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The Davis Strait proto-microcontinent: The role of plate tectonic reorganization in continental cleaving

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ABSTRACT

A prolonged period of rifting and seafloor spreading between Greenland and North America formed the Labrador Sea and Baffin Bay oceanic basins, connected by the Davis Strait. However, disagreement exists regarding the exact plate motions between Greenland and Canada, as well as the tectonic evolution of the Davis Strait, with previous models unable to explain the origin of anomalously thick continental crust within the seaway. Here, we present a new plate tectonic reconstruction of Greenland's separation from Canada, constrained by a new comprehensive set of mid-ocean ridge (MOR) and transform fault lineaments identified using free-air, vertical gradient, and filtered directional gradient maps from the Sandwell and Smith gravity data. Furthermore, the reinterpretation of seismic reflection data offshore West Greenland, along with a newly compiled crustal thickness model, identifies an isolated terrane of relatively thick (19–24 km) continental crust that was separated from Greenland during a newly recognised phase of E-W extension along West Greenland's margin. We interpret this continental block as an incompletely rifted microcontinent, which we term the Davis Strait proto-microcontinent. Our reconstruction suggests release of the proto-microcontinent coincided with a change in the spreading orientation from $\sim$ 58 to 49 Myr during the alignment of Canada and Greenland's rifted margins, indicating a fundamental control of lithospheric structure on plate motions. Proto-microcontinent separation was induced by transpression along a newly recognised NE-SW trending transform margin that joined the Labrador Sea and Baffin Bay, prior to development of the Ungava Fracture Zone (UFZ). The location of this transform margin is constrained using our crustal thickness model, which demonstrates a sharp NE-SW trending continent-ocean transition across the northern Saglek basin. We term this newly identified first-order tectonic feature the Pre-Ungava Transform Margin (Pre-UTM), which accommodated early NE-SW motion between Greenland and Canada. Our identified mechanism of microcontinent formation may be widely applicable to other microcontinents around the globe, and further study is merited to understand the role of plate motion changes and transpression in microcontinent calving.

1. Introduction

Microcontinents are defined as isolated fragments of rifted continental crust and lithosphere displaced from their original continent and surrounded by oceanic crust (Scrutton, 1976; Peron-Pinvidic and Manatschal, 2010; van den Broek and Gaina, 2020). Numerous studies have demonstrated the potential for rifting and passive margin development to be associated with microcontinent formation (Torsvik et al., 2013, 2015; Whittaker et al., 2016; Schiffer et al., 2018). However, our understanding of the conditions necessary for continental rifting and associated microcontinent formation remains incomplete. Mechanisms such as plume-induced thermal weakening (Müller et al., 2001), plate tectonic reorganisation (Whittaker et al., 2016), and the exploitation of heterogeneous structural weaknesses, which could include magmatic underplating (Yamasaki and Gernigon, 2010) and fossil suture zones (Schiffer et al., 2018), have all been proposed as key to the development of microcontinents. In light of this ambiguity, new microcontinents are still being discovered to this day (e.g. Icelandia, Foulger et al., 2020). Through well constrained tectonic modelling, as well as the re-examination of seismic reflection data and crustal thickness inversions, we investigate the formation of a proposed proto-microcontinent (i.e. a microcontinent that did not achieve full crustal separation) within the Davis Strait.

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The Labrador Sea, a 900 km wide oceanic basin, joins the 500 km wide Baffin Bay basin through the shallower Davis Strait seaway (Fig. 1). This region formed during Mesozoic to Cenozoic divergence between Greenland and Canada (Roest and Srivastava, 1989; Chian et al., 1995; Chalmers and Pulvertaft, 2001; Wilson et al., 2006; Oakey and Chalmers, 2012; Hosseinpour et al., 2013; Abdelmalak et al., 2018). Initial extension of the Labrador Sea and Baffin Bay began as early as the Late Triassic (223 Myr) and continued until continental breakup, with intermittent periods of thermal subsidence occurring from 130 to 120 Myr and from 100 Myr to 80 Myr (Chalmers and Pulvertaft, 2001; Larsen et al., 2009). Subsequent continental breakup and oblique NE-SW orientated seafloor spreading began first in the Labrador Sea, with the oldest undisputed seafloor spreading magnetic anomaly being chron 27 (62.2 Myr, magnetic anomaly ages from Ogg, 2020) (Chalmers, 1991; Oakey and Chalmers, 2012). However, other studies propose either chron 31 (68.3 Myr) (Roest and Srivastava, 1989; Keen et al., 2017) or between chrons 31 (68.3 Myr) and 27 (62.2 Myr) (Chian et al., 1995) as the oldest anomalies in the basin. Seafloor spreading later propagated into Baffin Bay during chron 26 (58.9 Myr) (Hosseinpour et al., 2013). Although, true oceanic spreading is thought to have never occurred in the Davis Strait (Funck et al., 2012; Suckro et al., 2013), which instead formed a transfer zone between the Labrador Sea and Baffin Bay, characterised by relatively large crustal thicknesses of up to 30 km (Welford and Hall, 2013). Between chrons 25 (57.1 Myr) and 24 (52.6 Myr), a reorientation of the spreading axes occurred, resulting in the anticlockwise rotation of Greenland and a ~ 50° change in the spreading azimuth (Müller et al., 2019), subsequently leading to N-S extension (Roest and Srivastava, 1989). This event also coincided with the onset of seafloor spreading in the North Atlantic, leaving Greenland to move independently (Roest and Srivastava, 1989; Oakey and Chalmers, 2012). Finally, oceanic spreading ceased at chron 13 (33.1 Myr), joining Greenland to the North American plate (Oakey and Chalmers, 2012; Welford and Hall, 2013; Welford et al., 2018). This termination in extension

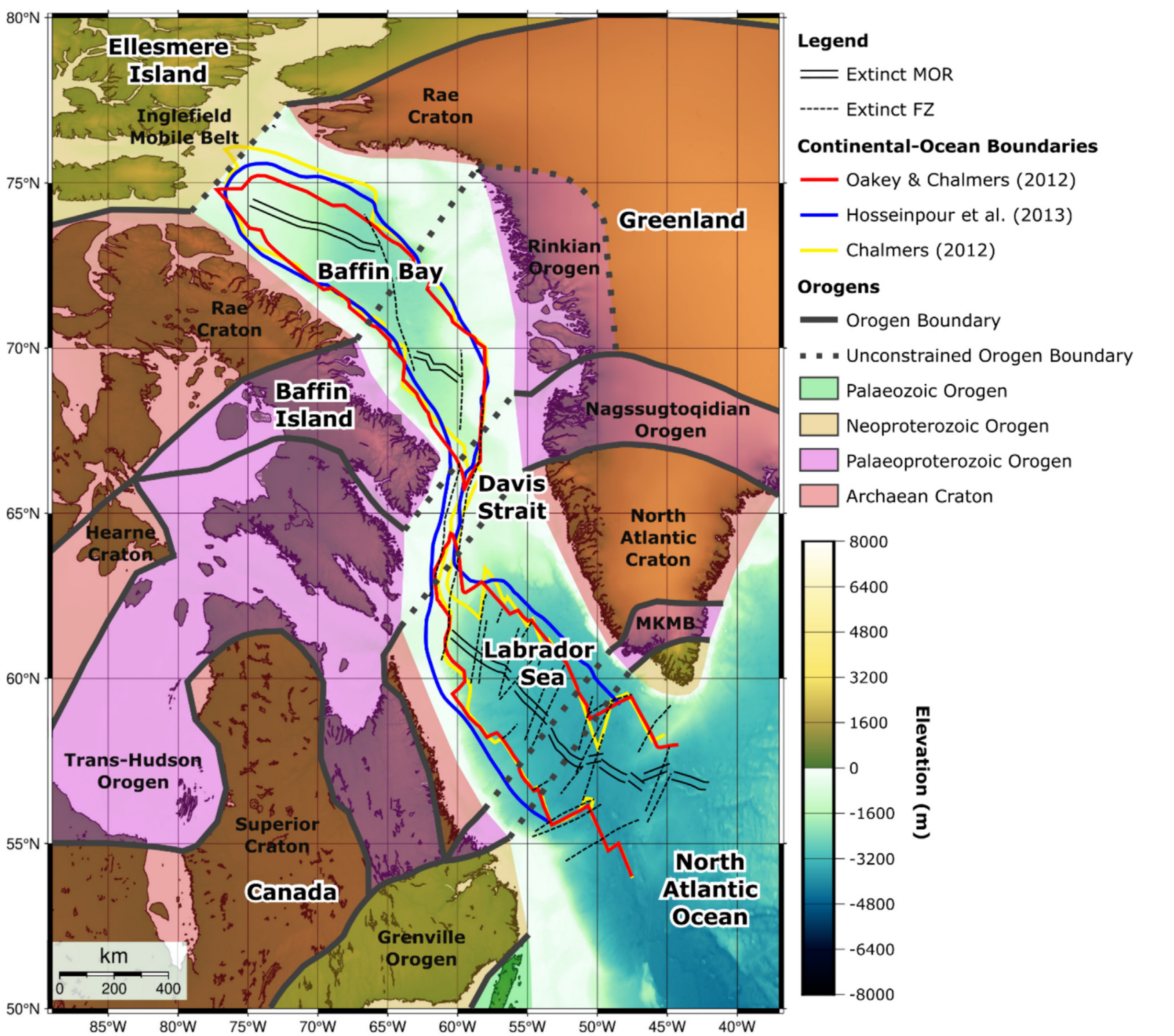

Fig. 1. Bathymetry map of the Northwest Atlantic (Smith and Sandwell, 1997). Overlain is a tectonic overview of the major terranes, continental blocks, and cratons colour coded by age (Schiffer et al., 2022). The extinct MORs and FZs are georeferenced from Abdelmalak et al. (2018). Previous interpretations of continental-ocean boundaries are also displayed.

also led to a 30° clockwise change in the spreading vector between Eurasia and Greenland, coinciding with breakup between Greenland and the Jan Mayen Microcontinent (Doré et al., 2016; Schiffer et al., 2018).

