Opening the Norwegian and Greenland Seas: Plate tectonics in Mid Norway since the Late Permian

Jon Mosar, Trond H. Torsvik & the BAT team

The opening of the Norwegian-Greenland Seas in Paleocene-Eocene times was preceded by a prolonged period of crustal stretching that had started in earnest by the Late Permian. A quantitative analysis of this rift-to-drift history and of the Mid Norway passive margin must address the entire margin, on- and offshore, and must incorporate a consistent set of rotation parameters for the plate reconstructions. We present a detailed analysis of this history by means of an introductory text to the base geology map of Scandinavia and the shelf (Figure 1) followed by a series of plate reconstructions for Europe-Greenland since the Late Permian. The plate reconstructions are preceded by an introduction to the plate model we employed; additional comments are added for each reconstruction and time period.

The map of Scandinavia

The geological map of the Scandinavian North Atlantic passive margin (Figure 1) highlights the onshore-offshore connections between extensional faults and successive, Permian-and-younger rift events. The map introduces the innermost boundary fault (IBF) system which corresponds to the location of a series of faults defining the present-day rift flank and hence, the easternmost portion of the Scandinavian North Atlantic passive margin. The IBF system is traced for ca. 2000 km, from SW to N and NNE, across the topographic crest of the Scandinavian mountain chain. The fault system separates a gently east-dipping domain to the east of the crest from the more rugged topography and glacial valleys to the west. This position of the IBF at the surface corresponds at depth to a zone of slight crustal thinning (Andersen 1998; Dyrelius 1985; Hurich & Kristoffersen 1988; Hurich et al. 1989; Hurich & Roberts 1997) and to the important negative Bouguer gravity anomaly of Scandinavia (Korhonen et al. 1999; Skilbrei et al. 2000; see also Chapter 1). The IBF trace also lies directly W of a series of small basement massifs which are themselves located above the shallow décollement of the Caledonides. The IBF as defined here reactivates former reverse or normal ductile faults of Paleozoic age along the occidental slopes of these massifs.

The IBF probably experienced several successive periods of extension since Late Permian time - not including the early origins of its numerous fault strands that were related to Caledonian tectonics - and was most likely active as recently as the Tertiary and possibly the Present. Critically, the width of the passive margin and related issues of the magnitude of extension through time are measured between the IBF and the continent-ocean boundary (COB). Essentially, by moving the IBF from a 'classic' nearshore (coastal) position to a continentward position, we alter the perspective geometries and crustal responses of Permian through Present rifted margin constructions.

With the COB and proposed position of the IBF as primary markers, we can make direct measurements of the passive margin width at different locations along the margin extent. The smallest width of some 165 km is found along a section across the Lofoten area, while the broadest margin width of ca. 710 km is measured along a section across the Vøring Basin into Sweden (Åre-Östersund). Some 550 km of extended margin are measured along a section through the Møre Basin and the Western Gneiss Region. These widths correspond to the finite extension of the margin since Late Permian and represent the cumulative effect of the successive rifting-stretching events from Late Permian to Present. In a simple, first-order, semi-quantitative attempt to measure the pre-rift margin width, we used a combined approach with plate tectonic reconstructions and line-length balancing of the top-to-basement surface. In agreement with other studies (Skogseid et al. 2000; Vågnes et al. 1998) and discussion in Brekke et al. (2001), we estimated an average total extension on the order of 200% (β=2), which means that the margin doubled its width since the Late Permian. Conversely, in Late Permian-Early Jurassic plate reconstructions, the COB can be restored considerably further inboard from its present position, and a very tight fit between Greenland and Scandinavia can be achieved (see Figure 9). This fit implies important restoration of the existing basins to their pre-Cretaceous widths and to physical positions of the basins in much closer proximity to their probable sediment source areas.

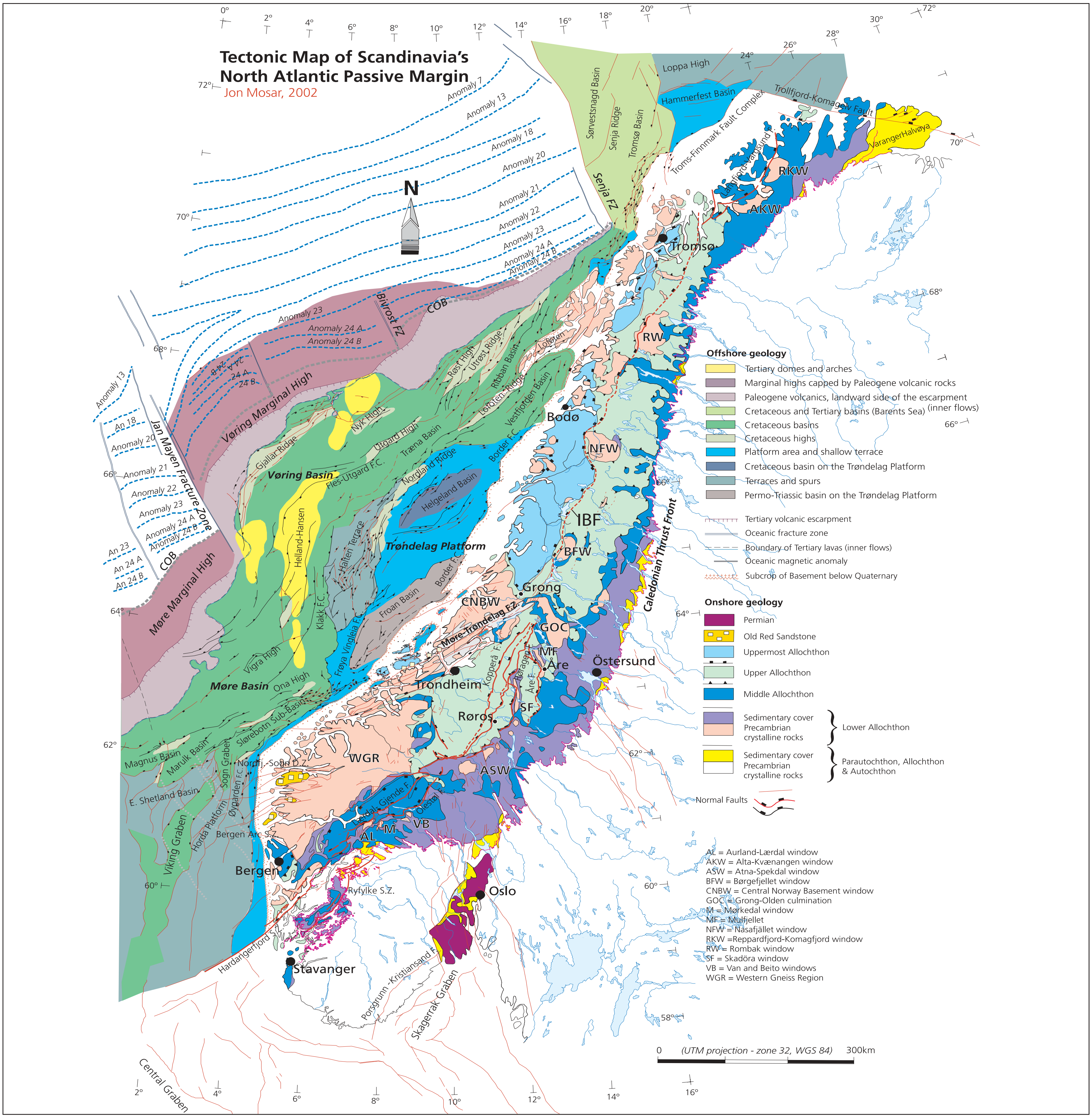

Figure 1.

