

Global reconstructions and North Atlantic paleogeography 440 Ma to Recent

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Global 1

In **Late Ordovician** times, Laurentia, Baltica, Siberia and the Chinese Blocks occupied subtropical and equatorial latitudes. Avalonia collided with Baltica along the Tornquist Margin with subduction beneath Avalonia. The combined landmass was separated from Gondwana by the Rheic Ocean. In Baltica the first appearance of warm-water, Bahamian-type reefs occurred at this time. Conversely, parts of northwest Gondwana were glaciated.

In **Late Silurian** times, Baltica collided with Laurentia and caused the Scandian phase of the Caledonian Orogeny. Prior to collision, a stationary Laurentia was situated at the equator whereas Baltica had a rapid north-westward-directed movement. Wholescale westward subduction of Baltic continental crust beneath Laurentia gave rise to extreme crustal thickening in the Caledonian Belt, exemplified by the preserved high-pressure eclogite-bearing terranes in western Norway. The Scandian event was followed by the start of Early Devonian (Emsian) extensional collapse, at least in the southwestern parts of Norway; from central Scotland to New York,

compressional events continued in the form of the Mid Devonian Acadian Orogeny.

In **Late Devonian** times, Laurussia stretched from low northerly latitudes to intermediate-high southerly latitudes. The Rheic Ocean narrowed as many of the former peri-Gondwanan continents (including the European Massifs which now constitute Variscan Europe) rifted off Gondwana and opened the Paleotethys behind them. Siberia was geographically inverted while Kazakhstan approached the Baltica margin from the East. Siberia remained northeast of Baltica until their terminal collision in Late Permian times.

In **Early Permian** times, the Pangea Supercontinent was centered around the equator. Pangea had started to form by the Early Carboniferous (ca. 330 Ma) and by Early Permian times it contained the bulk of the world continents except Siberia and Asian continents in the Paleotethys realm. The Variscan Belts of Central Europe and the Urals also formed during the Carboniferous. During the Late Carboniferous and Early Permian, the southern regions of Pangea (southern South America and southern Africa, Madagascar, Antarctica, India and Australia) were glaciated. The Central Pangean mountain range formed an equatorial highland which was the locus of coal production in an equatorial rainy belt during Late Carboniferous time.



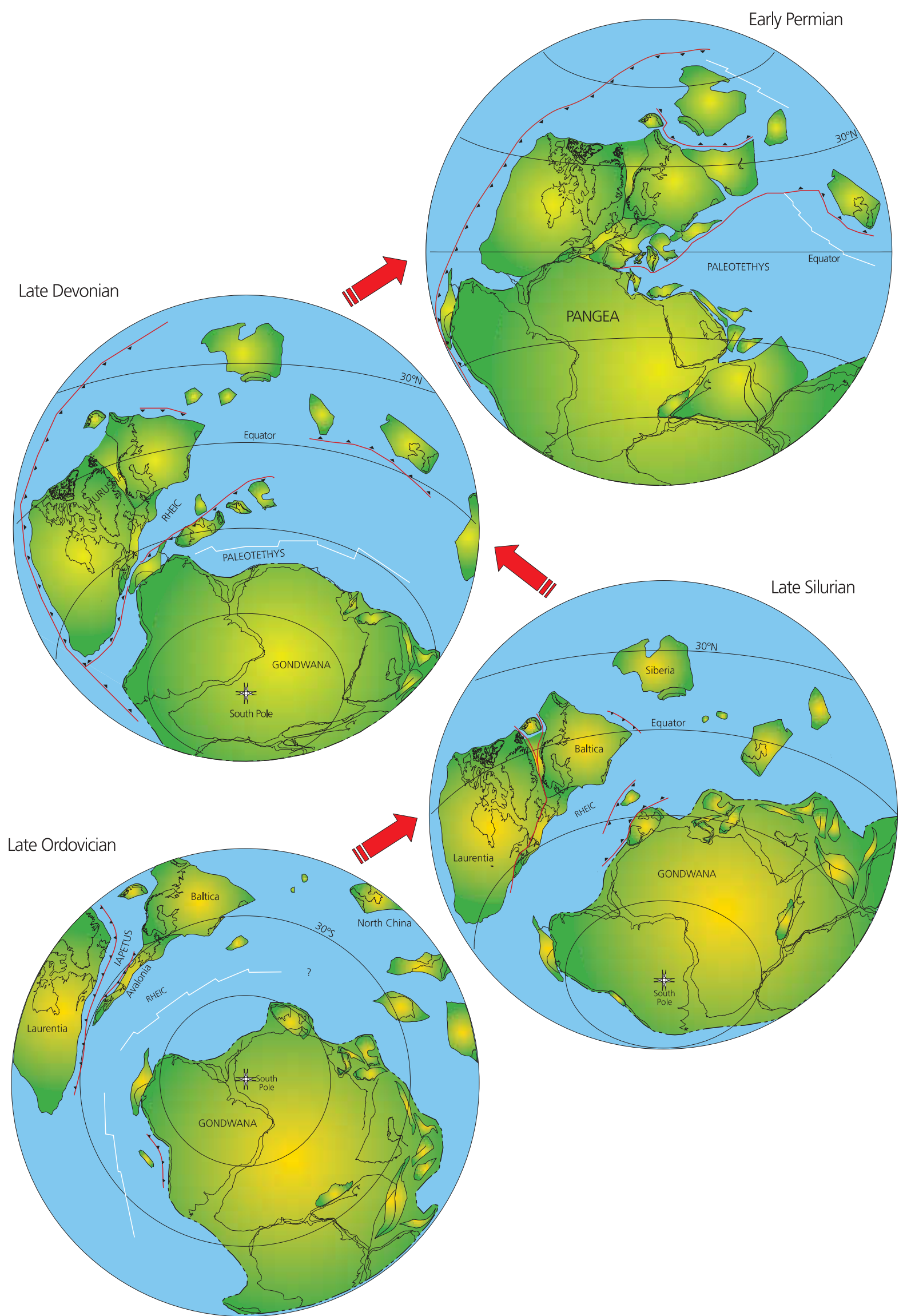
An eclogite is a high-density, mafic rock containing garnet (red mineral in photo) and omphacite (a pyroxene — green mineral in photo), and possibly also rutile, quartz, kyanite or amphibole. Eclogites and eclogite-facies mineral assemblages indicate high metamorphic pressures. In western Norway, ubiquitous eclogites within felsic continental crust were generated during subduction of western Baltica beneath Laurentia in Silurian-Early Devonian time ('Scandian' phase of the Caledonian orogeny).

Photo: Elizabeth A. Eide



Carboniferous tillite from southwestern Madagascar. Late Carboniferous-Early Permian tillites are found over much of what was southern Pangea and attest to glacial conditions appropriate for a position at low, southerly latitudes.

Photo: Elizabeth A. Eide



Regional 1

During the **Late Devonian**, Greenland and Scandinavia were largely centered between the equator and the subtropics (30-20°N). Evaporites are, therefore, essentially absent. The North Sea and the British Isles were dominated by Old Red Sandstone (ORS) deposits, mainly sand deposited in fluvial, lacustrine and aeolian systems. Intra-mountain basins formed as Scandian compression gave way to collapse and extension. Rift structures between Greenland and Norway followed the Caledonide structural grain northward to the SW Barents Shelf and connected to the Arctic rift system. In the southwestern part of the Barents Shelf, rifting occurred during Late Devonian-Early Carboniferous time and was linked to the subsequent

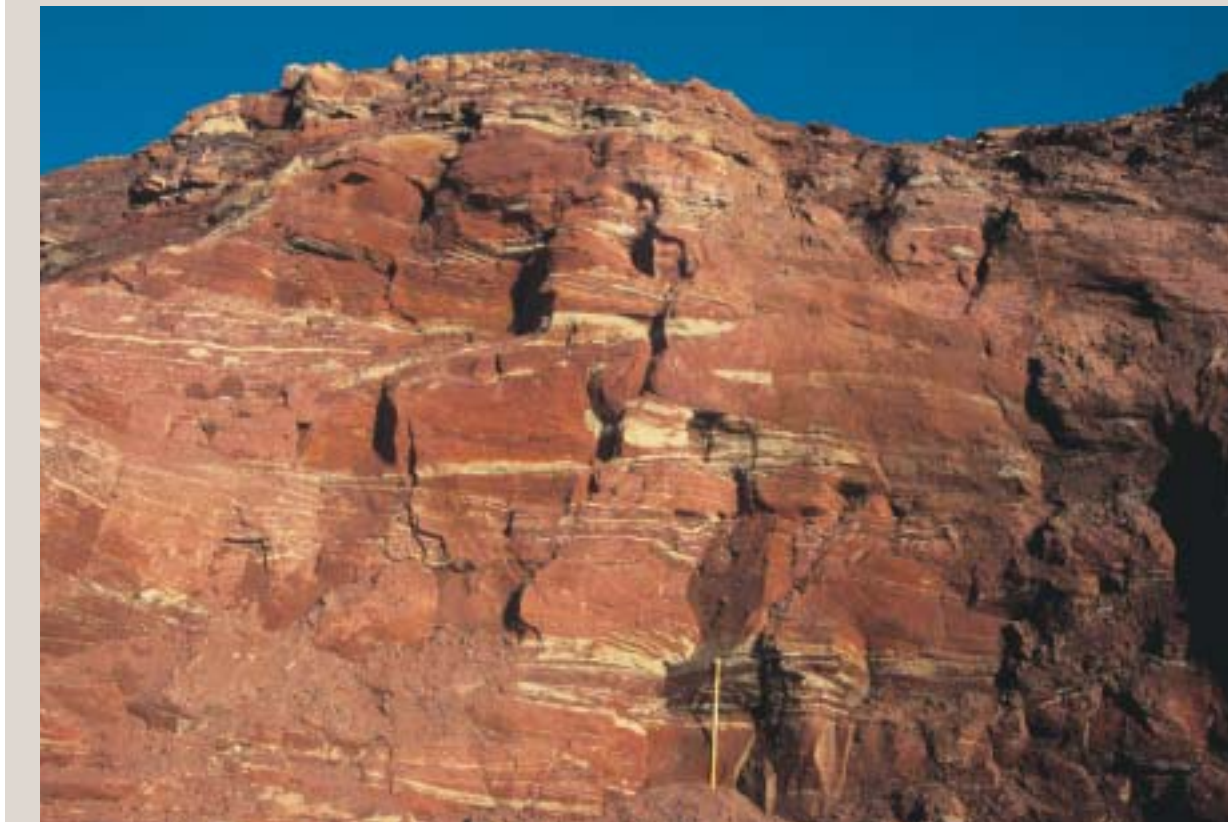


Devonian Old Red Sandstone (ORS; left half of the outcrop, red-brown units), Moskusoksefjord, East Greenland. The ORS lies unconformably on pre-Caledonian sediments, Caledonian granites and Precambrian gneisses (right half of the outcrop, including the pale tan unit in the middle). All units, including the Devonian ORS, are folded.

Photo: Ebbe Hartz

development of the Nordkapp, Tromsø, and Bjørnøya Basins. In Svalbard, Western Norway and East Greenland, the Devonian ORS basins are strongly folded. In Svalbard, this folding is clearly Late Devonian-Early Carboniferous in age. In Western Norway, folding commenced during deposition of Mid Devonian sedimentary basins, but continued into Late Devonian-Early Carboniferous time.















By the **Late Carboniferous-Early Permian**, northward drift of the Laurussia landmass carried the Barents Shelf into subtropical latitudes, and Greenland-Scandinavia-British Isles essentially stretched from 30°N to the equator. From Early Carboniferous time, this region became part of the Pangean supercontinent with orogenic accretion around its fringes associated with the Inuitian, Variscan and Uralian Orogenies. By the Late Carboniferous, the Variscan Orogen had become relatively inactive. In Central East Greenland, Late Carboniferous continental conglomerates and sandstones accumulated in N-S-oriented half-grabens. The Barents Shelf is marked by widespread deposition of shallow-to-deeper-shelf carbonates, especially during Late Carboniferous times. In the western part of the shelf, evaporites of Late Carboniferous to Early Permian age (subtropical conditions) were deposited along with carbonates in the subsiding Tromsø and Nordkapp grabens. A large undated evaporate basin offshore Northeast Greenland is probably of the same age. The Oslo region experienced several events that culminated with rifting and peak magmatic activity in the Early Permian. Magmatism affected large areas of the North Sea, the British Isles, Germany and SW Sweden where vast amounts of NW-SE-trending dikes intruded parallel to the Tornquist Margin.