The Davis Strait is identified as a submerged bathymetric high, although the nature of its crust and mantle lithosphere is debated. Keen and Barrett (1972) initially suggested the Davis Strait was composed of overthickened oceanic crust comparable to the thick crust along the Greenland-Iceland-Faeroes Ridge (e.g. Karson, 2016). Later, Keen et al. (1974) proposed the thick crust beneath the Davis Strait was the result of plume related igneous rocks mixed with fragments of continental crust. Alternatively, more recent studies based on seabed sampling (Dalhoff et al., 2006) and seismic refraction data (Suckro et al., 2012) have argued for predominantly continental affinity with some interpreting a strip of igneous material surrounding the Ungava Fracture Zone (UFZ) (Funck et al., 2007, 2012). The UFZ is a key feature in the Davis Strait and accommodated strike-slip motion between Greenland and North America from at least the Early Eocene. It has previously been interpreted as a leaky transform fault with upwelling melt producing a 100 km wide strip of igneous material surrounding it (Funck et al., 2007, 2012), however, plate tectonic reconstructions of the UFZ suggest a transpressional tectonic regime during the Paleocene (Hosseinpour et al., 2013; Oakey and Chalmers, 2012). Furthermore, previous concepts of the Davis Strait evolution have inferred that lithospheric inheritance may strongly control the evolution of the region (Peace et al., 2017; Schiffer et al., 2020), while modelling has shown ancient mantle scarring (Heron et al., 2019) or a segmented zone of transform faults could have controlled the formation of the Davis Strait (Farangitakis et al., 2020). Therefore, knowledge of the crustal structure and thicknesses within the Davis Strait are an important constraint on tectonic models of the Greenland-Canada separation.

Although reconstructions of continental breakup and subsequent seafloor spreading in the North Atlantic are becoming increasingly accurate, there remains discrepancy regarding: (1) the precise plate motions between Greenland and Canada, (2) the exact timing of continental rifting and seafloor spreading in the Labrador Sea and Baffin Bay, and (3) the tectonic evolution and crustal composition of the Davis Strait. In this paper, we present a comprehensive plate tectonic reconstruction that furthers our understanding of the Northwest Atlantic spreading kinematics, as well as the evolution of the Davis Strait. First, we identified gravity lineaments associated with mid-ocean ridges (MORs) and oceanic fracture zones (FZs) from free-air gravity, vertical gravity gradient, and filtered free-air gradient maps. These spreading-related features were then further examined in the context of seismic reflection and crustal thickness inversions offshore West Greenland.

Our tectonic model details the precise motion between Greenland and Canada following their breakup and explains the temporal and spatial patterns of normal and thrust faulting in the Davis Strait, as well as the presence of anomalously thick crust offshore West Greenland, which we interpret as a proto-microcontinent. Furthermore, our model suggests an analogous and predictable mechanism may be applicable to the formation of microcontinents and proto-microcontinents around the globe.

2. Methods

In this study, the distribution and orientation of FZs and extinct MORs were identified from gravity data and then used to construct a plate tectonic reconstruction of the Labrador Sea, Davis Strait, and Baffin Bay. Additionally, crustal thickness inversions and seismic reflection data within the Davis Strait were used to further constrain our tectonic model.

2.1. Gravity data and processing

The Sandwell and Smith gravity model (version 31.1) was used due to its high accuracy of ~ 2 mGal (Sandwell et al., 2014) following the addition of retracked CryoSat-2 and Jason-1 satellite altimetry data. This enhancement enables the detection of additional buried structures, specifically MOR segments and FZs due to the related lateral density contrasts between the sediment, crust, and mantle. Alongside the direct interpretation of the free-air gravity anomaly and vertical gravity gradient data, gaussian band-pass filters and directional derivatives were also employed to emphasize FZ and MOR structures.

Firstly, a gaussian band-pass filter was used to remove short (<50 km) and long (>100 km) wavelengths most likely relating to shallow density contrasts (e.g. seabed canyons) and deep crustal or mantle features, respectively, which are not of interest in this study. It was determined that wavelengths of 50–80 km (as suggested by Phethean et al., 2016) best highlighted FZs, although, wavelengths of 80–100 km improved MOR expression and aided in their interpretation (Fig. 2c).

After filtering, directional derivatives were applied to emphasize gravity lineaments related to linear MORs and FZs. To interpret structures with a high level of accuracy, directional derivative maps were created every 10° to cover all possible structural orientations within the basin (i.e. 0° to 180°; see supplementary Figure S1). Our generated directional derivative maps therefore emphasize structures of all orientations, allowing the effective interpretation of spreading related kinematic indicators of the basin, including previously interpreted MOR orientations between 70° and 130°, and FZ orientations of ~ 15° and ~ 60° (Abdelmalak et al., 2018). In our results, we display representative directional derivative figures with orientations of 180° and 90°, which best display MORs and FZs, respectively (Fig. 3a and Fig. 3c). Total horizontal derivative maps were also generated to aid in the interpretation of non-linear structures.

2.2. Gravity lineament analysis

Extinct MOR segments and FZs were then interpreted from the free-air, vertical gravity gradient, and filtered horizontal gravity gradient maps. For consistent interpretation of MOR and FZ segments, a set of characteristics used to distinguish the MORs and FZs was first defined.

2.2.1. MOR identification

Within passive margin bounded oceans, MORs are generally located along the basin's approximate centre of symmetry and are orientated roughly perpendicular to the final spreading direction. Furthermore, when visualized in gravity data these linear anomalies appear as free-air gravity lows thought to result from a low-density gabbroic root within the mantle (Jonas et al., 1991). Extinct MOR segments in the Labrador Sea and Davis Strait were therefore identified as: (1) large amplitude, linear free-air gravity lows; (2) orientated approximately E-W and perpendicular to the final spreading direction of the basin (Fig. 2; Abdelmalak et al., 2018); and (3) located near the Labrador Sea and Baffin Bay's axis of symmetry.

2.2.2. FZ and fault identification

Firstly, we define FZs as inactive oceanic transform faults (e.g. Lorenzo, 1997; Mercier de Lépinay et al., 2016), across which significant lateral displacement has occurred due to the strike-slip motion between two tectonic plates. FZs can be linear or curving, as they develop perpendicular to spreading/rotating MORs and parallel to past plate motions (Bellahsen et al., 2013). Across FZs, the age and depth of the oceanic lithosphere varies creating a dis-

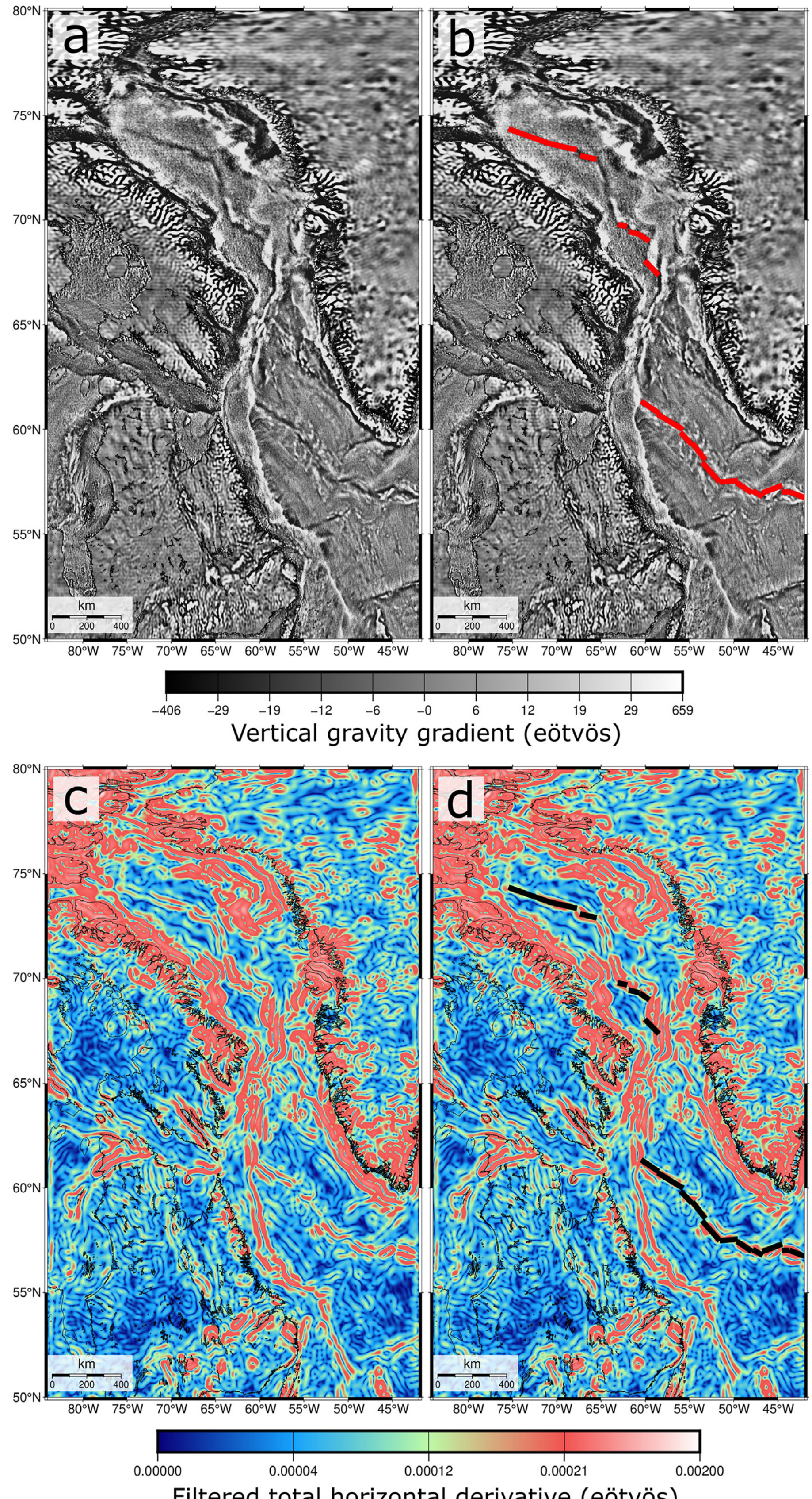

Fig. 2. (a) Uninterpreted vertical gravity gradient. (b) Vertical gravity gradient overlain with our interpreted MOR segments (red lines). (c) Uninterpreted horizontal derivative of a 100–80 km band-pass filtered free-air gravity gradient. (d) Horizontal derivative of a 100–80 km band-pass filtered free-air gravity gradient overlain with our interpreted Eocene MOR segments (black lines).