A number of direct and indirect pieces of geologic and geophysical evidence have led to the proposed existence of a 2000 km-long innermost boundary fault (IBF) system that runs through the heart of the Swedish-Norwegian mountain range, between the North Sea Central Graben and the Barents Sea. The IBF (red solid and dashed line traces along the spine of the Scandinavian Caledonides) is defined in western Norway by the Lærdal-Gjende-Olestøl (LGO) fault system, and in central Norway it includes the Åre and Kopperå faults and the Røragen detachment system (Andersen et al. 1998; Mosar 2000). This set of normal faults forming the southwest part of the IBF appears to merge northward near the northern tip of the Møre-≤ Trøndelag Fault Complex. Farther north, the proposed trace of the IBF follows the topographic culmination of the mountain chain and connects former ductile extensional faults located on the western slopes of basement windows: the Børgefjellet window, the Nasafjället window, and the Rombak window. In the Nordland area, the IBF and equivalent faults are hitherto undescribed and we propose the existence of a fault segment defined by the topographic crest, the location of the basement windows, and data documenting major basement offset in the structures obtained from potential field modeling. To the east and northeast of Tromsø in the Finnmark area, a set of large normal faults, including the Langfjord-Vargsund fault, form the northernmost branch of the IBF that terminates against the Trollfjorden-Komagelva fault at the edge of the Barents Sea (Siedlecka & Roberts 1996a, b). Further details on the IBF can be found in Mosar et al. (2002b). References to the map are as follows - Offshore map: from Blystad et al. (1995), Brekke et al. (1999), Gabrielsen et al. (1999), Smethurst (2000), and data from the Norwegian Petroleum Directorate, the Scandinavian Caledonides tectonostratigraphic map: Sveriges geologiska undersökning Ser. Ba nr. 35; compiled by Gee et al. (1985); Offshore magnetic anomalies: Skogseid et al. (2000).

The plate reconstructions

The reconstructions presented here are based on recent reviews of paleomagnetic poles (Torsvik et al. 2001b), paleomagnetic anomalies and rotation poles (Gaina et al. 2002; Roest & Srivastava 1989), and the ages of post-break-up anomalies in the North Atlantic (Cande & Kent 1995; Skogseid et al. 2000) for Eurasia, Greenland and North America. The series of reconstructions from Late Permian to Present demonstrates that the bulk of extension on the Norwegian Sea - Greenland Sea passive margin was accomplished during the Cretaceous, prior to the rift-drift transition in the Early Eocene. By relaxing the Bullard fit as the initial fit for Greenland we were able to achieve a better (tighter) fit of Greenland and Norway. This position is consistent with available information on the post- Early Permian extension/shortening (a 50% narrower pre-rift margin) observed on the Norway-East Greenland margins (Torsvik et al. 2001b). From Late Permian (250 Ma) to late Early Cretaceous (90-100 Ma) the opening direction between the present-day Norwegian shelf and East Greenland was E-W-directed, oblique to the present coastline (Figure 10). During the Late Cretaceous, the opening followed a more NW-NNW-direction, perpendicular to the margin's present coastline. Major changes in absolute displacement (in a hotspot reference frame) show a uniform northward movement of the coupled North American, Greenland and Eurasian plates from 130 to 80 Ma followed by a marked change of motion at 80 Ma. At 80 Ma, the three plates simultaneously changed direction and followed a uniform NW-directed motion until ca. 30 Ma when Eurasia diverged NE, away from the still NW-moving Greenland and North American elements. Around 20 Ma the Iceland plume merged with the North Atlantic spreading ridge.

The reconstruction prior to the rift-drift transition and the onset of oceanization is obtained from best fits of corresponding magnetic anomalies. Anomaly 24 (52.364-53.347 Ma) is the oldest normal polarity chron identified in the NE Atlantic, but sea-floor spreading might already have begun during the preceding reverse polarity chron (A24r); an absolute maximum age for initiation of sea-floor spreading would thus be 55.9 Ma, i.e. Late Paleocene (Late Thanetian age). Most, if not all, of the extension on the passive margins of the Greenland and Lofoten seas, separated by the Mohns Ridge system, was achieved at that time. Extension of the continental crust continued into the Tertiary in the Jan Mayen area, and in the Boreas Basin - Barents Sea - Svalbard domains (Figures 2-7). This Tertiary extension is associated with an important change in plate motion between anomaly 13 (33.3 Ma) and anomaly 7 (25 Ma) at which time the relative motion between Greenland and Norway changed from NNW-directed to WNW-directed. An important change in sea-floor spreading occurred with the abandoning of the Ægir Ridge system (Figure 4), and the northward propagation of the Reykjanes Ridge into areas west of the Jan Mayen microcontinent between anomaly 7 and 13 time (25-33.3 Ma) (Müller et al. 2001; Vogt 1986).

The plate reconstructions have been made using the rotation parameters described in Table 1. These rotation parameters are based on best fit analyses from magnetic anomalies in the Greenland Sea between Norway and Greenland (Torsvik et al. 2001a). The plate reconstructions are made with Europe fixed (the reference grid - latitude/longitude - is the present-day grid in polar stereographic projection).

BB = Boreas Basin	S-FZ = Spitsbergen Fault Zone
G-FZ = Greenland Fault Zone	TP = Trøndelag Platform
HGR = Hovgaard Ryggen	VB = Vøring Basin
JMTZ = Jan Mayen Tranform Zone	VK = Viking Graben
L = Lofoten	YP = Yermak Plateau
MB = Møre Basin	IBF = Innermost Boundary Fault
MFZ = Molloy Fault Zone	CTF = Caledonian Thrust Front

Age (Ma)	Mag. Anom	Period-Epoch/Age	Latitude	Longitude	Angle	Reference
10.3	A5	E. Tortonian	70.2	117.6	2.3	Torsvik et al. 2001a
19.6	A6	Burdigalian	68.8	132.3	4.8	Id.
25	A7	Chattian	68.7	131.3	6	Id.
33.3	A13	Rupelian	68	129.9	7.6	Id.
39.3	A18	Bartonian	59.81	129.63	8.26	New pole - best fit
47.1	A21	E. Lutetian	53.7	128.9	9.2	Torsvik et al. 2001a
54	A24	E. Ypresian	51.8	122.3	11.6	Id.
65	-	Cretaceous/Paleocene	43.6	123	12.2	Id.
83	-	Santonian/Campannian	40.1	123.9	12.1	Id.
90	-	Turonian	37.5	125.5	12	Id.
135	-	Valanginian	36.9	129.7	12.7	Id.
250	-	Late Permian-Triassic	31.2	133.9	12.8	Id.