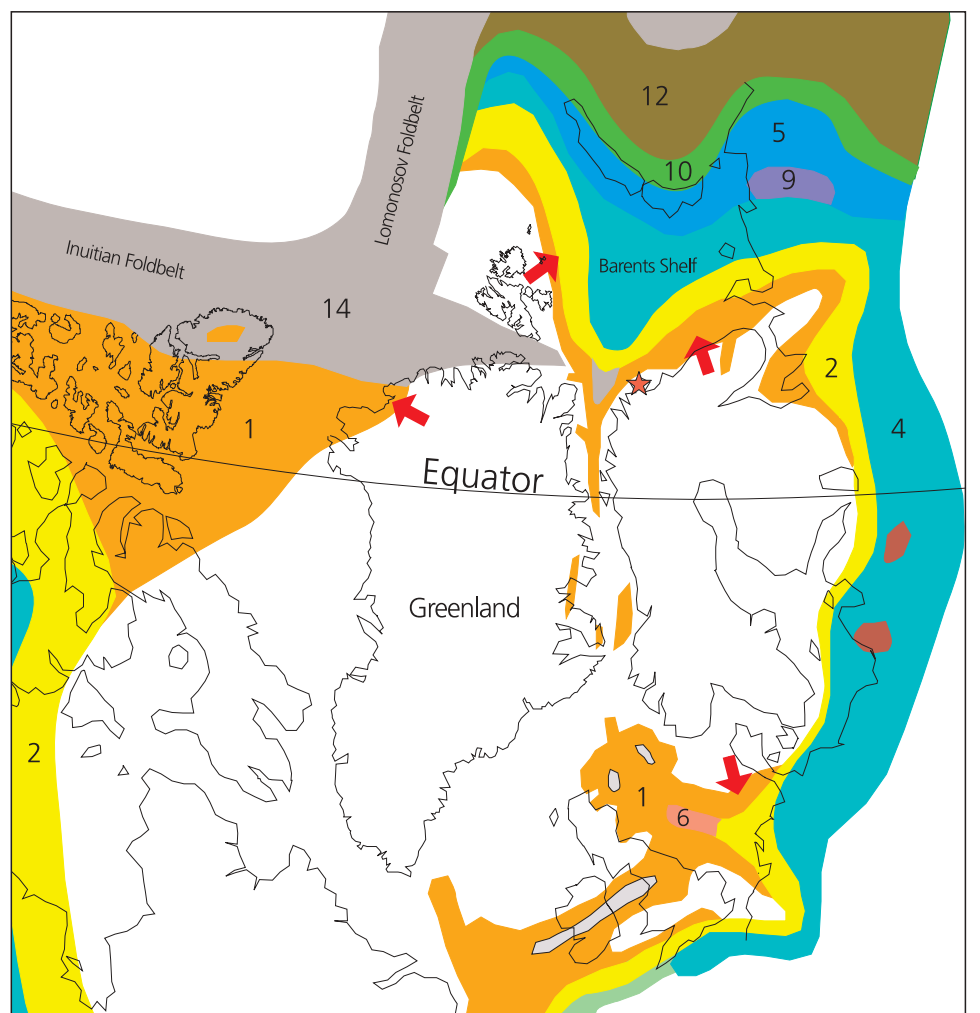
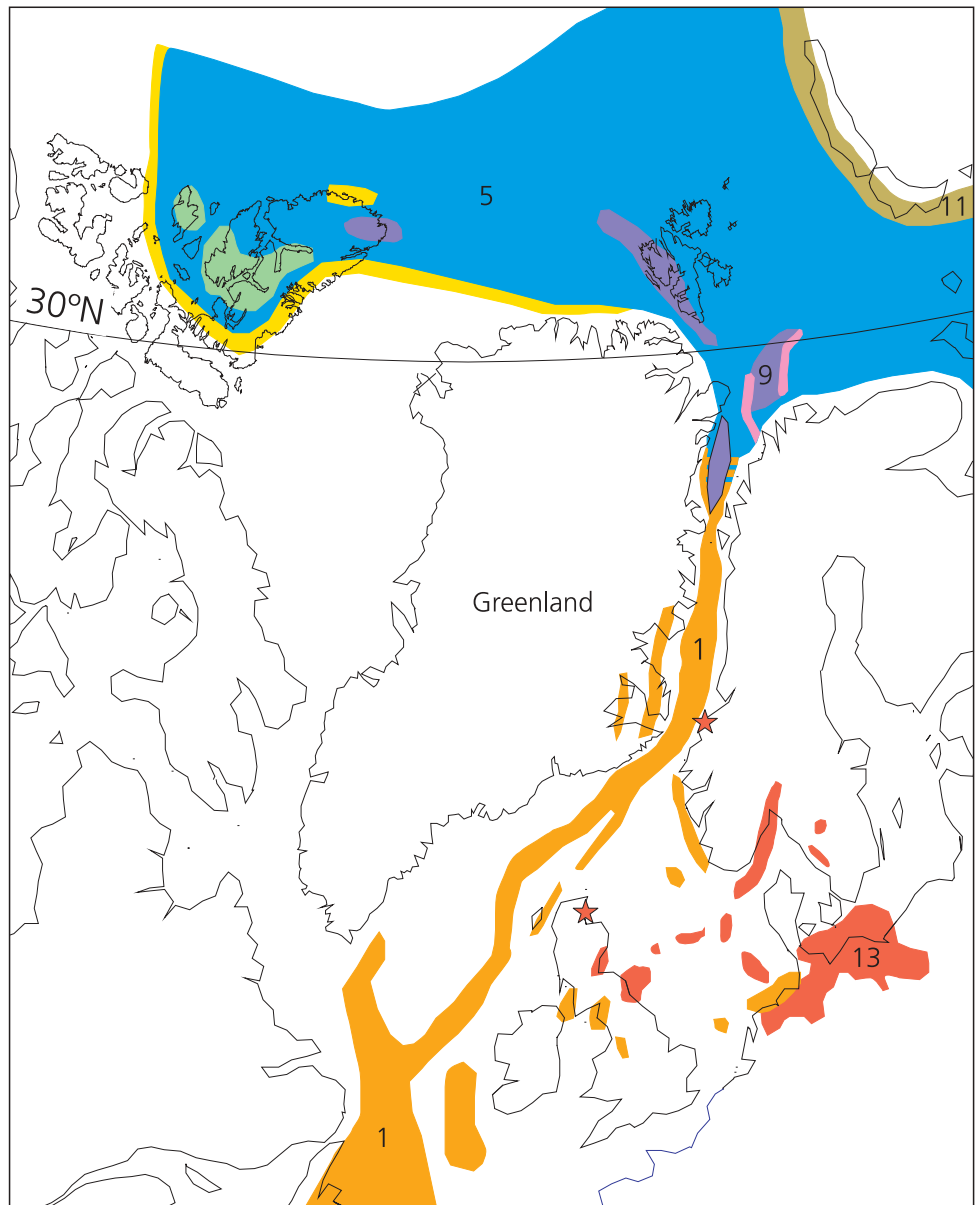


Carboniferous red beds from Kap Stosch, central East Greenland, occurring in N-S-trending grabens.

Photo: Ebbe Hartz

LATE CARBONIFEROUS-
EARLY PERMIAN (290 Ma)
Kasimovian-Sakmarian

- 1  mainly continental clastics
- 2  deltaic-shallow marine, mainly sands
- 3  shallow marine, mainly shales
- 4  shallow marine, carbonates and clastics
- 5  shallow marine, mainly carbonates
- 6  evaporites and clastics
- 7  mainly evaporites
- 8  evaporites, clastics and carbonates
- 9  evaporites and carbonates
- 10  deeper marine clastics &/or carbonates
- 11  deeper marine, mainly sands (flysch)
- 12  basins formed by oceanic crust
- 13  magmatism (local dikes)
- 14  active fold belt
- 15  inactive fold belt
-  direction of clastic influx
-  active sea-floor spreading axis
-  inactive/abandoned sea-floor spreading axis



LATE DEVONIAN (360 Ma)
Frasnian - Famennian

Global 2

By the **Late Permian**, Siberia collided with Baltica and Kazakhstan and joined the Pangea Supercontinent. This collision is almost coincident with extrusion of the largest known igneous province in the world, the Siberian Traps, which is temporally linked to the massive Permo-Triassic extinction event (251 Ma). Centered on the equator, Pangea stretched from the South Pole to the North Pole. During most of its existence, Pangea was encircled by large subduction systems. These were complemented by major extension in the interiors of Pangea (e.g. North Sea and Norwegian-Greenland region). Pangea did not actually include all the landmasses, and in the eastern hemisphere and in the Paleotethys realm, several Asian landmasses remained separated from Pangea in the Late Permian. In the Late Permian, an important rift to drift event occurred along the peri-Gondwana margin: the opening of the Neotethys. This opening initiated subduction and eventually destruction of the Paleotethys.

By the **Late Triassic**, Pangea had drifted northward. The Paleotethys was almost consumed at the expense of the Neotethys and many peri-Gondwanan terranes had become transferred to the European margin of Pangea. At the same time, crustal shortening took place in Arctic Siberia (Taimyr), Novaya-Zemlya and the Southern Barents Sea. Late Triassic coincided with onset of systematic changes in the continental configuration in northern Pangea, i.e. Greenland-Europe rotated counterclockwise relative to North America, possibly causing compression in the Baffin Bay area. Pangea was probably at its largest by Late Triassic time but intra-supercontinental rifting and continental re-organization were continually taking place.

By the **Mid Jurassic**, Pangea continued its stepwise break-up. After an episode of igneous activity along the east coast of North America and the northwest coast of Africa, the Central Atlantic Ocean opened as North America moved northwestward relative to Africa. This movement also gave rise to sea-floor spreading in the Gulf of Mexico. At the same time, on the other side of Pangea, extensive volcanic eruptions along the adjacent East Africa and Antarctica margins heralded the formation of the western Indian Ocean. The Mid Jurassic was, therefore, associated with two major global

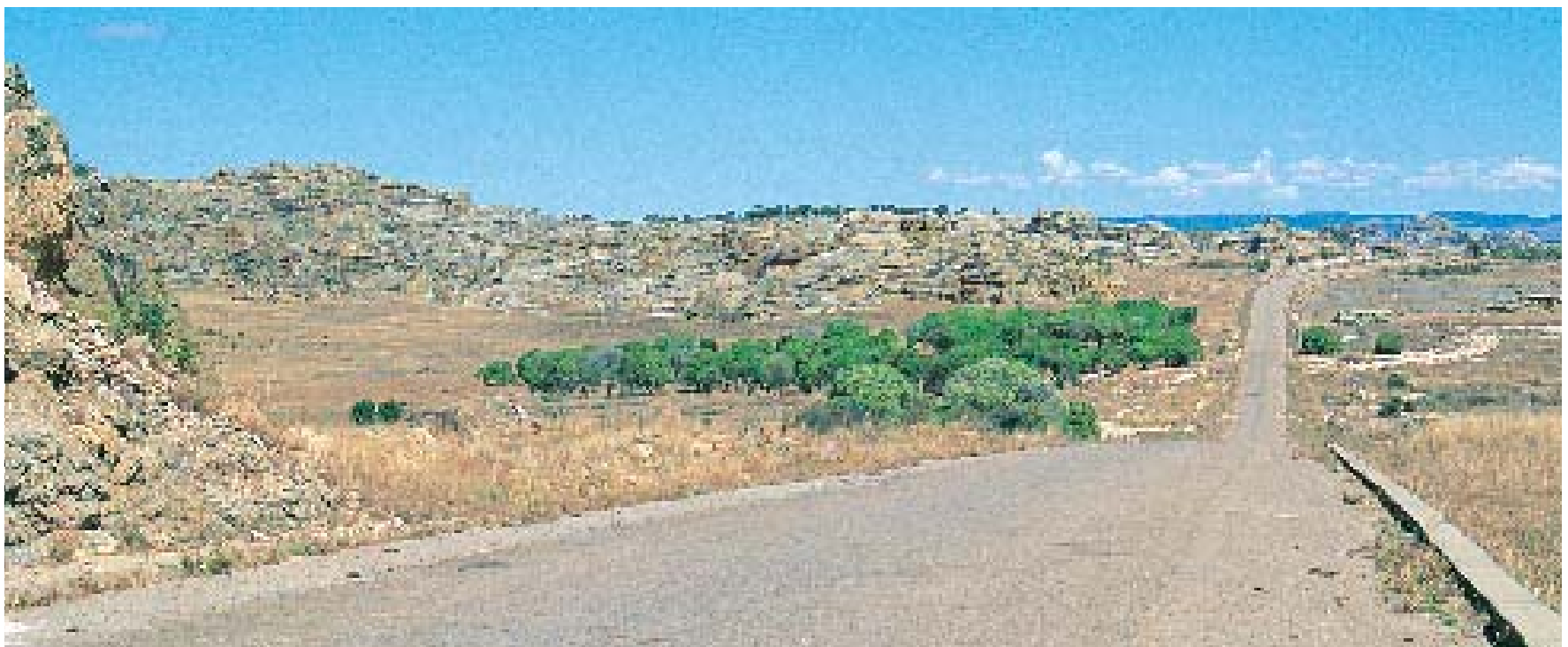


Folded Permian delta sequence from the Taimyr peninsula, northern Siberia. Folding affected the entire latest Precambrian through Early Triassic sedimentary sequence of Taimyr. Middle Triassic dolerites which intrude the Carboniferous-Early Triassic sedimentary section are also folded and thus give a maximum age for the shortening episode which affected Taimyr, Novaya Zemlya and the Southern Barents Sea. Robert Scott for scale.

Photo: Elizabeth A. Eide

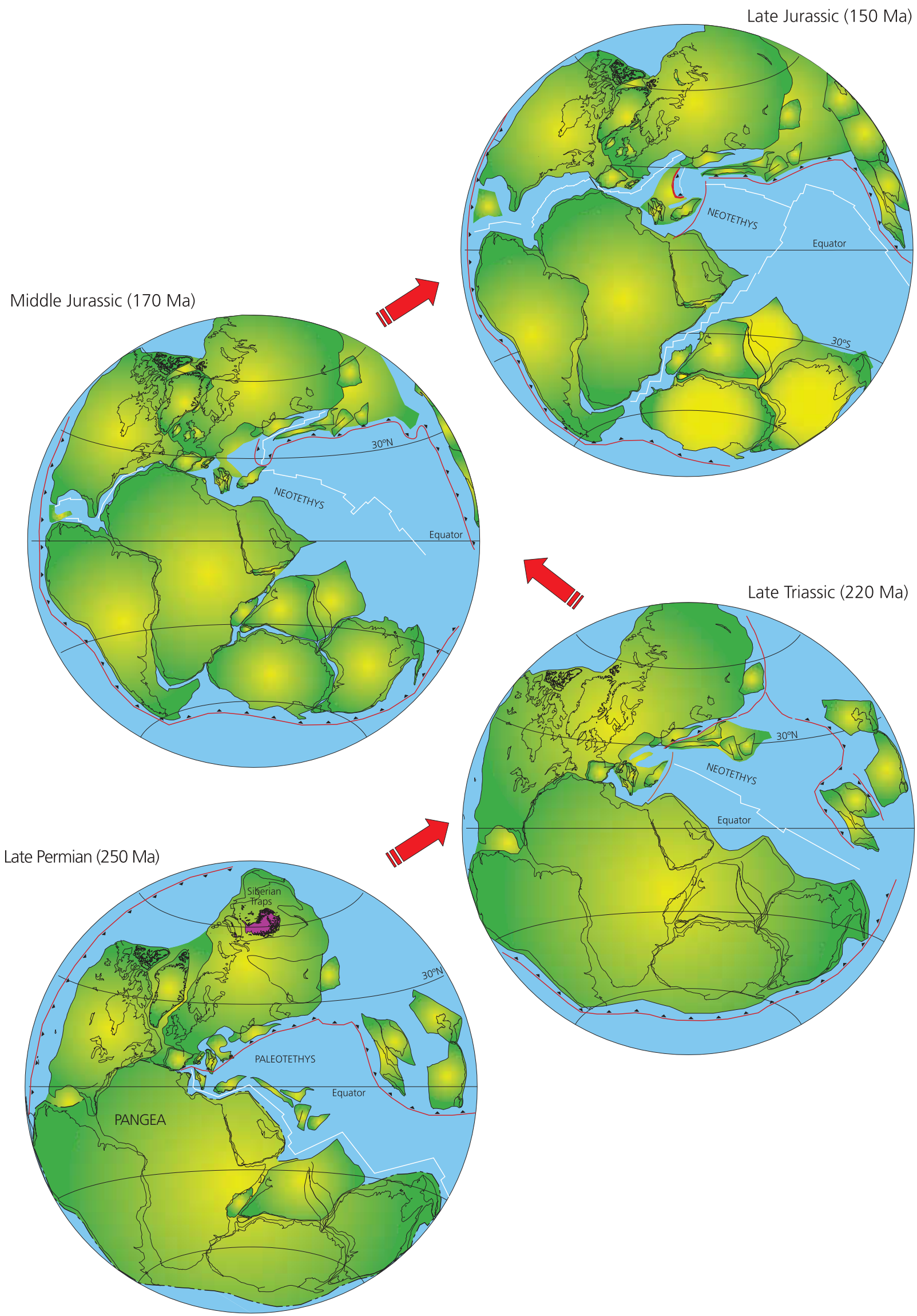
events that led to break-up of Pangea, i.e. initiation of sea-floor spreading in the Central Atlantic and Gulf of Mexico and rifting of the south-Pangea elements (Antarctica-Australia-Madagascar-Seychelles-India).

