atlantic hotspots are derived from Whittaker et al. (2013), and the locations of the magnetic anomalies are adopted from Müller et al. (2016). Plate tectonic reconstructions are based on Matthews et al. (2016). Reconstruction of the path of the hotspots was done using the open source software GPlates (www.gplates.org). The seismic interpretation was conducted using a seismic workstation (Petrel 2016). Standard seismic stratigraphic methods was applied as outlined by Emery and Myers (1996).

4 OBSERVATIONS

4.1 Potential field data

The use of free air gravity data gives excellent insights into the geometries of structural elements in the Northeast Greenland area (Fig. 2). The gravity data quite clearly show the location of the continental slope (Fig. 2), and the magnetic anomalies (Müller et al., 2016), shows the westward extent of the oceanic crust, as well as other key features of the Northeast Greenland shelf. The Danmarkshavn Basin stands out on the inner side of Northeast Greenland's continental shelf as a distinct low in the gravity field. In fact, the gravity low extends onshore Greenland, outlining the prominent sedimentary basins present there (Stemmerik, 2000). The Danmarkshavn Ridge is also outlined in detail as a positive gravity anomaly. The ridge is NE-SW striking and displays a noticeable right-lateral offset, separating the ridge into a north and a south segment (Fig. 2). It is also clear, that the deep faults observed on the shelf are parallel to the ridge, and that the faulting of the Cenozoic succession is focused at or near the ridge, with few exceptions (Fig. 2). Although a detailed description of the faults is given below, it is noted that faulting is also observed north of the Danmarkshavn Ridge gravity high. The Thetis Basin is seen as a relatively narrow, elongated gravity low parallel to the Danmarkshavn Ridge. This shape of the basin in the gravity data is controlled mostly by a very deep, narrow half graben created during the Mesozoic (Figs. 3a, b). The shape of the basin during the Cenozoic is wider however, and spans from the Danmarkshavn Ridge to the continental slope.

4.2 Seismic interpretation

Based on the observed seismic facies of the individual units, the sedimentary facies, depositional environment and tectonic evolution are evaluated. The methodology is briefly described in Emery and Meyers (1996), where they highlight the seismic expression of various depositional environments. Due to the lack of well control, the seismic facies interpretations in this study are associated with some uncertainty.

This study is based on the mapping of several seismic horizons across the Northeast Greenland shelf and onto the oceanic crust (Figs. 3-7). The shown seismic horizons all hold significant information about the tectono-sedimentary history during the Neogene of Northeast Greenland. By using conventional seismic interpretation techniques and seismic stratigraphic principles, it is possible to describe exhumation, subsidence and the relative timing of tectonic events. This study establishes a regional framework of tectonic events with good confidence due to the ~~availability~~ inclusion of the most comprehensive, high quality seismic database currently available (fig. 1). The seismic observations correlates well with the gravity data, confirming the control of deeper structures on the depositional pattern. (Fig. 2). Examples of both the seismic horizons and the interpreted faults are presented in seismic cross sections (Figs. 3-7), and in map form (Figs. 8, 9). Only one borehole is available for age correlation, namely the ODP 913 borehole (Thiede et al., 1995). The location of ODP 913 on the oceanic crust means that the pre-break-up succession is not penetrated. Due to the absence of any deep well bores on the Northeast Greenland shelf, all the ages of the pre-early Eocene seismic horizons are associated with some uncertainty. This study infers the ages of the seismic horizons from published regional studies (Engen et al., 2008; Hamann et al., 2005; Petersen et al., 2015; Tsikalas et al., 2012), and by correlating with plate tectonic events highlighted in this study.

Structure maps of key surfaces are also presented (Fig. 8a, b). These maps are all in Two Way Time (TWT) reported in seconds. All structure and thickness maps are interpolations of seismic data, within the extent of the interpreted horizon. This means that the outer boundary of a surface is defined by the absence of the seismic horizon due to either erosion or condensation, or due to the lack of resolution in the seismic data. The study also includes thickness maps used to highlight areas of deposition (Figs. 10-12).

The seismic units described below, subdivide the Paleogene and Neogene succession of the Northeast Greenland margin into three seismic units significant for the understanding of the tectonic evolution after the continental breakup. The interpretation and definition of the seismic units was based on their importance concerning structural evolution of the margin, especially during post-breakup times. Pronounced unconformities was the central focus, as they play a significant role in the identification of the location and timing of tectonic events on the Northeast Greenland shelf. Seismic facies in the respective units are also described in order to interpret the depositional mechanisms responsible for the deposited sediments and to constrain the structural evolution of the Northeast Greenland margin after the breakup.

4.3 Dating of the seismic units

All dating of the seismic units is done by correlation with the plate tectonic evolution as well as understanding of regional tectonic events in conjunction with the previously mentioned ODP 913 borehole. Previous studies have created a framework for the dating of the pre- and syn- breakup succession (Petersen et al., 2016, 2015). The current study further constrains the ages of the pre-breakup succession suggested in these studies by usage of better quality seismic data and closer correlation to the ODP 913 borehole. Furthermore, this study adds significant new knowledge about the post-breakup seismic units and their relative timing. The addition of reprocessed and recently acquired seismic data improves the reliability of these interpretations and adds additional information regarding the ages of the depositional events.

Prior to the onset of Paleocene deposition, a regional unconformity is observed in the Wandell Sea area, north of the current study area (Håkansson and Stemmerik, 1989). This and other observations are used by Hamann et al. (2005) to define the base of the Cenozoic succession in the Danmarkshavn Basin area. Furthermore, observations onshore Northeast Greenland in the Wollaston Foreland and Sabine Ø area (Fig. 2) confirms a hiatus between the Createaceous and the Paleogene (Nøhr-Hansen et al., 2011). A change from syn-tectonic halfgraben infill to parallel reflections mark the Mesozoic-Cenozoic transition in the Thetis Basin. The accuracy of the age of the unconformity is uncertain due to the lack of any means of direct dating. Furthermore, the interface is most likely diachronous across most of the study area, although early Cenozoic deposits appear relatively conformable at their base, with the exception of the south part of the study area, where Petersen et. al (2015) describe progadation from the southwest.

The Early Eocene Unconformity is relatively well dated due to its association with the breakup volcanism. Compelling evidence of deepening of the erosion towards the centre of the magmatic intrusions in the Danmarkshavn Basin, (Petersen et al., 2015), together with the coinciding gas v~~w~~ent structures from the intrusions (Reynolds et al., 2017) yields a relatively tight constraint on the age of this horizon (Fig. 5). This is achieved by utilizing the well-known absolute ages of the peak in magmatic intrusions onshore Northeast Greenland (Larsen et al., 2014). These observations are further corroborated by the availability of the high quality data for this study. Especially the northwards correlation of this event makes it possible to constrain the ages of the tectonosedimentary events in the north of the study area (Fig. 7b).

There are no direct means of constraining the age of the Erosional incision seismic horizon, so a relative dating of the horizon is suggested. The Erosional incision horizon clearly truncates the well-dated Early Eocene Unconformity (Figs. 4a-c), thus a post- Early Eocene age can be initially suggested. The erosional incision also truncates strata younger than early Eocene, so the incision must post-date the Early Eocene Unconformity by some margin. The upwards constraint of the age of the erosional incision is the Intra Miocene Unconformity, as this horizon is not truncated by the incision. However, a significant sedimentary succession is present between the two horizons, which hampers the possibility for a more accurate age for the Erosional incision horizon other than late Eocene—mid Miocene. An important observation in this context is that the Erosional incision horizon post-dates the continental breakup.

The Intra Miocene horizon is dated using the information from the ODP 913 borehole using the seismic tie from Berger and Jokat (2008). This is the only directly dated horizon in this study, but some uncertainty is still associated with the age of this horizon. Firstly, it is an unconformity, which is inherently a time-transgressive surface. Therefore significant lateral changes in the age of the horizon may occur. Secondly, the seismic correlation from the ODP 913 drill site and onto the Northeast Greenland shelf is associated with some uncertainty, due to sparse seismic data in the area and condensation across the continental slope. Still, this horizon remains possibly the most accurately dated seismic horizons of this study, and therefore it forms a significant anchor for the dating of the post-breakup events on the Northeast Greenland Shelf.

The youngest horizon interpreted in this study is the Top upper prograding unit seismic horizon. No direct methods for dating this horizon exists. It is clearly younger than the Intra Miocene unconformity horizon and it was affected by the uplift and rotation of the Danmarkshavn Basin and Ridge areas. This is evident from its location above a set of very steep clinoforms associated with the uplift (Fig. 3a). The only age constraint of this horizon is an age younger than mid Miocene, and predating the Quaternary glaciations of the shelf, since the shallow Quaternary erosion does not incise deeply into the unit (Fig. 4a).

4.4 Pre-Cenozoic units

It is beyond the scope of this study to conduct a detailed interpretation of the Palaeozoic and Mesozoic succession on the Northeast Greenland shelf. However, some general observations are of relevance to the further interpretation, and will be summarised here. For a more complete understanding of the pre-Cenozoic geology of the Northeast Greenland shelf, see e.g. Hamann et al. (2005). The Palaeozoic—Mesozoic Succession is largely conformable, but minor angular unconformities exist near the presumed Palaeozoic—Mesozoic transition (Figs. 3a, b). The succession is intersected and rotated by normal faults near the Danmarkshavn Ridge. The faults are all apparently deeply rooted (e.g. Fig. 5). The pre-Cenozoic succession of the Thetis Basin is largely deposited in a rotated half graben setting, with the controlling fault located along the east margin of the Danmarkshavn Ridge (Fig. 3b). The Cenozoic succession is thus underlain by several kilometres of Palaeozoic and Mesozoic sediments, intersected by faults mostly generated during Mesozoic rifting (Hamann et al., 2005).

4.5 Paleocene(?)—Early Eocene seismic unit

The unit is partially described in Petersen et al. (2015), in the southern part of the Danmarkshavn Basin. A more regionally cohesive interpretation is included in this study since it is important for understanding the structural framework, and it forms an important temporal constraint of the continental breakup. The Base Paleogene horizon is the base of this unit is and is regionally extensive and observed across most of the Northeast Greenland shelf area. It is primarily defined as an erosive unconformity, with a deepening incision towards the west in the Danmarkshavn Basin (Fig. 3a, b). A significant topographic break is observed at the transition from the Danmarkshavn Basin/Danmarkshavn Ridge and into the Thetis Basin (Figs. 3a, 8a), where the Base Paleogene lies significantly deeper. Towards the south, faulting offsets the Base Paleogene in the west part of the Thetis Basin (Figs. 3b, 4c). The Base Paleogene is delimited towards the west by erosion due to uplift and tilting of the Cenozoic succession. Towards the east, i.e. towards the continental slope, the Base Paleogene is truncated, since the continental rifting did not occur before the earliest Eocene (Gaina et al., 2009). The north and south extent of the unconformity is not resolved by the current data set.

In the Thetis Basin, east of the basin bounding fault system (Fig. 2), the Base Paleogene Horizon seems to be mostly conformable with the underlying Mesozoic sediments. There are however some evidence of faulting below the Base Paleogene, especially along the western margin of the Thetis Basin (Fig. 5). The Danmarkshavn Basin displays clear evidence of inversion following the Mesozoic rift phases, creating compressional structures such as folds and domes below the Base Paleogene (Fig. 5). These structures were subsequently eroded during a Late Cretaceous—Paleogene (?) and early Eocene erosional events (Figs. 3b, 4a). This compressional event is focused in the Danmarkshavn Basin and Ridge areas, in comparison with the more conformable nature of the Base Paleogene in the Thetis Basin. The seismic facies below the Base Paleogene show frequent examples of high amplitude, discontinuous reflections, often intersecting the bedding. These structures have previously been described as magmatic intrusions (Fig. 7b), (Petersen et al., 2015; Reynolds et al., 2017). Towards the eastern margin of the Thetis Basin, the seismic data shows a rise of the Base Paleogene (Fig. 8a). This rise coincides with the shelf to continental slope transition, which is also coinciding with a gravity high (Fig. 2). The high-amplitude, discontinuous reflectors are also very prominent below the rise.

The unit mostly consists of parallel, medium to high amplitude reflections, with the high amplitudes focused mainly in the Danmarkshavn Basin and the Danmarkshavn Ridge areas. The unit is thinning across the eastern margin of the Danmarkshavn Ridge, and there is evidence of internal erosion along the ridge margin, especially to the north (Fig. 3a).

The thickness map (Fig. 10) show a southerly-located depo-centre in the Thetis Basin, with a distinct thinning across the Danmarkshavn Ridge, and smaller depo-centres in the Danmarkshavn Basin, consistent with previous observations (Petersen et al., 2015). Diverging internal reflections towards the faults separating the Danmarkshavn Ridge from the Danmarkshavn Basin indicate syn-tectonic deposition related to normal faulting (Fig. 5). The truncation of the seismic unit that deepens towards the south is mostly controlled by structural rotation and uplift (Fig. 5). The horizon is heavily disturbed in some places, where deep (100-200ms TWT, *ca.* 100-200 m) and laterally extensive (<2 km) depressions or pockmarks are observed specifically at this level (Fig. 5). These features have been mapped previously and been interpreted as gas escape structures related to the earliest Eocene volcanism (Reynolds et al., 2017).