Table 1.
Rotation parameters to rotate Greenland back to Europe (with Europe fixed; angle negative clockwise); rotation pole for the Bartonian is a new pole obtained from best fit of corresponding magnetic anomalies 18.

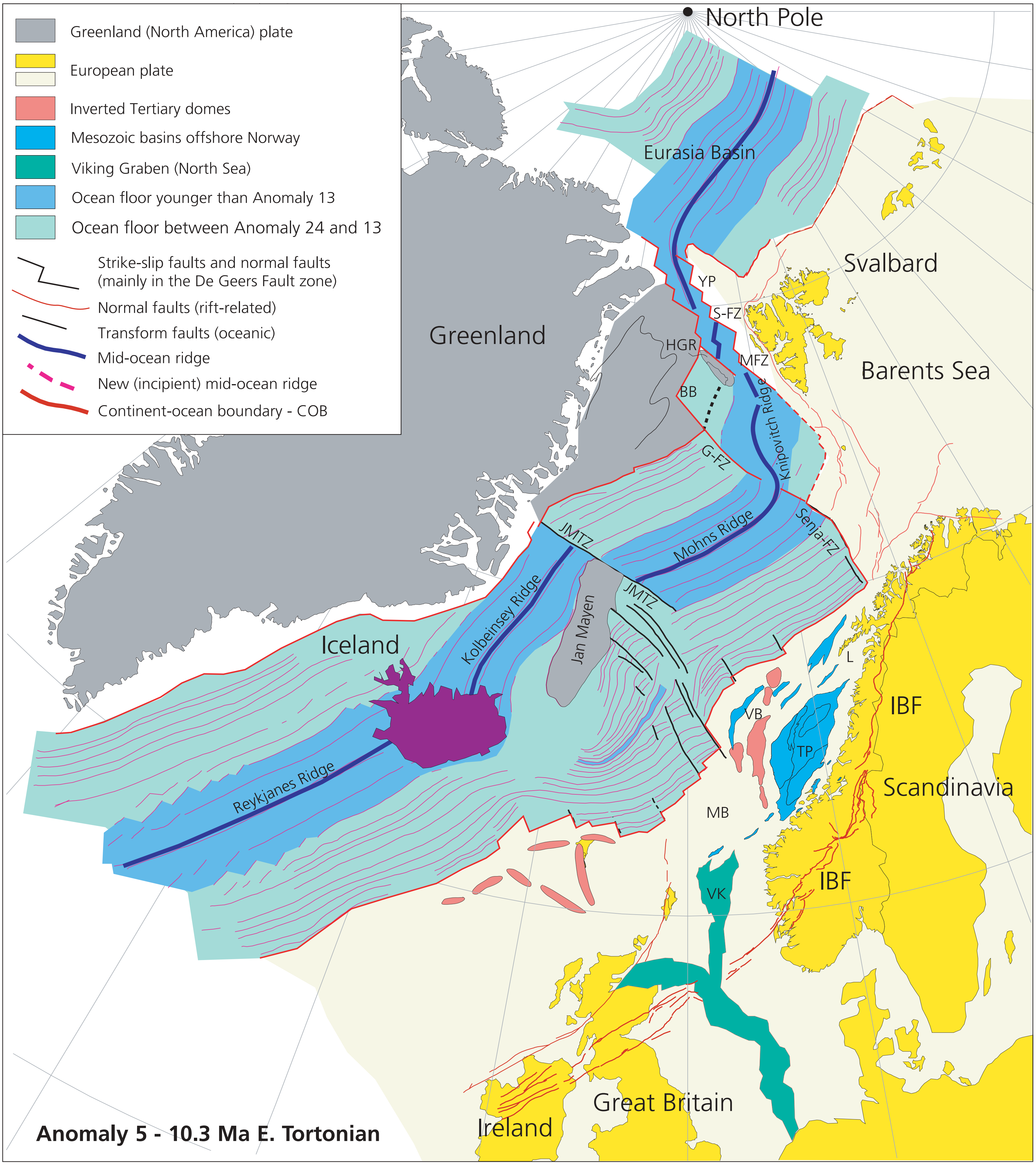

Figure 2.

Plate tectonic reconstruction at anomaly 5 - 10.3 Ma – Tortonian (Late Miocene). The mid-ocean ridge in the Boreas Basin changed its position and geometry to form a more ribbon-like structure, and a continuous ridge system thus developed between the North Atlantic and the Arctic Ocean. The Late Miocene oceanic configuration and structure is very similar to the Present situation.