In **Late Jurassic** times, sea-floor spreading in the Central Atlantic connected northeastward into the Neotethys realm via the major Azores-Gibraltar transform. At the same time, sea-floor spreading commenced between Africa and the combined Antarctica-Australia-Madagascar-Seychelles-India landmasses. This new oceanic domain connected with the main Neotethys domain. By the Late Jurassic or Early Cretaceous, the Asian landmasses collided with Europe to form Eurasia.



The Jurassic Isalo Group sandstone, southwestern Madagascar. These rocks were deposited in grabens developed during Mesozoic rifting related to breakup of Pangea.

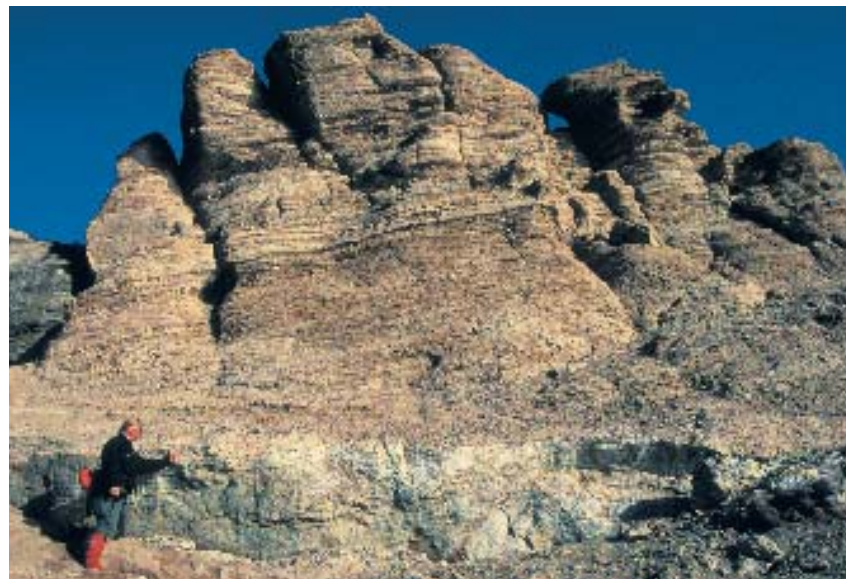
Photo: Elizabeth A. Eide



Regional 2a

During the **Late Permian**, the Barents Shelf region had drifted out of the subtropics and Mid Norway was located at around 35°N, whilst the North Sea area remained in the subtropics. Marine basins were developed in East Greenland in areas previously experiencing continental conditions. The North Sea was an arid environment. Flooding of the low parts of the Permian Basins occurred from the north as a result of rifting along the Viking Graben, combined with a sea-level rise. Catastrophic opening of a marine gateway led to deposition of black shales on aeolian sand dunes. Evaporites and minor marine carbonates of the Zechstein Group were deposited in restricted basins thereafter. Continued northward movement of Laurussia ended the conditions appropriate for carbonate platform and evaporitic environments in some areas of the Barents Shelf as the climate changed from warm and arid to more temperate and humid (open marine environment). Marine transgression also created deeper marine areas. In the eastern Barents Shelf, thick terrigenous deposits sourced from the Uralian fold belt to the east were deposited.

In the **Late Triassic**, relatively thin units of evaporites and evaporites/clastics were deposited in the Norwegian-Greenland Sea area. Mid Norway at this time was at around 45°N. The North Sea remained almost entirely under a continental-paralic regime, with periods of marine incursion coming from the Tethys realm in the southeast. In the Central and Northern Basins, sediments were predominantly coarse clastics but the episodes of marine transgressions brought minor halites and anhydrites in the Late Triassic. Lacustrine, anhydritic sediments and continental coarse clastics dominated the East Greenland area. On the Norwegian Shelf, continental clastics also dominated the Middle-Late Triassic with some periods of marine incursion. In the West Barents Shelf, Svalbard area, and the northern part of the Norwegian-Greenland Sea rift, rifting that started rapidly during the Permo-Triassic had abated by Middle Triassic. These areas began to subside and deep depocenters were developed.



Sedimentary rocks associated with the Late Permian marine transgression, Hold with Hope, East Greenland. Carboniferous aeolian sandstone at base is faulted into contact with a gypsum (evaporite) layer that is, in turn, overlain by a thick beach conglomerate. This sequence lies just below deep-marine black shales of the Ravnefjellet Formation. The evaporites attest to the arid conditions present in restricted basins as Greenland-Mid Norway drifted northward, out of the subtropics. Camilla Fjeldheim holds the gypsum layer.





Photo: Ebbe Hartz

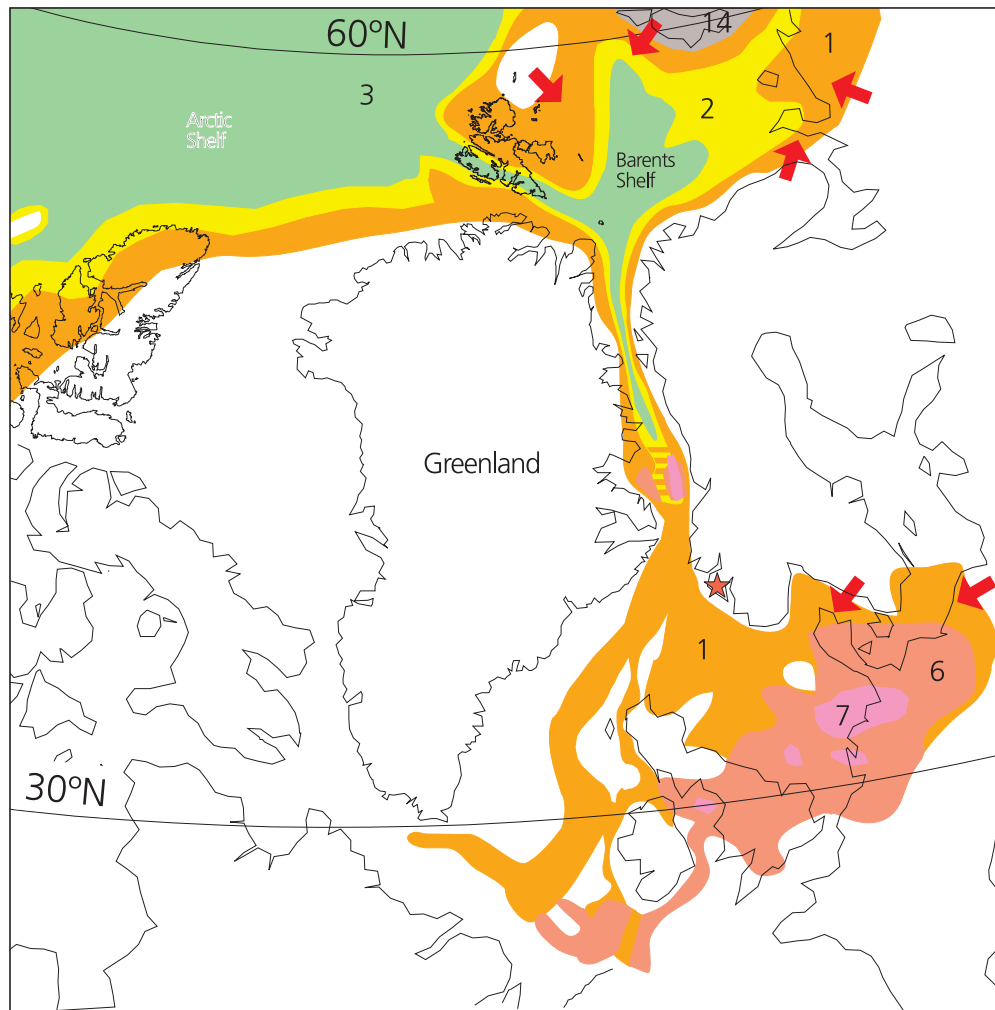


Triassic shales, sandstones and conglomerates (near outcrop and opposite wall) with >40 m high clinoforms, representing major deltas building northwards, northern Hold with Hope. The Triassic is overlain by Tertiary basalts, forming the uppermost units (partially snow-covered) on the left side of the photograph.

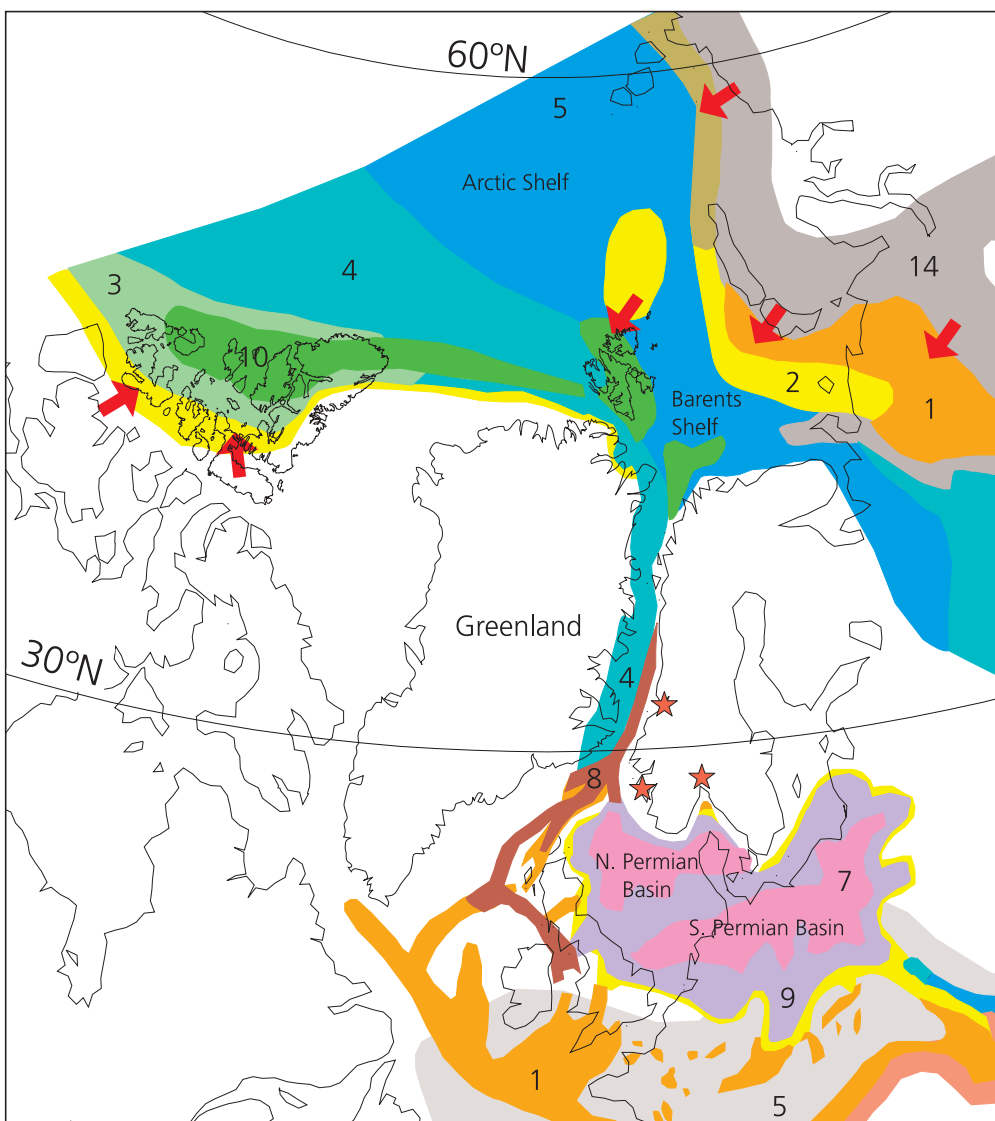
Photo: Ebbe Hartz

LATE TRIASSIC (220 Ma)
Carnian - Norian

- 1  mainly continental clastics
- 2  deltaic-shallow marine, mainly sands
- 3  shallow marine, mainly shales
- 4  shallow marine, carbonates and clastics
- 5  shallow marine, mainly carbonates
- 6  evaporites and clastics
- 7  mainly evaporites
- 8  evaporites, clastics and carbonates
- 9  evaporites and carbonates
- 10  deeper marine clastics &/or carbonates
- 11  deeper marine, mainly sands (flysch)
- 12  basins formed by oceanic crust
- 13  magmatism (local dikes)
- 14  active fold belt
- 15  inactive fold belt
-  direction of clastic influx
-  active sea-floor spreading axis
-  inactive/abandoned sea-floor spreading axis



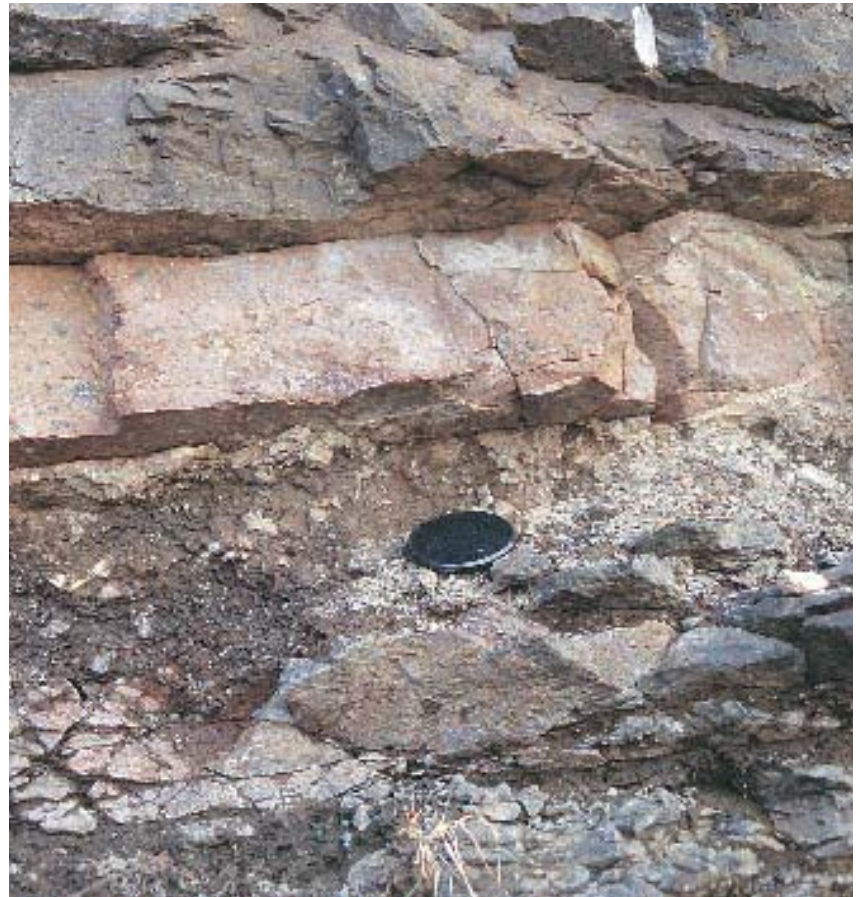
LATE PERMIAN (250 Ma)
Ufimian-Kazanian
'Zechstein'