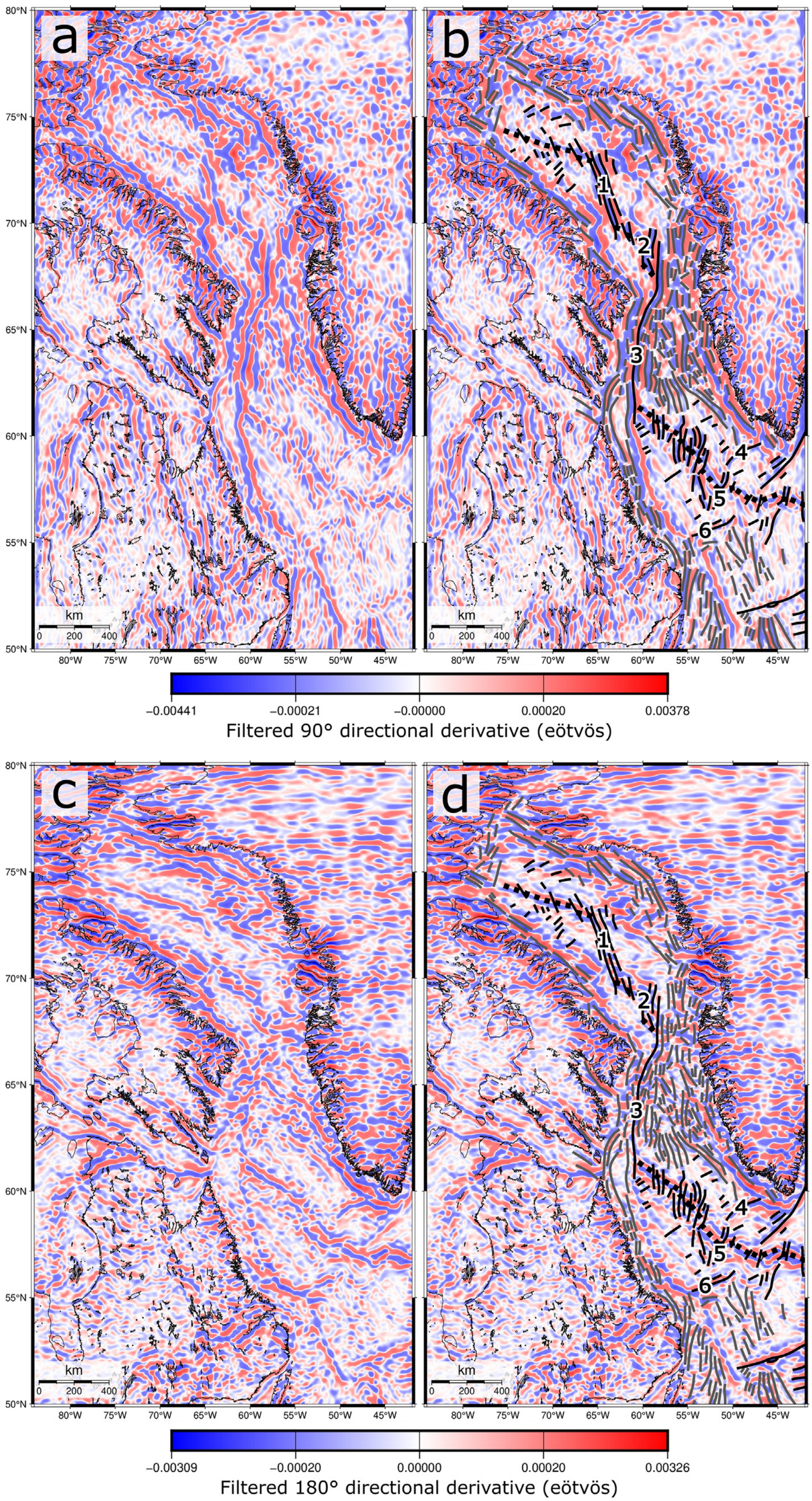

Fig. 3. (a) Uninterpreted 90° directional derivative of an 80–50 km gaussian band-pass filtered free-air anomaly. (b) 90° directional derivative of an 80–50 km gaussian band-pass filtered free-air anomaly overlain with our interpreted MOR segments (dotted black lines), FZs (black lines), and normal and thrust faults (grey lines). (c) Uninterpreted 180° directional derivative of an 80–50 km gaussian band-pass filtered free-air anomaly. (d) 180° directional derivative of an 80–50 km gaussian band-pass filtered free-air anomaly overlain with our interpreted MOR segments, FZs, and normal and thrust faults. 1 – 64°W Fracture Zone; 2 – 60°W Fracture Zone; 3 – UFZ; 4 – Julian Haab Fracture Zone; 5 – Minna Fracture Zone; 6 – Cartwright Fracture Zone.

tinct bathymetric anomaly. Bathymetric anomalies across FZs may also result from deviations in crustal thickness due to transpression or transtension (Menard and Atwater, 1969), melt supply (Blackman and Forsyth, 1991; Gente et al., 1995) or thermal contractions (Collette, 1974). However, as oceanic crust within the Labrador Sea and Baffin Bay is covered by up to 12 km of sediment, bathymetric irregularities are not directly identifiable (Chalmers and Pulvertaft, 2001). Nonetheless, as the density contrasts between crust and sediment are still preserved across the original bathymetry, we are able to detect associated FZs in the gravity data. These FZs are characterised by continuous gravity anomalies that are generally lower in amplitude than MOR segments and trend parallel to paleo-spreading directions. These lineaments were largely identified from the filtered horizontal derivative and filtered directional derivative data as linear minima, maxima or null anomalies (Fig. 3), or as gravity lows and highs within the free-air gravity anomaly (Fig. 4).

Large scale normal and thrust faults relating to regional extension and compressional events were also mapped. These faults share identifiable characteristics with FZs but are typically orientated parallel to the MORs and are located near the edges of basins within rifted continental crust. Lastly, to avoid distortions caused by continental shelf edge effects in the gravity data, no interpretations were made along gravity anomalies that ran parallel and overlapped with the continental shelf edge.

2.3. Seismic reflection data

We also reinterpret seismic reflection data from the Spectrum West Greenland 2012 Repro survey (originally presented in Peace et al., 2017) and combine this with existing literature interpretations of seismic reflection data to further understand the age and extent of tectonic events that occurred during the basin's development (Fig. 5c). We place specific emphasis on the interpretation of post-breakup structures in the East Davis Strait, bounding the Davis Strait crustal high, as these are most relevant to understanding the evolution of the region and the Davis Strait crustal anomaly. The timing of normal and reverse faulting, as well as folding events, were also established based on the ages of the uppermost deformed strata as determined from the Ikermiut-1 and Quelleq-1 wells. Seismic interpretations were then contextualised within our plate kinematic model to understand the tectonic drivers of

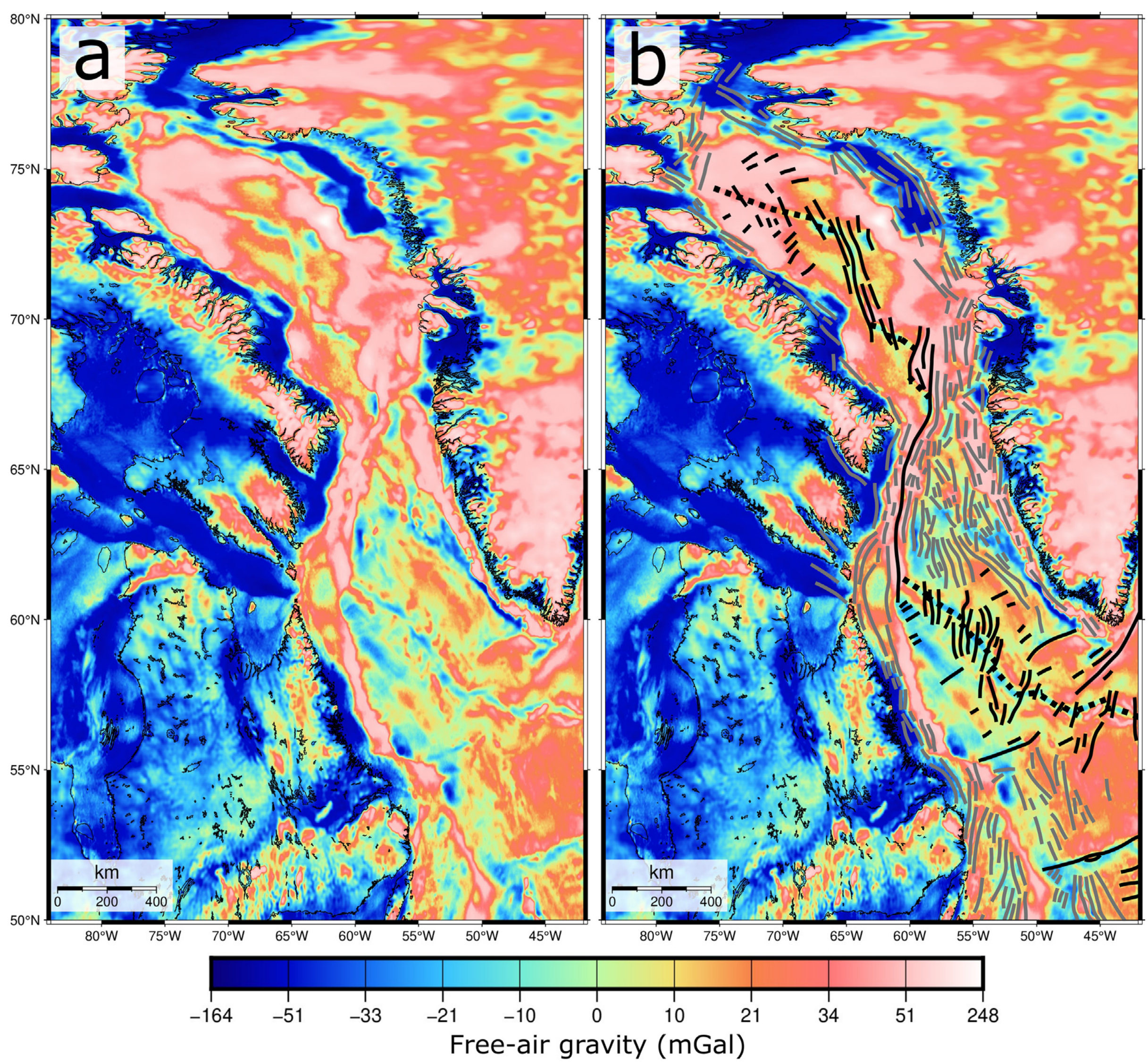

Fig. 4. (a) Uninterpreted free-air gravity anomaly. (b) Free-air gravity anomaly overlain with our interpreted MOR segments (dotted black lines), FZs (black lines), as well as our normal and thrust faults (grey lines).