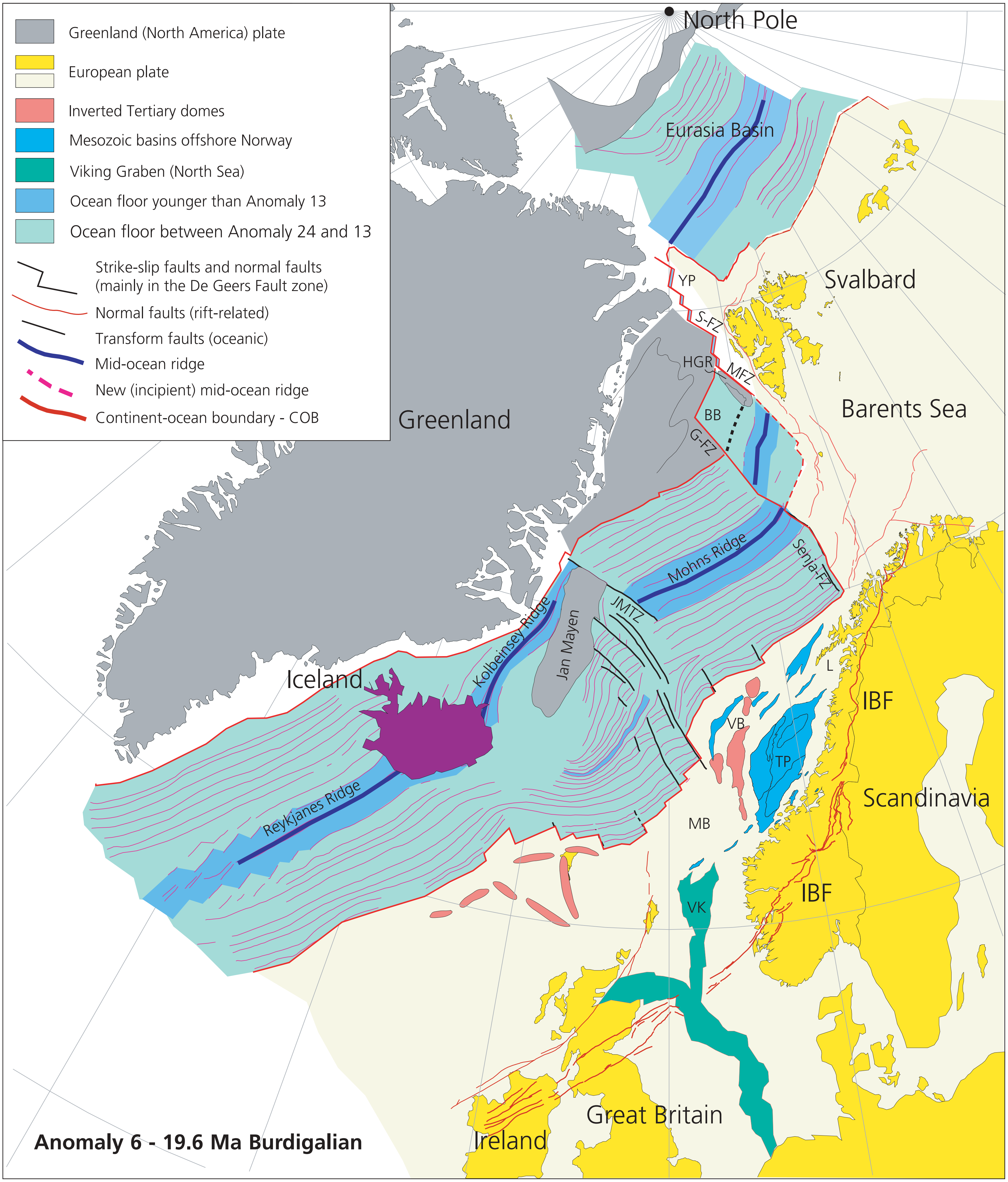

Figure 3.

Plate tectonic reconstruction at anomaly 6 - 19.6 Ma - Burdigalian (Early Miocene). The transform (strike-slip) margin between Greenland and Svalbard changed to a transform, passive-margin edge. A new continent-ocean boundary developed and the Molloy and Spitsbergen Fault Zones became operative. New ocean floor developed between the Svalbard and Greenland conjugate margins. The Jan Mayen continent was in the process of being completely cut off from Greenland by the NW migration of the Kolbeinsey Ridge.

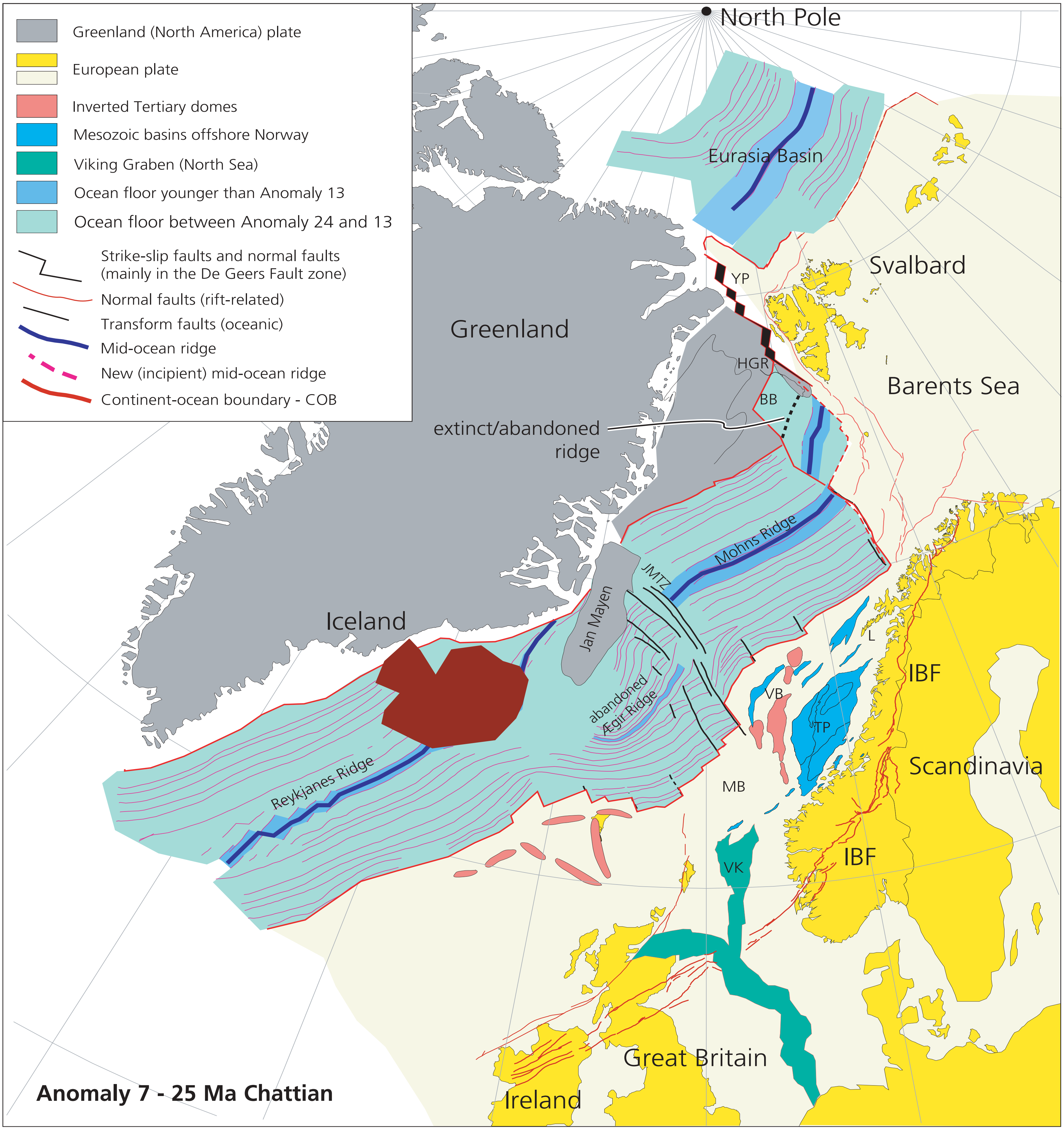

Figure 4.
Plate tectonic reconstruction at anomaly 7 - 25 Ma - Chattian (Late Oligocene). An important change in sea-floor spreading occurred with the abandonment of the Ægir Ridge system and the northward propagation of the Reykjanes Ridge into areas west of the Jan Mayen microcontinent between anomaly 7 and 13 time (25-33.3 Ma; Müller et al. 2001; Vogt 1986). Abandonment of the Ægir Ridge was coincident with a major reorganization of plate boundaries in the Arctic-North Atlantic domain, including termination of sea-floor spreading in the Labrador Sea-Baffin Bay (prior to anomaly 13; Srivastava & Tapscott 1986; see also Chapter 3); also at this time, Greenland joined the North American plate and Jan Mayen joined the European plate (Ziegler 1988). This ridge jump was also coincident with a change in both absolute and relative plate motion in the Oligocene at around 30 Ma (Torsvik et al. 2001a). This time period heralded the final separation of Europe and Greenland in the Svalbard area.

Subsequent to the displacement of the major strike-slip system to the E of the Hovgaard Ryggen a new mid-ocean ridge developed in the Boreas Basin (ridge jump!) in the direction of the Barents Sea shelf. This left the northern Boreas Basin with an abandoned ridge and its 'old' magnetic anomalies. The Hovgaard Ryggen microcontinental block moved along a strike-slip fault located to the NW. The area in black between NE Greenland and Svalbard indicates the overlap (or amount of extension) of the COB between anomalies 6 and 7 in this area.