Regional 2b

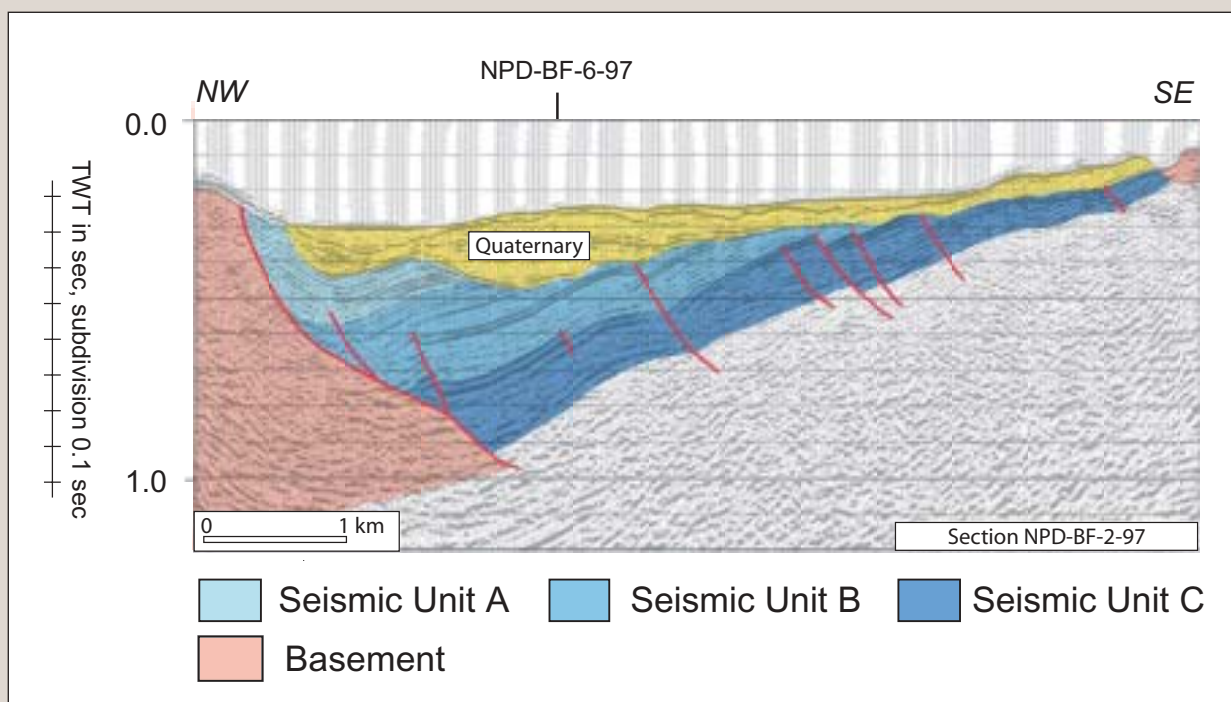
During the early **Middle Jurassic**, mantle-related up-warping of a large dome occurred in the central North Sea. Together with other uplifted areas, this led to restricted communications between the Arctic and Tethyan Seas, and caused total faunal provinciality between these realms. By late Middle Jurassic, the central North Sea rift-dome subsided and open marine conditions were reintroduced. Communications between the Arctic and Tethyan Seas resumed via the North Sea area and the Færoe-Rockall Rift. The uplifted area in the North Sea was centered on the triple junction of the Viking Graben, Central Graben and Moray Firth Basin and included Scotland. Basaltic lavas were extruded at the intersection of the three basins while subsidiary volcanic centers were established in the Viking Graben and in the Horda Basin. Rifting in the North Sea was associated with an extrusive center (Forties). The latter extrusives, probably of syn-rift origins, are also present in onshore areas in Scandinavia, e.g. volcanoes in SW Sweden (Scania). Mid Jurassic continental clastics and sands were deposited in non-marine to paralic environments (major reservoirs in the North Sea). Sea-level fall during the Bajocian caused rapid progradation of deltaic sediments along the Norwegian-Greenland Sea rift and the Barents Shelf (main reservoirs in the Mid Norway Basin and the southern Barents Shelf).

From the **Late Jurassic**, break-up of Pangea continued and was marked by step-wise northward propagation of the Central Atlantic sea-floor spreading axis. Rifting and fault-block rotation were widespread and most intense from latest Middle Jurassic to earliest Cretaceous. In addition to basin development observed offshore, this rifting phase is clearly represented onshore western Norway in the form of brittle reactivation of faults and genesis of fault-rock products. During the Late Jurassic, the main rift direction was E-W. Sea-level rise that commenced in early Bathonian continued to early Kimmeridgian. Dark organic-rich open-marine claystone deposition became widespread in the 'Kimmeridge Sea', stretching from southern England to the western Barents Shelf. The Arctic and Tethyan Seas were in open communication via the Norwegian-Greenland Sea rift and the basins of Western and Central Europe.



Brittle fault rock from Atløy, western Norway. The red breccia, of Late Jurassic-Early Cretaceous age, cuts sharply through a green, Permian breccia which in turn, opportunistically used and cross-cut a ductile, Devonian crustal-scale extensional detachment. The brittle fault rocks relate to the intensification of rifting and fault-block rotation in the North and Norwegian Seas, documented in offshore seismic sections.

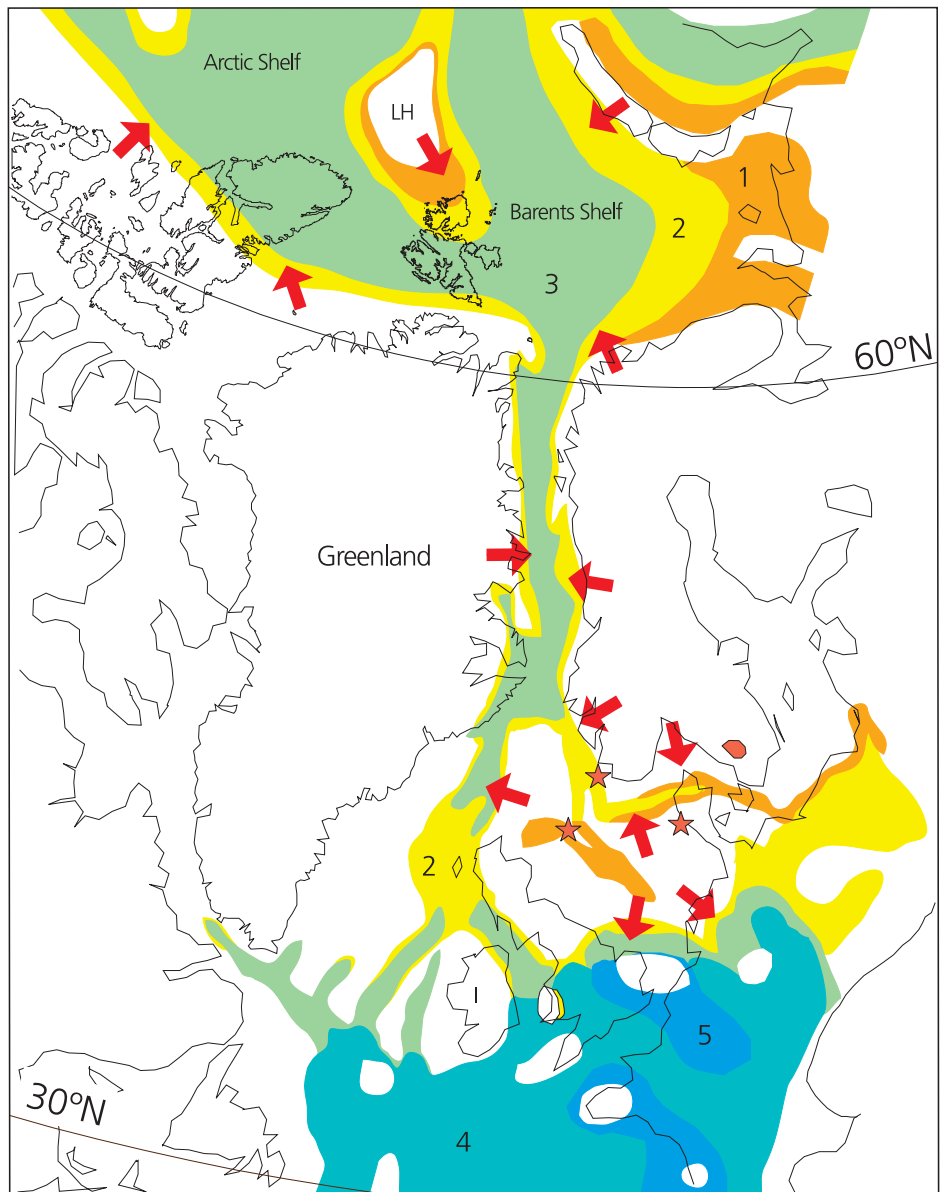
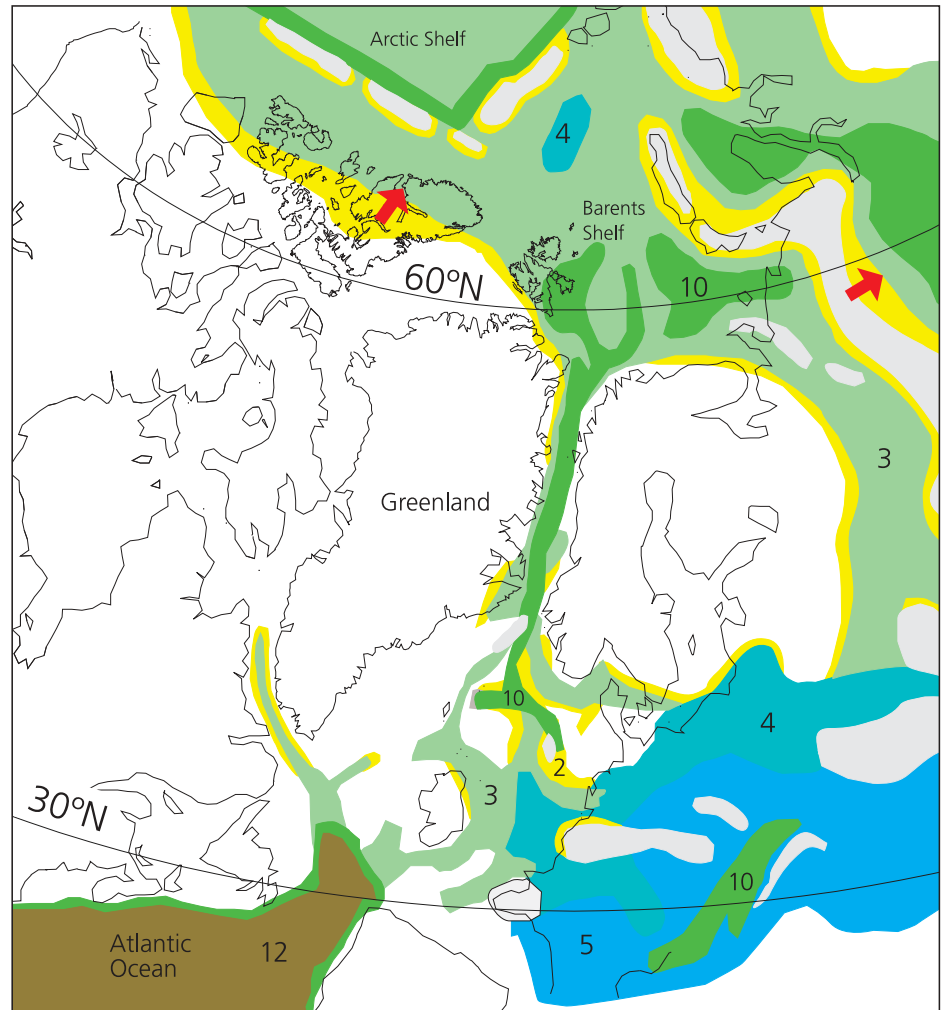
Photo: Elizabeth A. Eide



The Beitstadfjord Basin, within the north-westernmost portion of Trondheimsfjord, is one of a series of small Jurassic grabens located along the Mid Norway coast. The northwestern side of the Beitstadfjord Basin lies along the NE-SW-trending Verran Fault, a major strand of the Møre-Trøndelag Fault Complex. While the exact age of the units is uncertain due to the lack of in situ rock samples, Units A, B and C, interpreted from shallow seismic profiles have been constrained to the Middle Jurassic (Fangst Group) and early Late Jurassic (Viking Group). After Sommaruga & Bøe, in press.

LATE JURASSIC (150 Ma)
Oxfordian - Tithonian

- 1 mainly continental clastics
 - 2 deltaic-shallow marine, mainly sands
 - 3 shallow marine, mainly shales
 - 4 shallow marine, carbonates and clastics
 - 5 shallow marine, mainly carbonates
 - 6 evaporites and clastics
 - 7 mainly evaporites
 - 8 evaporites, clastics and carbonates
 - 9 evaporites and carbonates
 - 10 deeper marine clastics &/or carbonates
 - 11 deeper marine, mainly sands (flysch)
 - 12 basins formed by oceanic crust
 - 13 magmatism (local dikes)
 - 14 active fold belt
 - 15 inactive fold belt
- direction of clastic influx
 - active sea-floor spreading axis
 - inactive/abandoned sea-floor spreading axis



MIDDLE JURASSIC (170 Ma)
Bajocian - Bathonian

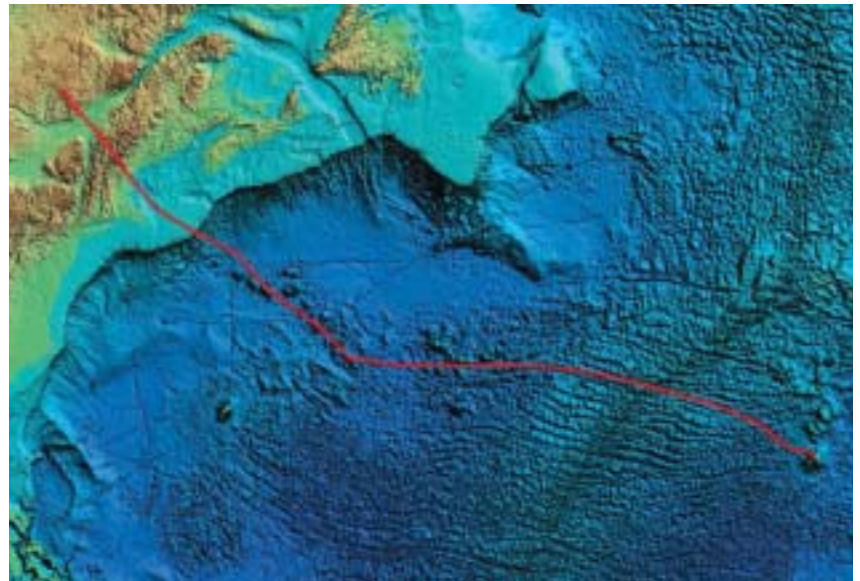
Global 3

During the **Early Cretaceous**, South America separated from Africa shortly after 130 Ma whilst sea-floor spreading in the Mozambique Ocean between Africa and the combined Madagascar-Seychelles-Greater India-East Antarctica landmasses ceased. The connection between the Central Atlantic and the Tethys persisted. Laurasia was now formed as the Asian landmasses had collided with Europe. From Early Cretaceous and onwards, the maps are based on a hotspot frame and velocity vectors are drawn on the maps (radius of circles on maps are approximately 1 cm/yr) along with mean plate-velocities. Selected hotspots are also shown (I=Iceland, G=Great Meteor, T=Tristan da Cunha, M=Marion, K=Kerguelen, R=Reunion).