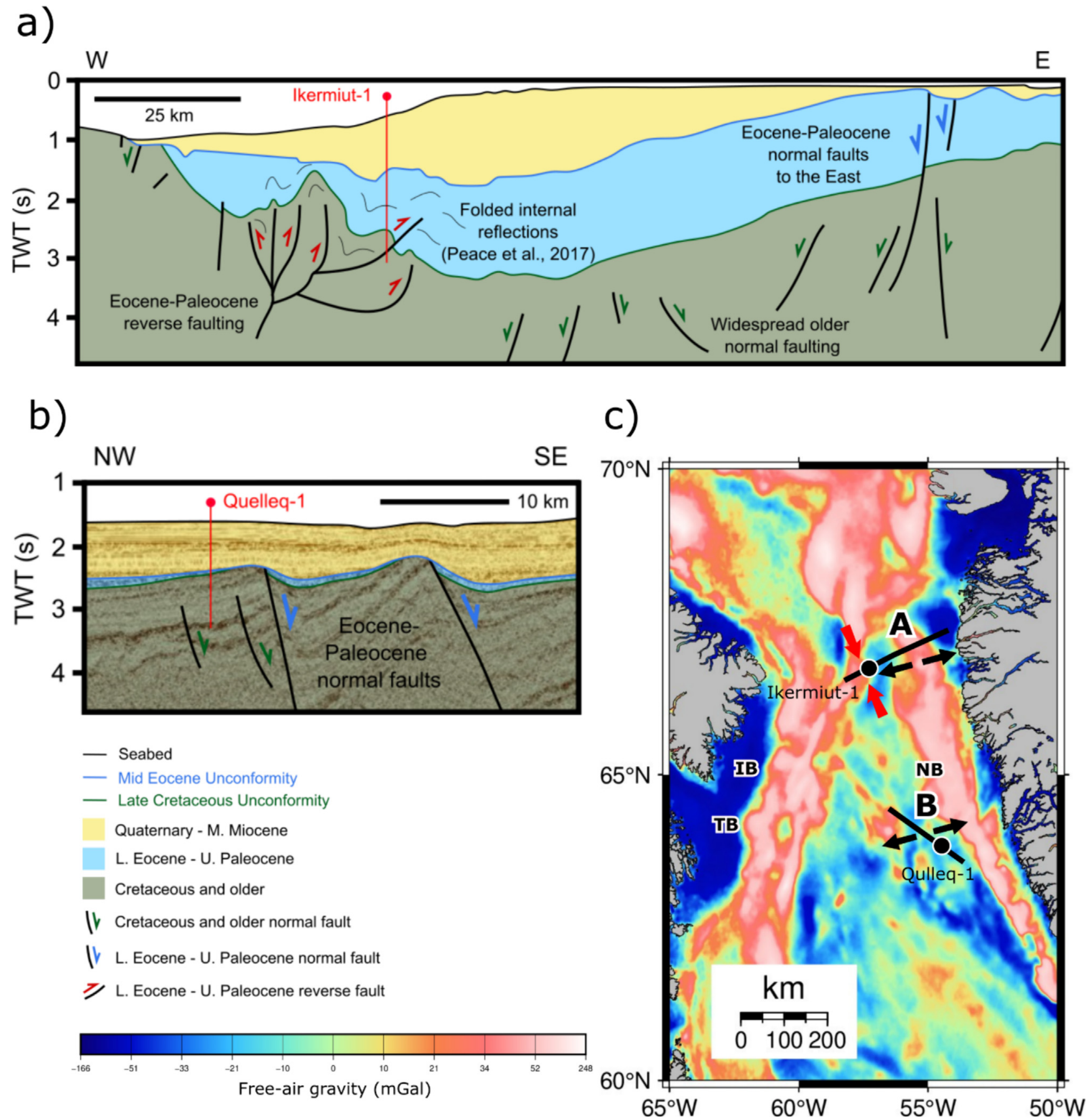

Fig. 5. Seismic reflection interpretations along the West Greenland margin. (a) E-W trending seismic reflection interpretation redrawn from Japsen et al. (2010). Internal seismic reflection structures are taken from a related interpretation from Peace et al. (2017). Cretaceous and older normal faulting is widespread along the seismic profile, whilst Eocene-Paleocene normal faulting is only prevalent in the East Davis Strait, and compressional structures are limited to the north of the basin. (b) NW-SE trending seismic reflection profile redrawn from Peace et al. (2017). Again, Eocene-Paleocene normal faulting can be seen along the East Davis Strait, although the full spatial and temporal extent of faulting is unseen due to erosion along the Middle Eocene Unconformity. (c) Free-air gravity map showing seismic interpretation locations and interpreted Eocene-Paleocene tectonic setting. IB – Imaqpik Basin. NB – Nuuk Basin. TB – Tariut Basin.

deformation events and the formation of the Davis Strait crustal high.

2.4. Crustal thickness modelling

Over time, the Northwest Atlantic region has been the subject of various crustal-scale geophysical studies. These primarily seismic based investigations (offshore with some limited onshore studies) in the Northwest Atlantic region have been incorporated in two gravity-Moho depth models offshore (Welford and Hall, 2013; Welford et al., 2018), as well as a compilation for the entire Arctic region (Lebedeva-Ivanova et al., 2019). Schiffer et al. (2022) have previously presented a region-wide crustal model by combining these three previous models. Here, we present a new model of the thickness of the crystalline crust, into which we have incorporated new results from receiver function inversions by Schiffer et al. (2022). Specifically, we assigned the estimated crystalline crustal thickness value to circular areas of 15 km around each station. The resulting model was then smoothed over a circular running window with a 30 km radius for the onshore areas. The smoothing-radius dropped across the continental shelf, so that no additional smoothing is applied in the marine areas and marine crustal thickness models are retained in their original form. By doing this, two models with different spatial resolutions are applied onshore and offshore with a smooth transition along the continental shelves and margins. Compared to Schiffer et al. (2022), the new receiver function data particularly updates the crustal thickness estimates in the coastal areas, where previously larger values were estimated, aiding our interpretation of continental blocks in the Davis Strait. Other considerable updates for the new model include up to 4 km thicker crust along the south of Baffin Island, up to 6 km thinner crust across northern Baffin Island, up to 6 km thinner crust in the central and north-westernmost North Atlantic Craton, and up to 4 km thicker crust in the south-westernmost Nagssugtoqidian (Fig. 1), thereby updating the crustal expression of the suture between both terranes in this area. Despite updated onshore crustal thicknesses, the biggest effect is a sharpening of the crustal thickness gradients across the continental shelf in areas where new receiver function data was added.

2.5. Plate kinematic reconstruction

After the locality of all observable FZs and MORs were identified, GPlates was loaded with coastline polygons (i.e. geometric shapes representing the outlines of coastal areas) and rotations from an established global plate kinematic model (Seton et al., 2012). The Seton et al. (2012) model was chosen as it accurately records the paleolocations of North America, Baffin Island, and Ellesmere Island, whilst leaving the spreading vector between North America and Greenland free to be edited with our new feature dataset. Next, synthetic flowlines were positioned at approximately 300 km intervals along the MOR, and where possible close to identified FZs, to track modelled plate motions. Plate rotations were then altered to align synthetic flowlines with the general trend of FZs interpreted from the gravity data. Changes were made to Greenland's plate motions at: 118 Myr, representing the start of significant extension (Roest and Srivastava, 1989; Seton et al., 2012); 61.27 Myr, the onset of NE-SW orientated seafloor spreading (Oakey and Chalmers, 2012; Chalmers, 1991); 55.9 and 53.3 Myr, relating to regional tectonic reorganisation of the region; 47.9 Myr reflecting the onset of N-S seafloor spreading; and 33.1 Myr, which marks the cessation of seafloor spreading (Müller et al., 2019). Subsequently, based on our interpretations derived from the crustal thickness inversions, we digitised any continental blocks that were displaced from their original continent as polygons, and utilizing our observations of extension and contraction from the seismic reflection data, we reconstructed them back to their original continent.

3. Results

The accurate interpretation of extinct MORs and FZs have allowed us to constrain a new high-resolution plate kinematic model using a unique set of best fit Euler rotation poles for the motion of Greenland relative to North America. Crustal thickness inversions within the Davis Strait have also been constructed to provide a new insight into the paleolocation of a rifted continental block, whilst seismic reflection interpretations further constrained the ages and locations of extensional, compressional, and strike-slip tectonics.