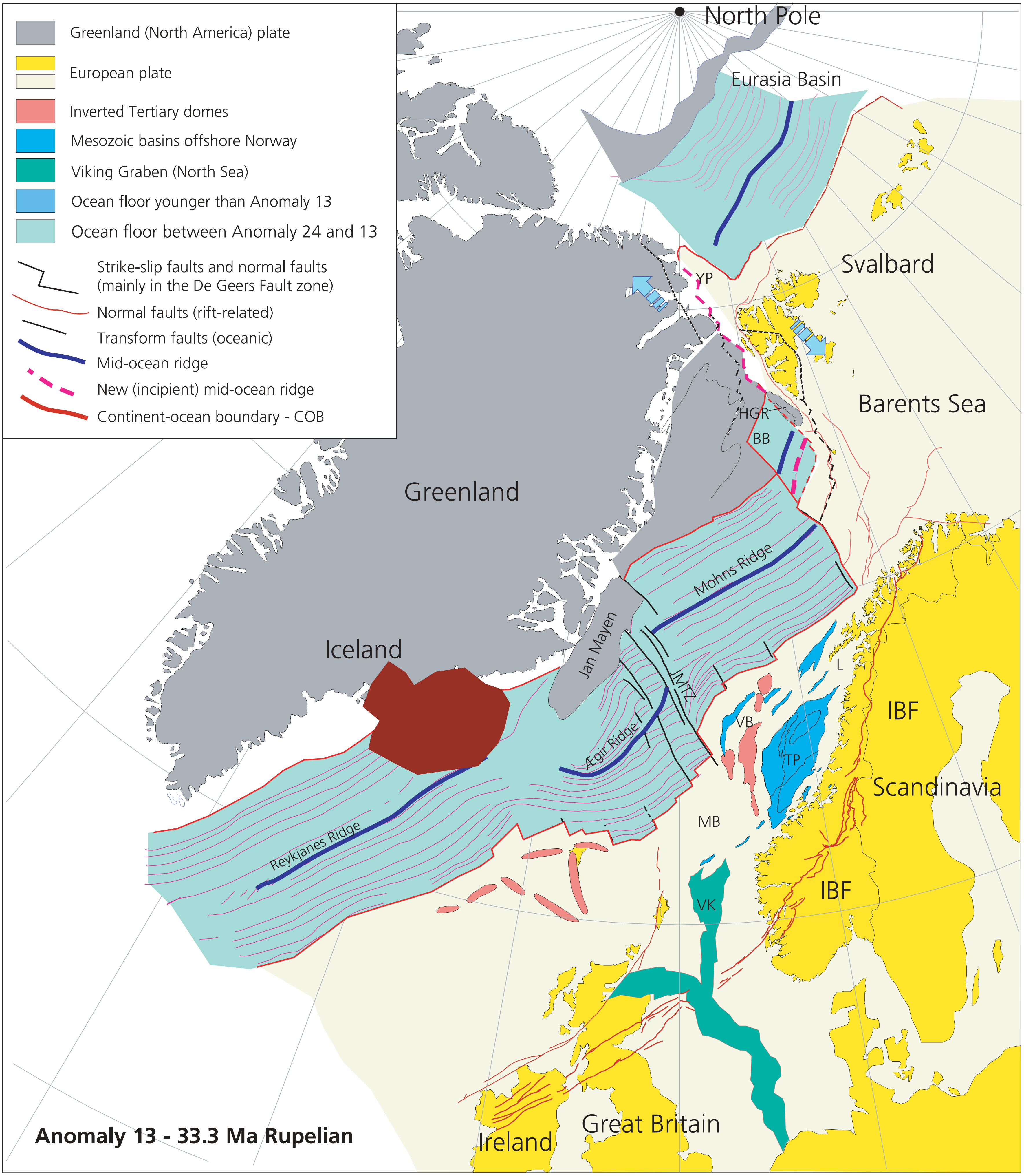

Figure 5.

Plate tectonic reconstruction at anomaly 13 - 33.3 Ma - Rupelian (Early Oligocene). Greenland and Svalbard started moving away from one another in a strike-slip fashion. The transform edge of the northern Boreas Basin was located to the SW of the Hovgaard Ryggen continental sliver which still pertained to the European plate. The spreading ridge in the Boreas Basin faced the Hovgaard Ryggen, probably inducing important uplift in the area which is corroborated by the discovery of continental spores and pollens in the region. The Ægir Ridge system was still active and connected the Mohns Ridge to the Reykjanes Ridge. The southwestern tip of the Jan Mayen microcontinent probably started extending and separating from Greenland, aided by the migration of the Iceland plume into the offshore domain, east of the edge of the Greenland plate. Following anomaly 13, an important change occurred in spreading direction between Greenland and Norway.