4.6 Early Eocene Unconformity

The Early Eocene Unconformity is a very prominent angular unconformity in the southern area of the Danmarkshavn Basin (Fig. 5), whereas it is mostly conformable across the Danmarkshavn Ridge and in the northern part of the Danmarkshavn Basin (Fig. 3a, b). It forms the upper boundary of the Paleocene(?)—Early Eocene seismic unit described above. Some indications of an angular unconformity below the horizon is also observed on the southern part of the Danmarkshavn Ridge (Fig. 4c). The Early Eocene Unconformity is truncated by the same tilt-induced incision along the western margin of the Danmarkshavn Basin as the underlying Base Paleogene horizon. The truncation occurs further east compared to the Base Paleogene, which inhibits interpretation of the Early Eocene Unconformity in most of the Danmarkshavn Basin (Fig. 3a).

The horizon is offset by deep-rooted, reactivated faults on both the west and east sides of the Danmarkshavn Ridge (Fig. 5). The angular unconformity in the Danmarkshavn Basin deepens towards the southwest. Towards the south, the Early Eocene Unconformity is erosionally truncated by the Erosional Incision horizon observed along the boundary between the Danmarkshavn Ridge and the Thetis Basin (Fig. 3b). Faulting of the Early Eocene Unconformity is also observed along the Intra Danmarkshavn Basin Fault (Fig. 6).

4.7 Erosional incision

This seismic horizon is a very distinct feature along the south segment of the Danmarkshavn Ridge, where it truncates the Early Eocene Unconformity and overlying strata (Fig. 3b). The incision is concave down towards the west and becomes subparallel to the bedding towards the Thetis Basin (Figs. 4a-c). The incision is clearly associated with the westwards bounding fault system of the Thetis Basin. Uplift of the Danmarkshavn Basin and Ridge created a dip along the eastern edge of the ridge (Figs 8a) above the angle of repose of the strata on the Danmarkshavn Ridge, which caused extensive mass wasting of material from the elevated Danmarkshavn Ridge and into the Thetis Basin (Fig. 5). The westward extent of the horizon is defined by the onset of the incision, and the eastward extent of the incision is defined by the transition to conformity (Fig. 3b). The incision is located further east of the Danmarkshavn Ridge and into the Thetis Basin towards the south. In the north, the incision is located<u> on the eastern margin of the</u> ~~*ca.* 5 km west of the~~ Danmarkshavn Ridge (Fig. 4a), whereas the incision is located about 10 km east of the ridge in the south (Fig. 4c). Furthermore, the mass wasting event seems more related to the Intra Thetis Basin Fault observed in the south Thetis Basin (Fig. 4c). The incision is a noticeable unconformity below the horizon, with very pronounced downlaps across the horizon (Figs. 4a-c). The steep incision is not observed north of the ~~in the~~ central part of the study area (Fig. 7a). However, other local erosional incisions are found along the north segment of the Danmarkshavn Ridge, and although they cannot be correlated with the incision seen in the south, this study indicates they are of similar age as the Erosional incision horizon and related to faulting between the Danmarkshavn Ridge and the Thetis Basin.

4.8 Eocene—Middle Miocene

The Eocene—Middle Miocene seismic unit directly overlies the Paleogene—Early Eocene unit, and is therefore bounded at its base by the Early Eocene Unconformity. The top of the unit is defined by the Intra Miocene Unconformity. The seismic facies in the Danmarkshavn Basin area are very similar to the underlying unit, with high amplitude, parallel reflectors (Figs. 3b, 4a). The Erosional incision horizon across the Danmarkshavn Ridge to Thetis basin transition is associated with steep, prograding clinoforms, extending out into the central part of the Thetis Basin (Figs. 4a-b). The clinoforms are most pronounced in the south of the study area, whereas they are absent in the north (Fig. 3a). The clinoforms are very specifically linked to the erosional incision horizon described above (Fig. 3b). The earliest clinoforms show very little accretion in the topsets, indication of a very rapid initial progradation. The later clinoforms are associated with more topset aggradation and less progradation. The eastern part of the Thetis Basin is dominated by the sub-parallel reflections of the toesets associated with the clinoforms, with a gradual condensation and thinning towards the continental slope (Fig. 3b). A very well defined depo-center along the south margin of the Danmarkshavn Ridge (Fig. 11) correlates with the location of the clinoforms. The thinning towards the shelf edge is also noticeable in the thickness map, as well as the fault control. Minor east-dipping normal faults with a relatively small offset (ca. 100 ms TWT, *ca.* 100 m) and no deep roots are present in several location above the steep prograding clinoforms (Figs. 4c-b). These faults appear to terminate in the Eocene—Middle Miocene seismic unit, and are thus not related to deep-rooted tectonics.

Theis upper boundary of this unit is the Intra Middle Miocene Unconformity, and is primarily defined based on correlation with the ODP 913 borehole, located on the oceanic crust (Fig. 1), and is thus temporally relatively well constrained based on an unconformity observed in the cores (Berger and Jokat, 2008; Døssing et al., 2016; Thiede et al., 1995). The incision caused by the structural tilt mentioned previously also truncates the Intra Miocene Unconformity along the centre of the Danmarkshavn Ridge. The horizon extends beyond the continental slope to the east, and mimics the same general topographic trends as the underlying horizons, with a steep, fault related slope along the Danmarkshavn/Thetis Basin interface, a deepening in the central Thetis Basin, and a topographic rise towards the shelf edge. The Intra Miocene Unconformity is a prominent downlap surface in the north of the study area. (Fig. 3a). In the south however, the horizon is located at the top of a prograding interval, and is largely conformable both below and above (Fig. 3b). The horizon is often intersected by minor faults, with offsets around 50-250 ms (or *ca.* 50-250 m). The faults are all located where the underlying clinoforms display the strongest progradation, and on a relatively steep slope (Figs. 4b-c, Fig. 5). In the northern part, where the Intra Miocene Unconformity is mainly overlying gently dipping strata, no evidence of faulting of the horizon is observed in the Thetis Basin (Fig. 3a, 4a).

4.9 Middle Miocene—Top Prograding Unit

The Top Prograding Unit seismic horizon defines the upper boundary of the upper prograding seismic unit, the Middle Miocene—Top Progading Unit. When comparing the horizon north to south, it is evident that very steep clinforms are present immediately below the horizon in the north (Fig. 3a), but the seismic unit is approaching subparallel reflections to the south (Fig. 3b). In the southernmost part of the study area, evidence of most likely Quaternary erosional truncation of the Top upper prograding unit horizon is observed at the sea floor as well (Fig. 4c). The horizon is only observed in the Thetis Basin and along the eastern margin of the Danmarkshavn Basin (Fig. 8b). A combination of either erosional incision or condensation defines the westwards extent of the horizon (Fig. 4a-c). Onlap of the Top Prograding Unit horizon onto the shelf edge high defines the eastwards extent, effectively constraining the top of this upper prograding unit to the Thetis Basin.

Towards the south, the seismic facies show a more or less continuous and conformable deposition with slight progradation and aggradation (Fig. 4c, b). The toesets thin considerably over the marginal high, where the unit condenses beyond seismic resolution. Towards the north, the unit is dominated by steep, rapidly prograding clinoforms, with very little topset accommodation (Fig. 3a, 7b). The upper part of the clinoforms show very high amplitudes, with a noticeable drop in amplitudes below the offlap break, indicative of either a facies change or simply scattering of seismic energy due to the steep geometry of the clinoforms (Fig. 7b). This unit displays a close correlation between the locations of the clinoforms and the depocentre, similar to that of the underlying unit. It is clear that the main progradation is located along the northern part of the Danmarkshavn Ridge (Fig. 12) as opposed to the underlying unit, where a more southerly depocentre is observed (Fig. 11).

4.10 Faulting and structures

This study maps a significant number of faults active during the post-breakup phase of the Northeast Greenland shelf. The fault pattern is used to constrain the timing, location and mechanisms related to the post-breakup tectonism and vertical motions observed. The faulting observed on the

Northeast Greenland shelf is mostly extensional, with some indication of transverse movement in the Danmarkshavn Basin (Fig. 6, 9). This is consistent with the tectonic setting of the North Atlantic since the Carboniferous, where rifting and continental spreading dominated (Ziegler and Cloetingh, 2004).

A prominent structural break is observed between the Danmarkshavn Ridge and the Thetis Basin, which affects the geometry of the seismic units described above significantly (Figs. 3a-b, 8a-b). West of this break, the Cenozoic succession in the Danmarkshavn Basin is dominated by a significant structural tilt and uplift towards the west (Fig. 3b), whereas the Thetis Bbasin remains mostly sub-horizontal. This in turn is associated with a westwards deepening erosional truncation of the Cenozoic succession. Cenozoic deposits are thus only preserved in the westernmost part of the Danmarkshavn Basin (Fig. 9). Seismic horizons up to and including the Top Upper prograding unit are affected by the tilt, although it is not possible to constrain it further due to the erosional incision.

The Danmarkshavn Ridge is a relatively complex structure. It is primarily a horst structure (Fig. 5) extending about 200 km across the Northeast Greenland shelf (Fig. 2). The Danmarkshavn Ridge also defines the orientation and dip of the main, basin bounding faults (Type 1 on Fig. 9). Towards the North, the ridge is dominated by inverted Palaeozoic—Mesozoic sedimentary basins overlying an uplifted crystalline basement (Fig. 3a), whereas the south segment of the ridge consists mostly of crystalline basement (Fig. 3b). The faults east of the ridge dips to the east to southeast, thus forming the border faults to the Mesozoic half graben Thetis Basin (Fig. 3b, 9). The faults separating the Thetis Basin and the Danmarkshavn Ridge show larger offsets in the seismic data in towards the south, although seismic reflection patterns suggest that similar faults also exist to the north. The base Cenozoic reflector is clearly downthrown from the Danmarkshavn Ridge (Fig. 5), although the structural style varies across the fault zone. The central section of the ridge show a complex transition with several listric faults constituting the border fault system (Fig. 7b). To the north, the vertical movement between the Thetis Basin and the Danmarkshavn Ridge is mostly accommodated by folding of Paleogene—middle Miocene strata across the transition from the Danmarkshavn Ridge and into the Thetis Basin (Fig. 3a). The Intra Thetis Basin fault parallel to the southern segment of the Danmarkshavn Ridge is located about 25 km east of the Danmarkshavn Ridge (Figs. 3b, 4c). The Intra Thetis Basin fault is aligned with the main fault system east of the northern segment of the Danmarkshavn Ridge (Fig. 9). It shows that the southern segment of the Danmarkshavn Ridge was not involved in the reactivation of the faulting along the east margin of the Thetis Basin during the Cenozoic.

The faults on the west side of the Danmarkshavn Ridge are all west dipping normal faults (Fig. 9), with the exception of a few antithetic faults (Fig. 3a). The faults clearly define~~s~~ the transition from the Danmarkshavn Ridge and into the deep Danmarkshavn Basin (Fig. 3b) in the south, whereas the northern segment is more ambiguous (Fig. 3a). The observation of faulting of the Cenozoic succession in the Danmarkshavn Basin is limited due to thinning and erosion. However, a fault on-trend with the south segment of the Danmarkshavn Ridge is observed in the Danmarkshavn Basin (Type 2, Fig. 9). It is tentatively suggested to be transpressional due to the localised, but intense compressional deformation in combination with a limited vertical offset of the deformed succession (Fig. 6). The fault is part of a zone that accommodates some shortening of the Danmarkshavn Basin, where the footwall block show strong eastwards tilting of Cenozoic strata close to the fault~~-~~ (Fig. 6). It is also observed that the Danmarkshavn Basin fault is associated with basin inversion of the Paleozoic—Mesozoic succession as well as a basement high (Fig. 3b).

The northwards termination of the Danmarkshavn Ridge is marked by increasing depth to the basement north of the ridge. This is also observed in the gravity field as a reduced positive gravity anomaly north of the Danmarkshavn Ridge (Fig. 9). Numerous faults intersect the Cenozoic succession north of the Danmarkshavn Ridge (Fig. 2, Fig. 9, Fault type 5), but show lower lateral extent~~s~~ and less organised orientations, although an easterly dip is prevailing. The less organised nature of the faults in the north of the study area is largely attributed to the presence of salt in this area (Figs. 7a-b). Diapirism is frequently observed, with salt diapirs rising close to the sea floor in many occasions. The faulting appear to be thin-skinned with a sole-out in the salt of most of the faults (Fig. 7a). The salt tectonics appear to have initiated during either Palaeozoic or Mesozoic times, which is confirmed by previous studies (Rowan and Lindsø, 2017). It is beyond the scope of the current study to give a detailed interpretation of the salt tectonics, but it would appear as if the Paleogene—earliest Eocene succession does not display any signs of salt-related thickness changes towards the salt diapirs (Fig. 7b, far left). Furthermore, the salt related faulting (Fig. 7a) shows little to no syn-tectonic deposition during this time. This indicates that the salt may have been activated during the post-breakup phase.