3.1. MOR segment trends

MOR segments have been identified from the Sandwell and Smith gravity model in both the Labrador Sea and Baffin Bay, with no segments recognized in the Davis Strait (Fig. 2). Whilst NW-SE trending coastline geometries along the Labrador Sea and Baffin Bay suggest NW-SE trending MOR segments may be present, the N-S orientation of younger FZs situated close to the centre of the Labrador Sea and Baffin Bay instead infers E-W trending MOR segments are likely. Overall, both trends are recognised with MOR segments orientated between 70° and 125° in the Labrador Sea, and similarly around 115° in Baffin Bay. Identified MOR segments range in length from 40 to 260 km long, with generally small (∼15 km) transform offsets separating them. The dominance of relatively high angle, non-E-W trending MOR segments, despite the apparent N-S final orientation of FZs, may also indicate a late-

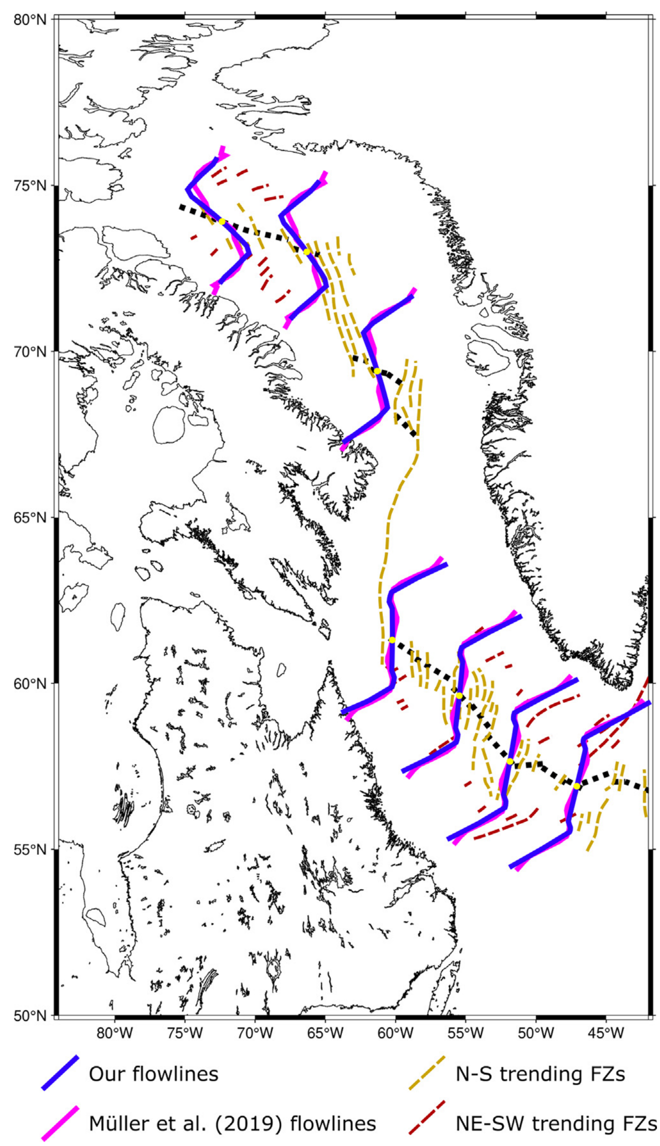

Fig. 6. Our new reconstructed flowlines compared with flowlines from Müller et al. (2019). Flowlines are approximately 300 km apart and are centred along our interpreted MOR (dotted line) where their origin is represented by a yellow dot. Our interpreted N-S orientated Eocene FZs and NE-SW orientated Paleocene FZs were used to constrain our flowlines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stage kinematic change and basin reorganisation shortly before the cessation of spreading.

3.2. FZ distribution and orientations

Overall, two distinct sets of FZs have been recognised (Fig. 6), exhibiting contrasting orientations and distances from the MOR. Ridge proximal Eocene FZs were found to be N-S trending, whilst Paleocene FZs trend NE-SW and are present along the outer portions of the basin. Both sets of FZs were mapped and subsequently used to constrain our plate tectonic reconstruction. Faults formed during extension and compression of the region have also been identified (Figs. 3 and 4, grey lines), although, their nature cannot be directly assessed from the gravity data alone they likely comprise both normal and thrust faults.

3.2.1. N-S trending FZs

Near to the identified MOR, N-S orientated FZs were observed (Fig. 6, dark yellow dashed lines), commonly resulting in displacement of the ridge itself. These FZs exhibit distinct relative lows in the free-air gravity reaching up to 50 mGal compared to the surrounding regions, although, their presence is most apparent using filtered horizontal and directional derivatives, which highlight the feature edges. The N-S trending FZs are orientated around 5° in the Labrador Sea and 350° in Baffin Bay. Typically, these FZs range from 35 to 410 km long, except for the UFZ, which is 850 km long and joins the spreading ridges of the Labrador Sea and Baffin Bay. N-S trending FZs were also found to occur between the magnetic anomalies chron 24 (52.6 Myr) and 13 (33.1 Myr), implying that these FZs were active during the Eocene as transform faults (Chalmers and Pulvertaft, 2001; Oakey and Chalmers, 2012).

Interpreted N-S FZs within the Labrador Sea and Baffin Bay also display two distinct differences. Firstly, FZs in the Labrador Sea generally display a more NNE orientation, whilst FZs in Baffin Bay trend more NNW. This flip in FZ trends reflects the positions of the Labrador Sea and Baffin Bay relative to Greenland's pole of rotation. Secondly, FZs in the Labrador Sea exhibit a slight westerly curve north of the MOR and an easterly curve south of the MOR, with this characteristic being most obvious in the FZs located in the centre of the Labrador Sea. This curvature is not seen in Baffin Bay where the FZs are typically straighter and shorter, suggesting a different response of Baffin Bay's FZs to kinematic change compared to the Labrador Sea, possibly related to spreading rate.

3.2.2. NE-SW trending FZs

NE-SW orientated FZs form a landward continuation of the N-S trending FZs (Fig. 6, red dashed lines) and are orientated between 40° and 75°. Due to increased sediment thickness towards the coastline, these FZs were most easily observed using total horizontal derivatives and directional derivatives, which enhance the detection of buried structures (Phethean et al., 2016). They range in length from 25 to 400 km, with generally shorter FZs in Baffin Bay compared to the Labrador Sea. However, this could be the result of poorer structural imaging in Baffin Bay caused by greater sediment thickness and/or sea ice cover, limiting interpretations of continuous FZs. Additionally, these FZs are located between the magnetic anomalies chron 27 (62.2 Myr) and 24 (52.6 Myr), suggesting they were active during the Paleocene (Chalmers and Pulvertaft, 2001), consequently reflecting the extensional direction following breakup. It should also be noted that any transform continental margins formed during rifting and breakup would, therefore, also have a NE-SW orientation parallel to these early FZs.

3.2.3. Normal and thrust faults

Normal faults form approximately perpendicular to extension during rifting events and occur along the continental margin flanks, whilst thrust faulting due to transpression has previously been interpreted to occur within the Davis Strait, having developed following the change in spreading direction (Sørensen, 2006; Oakey and Chalmers, 2012; Peace et al., 2017). Normal and reverse faults range from 20 to 400 km in length and are typically parallel to coastlines and MOR segments, where they share similar definable characteristics to previously interpreted FZs (Fig. 4, grey lines). Normal faults are usually found bordering the Labrador Sea and Baffin Bay within block faulted continental crust and transition zones (Oakey and Chalmers, 2012). However, in the Davis Strait, notably to the east of the UFZ, there is a greater concentration of observed fault structures, attributable to either normal or reverse faulting.

3.3. Seismic reflection interpretations

Offshore West Greenland and east of the UFZ, two key seismic reflection lines (presented by Peace et al., 2017, and Japsen et al., 2010) have been re-examined with an emphasis on the age, type, and location of faulting (Fig. 5). Overall, three different fault categories relating to different tectonic regimes were identified: (1) Extensive normal faulting older than ~ 58 Myr, related to initial rifting, (2) a previously unrecognised and elusive phase of normal faulting from ~ 58 to 49 Myr, related to a post-breakup phase of extension along sections of the West Greenland margin, and (3) reverse faulting and folding from ~ 58 to 49 Myr restricted to the NE Davis Strait.

The most prevalent faults identified were normal faults dated to be older than ~ 58 Myr, which do not cut the Late Cretaceous Unconformity (dated at ~ 58 Myr; Sørensen, 2006). These syn-rift faults are roughly N-S orientated and terminate at or below the basinwide Late Cretaceous Unconformity. Faults of this age are located throughout the eastern Davis Strait, frequently offset the basement horizon, and are generally shorter than the other two categories of faults. These faults coincide with initial rifting and extension of the region before seafloor spreading initiated at 62.2 Myr (Chalmers, 1991; Oakey and Chalmers, 2012).

A second set of N-S orientated syn-rift normal faults are interpreted to be active between ~ 58 and ~ 49 Myr (or younger) and are observed to the east of the Ikermiut-1 and Quelleq-1 wells (Fig. 5b and 6c). These faults are generally longer than pre-~58 Myr normal faults and cut Lower Eocene to Upper Paleocene sediments, indicating a late extensional reactivation event. These faults and their host sedimentary sequences have been severely eroded by the ~ 49 Myr Middle Eocene Unconformity, making the full spatial and temporal extent of this faulting event undeterminable. Nonetheless, as Lower Eocene stratigraphy is significantly offset by these faults (e.g. Fig. 5a) a significant period of post breakup extensional deformation can be inferred along the inboard West Greenland margin at this time (i.e. between the continent-ocean boundary and the coastline).

The final set of faults identified here are offset reverse thrust faults and are restricted to the NE Davis Strait. These NE-SW trending faults are spatially parallel to large-scale folds which formed contemporaneously with the reverse faulting. These faults and folds also deform Lower Eocene to Upper Paleocene stratigraphy, making them approximately coeval to the late extensional reactivation noted above. The dating of both late extensional reactivation and compressional faulting regimes overlaps with the change in the basin's spreading orientation at ~ 56 to 48 Myr.