Later in the **Early Cretaceous**, South Atlantic sea-floor spreading was well underway and was propagating northward. The South Atlantic spreading system became connected to a new spreading system, the Eastern Indian Ocean, which separated Madagascar-Greater India from East Antarctica-Australia. The Central Atlantic-Tethys connection ceased and instead the Central Atlantic system propagated northwards and resulted in the opening of the Bay of Biscay and counterclockwise rotation of Iberia relative to France. Sea-floor spreading in the Bay of Biscay was short-lived and terminated by 84 Ma.

In the **Late Cretaceous**, the Central Atlantic spreading system had abandoned the Bay of Biscay, and instead propagated northward into the Labrador Sea between Greenland and North America. Eurasia, Greenland and North America were all drifting northwestward, probably driven by far-field stresses, but differential velocities led to sea-floor spreading in the Labrador Sea and continued extension between Greenland and Eurasia. The South Atlantic spreading system propagated northward and connected with the Central Atlantic and Gulf of Mexico systems. In the Indian Ocean, India-Seychelles separated from Madagascar at around 85 Ma. The Late Cretaceous of Madagascar is characterized by widespread magmatism related to separation of Madagascar and India-Seychelles. This Western Indian Ocean spreading system probably connected with the Tethys that had narrowed considerably. The Cretaceous climate was considerably warmer than today, and mild climatic conditions were in part due to the fact that shallow seaways covered the continents during the Cretaceous. Higher sea level was due to rapid sea-floor spreading dispersed around the globe. Warm water from the equatorial regions was also transported northward, warming the polar regions. Shallow seaways covered most of the continental landmasses since sea level was 100-200 meters higher than today.

By the **Early Tertiary**, Greater India had separated from the Seychelles and caused a ridge jump in the Western Indian Ocean. Greater India separated from the Seychelles at around 65 Ma and collided with Asia at around 50 Ma. During break-up Greater India attained velocities of up to 18 cm/yr. This is the highest velocity recorded for any continental plate in Mesozoic and Cenozoic times, and was propelled by thermal buoyancy of the Reunion hotspot and subduction of old and dense Tethyan oceanic lithosphere beneath Asia. Sea-floor spreading between Greenland and Europe (NE Atlantic) commenced in the Early Tertiary (Anomaly 24; ca. 53 Ma), and was associated with vast igneous activity in the UK, Ireland, the F eroes, Greenland and the West Greenland-Baffin corridor. The igneous activity in the NE Atlantic shows a wide age-range, but peaks between 55 and 50 Ma.



Trace of the Great Meteor hotspot track. The Great Meteor hotspot first appeared between 136 and 118 Ma, as evidenced by magmatic rocks now exposed in the Monteregian Hills and White Mountains in North America. The New England seamounts (103 – 82 Ma) follow the NW-SE oriented leg of the track offshore. At ca. 80-82 Ma a marked change in direction of plate motion is observed by the change in orientation of the hotspot track from NW-SE to more E-W. The hotspot is active today (Great Meteor seamount).



Cooling cracks in a Late Cretaceous rhyolite from St. Mary's Island, just off the southwest coast of India. The rhyolites were part of a widespread magmatic system that is today exposed on Madagascar, Seychelles and India. The magmatism was related to the separation of India-Seychelles from Madagascar as Gondwana continued to disintegrate and the South Atlantic and Indian Oceans continued to widen.

Photo: Trond H. Torsvik

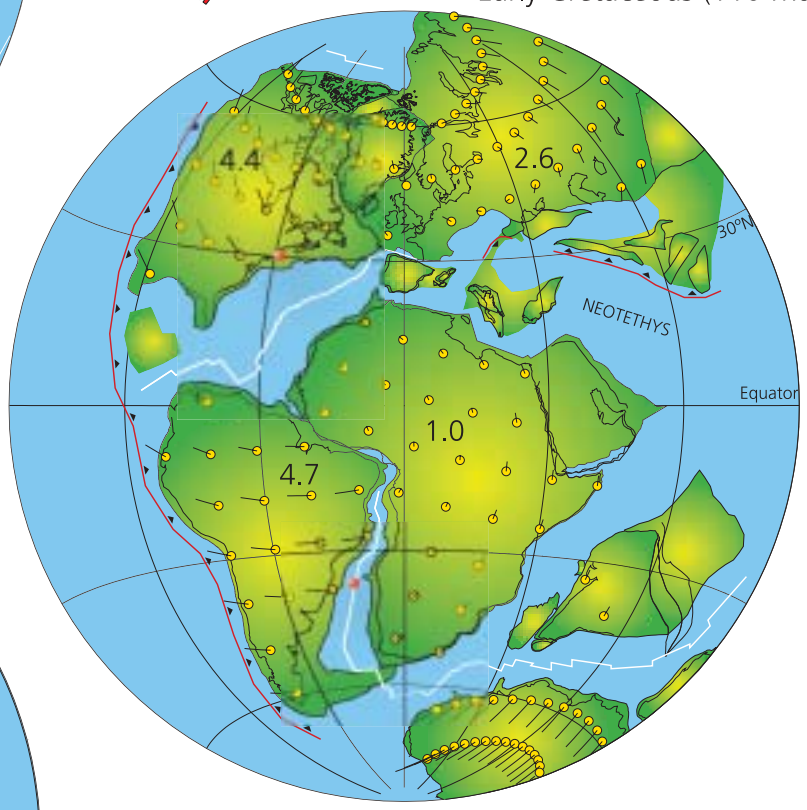
Late Cretaceous (80 Ma)



Early Tertiary (60 Ma)



Early Cretaceous (110 Ma)



Early Cretaceous (130 Ma)



Regional 3a

During the **Early Cretaceous** (Berriasian-Barremian), rifting changed from E-W-(Late Jurassic) to NW-SE-orientation, and a rift system was established from the Rockall Trough to the western Barents Sea. Rapid post-rift subsidence occurred in the North Sea, Norwegian-Greenland Sea rift, and on the Barents Shelf. However, structural highs and platform areas remained emergent – forming the sites of condensed sections with regional unconformities in the Hauterivian to Barremian. In the North Sea Basins, thick open-marine mudstones and shales were deposited in the basin centers whilst towards the flanks, shallow-marine sands became common. In the Norwegian-Greenland Sea, subsidence formed basinal areas along the rift-axis of the Møre and Vøring Basins where open-marine mudstones and shales were deposited. The emergent or high areas became the source for shallow-marine sands that were deposited on the fringes. Deltas were developed as a result of a sudden sea-level fall during Mid Barremian times. The Vøring Basin was linked via the Lofoten margin and Harstad Basin into the Tromsø and Bjørnøya Basins of the SW Barents Sea. Shallow basins within the platform areas (e.g. Helgeland, Jameson Land, Hammerfest and Nordkapp Basins) accumulated lime-rich, open-marine mudstone and shale. On the Barents Shelf, marine clastics were deposited in rim synclines of the Nordkapp Basin and in subsiding troughs west of Novaya Zemlya. Sea-level fall (forced regression due to Alpha plume) resulted in renewed delta propagation from the transgressed land areas in Svalbard, Franz Josef Land and Sverdrup Basin.



















Later in the **Early Cretaceous** (Aptian-Albian), renewed regional marine transgression occurred. This event was linked to the northward propagation of the Atlantic rift system. The transgression slowly submerged most of the area, not only the intra-basinal highs but also the crystalline basement in East Greenland and the northern Norwegian mainland. An open seaway from southern England to the Barents Shelf was created, finally establishing faunal connections from Spitsbergen to the Mediterranean by Mid Albian times. Sea-floor spreading along the North Atlantic continued to propagate northwards. An attempt to initiate sea-floor spreading along the southern Rockall Trough occurred. In the North Sea, rejuvenation of older landmasses resulted in the progradation of shelfal sands all around the fringes of the North Sea Basin. The Norwegian-Greenland rift system continued to expand at this time. The area experienced deep-water conditions due to the combined effects of extensive crustal extension/subsidence and a eustatic rise in sea level. Hence, the dominant Lower Cretaceous sediments are deep-water carbonates and clastics. The Møre and Vøring Basins experienced rapid subsidence and sedimentary infill with sills and/or lava flows. The Barents Shelf was subsiding beneath the wave-base and experienced sediment starvation and the dominant sediments became shallow-marine shales (important source rocks). The western part of the Barents Shelf contains major Cretaceous distal prodelta and pelagic clays with low organic carbon content.

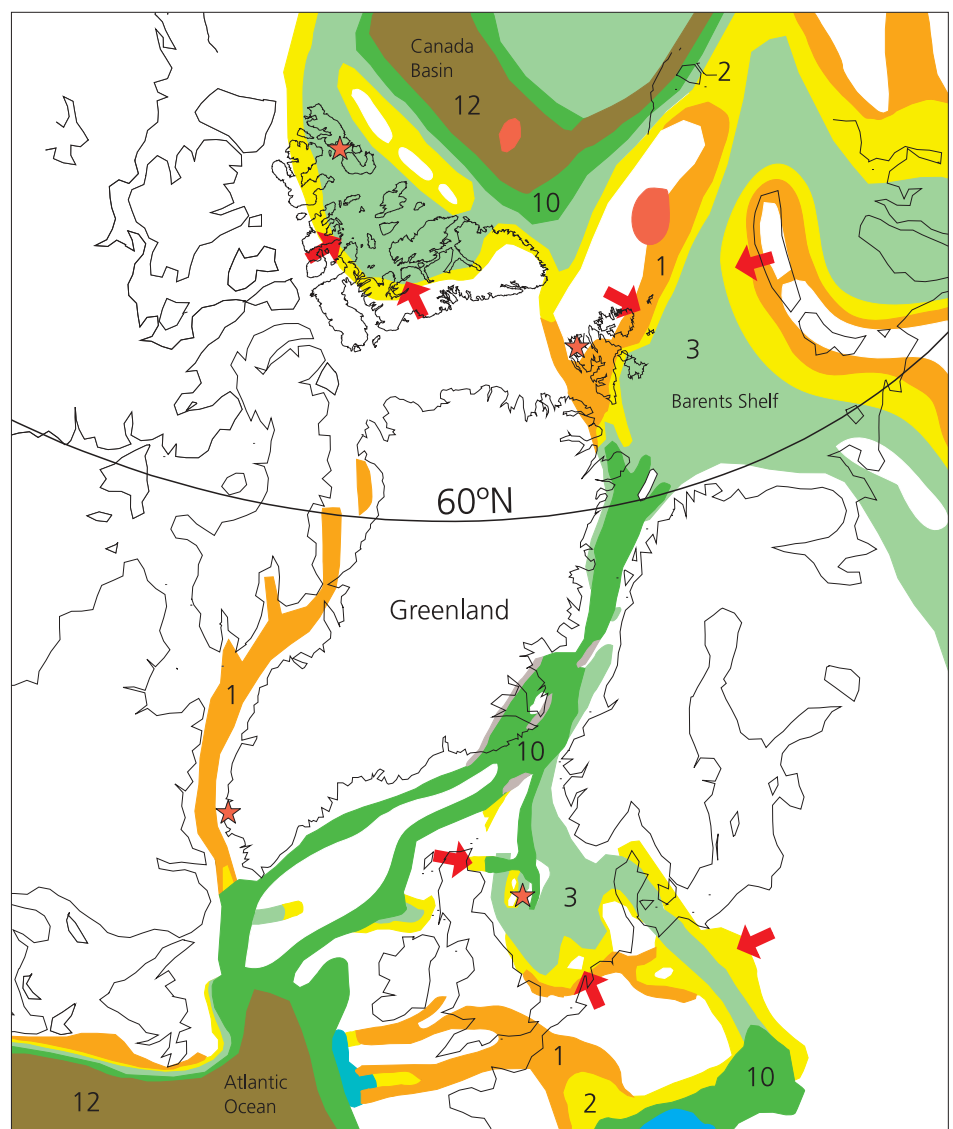
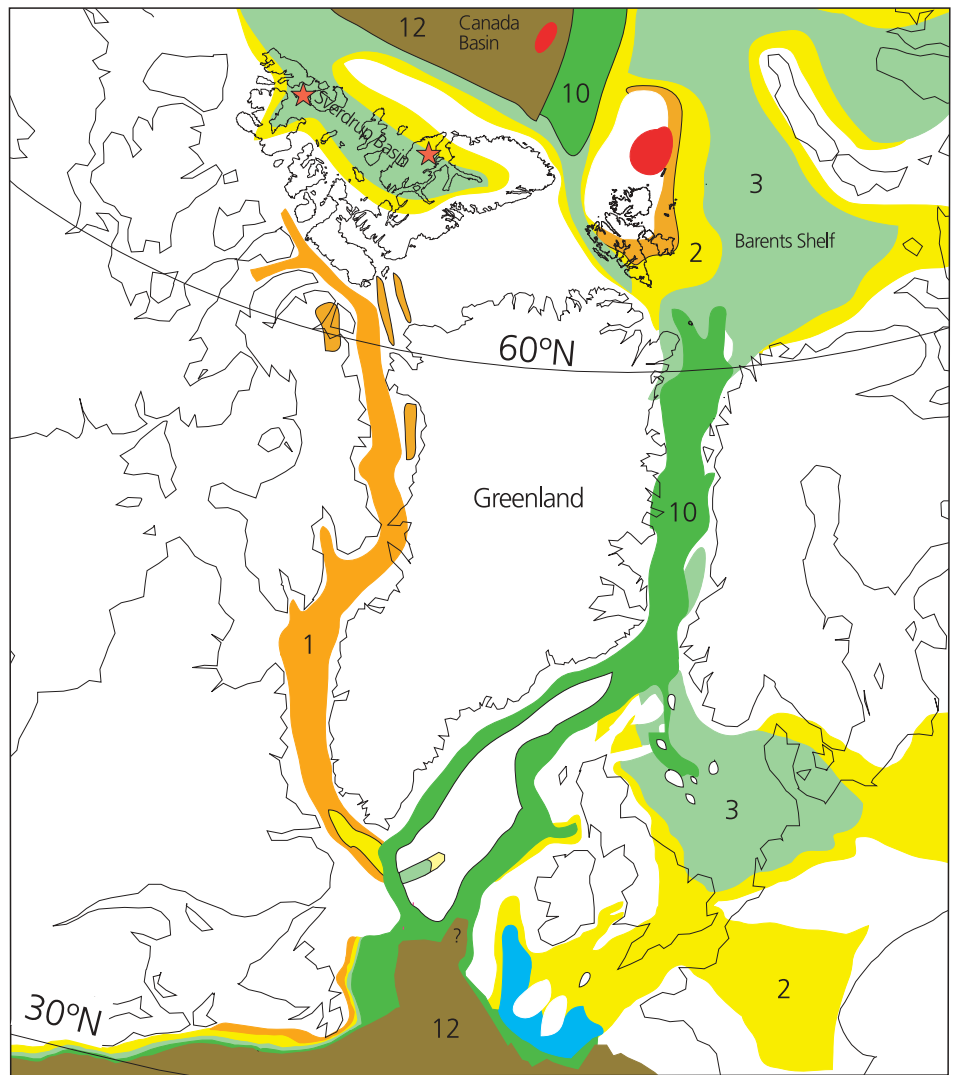


Lower Cretaceous (Aptian-Albian) tidal deposits of the Gulelv Member (pale yellow cliff-forming unit comprising the upper third of the outcrop), Steensby Bjerg Formation, East Greenland. Below the Gulelv, a thin Jurassic unit is underlain by a thick sequence of Triassic shallow-marine deposits. All three units are separated by unconformities marking Late Jurassic to Early Cretaceous fault events.