5 DISCUSSION

The results of this study of recent seismic data clearly shows a highly dynamic post-breakup tectonic setting with pronounced, kilometre-scale fault offsets, uplift and tilting of the Danmarkshavn Basin and pronounced progradational events. The large-scale structures and pre-breakup tectonostratigraphy have previously been described (Hamann et al., 2005; Petersen et al., 2015; Tsikalas et al., 2005). This study however presents new details on the causes and timing of the post-breakup tectonics. Based on tectonostratigraphic interpretations and integration of data from the ODP 913 borehole, this study constructs a temporally robust model for the tectonosedimentary evolution during the late Palaogene—Early Neogene period.

5.1 Seismic facies

The plane-parallel, high amplitude seismic facies of the Paleocene—early Eocene succession indicates deposition of well-bedded, laterally cohesive sediments in a quiet setting, such as a marine setting below wave base. However, previous studies find small-scale, prograding clinoforms in the southwest of the study area (Petersen et al., 2016, 2015). This is confirmed in the current study both in map view (Fig. 10), where the clinoforms correlate with depo-centres, and in seismic section (Fig. 6). Such clinoforms indicate that initial infill of the Danmarkshavn basin was controlled by a channelized system, most likely in a shallow water setting. Such clinoforms are likely to be sand prone, whereas the plane parallel seismic facies present elsewhere is more consistent with a clay prone sedimentary facies.

Cenozoic deposits are very scarce onshore East and Northeast Greenland, but Nøhr-Hansen et al. (2011) describes early Paleocene fluvial deposits in the Wollaston Forland and Sabine Ø Area, south-west of the study area (Fig. 2). A sediment fairway from the south-west during the Paleocene is consistent with the prograding clinoforms observed in the seismic data in the southwest part of the study area.

The Eocene—mid Miocene succession is comprised of two main seismic facies types. In the Danmarkshavn Basin and Ridge, the facies strongly resemble that of the underlying unit, suggesting a continued deposition in a marine, sub-wave base, clay-rich environment. In the Thetis Basin however, the seismic facies are dominated by the steep, prograding clinoforms (*e.g.* Figs. 5, 7) associated with the uplift and tilting of the Danmarkshavn Basin and the faulting that intersects the Cenozoic deposits across the east margin of the Danmarkshavn Ridge. Evidence of one or several mass wasting events following rapid motion on the fault system east of the Danmarkshavn Ridge is observed (Fig. 5).

The prograding clinoforms are indicative of more coarse-grained material, most likely sand prone in the proximal part, and fining in the distal direction, i.e. towards the centre of the Thetis Basin. The topsets of the prograding succession (Fig. 4b) may be composed of either typical delta top deposits such as overbank fines and fluvial deposits, or alternatively a form of sub-marine fine-grained top-set deposit.

The focus of the prograding clinoforms during the Eocene—mid Miocene is located in the south part of the Thetis Basin, along the edge of the Danmarkshavn Ridge (Fig. 11). This implies that the south Danmarkshavn Ridge, Danmarkshavn Basin and the area onshore Northeast Greenland south of

Store Koldewey most likely acted as the source area for this progradational event. The presence of fluvial deposits of an latest Paleocene—earliest Eocene age in the Wollastand Forland and Sabine Ø area (Nøhr-Hansen et al., 2011), highlights the presence of a fluvial system southwest of the study area during the time of deposition of the clinoforms. It seems highly likely that this fluvial system transported the sediment forming the Eocene—mid Miocene clinoforms to the margin.

The interpretation of whether the erosional incision of the uplifted footwall of the Danmarkshavn Ridge occurred in a marine or terrigenous environment have obvious implications for the understanding of the depositional evolution of the Northeast Greenland margin. If the erosional incision was~~were~~ terrigenous, it would imply a very dramatic change in depositional environment, from below (storm) wave base to subaerial exposure due to fault related uplift of the Danmarkshavn Ridge. However, erosional incision and prograding clinoforms may as well occur in a marine setting, and the continuous, uniform nature of the topsets and the overlying strata seems to be more consistent with deposition in a marine environment. This does not however imply that there was no tectonic motion. In fact, the steepness of the incision, in combination with the chaotic nature of the material transported into the Thetis Basin resulting from the mass wasting event, indicates a rapid and significant tectonic movement (Fig. 5).

The post-mid Miocene, upper prograding unit, displays very similar facies patterns as the underlying unit. However, as described above, the location of the clinoforms are shifted further north in the Thetis Basin (Fig. 12). The seismic facies of the clinoform-dominated northern part of the unit show a very distinct proximal to distal facies change (Figs. 3a, 7b). The high amplitudes of the topsets indicate~~s~~ a highly heterogenic depositional environment, with interbedded sand and shale. The foresets are most likely dominated by lateral sand-on-sand contacts, as the amplitudes show a marked dimming, resulting from relatively homogenous sediments. The chaotic to moderately well bedded toesets are consistent with basin floor fan deposition dominated by various mass wasting deposition such as slides, slumps and turbidites. The northwards shift of the clinoforms indicates a change in the drainage pattern of the Northeast Greenland shelf, and possibly also onshore Northeast Greenland, from mainly focused south of Store Koldewey for the lower prograding unit to north of Store Koldewey for the upper.

5.2 Structural evolution

The seismic data offshore Northeast Greenland clearly demonstrate that tectonics play a prominent role in the sedimentation pattern after the continental breakup. The post-breakup faulting observed mainly around the Danmarkshavn Ridge is extensional in nature, as all faults have some degree of a normal motion on them. However, the total extension of the shelf after the continental breakup is interpreted to be relatively modest due to the steep dips of the fault planes and low amount of heave on the individual faults.

The two main tectonic events are the tilting and uplift of the strata in the Danmarkshavn Basin, and the 1-2 s TWT throw on the western boundary fault system in the Thetis Basin. Both events clearly post-dates the Early Eocene Unconformity, as this horizon is involved in both the structural tilt and intersected by the faulting. The relative timing between these two events indicates that the western boundary fault of the Thetis Basin was reactivated prior to any significant tilting in the Danmarkshavn Ridge or Danmarkshavn Basin area. Tilting might however have initiated west of the Danmarkshavn Basin at an earlier stage.

The intra-Thetis Basin fault (Fig. 4c) display normal faulting of the entire Cenozoic succession in the southern area of the basin. Although the fault throw is relatively modest, the initiation of the fault is significant, as it controls the location of the footwall erosional escarpment, and seems to be aligned with the northern segment of the Danmarkshavn Ridge. It also indicates that the southern segment of the Danmarkshavn Ridge was not tectonically active after the breakup.

A significant amount of vertical offset has accumulated between the Thetis Basin and the Danmarkshavn Ridge during the Eocene—Miocene(?) period, amounting to 1-2 s TWT. By assuming an average seismic velocity of 2000 m/s (Berger and Jokat, 2008) this equates to 1-2km of vertical offset. As mentioned above, extension appear to be limited during the Cenozoic. Therefore, it seems likely that the vertical offset was created by a steep, listric fault with a sole-out at the base of the crust. This is consistent with the seismic observations in this study and with other geophysical observations (Tsikalas et al., 2005). Some of the post-breakup subsidence may be caused by differential compaction between the Danmarkshavn Ridge and the Thetis Basin. However, the abrupt nature of the subsidence, causing slope failure on the footwall, seems in contrast to relatively slow and continuous compaction-related subsidence.

In a regional perspective, it is apparent that the extensional faulting observed around the Danmarkshavn Ridge and in the Thetis basin is oriented sub-parallel to the main extensional axis created during continental breakup (Fig. 2), even though some of the faulting post-dates the breakup by >40 Ma. This is clear evidence that the structural grain created during the Mesozoic rifting (Tsikalas et al., 2012) was reactivated during the post-breakup extensional tectonics.

The timing of the salt movement can in the context of the current study yield important information about tectonic events. Remobilised salt is observed throughout the northern part of the study area (Fig. 2), and is associated with a complex fault pattern (Fig. 9). Salt diapirs frequently rise to or close to the sea floor, indicating that salt mobilisation has been occurring close to present time, although presumed Quaternary erosion truncates the crests of the diapirs, hampering a more accurate constraint on the timing (Figs. 7a, b). Since there is no evidence of Paleocene—Eocene rim synclines, no pre-breakup salt mobilisation is interpreted. Since the salt was not activated during the continental breakup, it seems likely that most of the tectonic deformation during the breakup (at *ca.* 55 Ma) was focused along the margin of the shelf, away from the Danmarkshavn Basin. The lack of pre-breakup tectonism on the shelf, apart from the thermally induced uplift in the earliest Eocene, further confirms this observation. It then seems more likely that the salt mobilisation is linked to the same post-breakup tectonics seen in the data as movement of the Thetis Basin boundary fault and tilting of the Danmarkshavn Basin.

5.3 Uplift and erosion

The Northeast Greenland shelf displays a series of uplift events from the Late Cretaceous through the Neogene (Hamann et al., 2005; Petersen et al., 2016, 2015). The unconformity below the Cenozoic succession is a surface of regional significance, also observed onshore Northeast Greenland (Nøhr-Hansen et al., 2011). In the current study, the unconformity is mostly observed in the Danmarkshavn Basin and on the Danmarkshavn Ridge, and is particularly well developed in the south of the study area. This trend is seen in subsequent uplift events as well, where uplift events are most pronounced towards the south. The uplift and related intrusions of hot magma, peaking around *ca*. 55 Ma (Larsen et al., 2014) reported previously (Petersen et al., 2015; Reynolds et al., 2017), also display a deepening incision in the south part of the Danmarkshavn Basin, associated with progradation of clinoforms into the Danmarkshavn Basin (Petersen et al., 2016, 2015). Some minor basin inversion is also observed at the earliest Eocene times (Fig. 5), although this is in contrast to the generally extensional tectonic regime of the shelf during the Cenozoic. However, compression may be caused by counter-clockwise rotation of Greenland during the Palaeocene, which may have caused minor NE-SW compressional stresses to be transmitted onto the Northeast Greenland shelf (Guarnieri, 2015). However, this mechanism seems unable to account for neither the geometry nor the amount of uplift observed on the Northeast Greenland shelf.

The gradual uplift and associated denudation of the Cenozoic deposits of the Danmarkshavn Basin and Ridge area most likely post-dates the intra Miocene unconformity. The exhumation of the inner part of the shelf and its association with steep, prograding clinoforms with downlaps onto the Intra Miocene Unconformity (Fig. 3a), points to a post-mid Miocene age for the cessation of the uplift of the inner Northeast Greenland shelf. The vertical motions seems to stop or slow significantly around the time of the Top upper prograding unit seismic horizon (Fig. 7b). The end of the main denudation phase is therefore poorly constrained, since the age of the Top upper prograding unit can only be attributed to a post-mid Miocene age. It is suggested in this study, that the main cause of uplift and tectonics following the continental breakup is caused by thermal uplift and dynamic topographic effects associated with the Icelandic mantle plume. (Fig. 13)

A central feature of the post-breakup denudation of the inner Northeast Greenland shelf is the time transgressive nature of the uplift, as indicated by the prograding units and their migration northwards over time. This is evident when comparing the thickness maps of the two uppermost late Paleogene—Neogene units (Figs. 11 and 12), but in fact, the north to south migration of clinoforms seems to start potentially as early as the Palaeocene (Petersen et al., 2015). This northwards move of the main depocentre indicates that the uplift and exhumation of the Northeast Greenland shelf must have been focused east, southeast or south of the current study area. This initially created a structural tilt of the Danmarkshavn Basin towards the west, but with a minor northwards component as well. The earliest observations of clinoforms in the south is dated as Paleocene, and the youngest clinoforms are post mid-Miocene, a period of about 45 Ma. This implies a slow northwards tilting of the Northeast Greenland shelf. Alternatively, it is possible that the northwards tilting occurred much faster, but that the sedimentation occurred in pulses related to hinterland uplift.

5.4 Effect of mantle plume path on deposition

The Icelandic hotspot and its effect in the North Atlantic realm, in particular in relation to the continental breakup, has been the source of much debate (Campbell, 2007; Clift et al., 1998; Storey et al., 2007). In the current study, it is suggested that the mantle plume system at present day located beneath Iceland and Jan Mayen (Rickers et al., 2013), was instrumental in the uplift of the inner Northeast Greenland shelf, and that it was responsible for a gradual, northwards shift of the main sediment fairway. The central argument for this interpretation is that the Icelandic plume system moved along a trajectory south of the study area during the Cenozoic, which is in good agreement with the time-transgressive northward movement of the prograding units observed in this study.

The plume activity, its trajectory and its morphology are all influencing the depositional patterns observed during the Cenozoic on the Northeast Greenland shelf. The plume underneath the North Atlantic show a significant lateral extent, with an origin observed down to the lower mantle (Rickers et al., 2013). Døssing et al (2016) concludes that the thermal perturbation at 2-15 Ma (mid Miocene--Pilocene) is linked to the IMU (Intra Miocene Unconformity) observed around the East Greenland Ridge, indicating a clear link between the thermal pertubations of the passing hotspot and tectonism in the region.