3.4. Crustal thickness interpretation

Using new results from receiver function inversions (Schiffer et al., 2022) an updated region-wide crustal thickness model has been produced (Fig. 7) to locate regions of relatively thick conti-

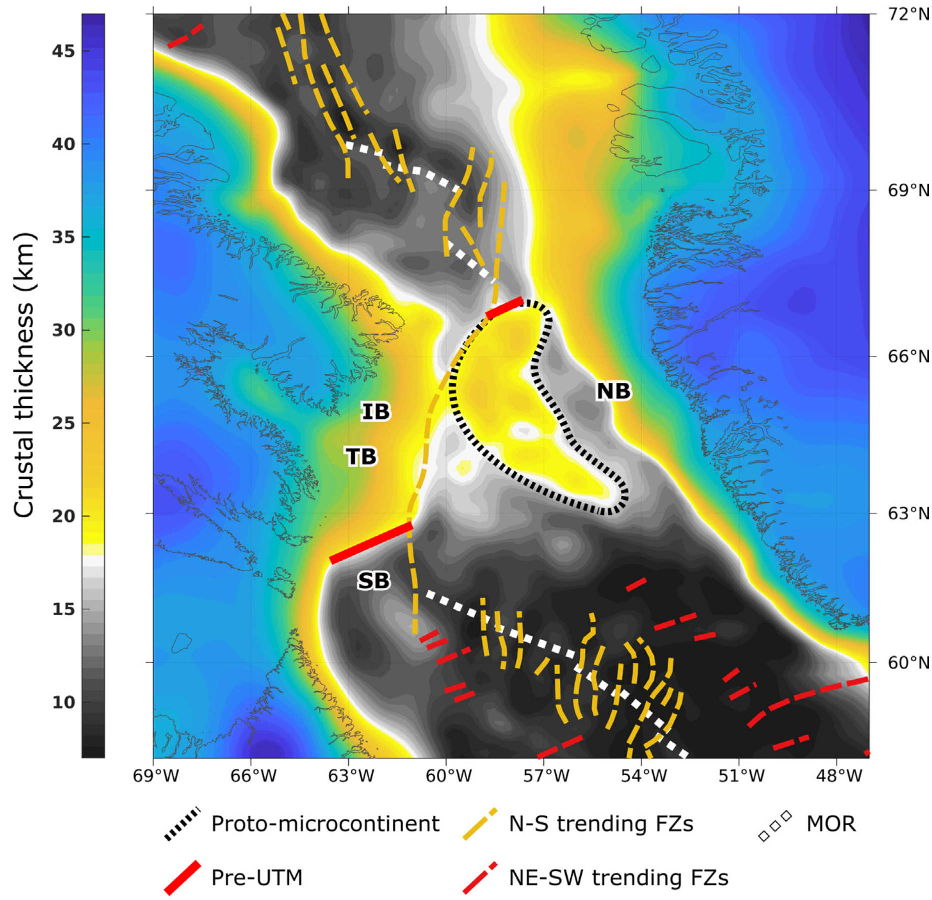

Fig. 7. Crustal thickness inversion overlain with our proposed extent of the Davis Strait proto-microcontinent, our interpreted continent-ocean boundary representing the Pre-UTM, MORs, N-S orientated Eocene FZs, and NE-SW orientated Paleocene FZs. IB – Imaqpik Basin. NB – Nuuk Basin. SB – Saglek Basin. TB – Tariut Basin.

nental crust associated with isolated blocks of rifted continent. To aid in highlighting thicker continental material from thinner oceanic crust, the colour bar was adjusted so crustal thicknesses of 18 to 26 km appear in shades of yellow, corresponding to thinned continental crust or overthickened igneous crust. Additionally, shades of green and blue (>26 km thick) correspond to thick, unrifted continental crust, whilst light grey colours (8–17 km) cover a range more commonly associated with thickened oceanic crust or highly thinned continental crust.

Our compiled crustal model of the Northwest Atlantic region shows a relatively thick (19–24 km) terrane in the Davis Strait (Fig. 7, black dotted line) surrounded by two corridors of generally thinner crust (15–17 km), separating it from mainland Greenland and Baffin Island. Although it has previously been inferred that this thickened crust may be a result from excess magmatism (Keen and Barrett, 1972), we interpret this isolated region as thinned continental crust which is in line with previous wide angle reflection studies (Funck et al., 2007,2012; Suckro et al., 2012). Furthermore, additional continental material is also required in this region to overcome crustal thickness gaps in our plate tectonic reconstruction (see supplementary Figure S3).

3.5. Plate tectonic reconstruction

Using our new interpretation of FZ and MOR lineaments, we modified the Seton et al. (2012) flowlines to develop a new plate tectonic reconstruction for the separation of Greenland from North American (Fig. 8). We also reconstructed our interpreted Davis Strait continental block (Fig. 7, black dotted line) back towards its pre-rift location along West Greenland.

Initial extension of the region began at 118 Myr (Fig. 8a) before continental breakup occurred at approximately 61.27 Myr in the Labrador Sea (Fig. 8b). Rifting and seafloor spreading both commence in a NE-SW orientation, where the significant offset between the axes of the Labrador Sea and Baffin Bay requires a NE-SW sinistral transform fault to link these basins through the developing Davis Strait. The presence of this transform fault, which we term the Pre-UTM, is supported by the observation of a linear NE-SW trending rapid transition between continental and oceanic domains along the northern Saglek Basin in crustal thickness data, (Fig. 7, thick red lines) consistent with a transform margin geometry, as well as plate kinematic arguments requiring a transform margin in this location to reconstruct continental crust back into the Saglek Basin and inboard of the Ungava Fracture Zone, where highly extended continental or oceanic crust is presently indicated. At 55.9 Myr, an anticlockwise rotation in the spreading orientation begins (Fig. 8c), and by 47.9 Myr the spreading azimuth has rotated $\sim 55^{\circ}$ to become approximately N-S orientated. Additionally, flowlines at this time are orientated roughly parallel to the UFZ (Fig. 8d). Subsequently, the anticlockwise movement of Greenland causes it to collide into Ellesmere Island leading to the Eurekan Orogeny and halting spreading by 33.1 Myr (Fig. 8e). It is also possible that during the final stages of spreading, the Eurekan Orogeny modified the plate vector of Greenland towards a more NE-SW orientation, resulting in a short-lived reorientation of MOR segments to trend NW-SE as observed in our MOR and FZ gravity interpretations (Fig. 6).

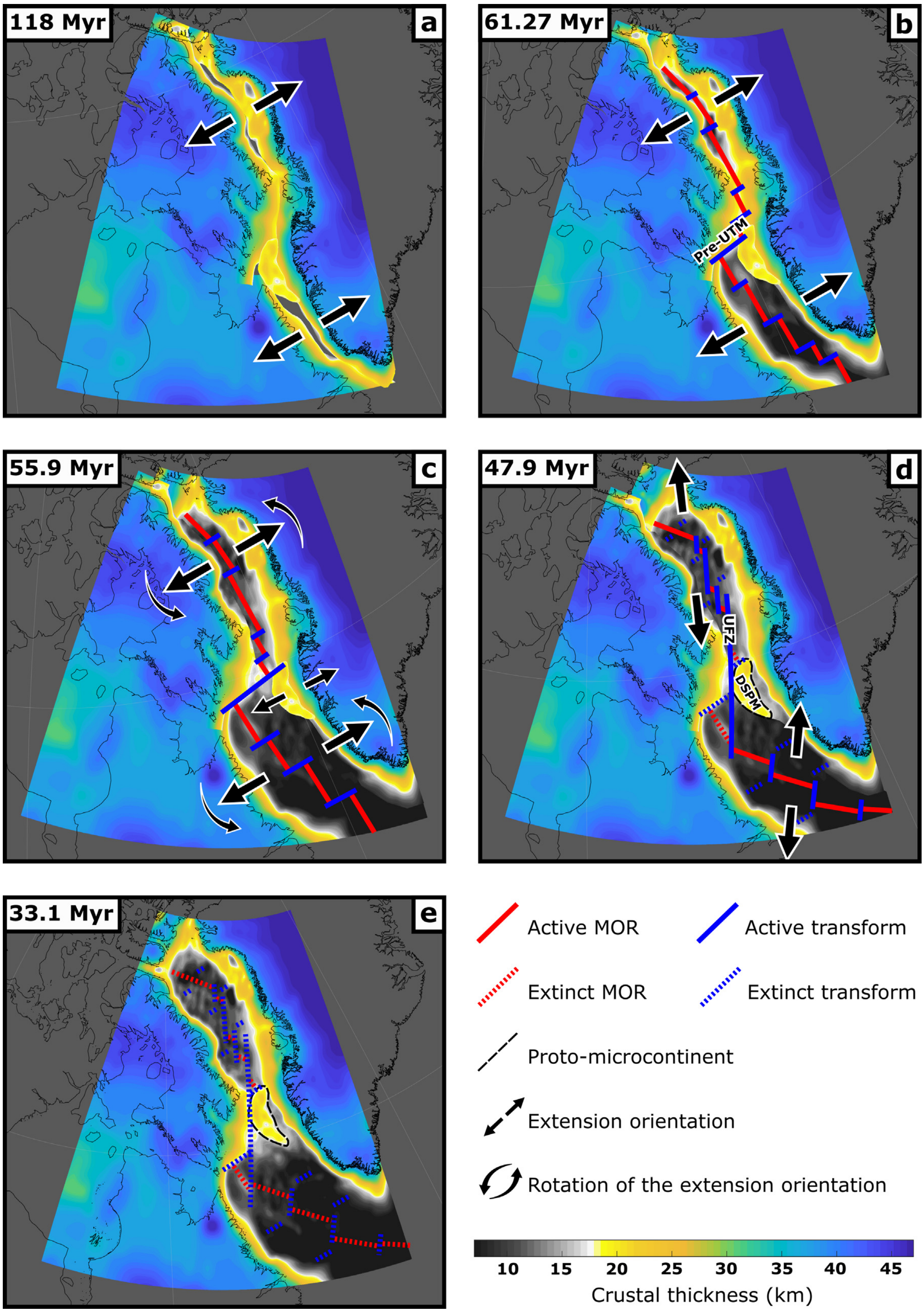

Fig. 8. The proposed plate tectonic model in GPlates overlain with the present-day crustal thickness data and the approximate location and angle of MOR and FZ segments. Model can be summarised as: (a) initial pre-rift fit of Greenland, Canda, and Baffin Island with the Davis Strait proto-microcontinent located between them. (b) NE-SW seafloor spreading begins in the Labrador Sea, also the Pre-UTM begins to develop. (c) Following NE-SW seafloor spreading in the Labrador Sea and Baffin Bay the spreading axis begins to rotate anticlockwise. Simultaneously, the Davis Strait proto-microcontinent begins extending away from the West Greenland margin, based on seismic reflection data in the East Davis Strait indicating a period of extension occurring at this time. (d) Greenland stops rotating and extension is N-S orientated forming the UFZ through the Davis Strait. The Davis Strait proto-microcontinent also stops extending away from West Greenland. (e) Spreading ceases with Greenland now attached to the North American plate. DSPM – Davis Strait proto-microcontinent.