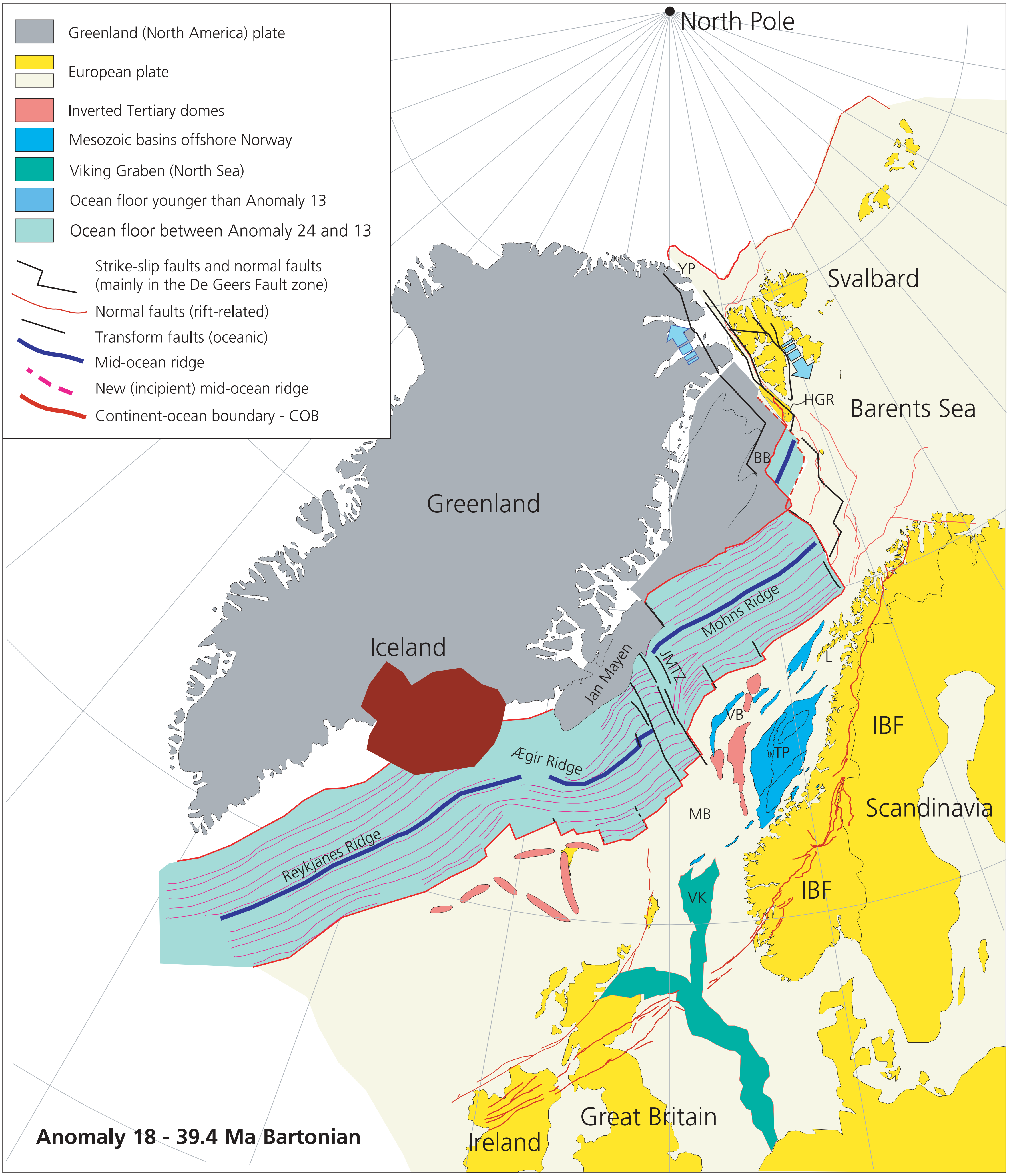

Figure 6.

Plate tectonic reconstruction at anomaly 18 - 39.4 Ma - Bartonian (late Middle Eocene). The convergence of Greenland and Svalbard was at its climax during this period and a compressional strike-slip regime governed the structural development in Svalbard and NE Greenland. Just prior to anomaly 18 the rift-drift transition occurred between the Barents Sea shelf and the NE Greenland offshore crust; this led to the opening of the Boreas Basin, the development of passive margins and the formation of oceanic crust.

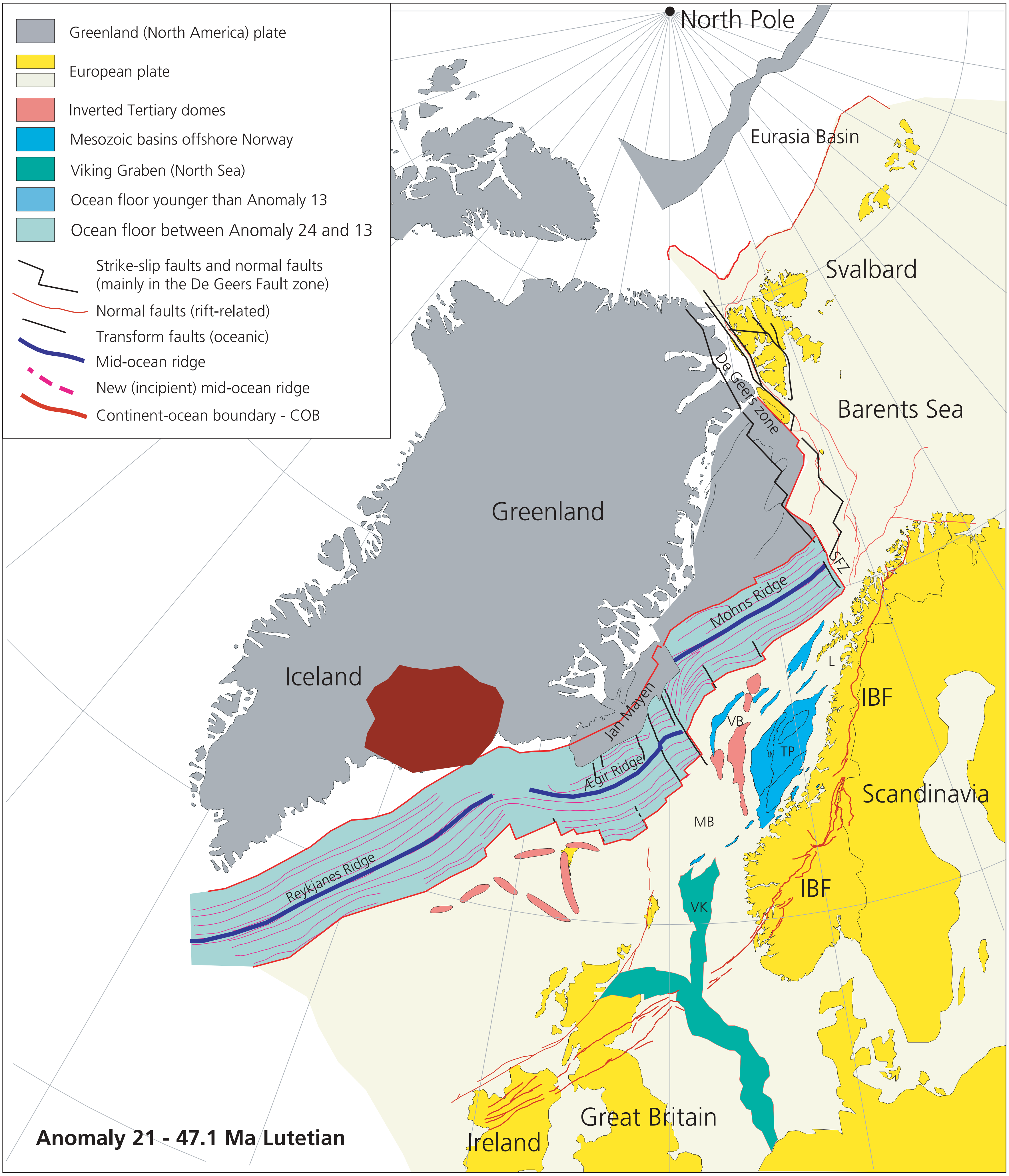

Figure 7.

Plate tectonic reconstruction at anomaly 21 - 47.1 Ma - Early Lutetian (Middle Eocene). Continued ocean-floor production along the Reykjanes, Ægir, and Mohns Ridges further separated the Greenland passive margin from its Scandinavian conjugate margin. On the SW Barents Sea shelf a transform COB developed along the Senja Fault Zone. The more northerly portions of the future Barents Sea margin and its conjugate on NE Greenland (mainly offshore) reached a stage of maximum rifting, just prior to break-up and oceanic crust formation. The De Geers zone, separating Svalbard and NE Greenland, was mainly active as a shear zone.