The coupling between the Atlantic mantle plume system and the North Atlantic Igneous Province is well established (e.g. Ganerød et al., 2010; Hansen et al., 2009; Larsen et al., 2014; Storey et al., 2007). Onshore Northeast Greenland, the accurately dated igneous rocks show a distinct trend of younger igneous rocks towards the north (Larsen et al., 2014). The youngest igneous rocks (40-20 Ma) observed according to Larsen et al.(2014) are all found north of 67° N (Fig. 13), further indicating a south to north time transgressive impact of the passing Icelandic mantle plume system. The location of the Icelandic and Jan Mayen hotspots directly south of the study area during mid Miocene times (Fig. 13), is in very good agreement with uplift in the south and tiliting of the margin towards the north during the mid Miocene—Quaternary.

6 CONCLUSIONS

This study utilizes a vast database of the most recent seismic data and presents a series of novel observations on the tectonosedimentary development of the Northeast Greenland shelf following the continental breakup. A summary of the tectonic and sedimentary events described in the current study is presented in Fig. 15.

It is demonstrated that significant vertical motion and associated extensional faulting are observed after the continental breakup at *ca.* 55 Ma. Differential subsidence, some of which may be attributed to deep-rooted faults, in the order of 1-2 k~~K~~m is observed along the west boundary of the Thetis Basin, during the Eocene to post-Miocene times. The faulting occurred simultaneously with a pronounced uplift and eastward tilt of the inner Northeast Greenland shelf.

Several progradational events are interpreted based on the seismic data. The earliest clinoforms are of a pre-breakup age, and located in the south Danmarkshavn Basin. The clinoforms are however more pronounced after the earliest Eocene breakup, where steep, rapidly prograding clinoforms oversteps the Danmarkshavn Ridge and progrades into the Thetis Basin. These clinoforms display a northward migration over time, with a significant clinoform succession formed in the north of the Thetis Basin sometime after the mid Miocene.

The Icelandic hot spot is suggested as the main cause of uplift, rotation and extensional faulting of the shelf. The trajectory of the Icelandic hot spot south of the Northeast Greenland shelf during the Neogene fits very well with a gradual, northwards shift of progradation due to thermally induced uplift and dynamic topography.~~,~~ ~~which~~ This is observed in the seismic data as northwards tilting of the shelf during post-breakup times. Lastly, the reactivation of the fault system separating the Danmarkshavn Ridge and the Thetis Basin is also attributed to the thermal uplift caused by the passage of the Icelandic hotspot.

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Captions

Fig. 1. Overview of the study area and the seismic database. The data are composed of two vintages. The AWI seismic data, collected during the nineties, and the TGS data collected 2008-2014. The TGS data are of both better quality and much higher density, as shown on the map. The AWI data covers the important transition from continental to oceanic crust however. All data are courtesy of TGS and Spectrum. Approximate locations of the seismic cross sections are also highlighted.

Fig. 2. Map of the main structural elements, traces of the interpreted faults, free air gravity anomalies, as well as magnetic isochrons. The map shows the NNE-SSW elongated Danmarkshavn Basin (DKHB), the Danmarkshavn Ridge (DKHR), right-lateral transfer zone (TS) and the Thetis Basin located on the easternmost side of the shelf. The East Greenland ~~Ridgde~~Ridge (EGR), Store Koldewey (SKW) and Wollaston Forland (WSF) are also shown. Gravity data are courtesy of DTU Space DNSC08GRA and DTU10 data sets (Andersen 2010 and Andersen et al 2010).

Fig. 3. (a) Regional west to east oriented seismic profile through the northern part of the study area. The section shows a thick Palaeozoic and Mesozoic succession that overlies the northernmost extent of the Danmarkshavn Ridge basement high. The section shows a distinct step down of the Base Paleogene horizon from the Danmarkshavn Ridge and into the Thetis basin caused by ductile accommodation of normal reactivation of faults at the Danmarkshavn Ridge to Thetis Basin transition. To the west, in the Danmarkshavn Basin, the Cenozoic succession shows evidence of tilting and erosional incision, associated with pronounced progradation in the Thetis Basin, above the Intra Middle Miocene reflection. (b) Regional west to east oriented seismic profile through the southern part of the study area. The Cenozoic succession displays a significant uplift and tilt to the east across the Danmarkshavn Basin and Danmarkshavn Ridge. Faulting is present in the Danmarkshavn Basin, where it offsets the Cenozoic ~~succession(~~succession (IDBF: Intra Danmarkshavn Basin Fault). Faulting is also present between the Danmarkshavn Ridge and Thetis Basin, as well as in the Thetis Basin, with the faults downfaulting the Cenozoic succession towards

the East along the Intra Thetis Basin Fault (ITBF). Evidence of a steep erosional scar infilled with prograding clinoforms is present across the Danmarkshavn Ridge. Seismic data are courtesy of TGS and Spectrum.

Fig. 4. Seismic examples of the Danmarkshavn Ridge to Thetis Basin transition at the southern segment of the Danmarkshavn Ridge. (a) The Palaeocene to Miocene(?) seismic facies across the Danmarkshavn Ridge is dominated by parallel, high amplitude reflections unconformably overlying the Danmarkshavn Ridge. A concave erosional truncation of the Palaeocene to Miocene(?) marks the transition from the Danmarkshavn Ridge to the Thetis Basin, where two east dipping normal faults off sets the Paleogene succession by >1 s TWT down into the Thetis Basin. Steep, prograding clinoforms fills out the accommodation space created by the erosional incision and extends out into the Thetis Basin. (b) Seismic section further south compared to (a). The two faults still mark the transition from the Danmarkshavn Ridge to the Thetis Basin. The prograding clinoforms persist, reaching far out into the Thetis Basin. Small-scale faults intersect the succession between the Early Eocene Unconformity and the Top upper prograding unit. (c) Seismic example from the southernmost Danmarkshavn Ridge. Note the increase in distance between the Danmarkshavn Ridge and the Intra Thetis Basin Fault (ITBF). The erosional incision is located east of the Danmarkshavn Ridge, indicating that the ITBF triggered the incision. Note the pronounced angular unconformity below the Early Eocene Unconformity to the far west. Seismic data are courtesy of TGS and Spectrum.

Fig. 5. Seismic section through the central study area covering the Danmarkshavn Basin, the Danmarkshavn Ridge and the Thetis Basin. The seismic section clearly show domal uplift and truncation below the Early Eocene Unconformity in the Danmarkshavn Basin, with some indications of minor compression and inversion are observed along the west margin of the Danmarkshavn Ridge. To the far NW of the profile, disturbances in the reflections below the Early Eocene Unconformity indicates gas venting and a pockmark associated with volcanic activity. The bounding

fault between the Danmarkshavn Ridge and the Thetis Basin offsets the entire succession above the Base Paleogene, but the Erosional incision seismic horizon and prograding clinoforms are confined to the Thetis Basin. Chaotic seismic facies indicate mass deposited sediments below the Erosional incision reflection. Seismic data are courtesy of TGS and Spectrum.

Fig. 6. Seismic profile across the largest fault in the Danmarkshavn Basin, the Intra Danmarkshavn Basin Fault (IDBF). There is a distinct offset of the Palaeogene succession along the fault, and several minor associated faults are present. Also, notice the prograding clinoforms west of the fault. Seismic data are courtesy of TGS and Spectrum.

Fig. 7. (a) Seismic example north of the Danmarkshavn Ridge. The structural style here is heavily affected by the salt, which forms a detachment plane at the base of the faults. Salt diapirism is also observed. (b) Seismic section showing the structural complexity of the Danmarkshavn Ridge in the central part of the study area. Several eastwards dipping, listric faults comprise the Danmarkshavn Ridge to Thetis Basin transition. At the westernmost edge of the profile, a salt diapier rises close to the seafloor. Note how the main progradational event is now above the Intra Miocene Unconformity. For comparison, see fig. 4. Seismic data are courtesy of TGS and Spectrum.

Fig. 8. (a) Structure map of the Base Palaeogene horizon in TWT with fault traces of the main faults that outline the Danmarkshavn Ridge overlain. The map clearly shows the steep transition from the relatively elevated Danmarkshavn Basin/Ridge area and lower lying Thetis Basin. Also, note the coincidence between the faulting and the steep transition zone. (b) Structure map of the Upper prograding unit horizon in TWT with fault traces of the main faults that outline the Danmarkshavn Ridge trace overlain. The steep slope along the northern Danmarkshavn Ridge is due to steep, prograding clinoforms rather than structural deformation. Note the eastwards movement of the western limit of the unit.

Fig. 9. Overview and classification of the faults interpreted in this study overlain the free air gravity data. Faults are subdivided into five categories: Main, ridge-delineating faults (type 1, black), Intra-Danmarkshavn Basin faults (type 2, green), pre-Cenozoic faults that are not reactivated (type 3, grey), Intra-Thetis Basin faults (type 4, blue), and salt related faults (type 5, magenta). The white fault is a hybrid between the ridge delineating fault and the salt related fault types. The ridge delineating faults are all located on the margins of the NE-SW oriented positive gravity anomaly associated with the Danmarkshavn Ridge. A right-lateral transfer zone between the north and south segments of the Danmarkshavn Ridge is highlighted. Note that all the salt related faults are located in the northern part of the study area, where the gravity anomaly is relatively low. The westwards erosional truncation of the Cenozoic deposits is also highlighted (grey line).

Fig. 10. Thickness map (in TWT) of the succession between the Early Eocene and the Base Paleogene, corresponding to the Palaeocene—lowermostst Eocene. The main depo-center is located in the southernmost part of the Thetis Basin, and thins substantially on the Danmarkshavn Ridge. A potential northerly depo-center is also tentatively interpreted from the data. The Location of the Danmarkshavn Ridge and the right-lateral transfer zone are shown for reference together with the main, basin delineating faults.

Fig. 11. Thickness map (in TWT) of the succession between the Early Eocene and the Intra middle Miocene horizons, corresponding to the Eocene—lower Miocene interval dominated by early prograding clinoforms. The main depo-center is prominently located immediately west of the southern segment of the Danmarkshavn Ridge. The Location of the Danmarkshavn Ridge and the right-lateral transfer zone are shown for reference together with the main, basin delineating faults.

Fig. 12. Thickness map (in TWT) of the succession between the Intra middle Miocene and Upper prograding unit horizons, dominated by the late prograding event. The upper age of this interval is poorly constrained to a post-Miocene age. The depo-centre is located NE of the Danmarkshavn Ridge. Compared to fig. 11, it is evident that the depo-center shifts further north and further into the

Thetis Basin. The Location of the Danmarkshavn Ridge and the right-lateral transfer zone are shown for reference together with the main, basin delineating faults.

Fig. 13. Overview map showing the path and estimated extent of the Jan Mayen-Iceland hotspot system after Rickers et al. 2013, shown together with free air gravity anomalies. Ages of the observed, onshore volcanics (Larsen et al. 2014) show a trend of younger magmatic rocks towards the north (italics, stars and horizontal lines). A relatively good correlation between the passage of the hot spots and the ages of the intrusions are seen, with the Jan Mayen plume branch a likely candidate for the northern (and younger intrusions). The observed northwards shift in prograding clinoforms, southwards deepening erosion during the latest Eocene and the area with seismic observations of volcanics are shown as reference.

Fig. 14. Summary of tectonostratigraphic events during the early-mid Cenozoic period of the Northeast Greenland shelf. Red arrows show uplift, blue arrows show normal faulting/subsidence. Note how the clinoforms shift northwards during Eocene—Miocene period. The Thetis Basin is dominated by varying degrees of subsidence (blue minus), but the Danmarkshavn Ridge and Danmarkshavn Basin show a more complicated history of uplift (red plus) and erosion (grey hatched).