To achieve satisfactory initial crustal thickness distributions in our model, the new crustal thickness model was used to accurately constrain the location of the Davis Strait continental block before reconstruction. The identified continental block was digitised as a continental fragment polygon in GPlates to then be reconstructed back to its original position. As our seismic reflection interpretations indicate an extensional event in the eastern Davis Strait between 58 and 49 Myr, spatially coincident with the zone of thinnest continental crust between the continental fragment and Greenland, we infer this extensional event led to the separation of this fragment from Greenland. Specifically, based on widespread extensional/compressional faulting coinciding with the change in spreading orientation, we reconstruct the continental block back towards West Greenland during the change in spreading orientation, which in our model occurs between 55.9 and 47.9 Myr (Fig. 8c and 8d).

4. Discussion

4.1. Continental crust in the Davis Strait

To understand the rifting history and nature of the crust within the Davis Strait, we use a combination of seismic, gravity, and geological evidence. Seismic refraction and reflection lines across the Davis Strait have previously suggested the region is predominantly composed of stretched and thinned continental crust overlain with thick sedimentary deposits and interbedded basalt layers (Sørensen, 2006; Funck et al., 2012; Suckro et al., 2013). Seabed sampling across the central and eastern Davis Strait also recovered basalt samples contaminated by continental material, confirming the seaway is largely composed of continental crust (Dalhoff et al., 2006). The region occupied by the Davis Strait also falls within the connection of the Trans-Hudson and the Nagssugtoqidian Orogens (Fig. 1), which both exhibit thicker crust than the surrounding cratons. It has therefore been suggested that the formation of the Davis Strait and its continental crust may be related to a different rheology in the Nagssugtoqidian Orogen, compared to the surrounding cratons or of the suture zones between these (Foulger et al., 2020, Heron et al., 2019). Conversely, seismic refraction lines across the southern Davis Strait interpreted a 100 km wide region of igneous crust bordering the UFZ (Funck et al., 2007, 2012). This igneous material is thought to have formed as a result of the UFZ acting as a leaky transform fault where periods of transtension resulted in the upwelling of melt which cooled to form igneous crust (Funck et al., 2007; Storey et al., 1998). However, distinguishing between crustal compositions is difficult due to their similar geophysical characteristics, and our plate tectonic model instead suggests that during the Paleocene the UFZ was under a transpressional tectonic regime (Oakey and Chalmers, 2012; Hosseinpour et al., 2013).

The compiled crustal thickness model also helps constrain the presence and geometry of continental crust within the Davis Strait, where we identify a distinct continental block (Fig. 7, black dashed line) in the centre of the seaway. This region of continental crust also contains the Davis Strait High, a region of relatively thick (>20 km) continental crust and marked by a line of positive NNE-SSW orientated free-air gravity anomalies (Sørensen, 2006; Gregersen and Bidstrup, 2008; Oakey and Chalmers, 2012). Additionally, this region of thick continental crust is separated from Baffin Island by thinner crust near the Tariut and Imaqpik Basins, and from the continental margin of Greenland to the east by the Nuuk Basin (Abdelmalak et al., 2018; Jauer et al., 2019). Within the Nuuk basin, we have interpreted a widespread re-rifting episode from seismic reflection data, which formed and reactivated high angle normal faults between the Lower Eocene and Upper Paleocene. Previous interpretations of the Davis Strait High have suggested that it formed because of over thrusting of crustal material along the UFZ as a result of transpressional forces (Oakey and Chalmers, 2012). However, this model does not explain the anomalously thin crust across the eastern Davis Strait. Instead, we propose that the Davis Strait High and the surrounding region of thick continental crust represents a proto-microcontinent, which we refer to here as the "Davis Strait proto-microcontinent", with the thinner crust to the east signifying a failed spreading ridge where continental rifting ensued. This interpretation also stays consistent with previous numerical models where the Davis Strait evolved through a large, segmented zones of transtensional transforms accommodating plate motion changes that could have potentially led to continental rifting (Farangitakis et al., 2020).

4.2. Pre-Ungava transform margin

While many reconstructions of Greenland's separation from Canada acknowledge the UFZ as a transform that linked spreading in the Labrador Sea to Baffin Bay, many do not interpret any previous major transform system (e.g. Oakey and Chalmers, 2012; Hosseinpour et al., 2013). Here, our plate tectonic modelling and crustal thickness model indicate a major pre-existing transform fault, referred to in this study as the Pre-UTM, that acted as a NE-SW oriented continent–continent transform plate boundary between Greenland and Canada, prior to plate motion changes in the Early Eocene (~56 Myr). Our proposed tectonic model (Fig. 8) demonstrates how the Pre-UTM initially linked spreading in the Labrador Sea to Baffin Bay through the Davis Strait as a NE-SW orientated sinistral transform since the onset of seafloor spreading until the Early Eocene spreading reorganisation. This change in spreading orientation caused the Pre-UTM to undergo transpression, where the UFZ later developed as a ~ N-S orientated transform fault cross-cutting and replacing the Pre-UTM as the active plate boundary between Greenland and North America. Previous numerical models by Farangitakis et al. (2020) also provide a similar interpretation of how the Davis Strait developed, where a low angle continent–continent transform initially joined two offset oceanic basins before a change in the extension orientation caused a second more obliquely orientated transform to develop and cut through the previous transform system.

To constrain a more precise location for the Pre-UTM, crustal thickness inversions were utilised. Crustal thickness inversions can be used to identify continental-oceanic transitions as regions where thicker continental crust meets thinner oceanic crust. Within the West Labrador Sea, crustal thickness inversions show a distinct NE-SW trending region where thicker (>20 km thick) continental crust rapidly transitions into thinner (<14 km thick) crust of oceanic affinity (Fig. 7, thick red lines). Here, we suggest a sharp oceanic-continental transition runs along the NW boundary of the Labrador Sea, reflecting the location of the Pre-UTM. The orientation of this transition is also parallel to that of early NE-SW trending FZs (Fig. 7), and its location coincides with the predicted position and orientation of the Pre-UTM from our tectonic model. Furthermore, our tectonic model also suggests that the UFZ cut through the Pre-UTM, indicating that an easterly segment of the Pre-UTM would be located at approximately the northern margin of the proposed Davis Strait proto-microcontinent.

4.3. Plate tectonic model and formation of the Davis Strait proto-microcontinent

Microcontinents were originally defined by Scrutton (1976) as distinct morphological features that contain pre-rift basement rocks of continental affinity that formed between two spreading ridges and were horizontally displaced from their original continent and surrounded by oceanic crust. Subsequently, more modern studies have shown microcontinents have varying sizes and crustal thicknesses, for instance the Jan Mayen Microcontinent is ~ 150 km wide and up to 15 km thick (Kodaira et al., 1998; Peron-Pinvidic and Manatschal, 2010), while the East Tasman Rise is only ~ 12 km wide and ~ 3 km thick (Gaina et al., 2003; Abera et al., 2016). Microcontinents may also be attached to fragments of simultaneously deformed oceanic crust (Peron-Pinvidic and Manatschal, 2010), with Schiffer et al. (2018) defining these larger features containing sub-plates of oceanic and continental affinity as microplate complexes, suggesting that a true microcontinent is purely composed of continental lithosphere. Additionally, microcontinents are observed to be calved from established rifted margins of major continents during younger re-rifting events, which may be triggered by plate motion changes (Whittaker et al., 2016) or mantle plumes (Müller et al., 2001). Here, we define proto-microcontinents as related regions of relatively thick continental lithosphere separated from major continents by a zone of thinner continental lithosphere. Specifically, proto-microcontinents are only partially separated from a continent during a younger re-rifting event along a continental margin, which ended before continental breakup was achieved. In this process-oriented description of proto-microcontinents, we emphasise the implication that if re-rifting of a continental margin had continued (i.e. was undisrupted by external plate tectonic events), a region of continental crust would be expected to achieve continental breakup. This distinguishes proto-microcontinents from continental ribbons and related features (Peron-Pinvidic and Manatschal, 2010), who's similar geometries are thought to form from strain localisation processes during early rifting and would not be expected to result in a separate continental breakup event.

Previous tectonic models for microcontinent formation (e.g. Nunns, 1983; Müller et al., 2001; Whittaker et al., 2016) can be summarized as: (1) two MORs are separated by a long-offset transform fault, (2) a spreading ridge relocates through continental crust, and (3) continental rifting leads to microcontinent calving from a major continent. Several different mechanisms have previously been suggested to facilitate MOR reorganisation and subsequent microcontinent calving. Müller et al. (2001) suggested that mantle plumes drive microcontinent break up, where plume-induced thermal weakening of continental crust leads to rifting of a passive continental margin followed by asymmetric seafloor spreading and minor volcanism (e.g. Gaina et al., 2003). However, subsequent studies have advocated for plate tectonic reorganisation to be the dominant mechanism in microcontinent formation (Gaina et al., 2009; Whittaker et al., 2016). This model is typified by changes in plate motion inducing transpression and stress build up across a long-offset transform fault, forcing the spreading axis to relocate through the less resistive passive margins of the continent (Whittaker et al., 2016). Although, Whittaker et al. (2016) did acknowledge that thermal weakening by a mantle plume may also play a role in formation of the Batavia and Gulden Draak microcontinents. Subsequent work by Schiffer et al. (2018) has built on the model of Whittaker et al. (2016) to suggest that pre-existing structures also play a key role in the relocation of spreading ridges, where continental rifting develops preferentially along rheological weaknesses. These weaknesses could relate to regions of magmatic underplating (Yamasaki and Gernigon, 2010), fossil suture zones (Petersen and Schiffer, 2016) or other geological weaknesses (van Wijk and Blackman, 2005; van Wijk et al., 2008; Petersen and Schiffer, 2016). Since the Labrador Sea and Baffin Bay represent two offset oceanic basins that underwent a significant change in plate motion, this region provides a natural laboratory for the study of processes controlling continental rifting during microcontinent formation.