Photo: Ebbe Hartz

EARLY CRETACEOUS (110 Ma)
Aptian - Albian

- 1  mainly continental clastics
 - 2  deltaic-shallow marine, mainly sands
 - 3  shallow marine, mainly shales
 - 4  shallow marine, carbonates and clastics
 - 5  shallow marine, mainly carbonates
 - 6  evaporites and clastics
 - 7  mainly evaporites
 - 8  evaporites, clastics and carbonates
 - 9  evaporites and carbonates
 - 10  deeper marine clastics &/or carbonates
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 - 15  inactive fold belt
-  direction of clastic influx
 -  active sea-floor spreading axis
 -  inactive/abandoned sea-floor spreading axis



EARLY CRETACEOUS (130 Ma)
Berriasian - Barremian

Regional 3b

During the **Late Cretaceous**, the Atlantic rift propagated northwards and sea-floor spreading was initiated in the Labrador Sea. Rifting between Greenland and the Rockall Plateau also took place. Increased spreading activity caused a tectonically-induced sea-level rise, probably 100-300 meters above the present sea level, and connected the Arctic oceans with the southern Tethys Ocean. In the North Sea, rifting and transgression had flooded most of the low-lying areas, cutting off clastic input, and leading to the deposition of pelagic chalky limestones. Sea-level rise peaked during Campanian-Maastrichtian times when only the Scottish and Norwegian Highlands and Greenland remained emergent. Norwegian-Greenland Sea rifting increased in axial areas during the Late Cretaceous. Marine transgression overstepped the eroded rift margins in the Mid Norway offshore area, and submerged most of the remnant highs. Tectonism became more active during latest Turonian times and included faulting, accelerated basin subsidence and conjugate uplift, tilting and emergence of the bounding platform areas of the Møre and Vøring Basins. During this regional marine transgression, the Northern Barents Shelf was uplifted. The transgression, therefore, produced only a shallow shelf, leaving a condensed marine sedimentary sequence. Svalbard and the NW Barents Sea were subjected to intense erosion as the degree of uplift increased northwestwards. The Møre and Vøring Basins and East Greenland experienced faulting and subsidence while their flanks were uplifted and eroded.

In the **Early Tertiary**, the Norwegian Sea was marked by a transition from a continental-rift setting to a drift and passive-margin setting. Regional uplift, preceding break-up and sea-floor spreading, occurred in the entire Norwegian-Greenland Sea and surrounding areas, and was related to the influence of the Iceland plume. Most of the North Sea was cut off from oceanic circulation due to continued uplift from the Norwegian-Greenland Sea area, creating a basin-wide anoxic environment. A wide portion of the Norwegian-Greenland Sea and surrounding areas was uplifted due to an increase in heat flow. A general shallowing of the Møre and Vøring Basins occurred as a result of the regional uplift. The uplift created a major unconformity in the late Danian/early Thanetian along the marginal highs and basin flanks of both basins, and across the Vøring Basin. In the Vøring Basin, sediments eroded from the emergent flanks were deposited in shallow synclinal areas. In the Møre Basin and northern North Sea, thick Paleocene/Early Eocene sedimentary wedges propagated from the platform areas on both flanks and downlapped the base-Paleocene unconformity. By Early Eocene, the Reykjanes-Ægir-Mohns ridge system started to generate sea floor in the Norwegian-Greenland Sea. This was accompanied by extrusion of basaltic lavas that flooded the eroded marginal platforms.

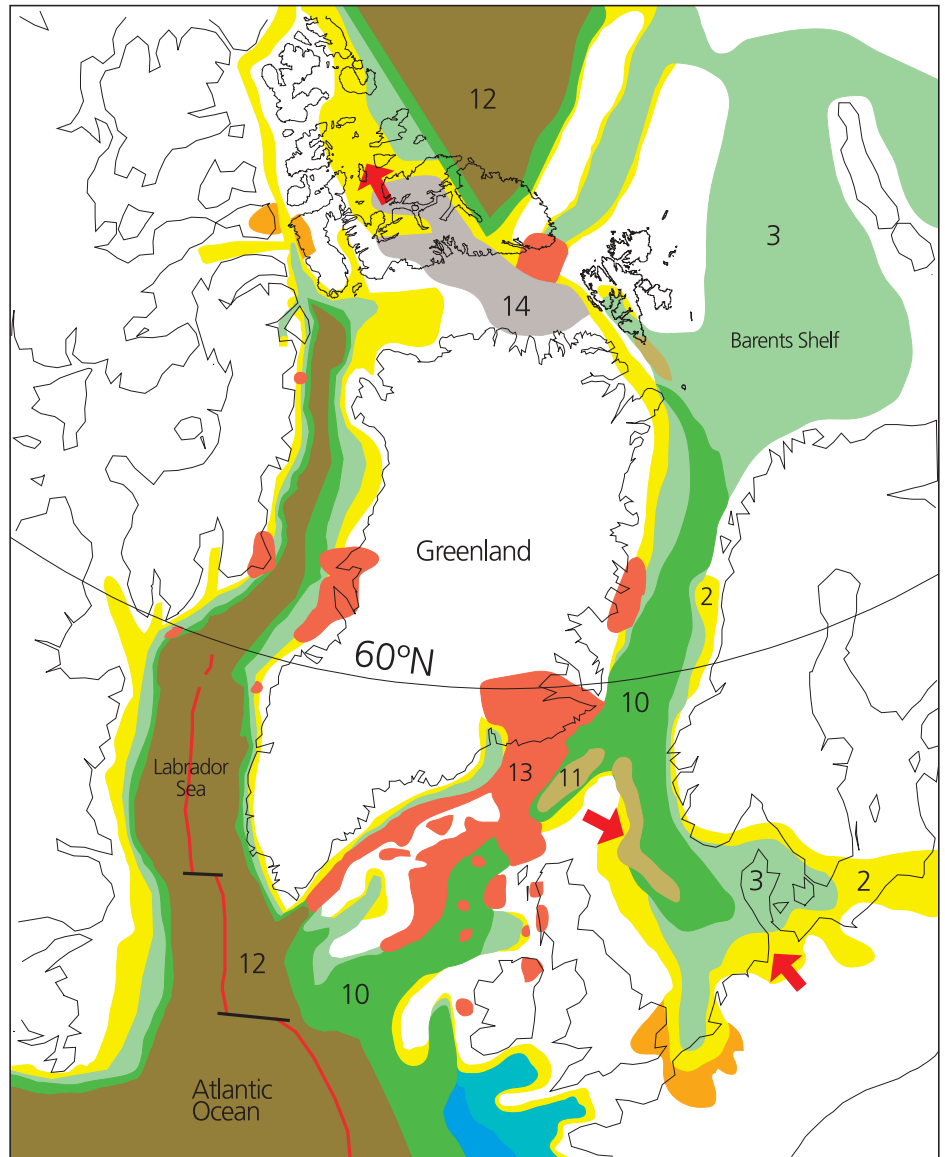


Mid Cretaceous through Tertiary sections from Reamurfjellet on Midterhukun, Svalbard. The upper sands are the Tertiary. Below are the Cretaceous Zillerberget (shale dominated), Langstakken (sand dominated), and Innkjegla (thick recessive unit) Members of the Carolinefjellet Formation. The top of the Dalkjegla Member is represented by the sands at the base of the section, through which a small gorge cuts.

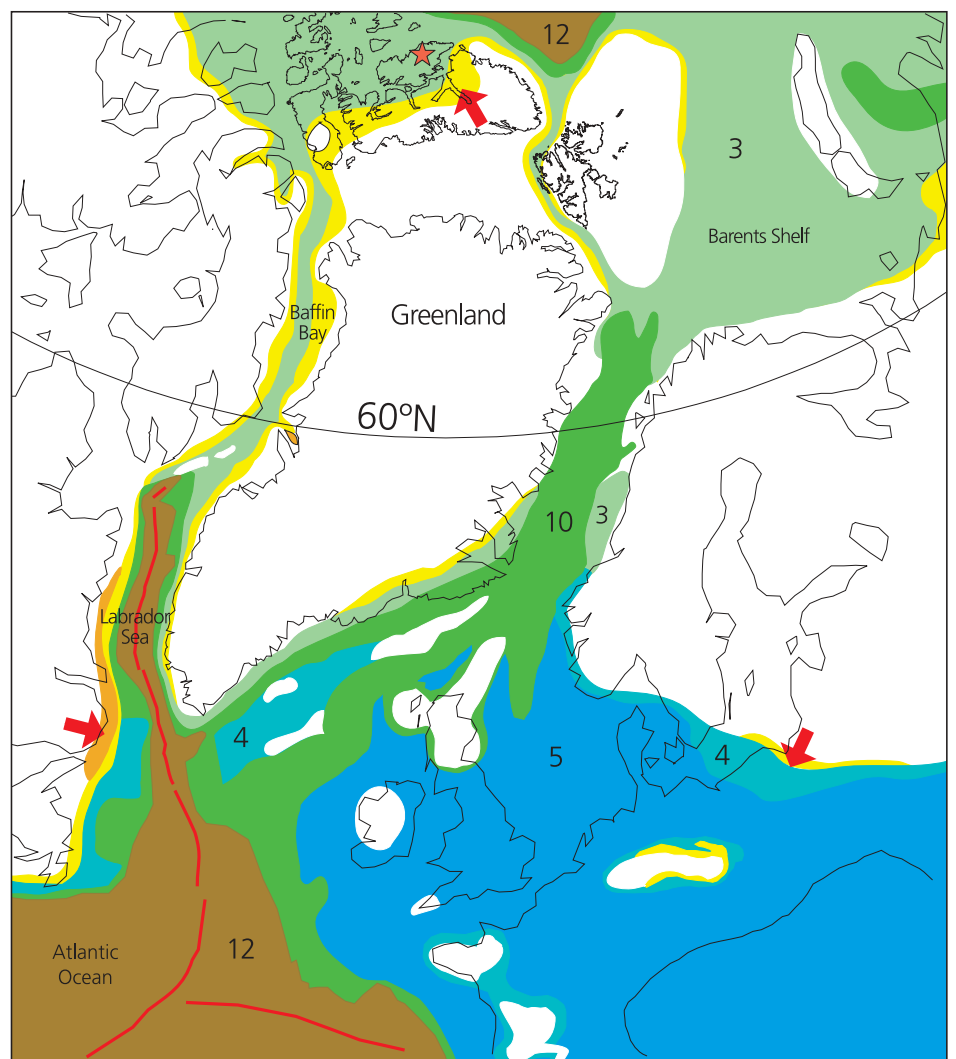
Photo: Harmon D. Maher, Jr.

EARLY TERTIARY (60 Ma)
Paleocene

- 1  mainly continental clastics
- 2  deltaic-shallow marine, mainly sands
- 3  shallow marine, mainly shales
- 4  shallow marine, carbonates and clastics
- 5  shallow marine, mainly carbonates
- 6  evaporites and clastics
- 7  mainly evaporites
- 8  evaporites, clastics and carbonates
- 9  evaporites and carbonates
- 10  deeper marine clastics &/or carbonates
- 11  deeper marine, mainly sands (flysch)
- 12  basins formed by oceanic crust
- 13  magmatism (local dikes)
- 14  active fold belt
- 15  inactive fold belt
-  direction of clastic influx
-  active sea-floor spreading axis
-  inactive/abandoned sea-floor spreading axis



LATE CRETACEOUS (80 Ma)
Turonian - Campanian

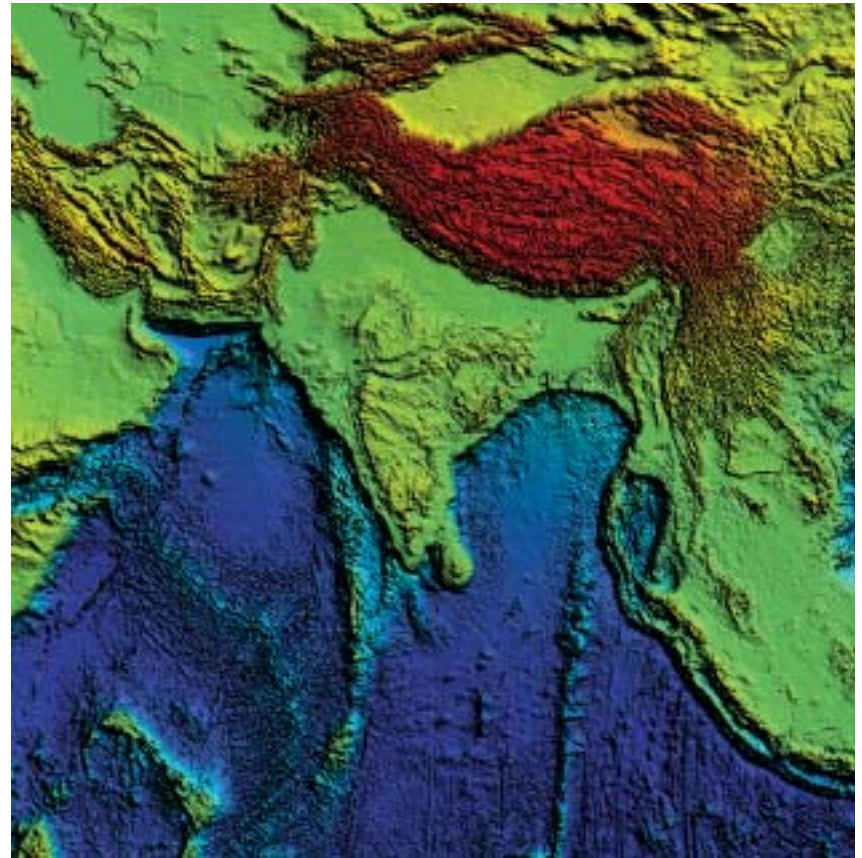


Global 4

During the **Eocene**, India collided with Asia (ca. 50 Ma). Sea-floor spreading in the NE Atlantic (between Greenland and Europe) had commenced (A24; ca. 53 Ma) and spreading in the Labrador Sea propagated northwards into the Baffin Bay.