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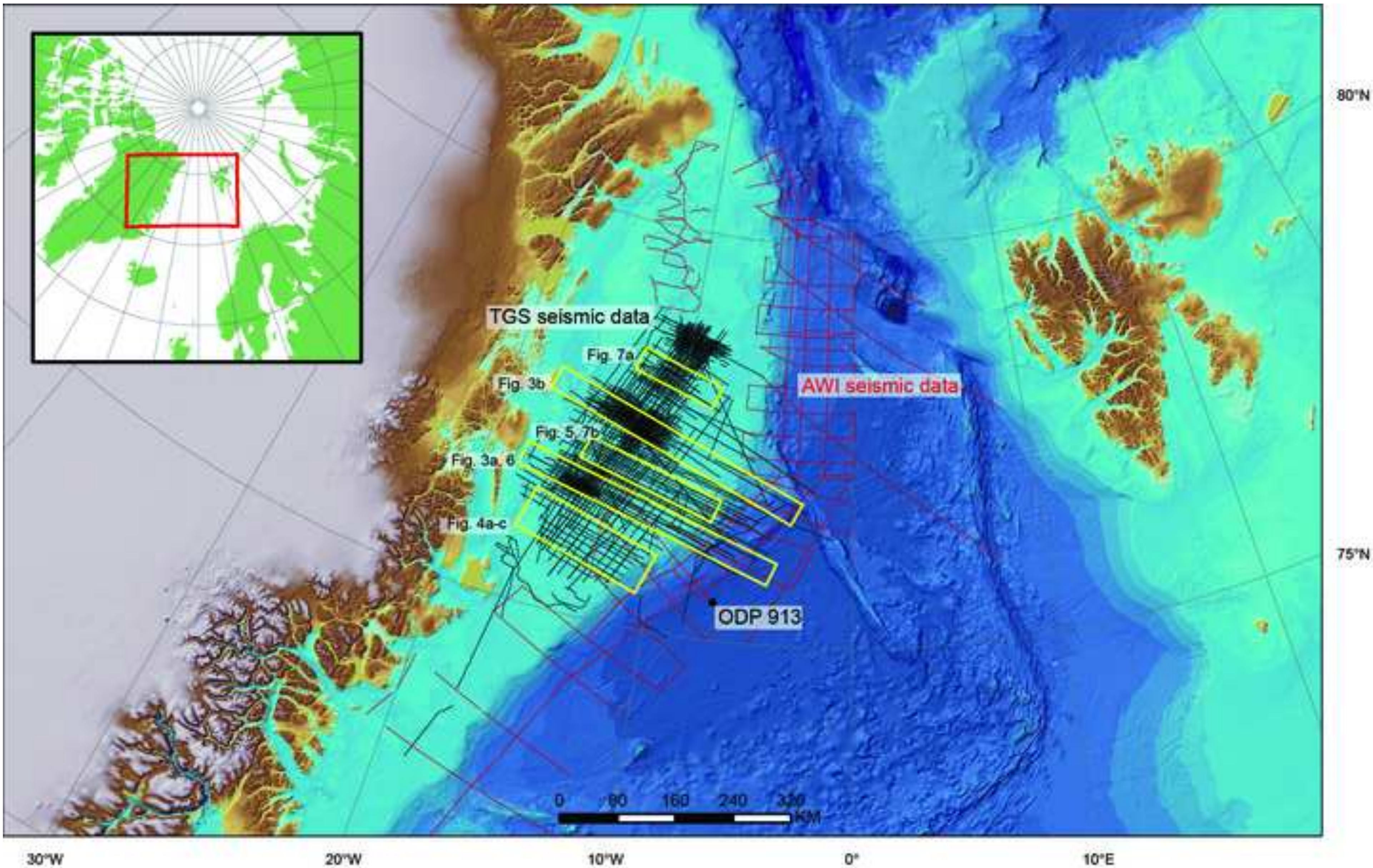

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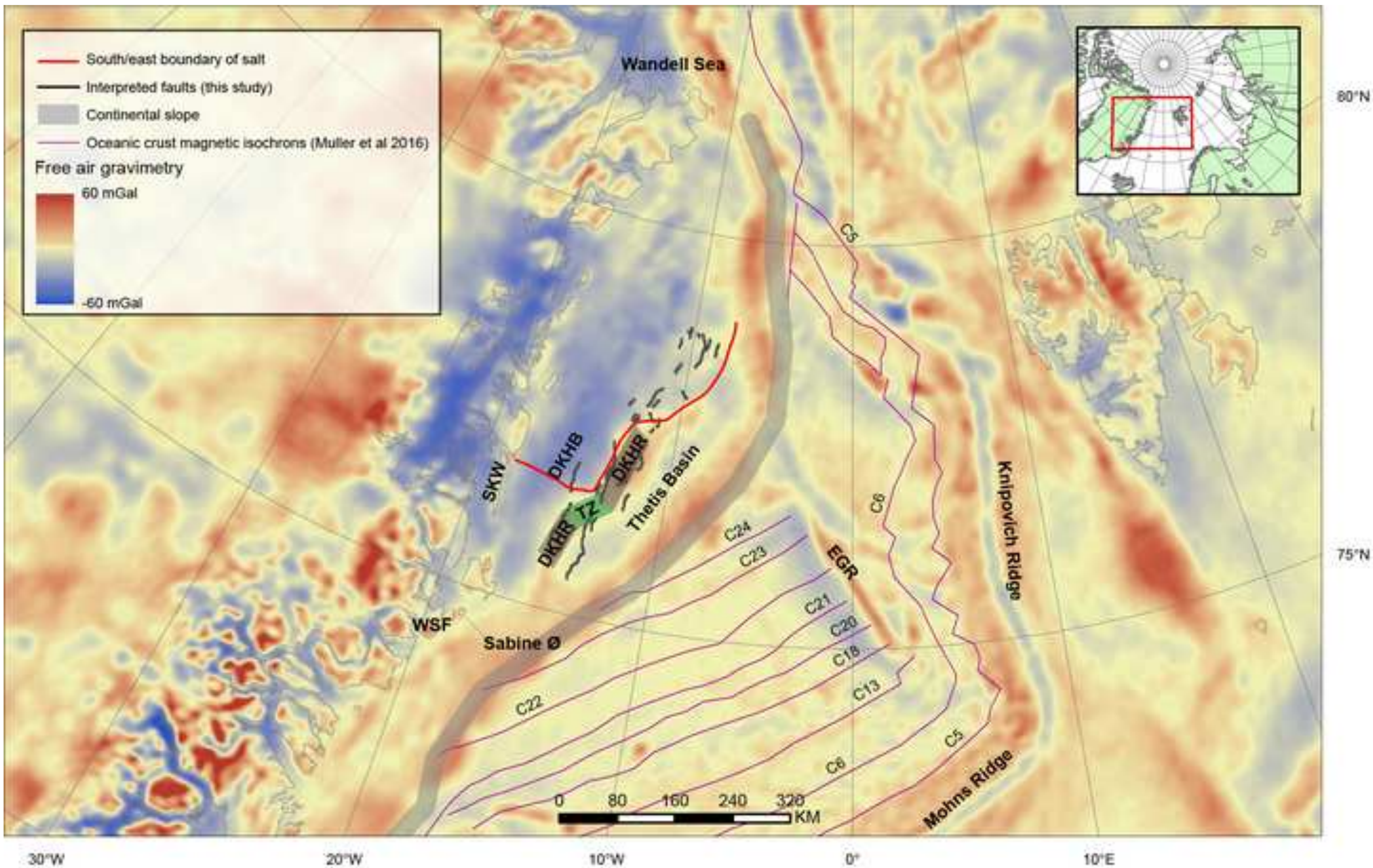

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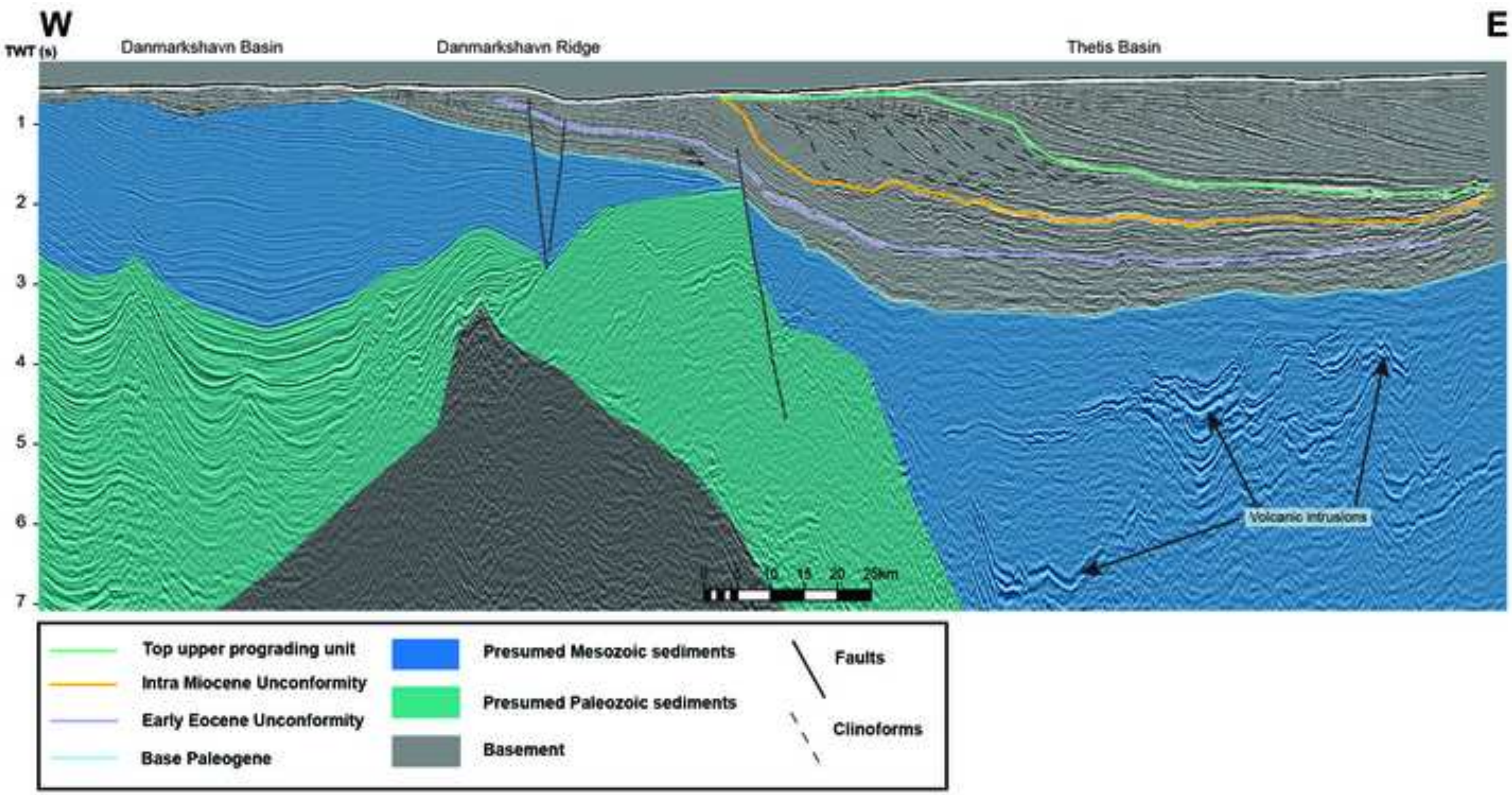

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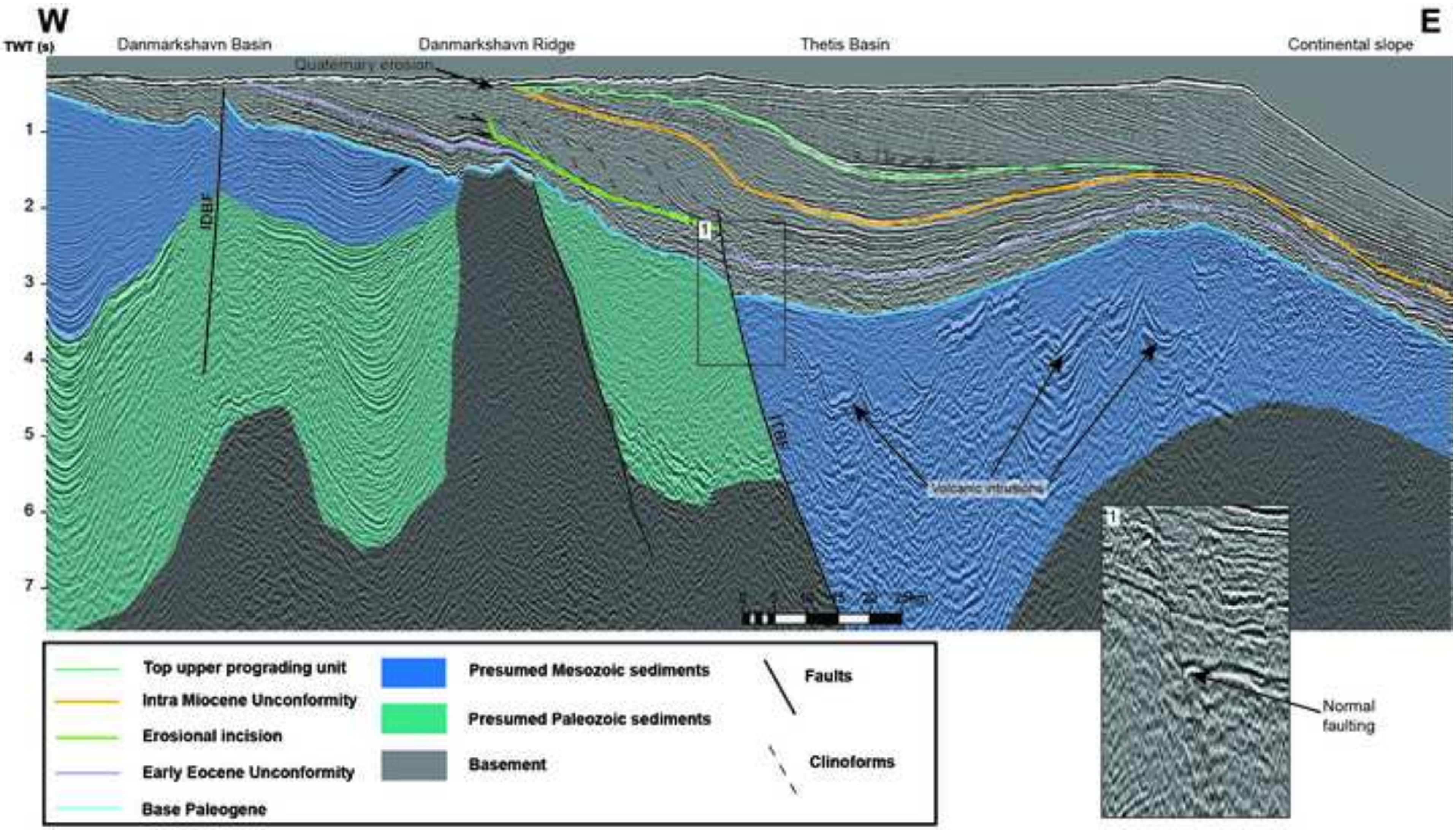