We propose a new tectonic model for the development of the Labrador Sea, Baffin Bay, and Davis Strait (Fig. 9). This model includes the formation of the Pre-UTM as well as the Davis Strait proto-microcontinent which explains the large number of extensional faults located offshore West Greenland that developed following tectonic reorganization. Our model is summarized by the following key stages:

1. Early Cretaceous (~120 Myr). The start of major extension as rifting propagates from the North Atlantic into the Labrador Sea and then Baffin Bay via the Davis Strait, with Greenland fixed to Eurasia (Roest and Srivastava, 1989; Chalmers and Pulvertaft, 2001; Larsen et al., 2009).
2. Early Paleocene (~61 Myr). NE-SW orientated seafloor spreading initiates in the Labrador Sea (Fig. 9a), while the Davis Strait and Baffin Bay experience continued continental rifting. Sinistral motion through the Davis Strait causes the Pre-UTM to begin development and the Saglek Basin to begin opening. Studies also show that the Iceland plume lay beneath the Davis Strait, heating and underplating the continental lithosphere from ~ 62 Myr (Storey et al., 1998).
3. Mid Paleocene (~59 Myr). Seafloor spreading propagates into Baffin Bay with continued rifting in the Davis Strait (Fig. 9b). The Pre-UTM fully develops as a transform plate boundary joining MORs in the Labrador Sea and Baffin Bay through the Davis Strait.
4. Early Eocene (~56 Myr). Tectonic reorganization causes the spreading axis to begin transitioning to a N-S orientation (Fig. 9c). This coincides with the commencement of seafloor spreading off East Greenland's margin, causing Greenland to start moving as an independent plate (Oakey and Chalmers, 2012). Oblique extension initiated transpression along the Pre-UTM, leading to NE-SW orientated reverse faulting and folding around the north and south Davis Strait, as well as E-W rifting along West Greenland's margin as the Baffin Bay spreading centre propagates south, separating the Davis Strait proto-microcontinent (Fig. 9d).
5. Mid to Late Eocene (~48 Myr). The UFZ develops as a new transform margin (Fig. 9e) and acts as the plate boundary between North America and Greenland. This subsequently caused rifting in the Davis Strait to cease before continental breakup could occur. Oceanic spreading never fully ensued in the Davis Strait, potentially as a result of structural weaknesses being unfavorably orientated (Peace et al., 2017; Heron et al., 2019), the MORs being too far offset (Farangitakis et al., 2020; Neuharth et al., 2021), the continental lithosphere being too thick and strong (Neuharth et al., 2021), or the Davis Strait being too weak causing it to flow and preventing it from breaking up (Petersen and Schiffer, 2016).
6. Latest Eocene (~33 Myr). Eocene seafloor spreading caused Greenland to rotate anticlockwise causing it to collide with the Ellesmere and Axel Heiberg Islands forming the Eurekan orogeny (Stephenson et al., 2018), locking the MORs and causing spreading to terminate (Fig. 9f).

Our proposed model of the Northwest Atlantic region is comparable to the Whittaker et al. (2016) microcontinent formation model, where plate tectonic reorganization is the main driving force for the relocation of a plate boundary through a region of West Greenland. However, while the region where the spreading ridge was relocated through may have been heated, eroded, and underplated by the Iceland plume, the plume was likely not the trigger for continental rifting, as during rifting the Iceland Plume was located under East Greenland (Storey et al., 1998; Gaina et al., 2017). Instead, continental rifting very accurately coincides with tectonic reorganization, similarly to how the Jan Mayen

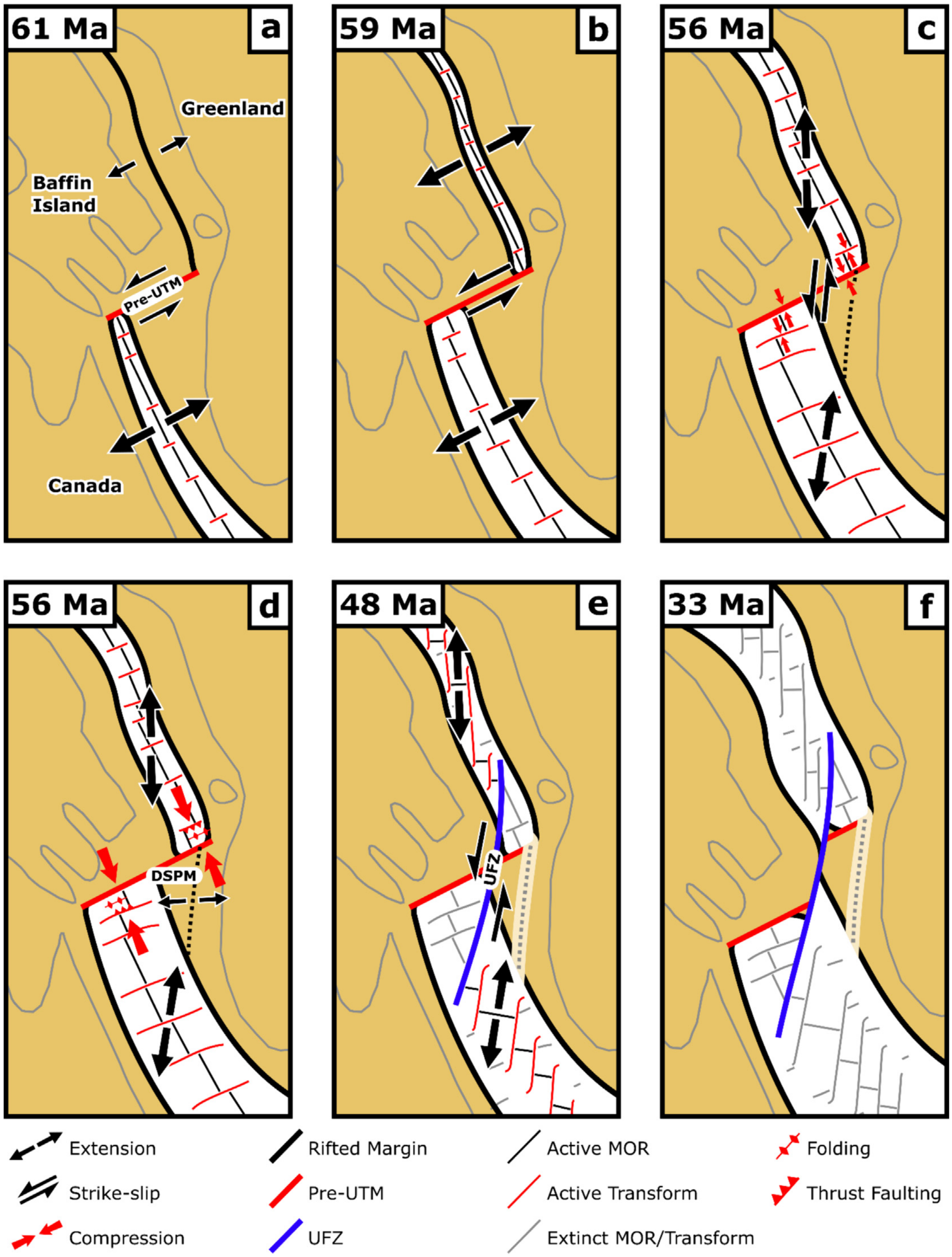

Fig. 9. Schematic diagram of key events in the Labrador Sea, Baffin Bay, and Davis Strait. Key events are summarised as: (a) NE-SW seafloor spreading starts in the Labrador Sea concurrently with the formation of the Pre-UTM. (b) NE-SW seafloor spreading starts in Baffin Bay. (c) The orientation of seafloor spreading begins to rotate so becomes N-S orientated causing compression around the Davis Strait and forming NE-SW orientated thrusts and folds. (d) The Baffin Bay spreading ridge is diverted through the East Davis Strait causing significant normal faulting and extension. This extension causes West Greenland to begin rifting forming the Davis Strait proto-microcontinent. (e) The UFZ develops joining the Labrador Sea and Baffin Bay MORs, which causes rifting to cease in the Davis Strait. (f) Spreading ceases and faults become inactive. DSPM – Davis Strait proto-microcontinent.

(Schiffer et al., 2018), Batavia, and Gulden Draak microcontinents developed (Whittaker et al., 2016). This infers that a model of tectonic reorganization leading to transpression along long-offset transform faults and rifting along weaker continental margins presents the most likely formation mechanism for the Davis Strait proto-microcontinent. This mechanism may also be widely applicable to microcontinent and proto-microcontinent formation around the globe, and further research should investigate if this model could ubiquitously explain microcontinent formation.

5. Conclusions

Utilising a new crustal thickness model, which combines prior crustal thickness inversions with new receiver function constraints, we have identified an isolated fragment of relatively thick (19–24 km) continental crust within the Davis Strait, as well as a sharp NE-SW trending continent-ocean transition along the northern Saglek Basin. The reinterpretation of seismic reflection data offshore West Greenland also reveals an enigmatic Lower Eocene to Upper Paleocene rifting event along Greenland's continental margin. We account for these observations using a high-resolution plate kinematic model of Greenland's separation from Canada during the Cretaceous-Paleogene, which is constrained by extinct MOR and FZ segments identified using free-air, vertical gravity gradient, and filtered free-air gravity maps from the Sandwell and Smith gravity data.

Our tectonic model is characterised by NE-SW orientated seafloor spreading in the Labrador Sea and Baffin Bay during the Paleocene, accompanied by NE-SW sinistral strike-slip motion in the Davies Strait. To accommodate this strike-slip movement, we interpret a new transform margin termed the Pre-UTM, which developed prior to the N-S trending UFZ. From $\sim$ 56 to 48 Myr a spreading reorientation occurred that resulted in the anticlockwise movement of Greenland. This oblique extension induced transpression across the Pre-UTM resulting in significant folding and reverse faulting within the north and south Davis Strait. This transpression also coincided with the observed rifting along West Greenland's continental margin, leading to the partial separation of a continental block into the Davis Strait that we term the Davis Strait proto-microcontinent. At $\sim$ 48 Myr, before complete separation of the microcontinent occurred, localisation of strain along the developing UFZ led to the cessation of re-rifting and joining of the Davis Strait proto-microcontinent to Greenland. In addition, we postulate that prior to the cessation of spreading at $\sim$ 33 Myr, a short phase of late NE-SW extension may have been induced by the onset of the Eurekan Orogeny, as supported by the unanticipated dominance of relatively high angle MOR segments along parts of the Labrador Sea spreading axis. Overall, this work not only recognises several new first order tectonic features of the Earth, the Pre-UTM and Davis Strait proto-microcontinent, but also points to a strong lithospheric control on plate motion directions. It is therefore fundamentally important to further study this phenomenon to understand the operation of plate tectonics on our planet.

CRediT authorship contribution statement

Luke Longley: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Jordan Phethean:** Project administration, Software, Supervision, Writing – review & editing. **Christian Schiffer:** Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gr.2024.05.001.

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