By the **Miocene** (ca. 20 Ma), spreading between Greenland and North America had ceased and Greenland had collided with Ellesmere (Eurekan foldbelt). By this time a connection was almost established between the Norwegian-Greenland Sea and the Arctic spreading system. In the NE Atlantic, the Ægir Ridge had become extinct and a new spreading system had been established along the Eastern Greenland margin. This assisted the final separation of the Jan Mayen microcontinent from Greenland. In the Tethyan realm, Africa had collided with Eurasia, and Corsica-Sardinia, along with the southernmost part of Sicily, rifted off Iberia. During Late Cretaceous and Early Tertiary times, Eurasia showed predominantly NW drift, but during the Early Miocene Eurasia changed its course to a NE direction that coincided with the plate directions of both Africa and India. This suggests a strong plate coupling from the Miocene which is similar to that observed today.

Today, the Eurasian and the African plates are moving northeastward at speeds of 2.3 and 3.0 cm, respectively. The combined Greenland-North America landmass drifts northwestward at a speed of 2 cm/yr. Current half-spreading velocities between Greenland and Eurasia approximate 1 cm/yr. Absolute plate directions are similar to those established during the Late Oligocene-Early Miocene (30-20 Ma) but individual plate speeds differ somewhat.



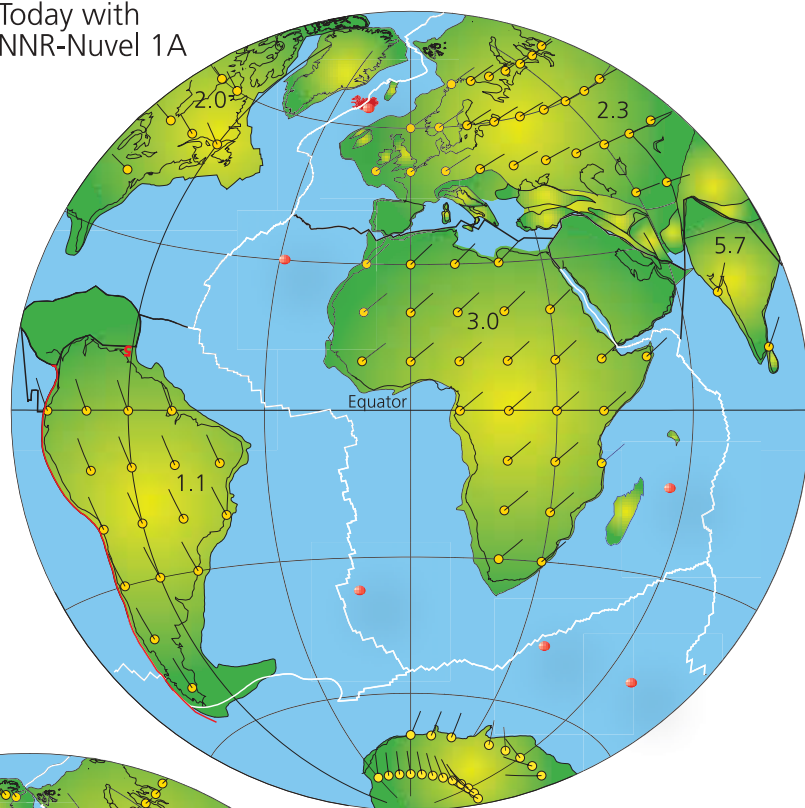
Mountain-building processes in evidence with the mass of the Himalaya and Tibetan Plateau, generated during a long period of subduction and terrane accretion that culminated in collision of India with Asia at ca. 50 Ma. The trace of the Reunion hotspot, which aided in separating India from the Seychelles, is manifested as the semi-linear feature in the ocean topography that intersects SW India. The subparallel linear feature to the east, trending into the Bay of Bengal toward Myanmar, is the Ninetyeast Ridge.

Cross-bedded, shallow-marine (tidal) bioclastics, Monte San Angelo Formation, St. Florent Basin, Corsica. In the Tyrrhenian Sea area in the Miocene, post-Alpine extension led to large-magnitude detachment faulting, core-complex denudation and extensional basin formation. Marine incursion into extensional half-grabens was locally characterized by mixing of coarse, continentally derived clastic material with carbonate mud and abundant bioclastic material.

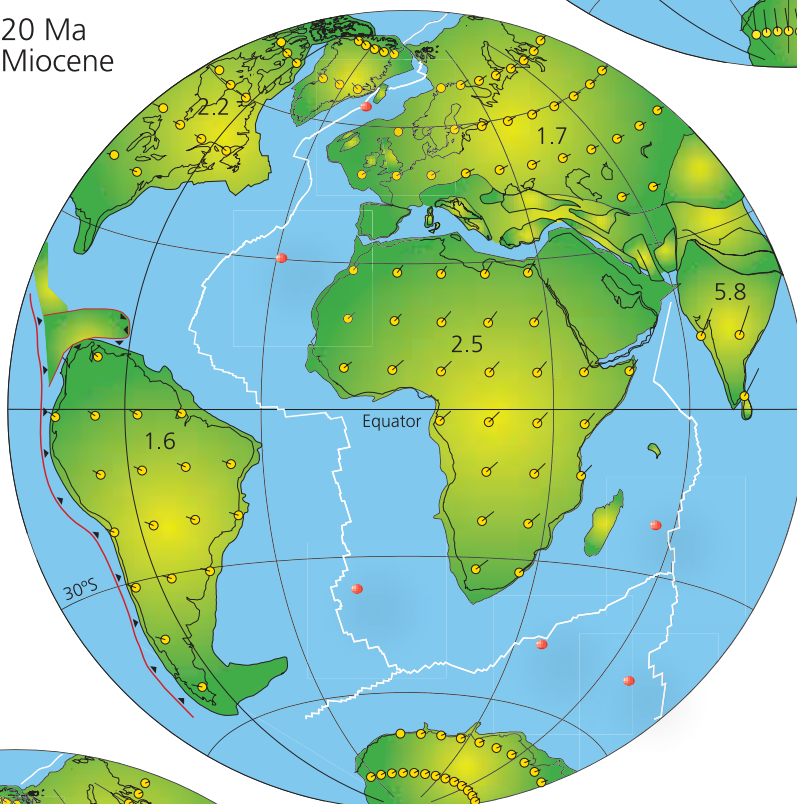
Photo: Per Terje Osmundsen



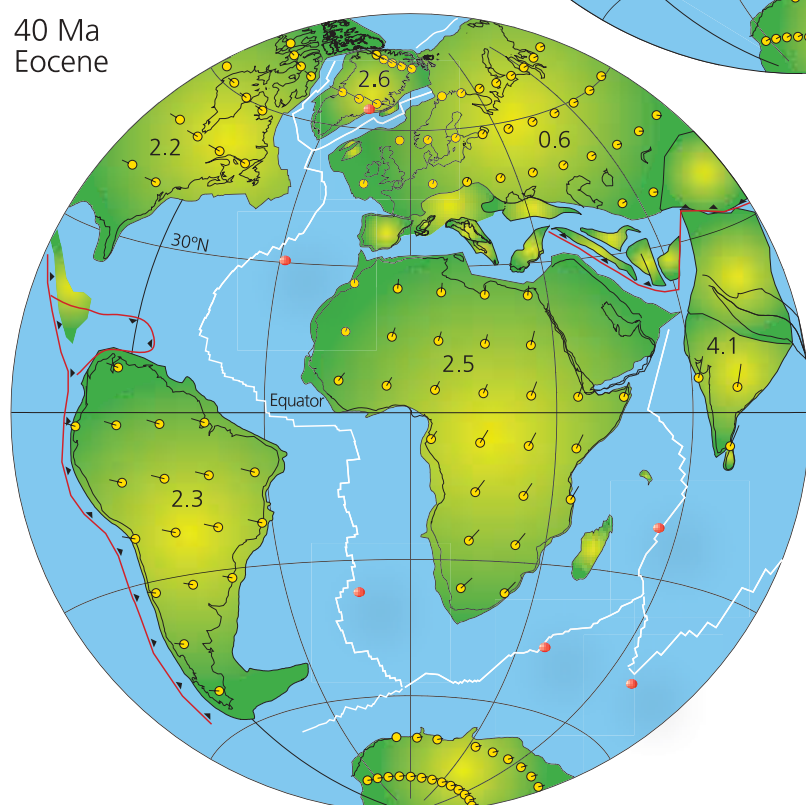
Today with
NNR-Nuvel 1A



20 Ma
Miocene



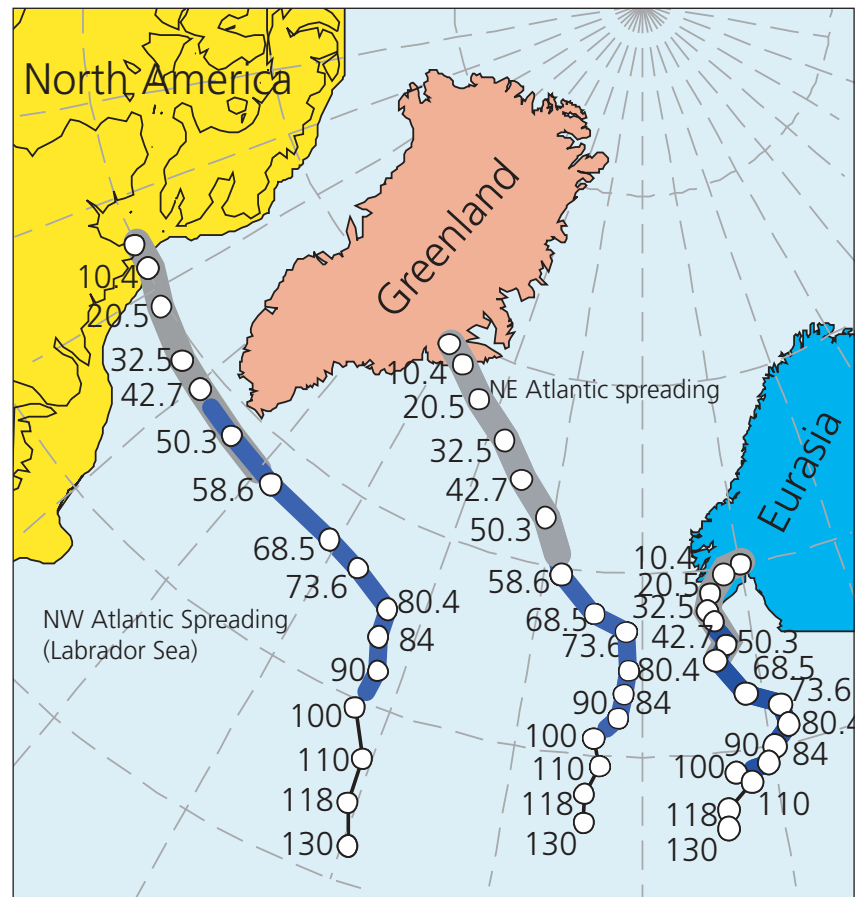
40 Ma
Eocene



Regional 4a

In the **Late Oligocene**, the Mid Norway area had drifted to 60–65°N. Spreading between Greenland–North America had ceased and spreading along the Ægir Ridge had become extinct and replaced by the Kolbeinsey Ridge. Conversely, the Reykjanes and Mohns Ridge continued to be active. Oligocene strata in the North Sea mainly consist of pelagic and partly deeper water clays. In the Central North Sea, clays were deposited in a basinal facies. Sands were mostly derived from the uplifted Shetland Platform, where delta complexes were developed. Along the southern margin of the North Sea Basin, prograding thin deltaic sheet sands were deposited. Following crustal separation between Greenland and Norway in the Early Eocene, Eocene to Oligocene-age deep-water clastics accumulated in the Møre and Vøring Basins. In the Middle Cenozoic, compressional features such as arches and domes were created within the Vøring Basin and around the Færøe Islands. This was followed and overlapped by a distinct divergence in plate motion between North America and Europe in the earliest Miocene. Otherwise, a marine, passive-margin environment dominated the period across the Norwegian continental margin. During the Late Oligocene to Mid Pliocene, much of the Barents Shelf was emergent and thus subjected to erosion. The eroded sediments formed the fan deposits seen in the present-day Barents Sea.