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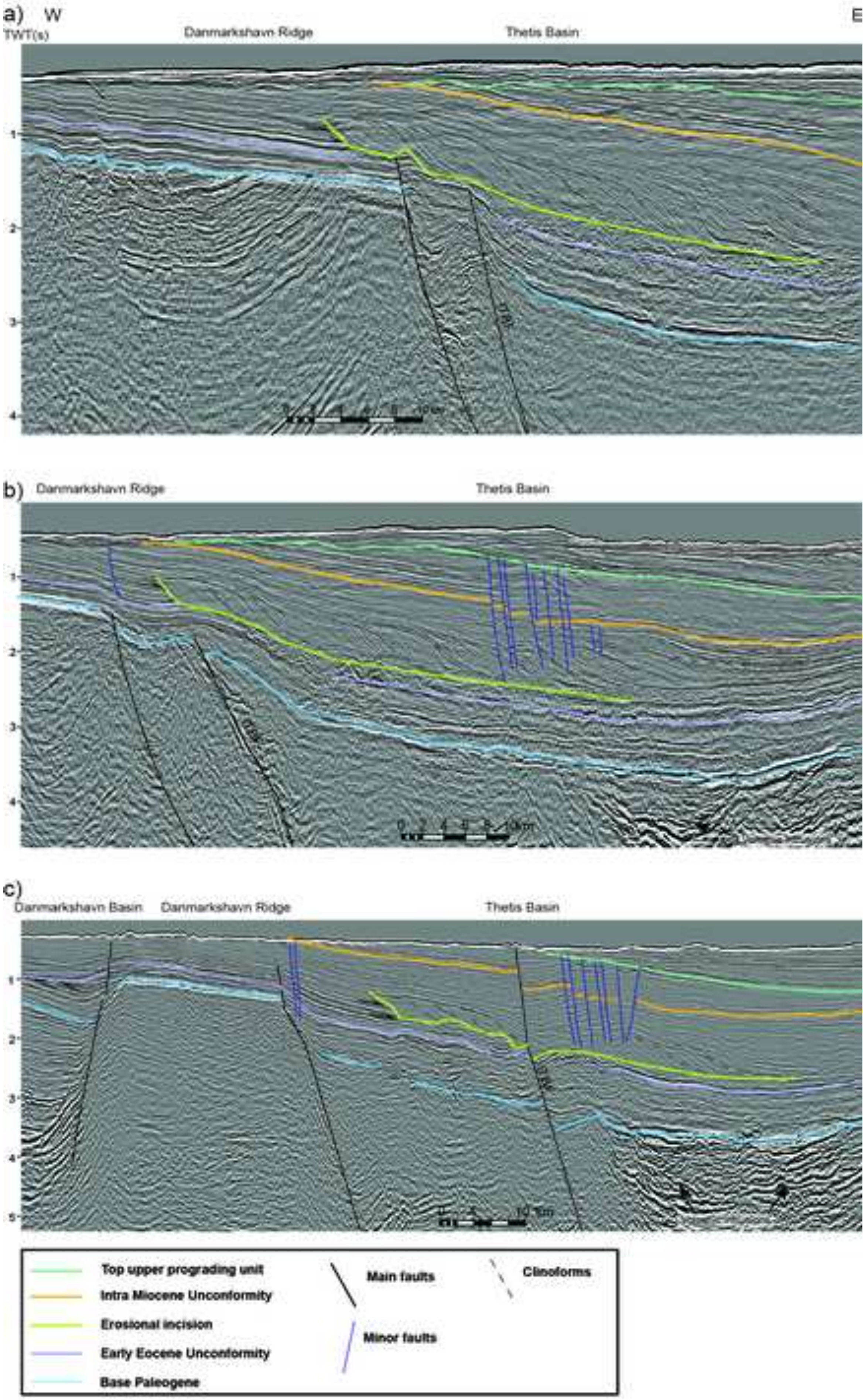

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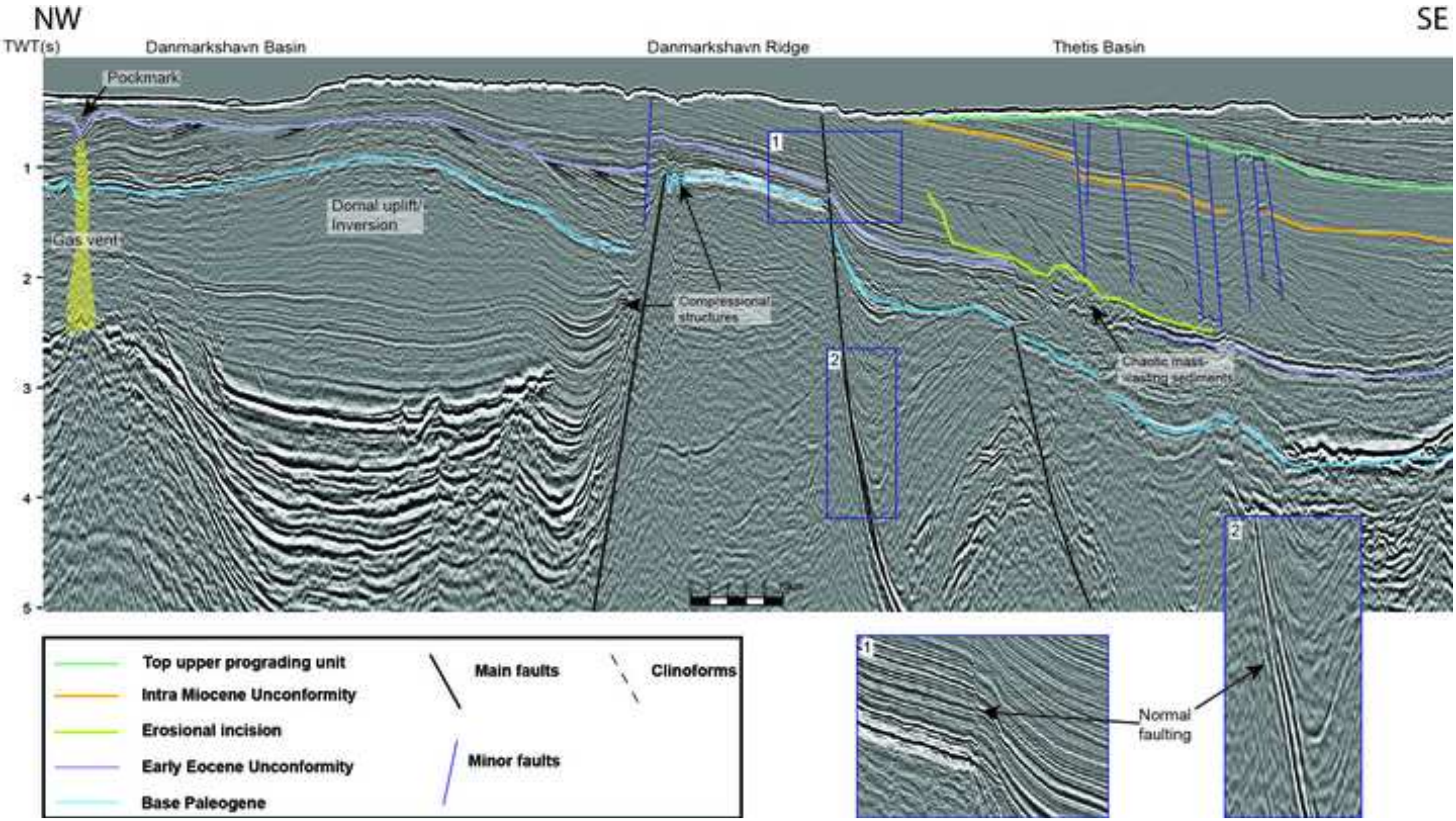

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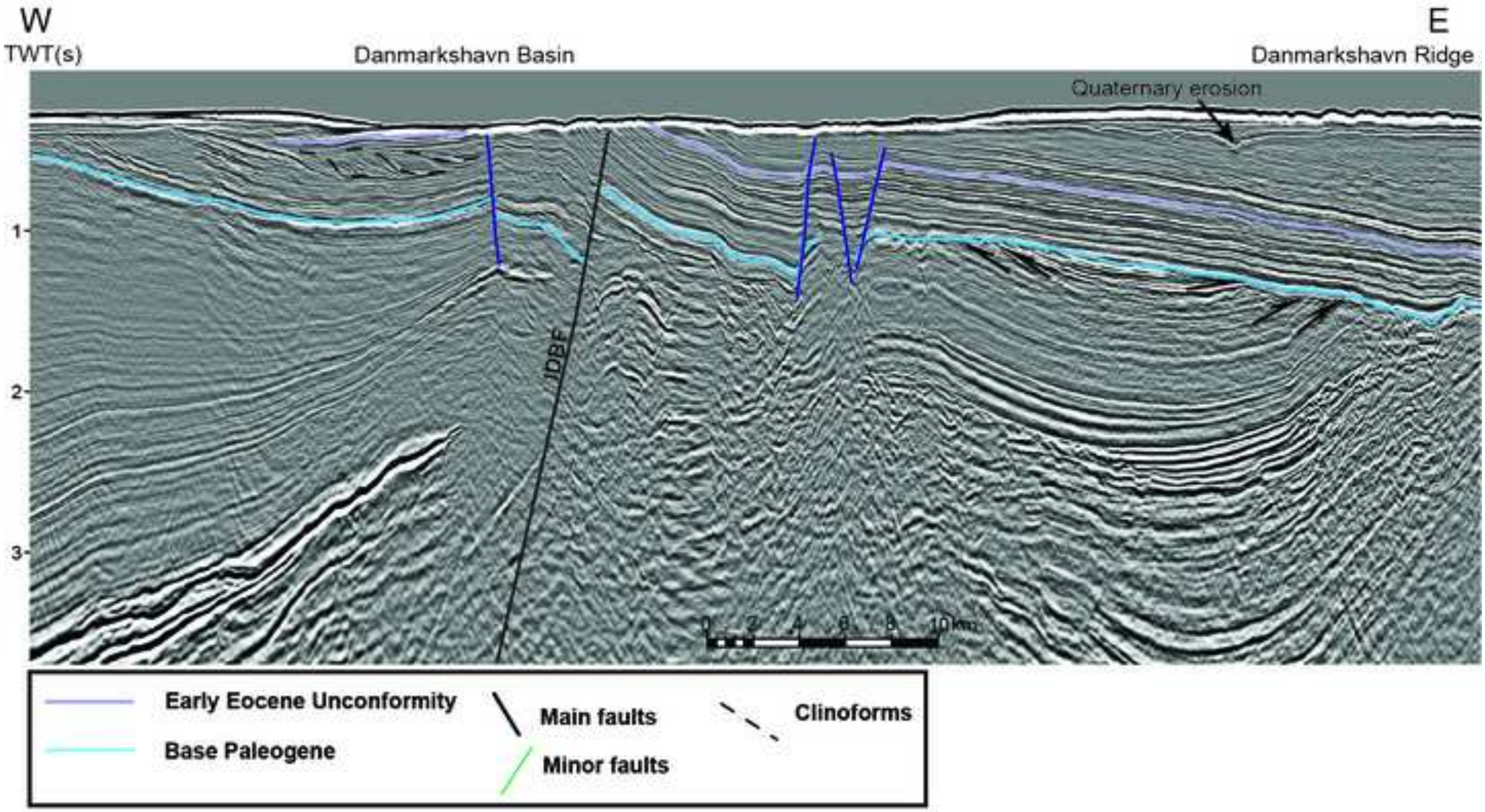