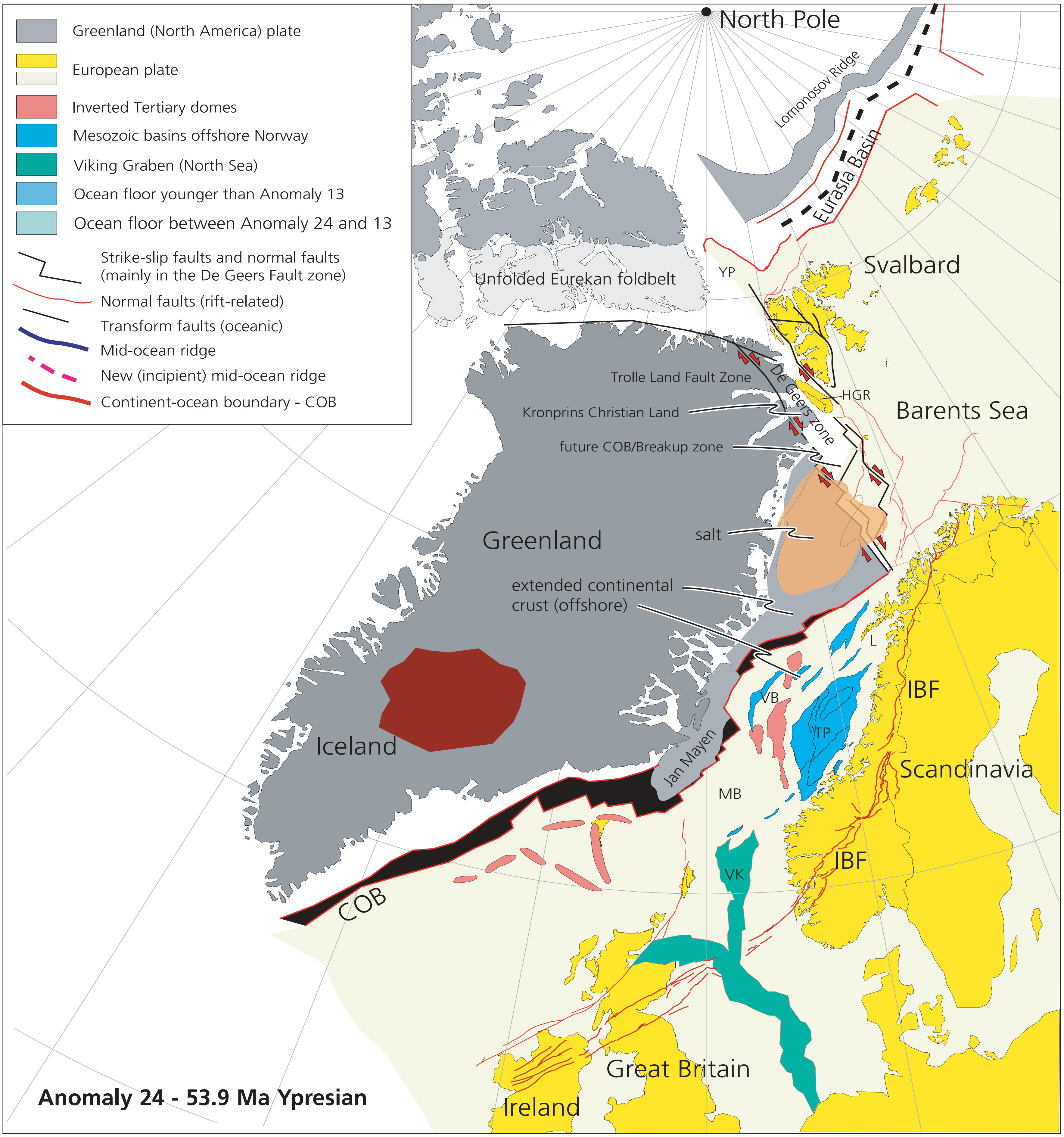

Figure 8.
Plate tectonic reconstruction at anomaly 24 - Eocene/Paleocene, more or less at 54 Ma, just prior to sea-floor spreading. This is the time frame when Greenland was about to separate from Norway. The conjugate passive margins were in a 'best-fit' position, except for the northernmost offshore part of NE Greenland and its counterpart on the Barents Sea shelf. Since extension appears to be limited in the Barents Sea area, the excess overlap has to be transferred to the Greenland plate. This includes cutting off Kronprins Christian Land and moving it towards the NW along the Trolle Land Fault Zone. The Trolle Land Fault Zone is considered part of the De Geers zone, which can be seen as a broad strike-slip zone separating Svalbard from NE Greenland.

The space between the paleoposition of the Arctic Islands and NW Greenland is 'filled' with the unfolded Eurekan fold-belt (Ziegler 1988). In black is shown the discrepancy in overlap of the SE Greenland margin and the Shetland margin which probably reflects an uncertain location of the COB. Jan Mayen has been distorted to fit the available space between Greenland and Scandinavia. The overlap of Jan Mayen with Greenland reflects the amount of shortening required for a best fit (similar in the other reconstructions). This shortening was probably distributed on both margins: Greenland and Jan Mayen.