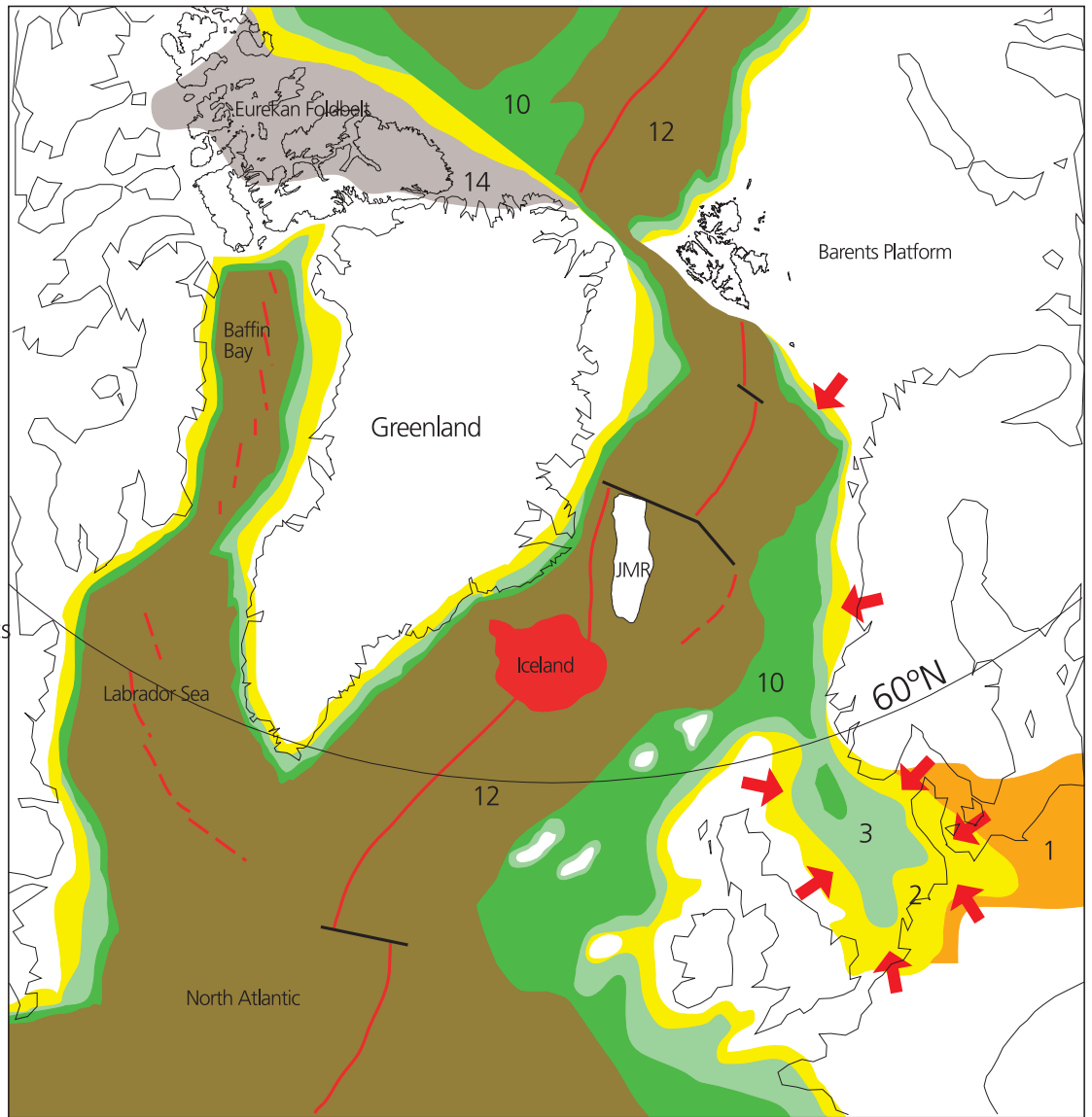
During the **Middle Miocene**, Mid Norway was located at around 65°N. The continued widening of the Norwegian Sea describes this period. There were repeated sea-level fluctuations throughout the North Sea during the Miocene, continuing up to Plio-Pleistocene. Deltaic conditions dominated much of the area. Progressive shallowing in the area is also recorded by warm-water microfaunas and prograding delta complexes near the Shetland Platform going into the Viking Graben. Sedimentation rates increased and outpaced subsidence. The Møre and Vøring Basins remained in a deep-water setting, with sedimentation consisting mostly of deep-marine mud and siliceous oozes. The tectonically-created, ocean-bottom topography was filled until a period of non-deposition in late Early-early Late Pliocene time. The Knipovich Ridge linked the Mohns Ridge with the Nansen Ridge. This resulted in a mid-oceanic ridge system from the Arctic to the North Atlantic. It also caused the northwestern shelf edge of Svalbard to separate completely from Greenland. The Barents Shelf was subjected to several periods of uplift during the Neogene, but it was only during the Plio-Pleistocene that uplift and erosion became more intense.



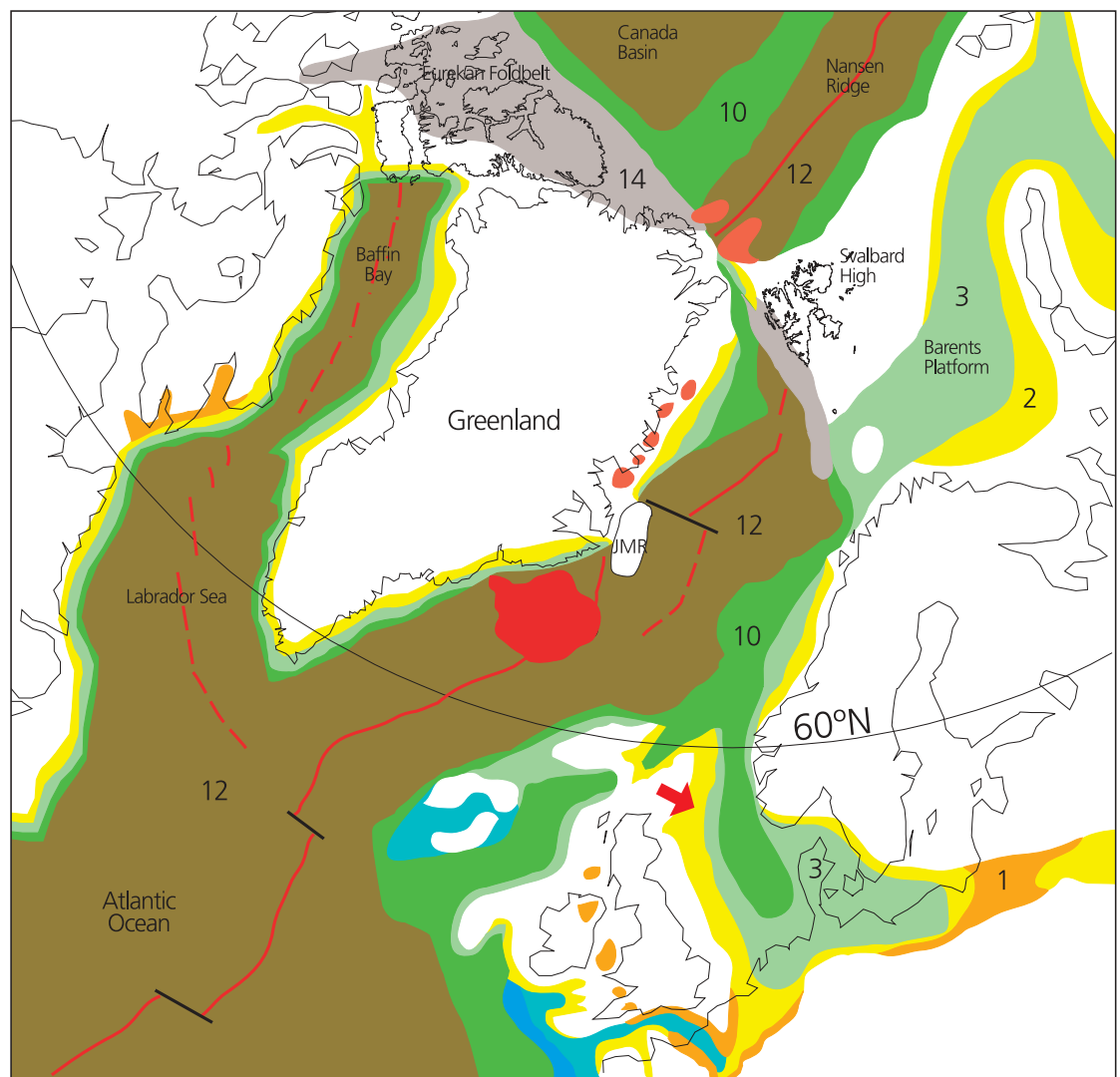
Reconstructions with plate motion tracks for North America, Greenland and Europe for the last 130 million years using a hot spot reference frame. The reconstructions show uniform NE-directed movement of the coupled North American, Greenland and Eurasian plates through 80 Ma, whereupon all three plates changed direction and followed a similar NNW-directed path. In the Early Miocene (ca. 20 Ma), Eurasia diverged NE, away from the paired Greenland–North America elements. This divergence in absolute plate motions between Europe/Eurasia and North America occurred long after sea-floor spreading had commenced in the North Atlantic. Absolute plate divergence apparently unrelated to initial sea-floor spreading is somewhat enigmatic and suggests more complex interactions between mantle and crust than standard ridge-push/slab-pull models would allow. The divergence at 20 Ma implies combined influence of mantle flow, the Iceland plume interaction with the spreading ridge, and perhaps, strong coupling between Africa and Eurasia. Adapted after Torsvik et al. (2001a).

LATE TERTIARY (15 Ma)
Middle Miocene

- 1 mainly continental clastics
 - 2 deltaic-shallow marine, mainly sands
 - 3 shallow marine, mainly shales
 - 4 shallow marine, carbonates and clastics
 - 5 shallow marine, mainly carbonates
 - 6 evaporites and clastics
 - 7 mainly evaporites
 - 8 evaporites, clastics and carbonates
 - 9 evaporites and carbonates
 - 10 deeper marine clastics &/or carbonates
 - 11 deeper marine, mainly sands (flysch)
 - 12 basins formed by oceanic crust
 - 13 magmatism (local dikes)
 - 14 active fold belt
 - 15 inactive fold belt
- direction of clastic influx
 - active sea-floor spreading axis
 - inactive/abandoned spreading axis



MID - TERTIARY (25 Ma)
Late Oligocene



Regional 4b

In the **Late Miocene**, continued sea-floor spreading along the Kolbeinsey Ridge caused the Jan Mayen Block to drift farther to the east, and the NE Atlantic was slowly widening at half-spreading rates of ca. 1 cm/yr.

During the **Pliocene**, uplift and erosion in the Barents Shelf, Scandinavia, and the British Isles became more extensive due to several cycles of glaciations and deglaciations, beginning at 2.7 Ma. Net uplift occurred during each interglacial as a result of isostatic response due to lithospheric unloading. Up to 1000 m of uplift have been recorded on the Norwegian mainland and 3000 m in the Barents Shelf. The Neogene tilting of northern Fennoscandia is consistent with a retreating scarp model. The more dome-shaped Neogene uplift of southern Norway and a number of other areas may be related to a thermal mantle instability related to the Iceland hotspot. Large volumes of sediments were deposited as fans and deltas in the Barents Sea and the Mid Norwegian shelf. The thickest piles are found in the Arctic Ocean, west of Bjørnøya, and in the Møre Basin area at the mouth of the Norwegian Channel. The Scandinavian landmass continued to experience postglacial uplift up to the present, causing erosion and deposition of thick sediments into the NW Atlantic margin. From 1 to 5 cm of uplift have been recorded, mainly in present-day Norway, but uplift in the order of 9 cm/yr is presently occurring in the Gulf of Botnia.



Aerial photograph of the Stuuragurra Fault as it crosses Finnmarksvidda. Photo taken from the west. Large amounts of groundwater poured out of the escarpment to the right sometime between an earthquake on January 21, 1996 and August 1996. The fault was formed after the deglaciation at approximately 9300 BP.



















Photo: Odleiv Olesen

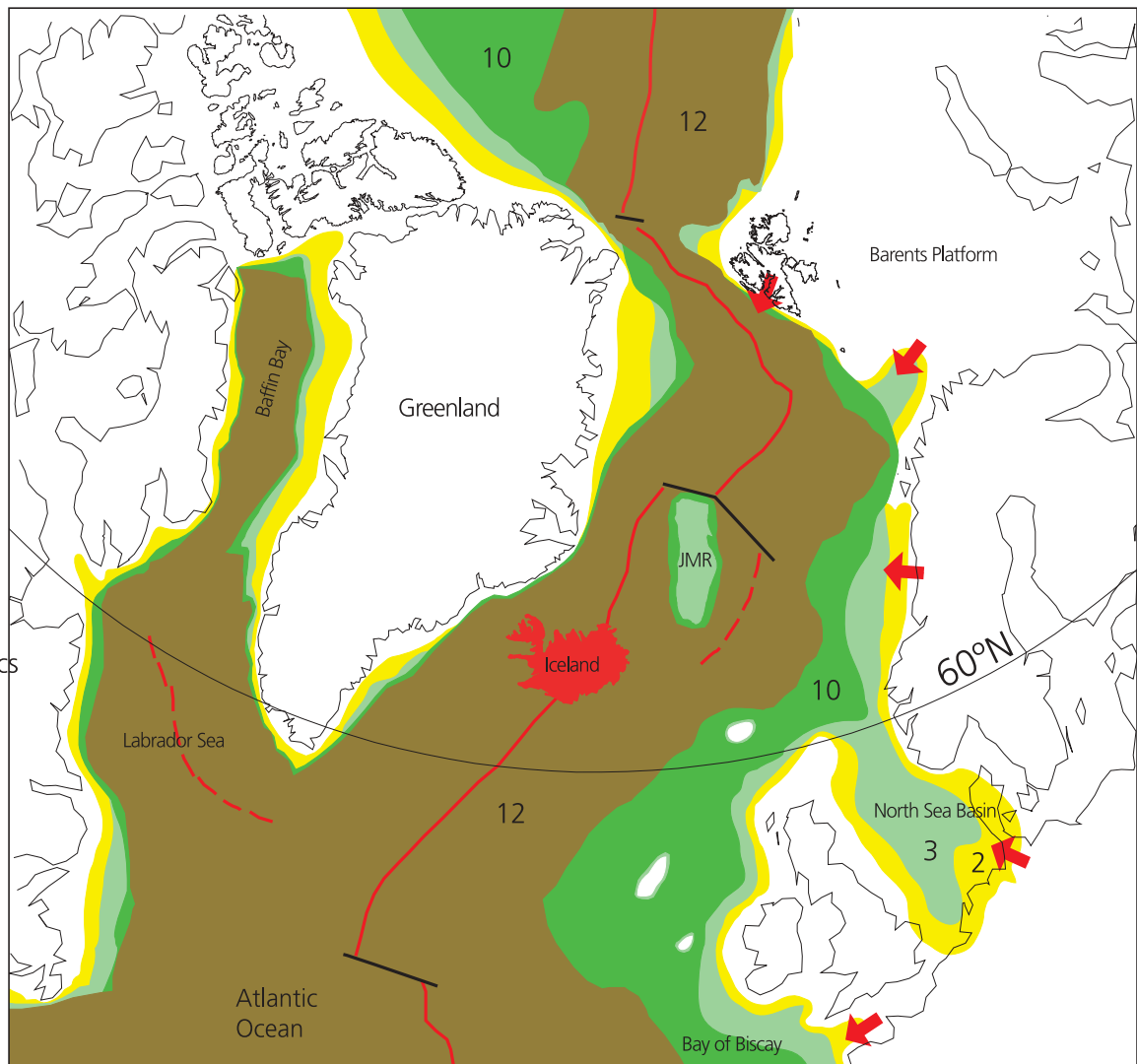


Late Miocene (10 Ma) hyaloclastites and flood basalts filling valleys carved into Devonian sediments, Scot Keltie mountain, Andree Land, NW Spitsbergen.

Photo: Asle Strøm, Statoil Geo2000

LATE TERTIARY (3 Ma)
Pliocene

- 1  mainly continental clastics
 - 2  deltaic-shallow marine, mainly sands
 - 3  shallow marine, mainly shales
 - 4  shallow marine, carbonates and clastics
 - 5  shallow marine, mainly carbonates
 - 6  evaporites and clastics
 - 7  mainly evaporites
 - 8  evaporites, clastics and carbonates
 - 9  evaporites and carbonates
 - 10  deeper marine clastics &/or carbonates
 - 11  deeper marine, mainly sands (flysch)
 - 12  basins formed by oceanic crust
 - 13  magmatism (local dikes)
 - 14  active fold belt
 - 15  inactive fold belt
-  direction of clastic influx
 -  active sea-floor spreading axis
 -  inactive/abandoned spreading axis



LATE TERTIARY (6 Ma)
Messinian/Late Miocene