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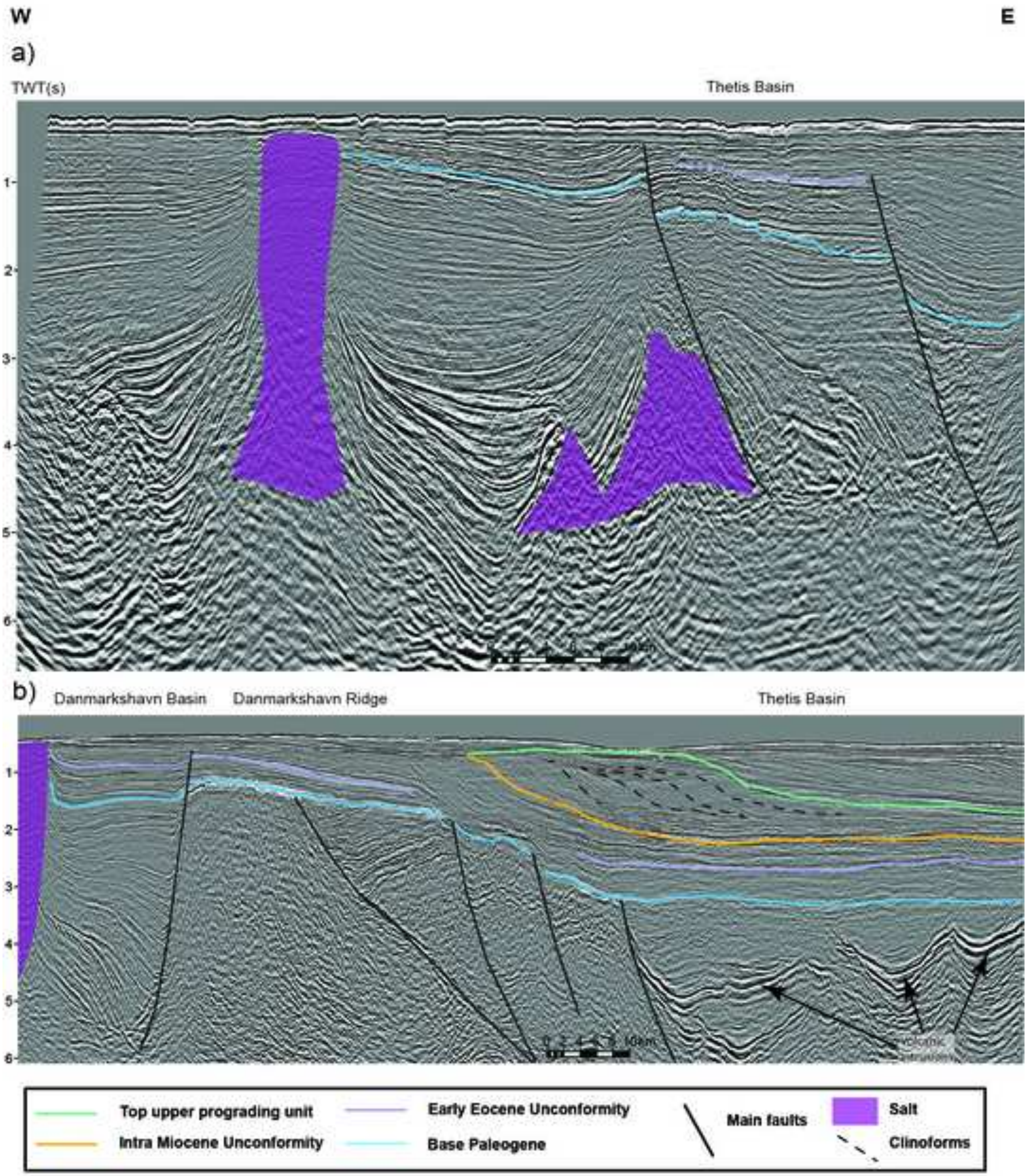

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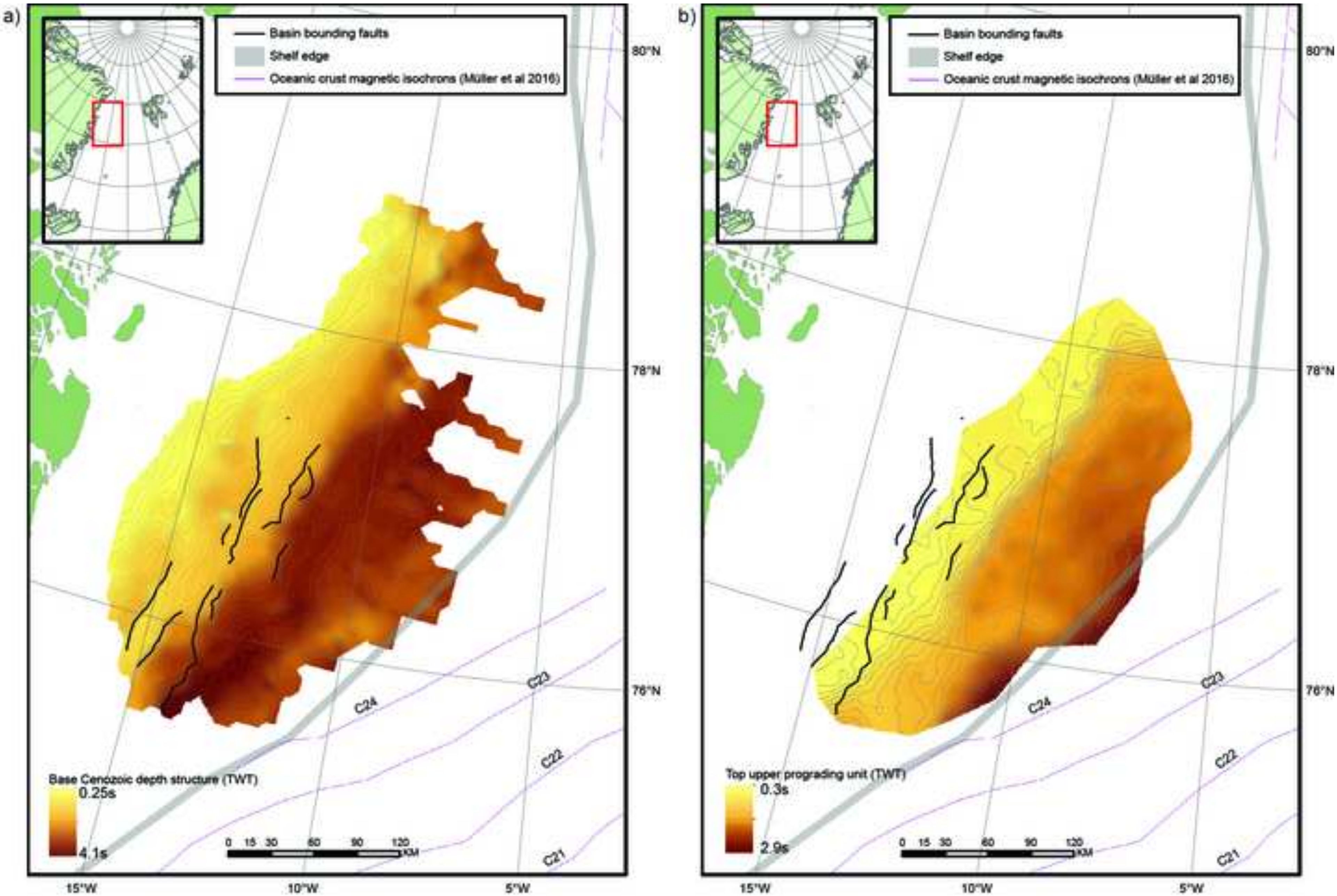

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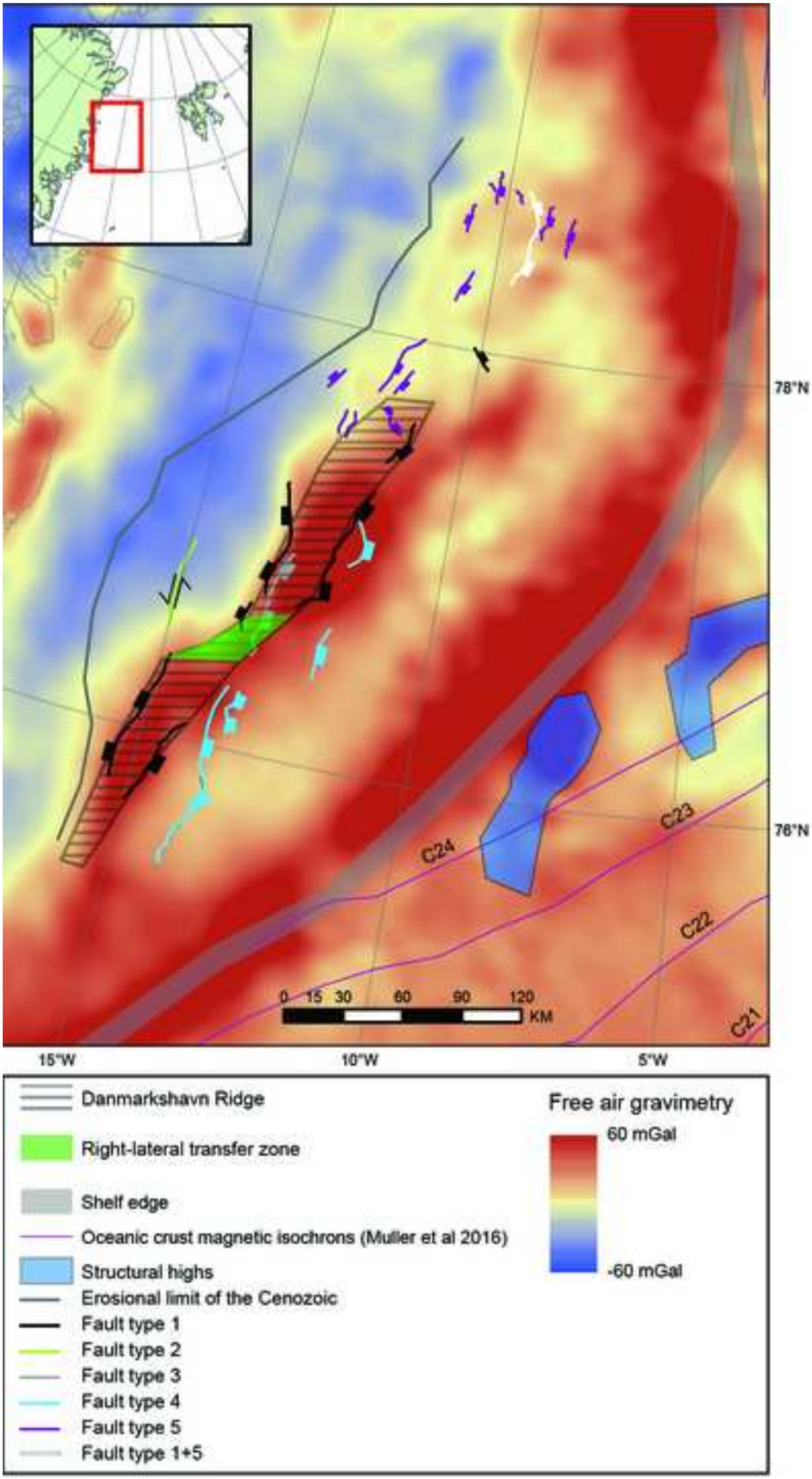

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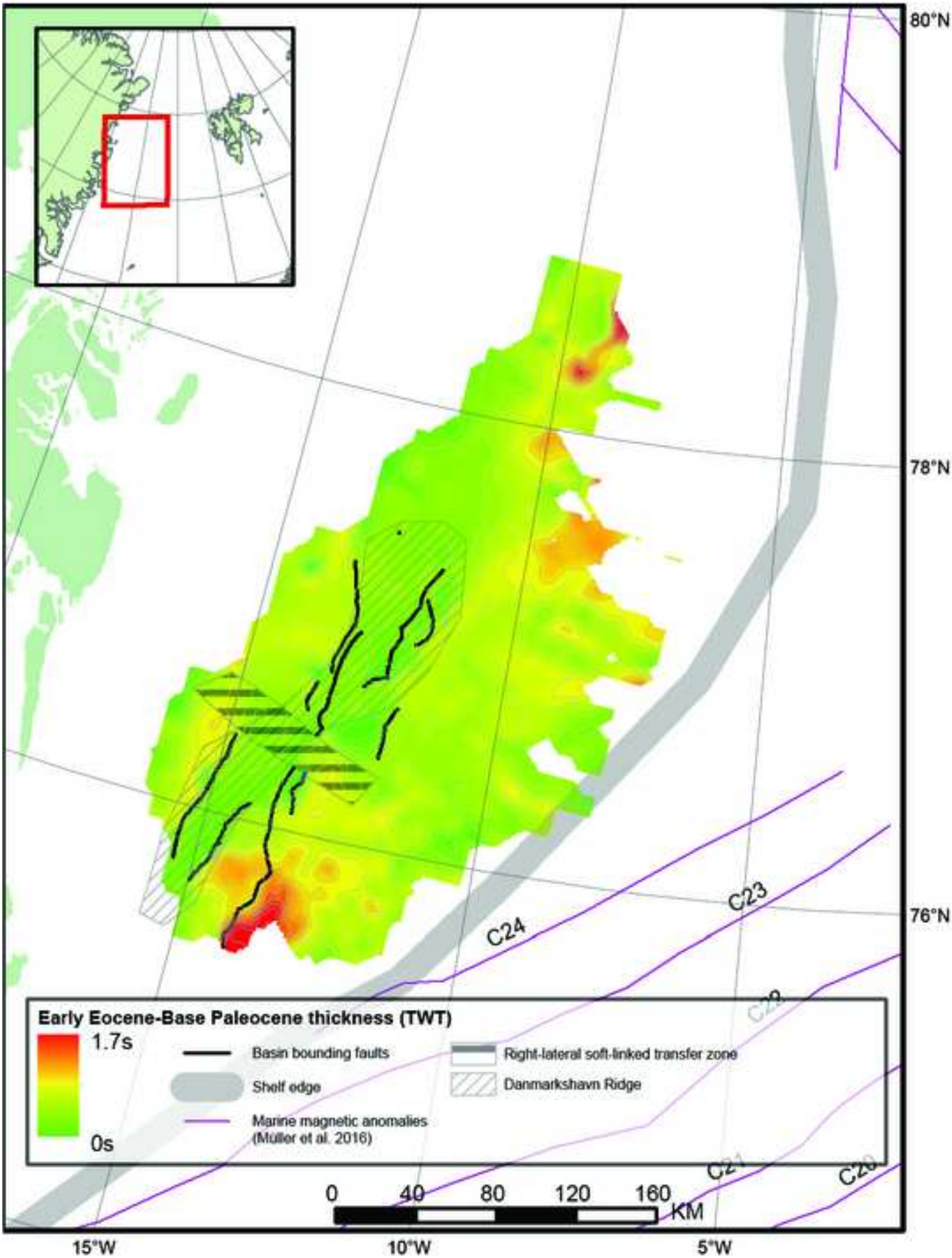