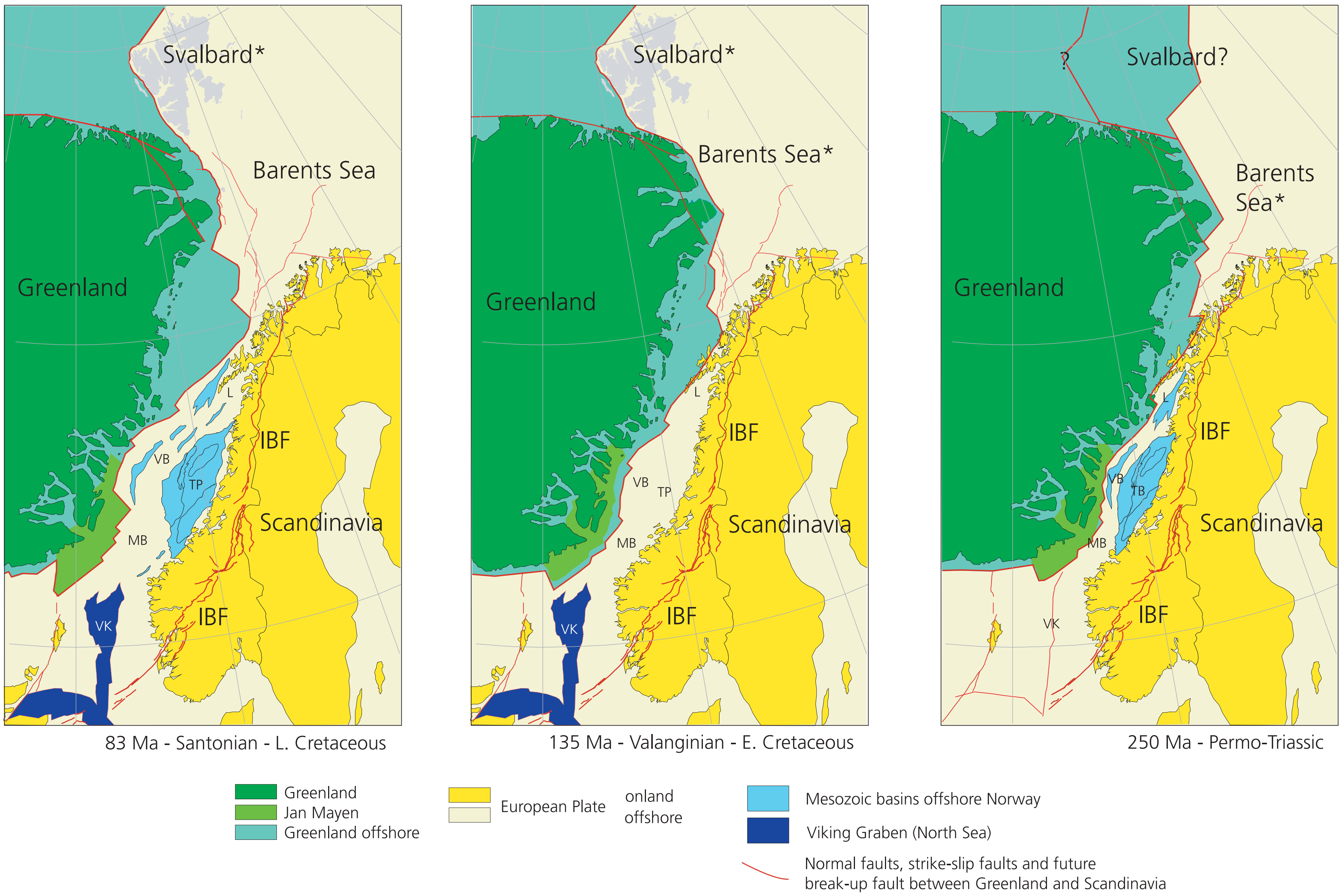

Figure 9.

Pre-break-up plate tectonic reconstructions during Late Cretaceous (83 Ma - Santonian/Campanian), Early Cretaceous (135 Ma – Valanginian), and Late Permian (250 Ma). The Permian reconstruction highlights the very tight fit proposed in this model. To better understand the shortening required in the sedimentary basins offshore Mid Norway, we have made tentative restorations showing the possible positions of the different offshore basins. The restorations/retrodeformation of the different basins are shown for the Santonian and Permo-Triassic only. Restoration and retrodeformation are qualitative and are based on semi-quantitative estimates of possible positions and of a total margin extension since Late Permian of some 200%. Thus, the distance of the COB to the IBF in the Permo-Triassic has been halved with respect to the present situation (equivalent also to the pre-break-up situation). Restoring the position of Greenland with respect to Europe and closing the rift space between NE Greenland and the Barents Sea results in an important overlap of NE Greenland and the Barents Sea. This implies important shortening during the Mesozoic in the Barents Sea area and a decoupling of Svalbard from both Greenland and more importantly, from Europe (see also discussion in Torsvik et al. 2001b). For the Permo-Triassic reconstruction the Viking Graben has been closed. The exact dimensions of the Jan Mayen microcontinent remain speculative, but are consistent with the models presented here.
* = Svalbard and Barents Sea shown in present-day positions (Svalbard and Barents Sea were not retrodeformed in these models).

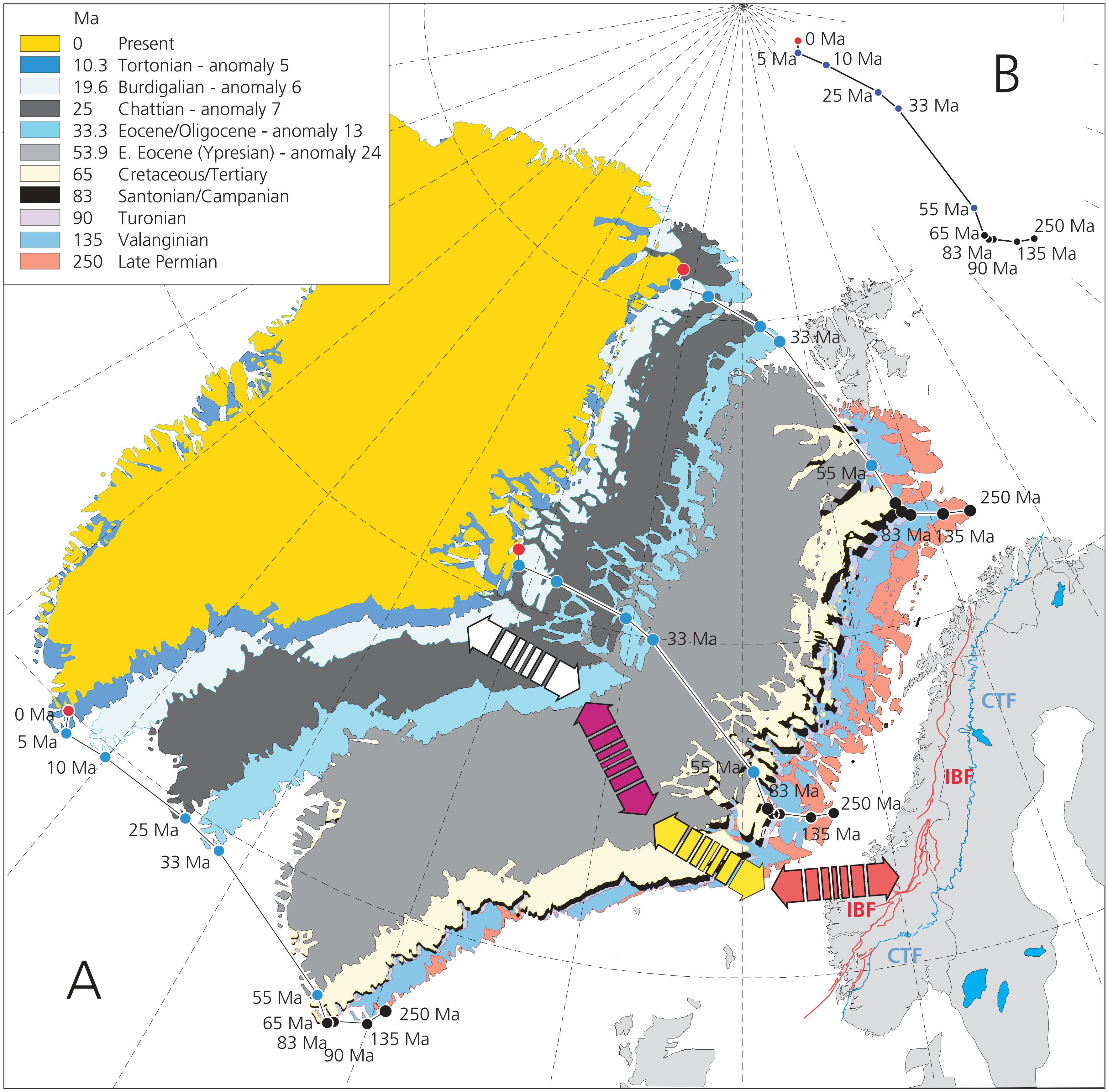

Figure 10.

Sequential reconstruction of separation between Greenland and Scandinavia. A. To highlight opening directions, the successive positions of Greenland are shown, and the dots and connecting lines show the trajectories of three distinct points on Greenland. The large arrows qualitatively indicate the main, different, successive opening directions. B. Displacement path of a point on Jameson Land (same as central path of A) with age attribution for each successive opening stage.