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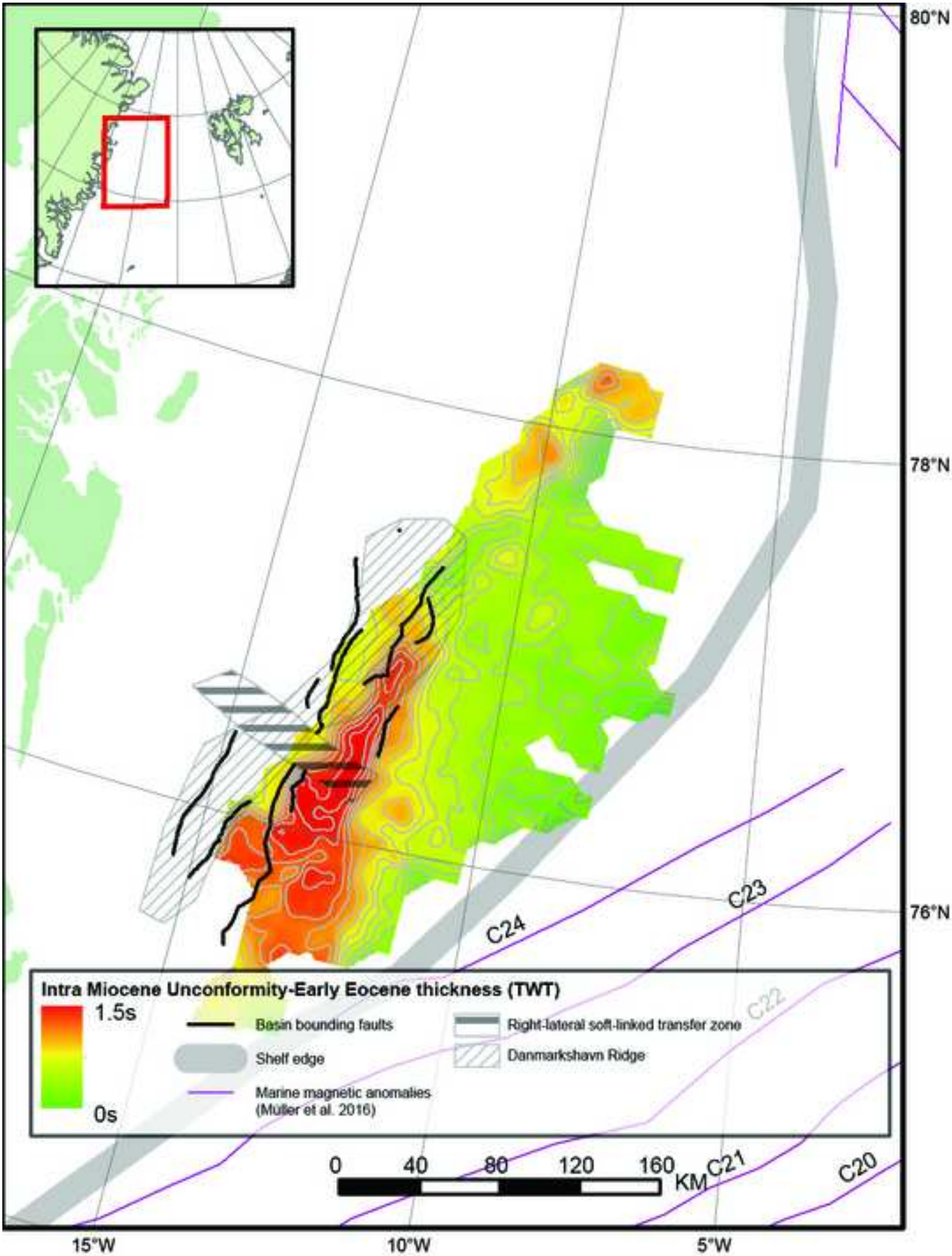

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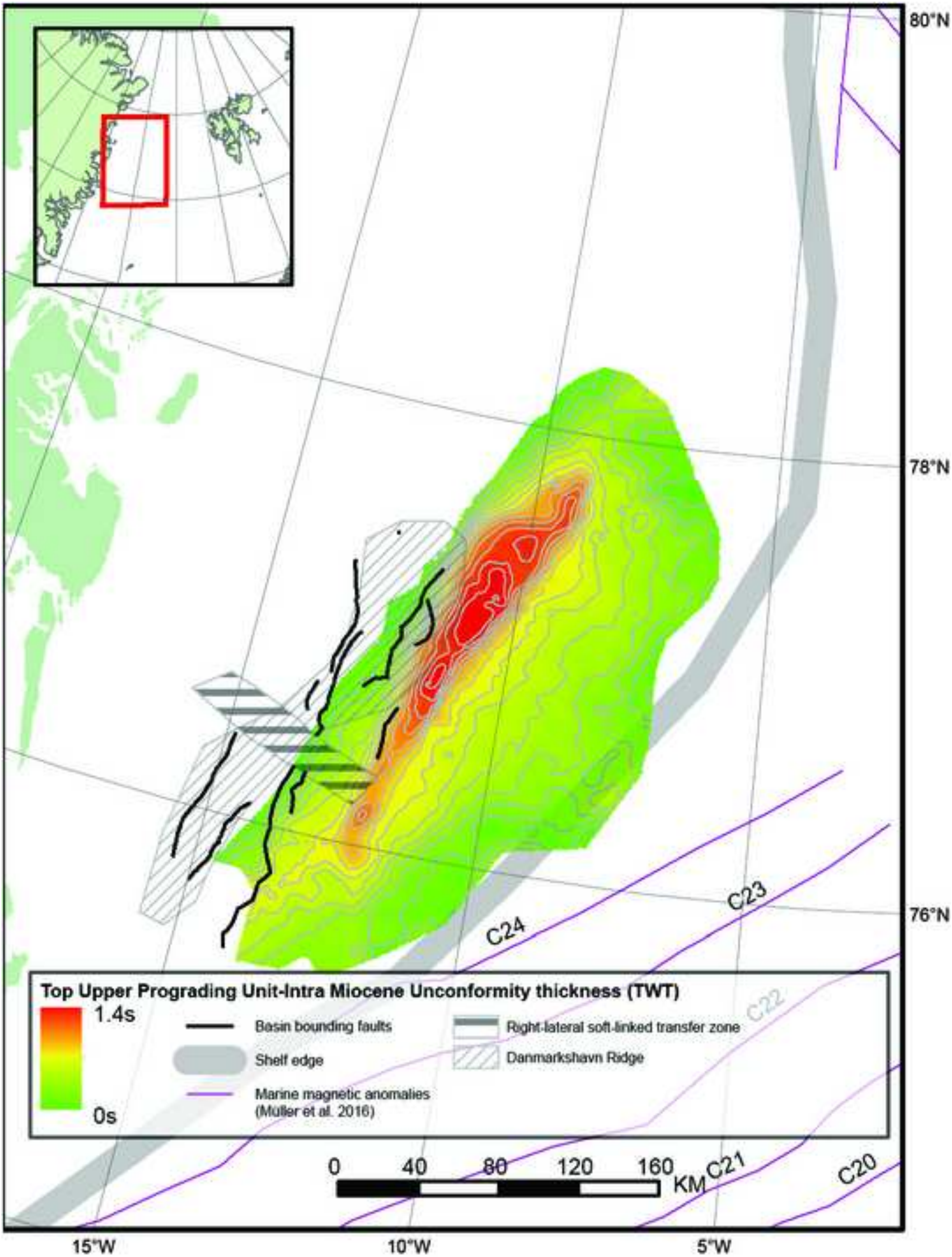

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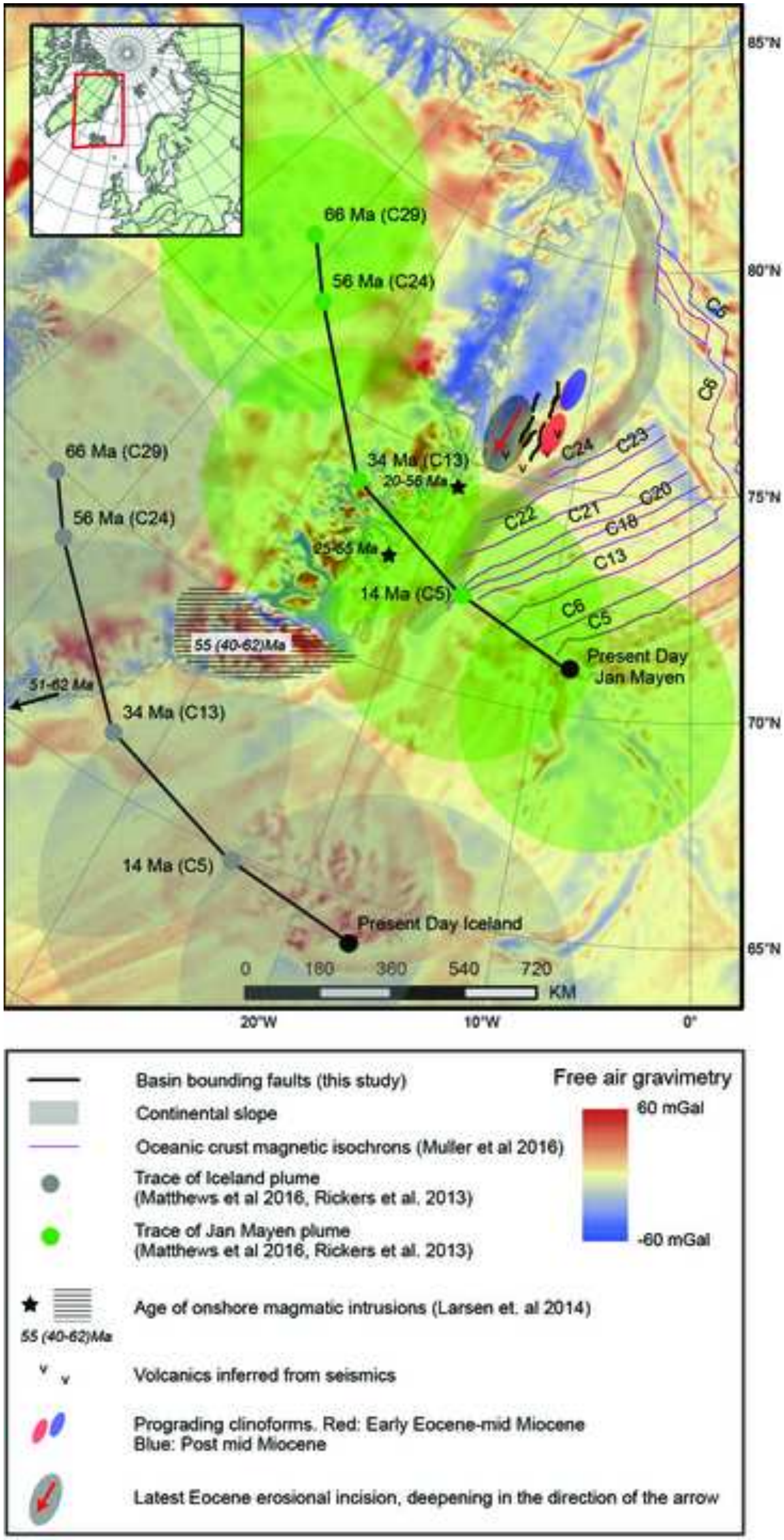

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