Norway in space and time: A Centennial cavalcade

Trond H. Torsvik & L. Robin M. Cocks

Torsvik, T.H. & Cocks, L.R.M.: Norway in space and time: A Centennial cavalcade. *Norwegian Journal of Geology*, Vol. 85, pp. 73-86, Trondheim 2005. ISSN 029-196X.

From her Archaean roots to her Neogene post-glacial rebound, Norway displays a magnificent array of varied geological structures and concepts. This review outlines the geological history of the country, emphasising the enormous amount of geological discoveries that have been made in the past century. The boundaries of the ancient terrane of Baltica run beneath the extended Mesozoic margin offshore Norway, the Trans-European Suture Zone lies to the southwest and the Ural Mountains to the east. Baltica became isolated after the break-up of the Rodinia supercontinent and its Late Vendian separation from Laurentia (opening of the Iapetus Ocean), and continued so until the latest Ordovician and Silurian, when she first collided softly with Avalonia and then more forcefully with Laurentia to shape Laurussia during the Scandian part of the Caledonide Orogeny. Further terranes subsequently amalgamated with Laurussia to form Pangea by the end of the Palaeozoic. Pangea broke up in stages during the Mesozoic, leaving Norway at the northwestern margin of Eurasia, where she remains today. A revised apparent polar wander path and palaeogeographic reconstructions of Norway through time are presented and discussed.

Trond H. Torsvik, Geological Survey of Norway, NO-7491 Trondheim & Institute for Petroleum Technology and Applied Geophysics, NTNU, NO-7491 Trondheim, Norway & School of Geosciences, University of the Witwatersrand, WITS, 2050 South Africa (e-mail: trond.torsvik@ngu.no); L. Robin M. Cocks, Department of Palaeontology, The Natural History Museum, Cromwell Road, London SW7 5BD , United Kingdom (e-mail:r.cocks@nhm.ac.uk)

Introduction

In relatively earthquake-free areas we are commonly lulled into believing that the land is static and only weather and the oceans are dynamic. What a brief time scale we inhabit! Yet Norway, through the ages, has been far from passive. Her margins, her mountains and her very blood, petroleum, were formed in the cauldron of Plate Tectonics. Plate tectonics models the complex and dynamic evolution of the Earth through endless ages, and addresses and explains the fascinating history of continents that move, split apart, collide and deform through the processes of sea-floor spreading and subduction. At times, continents have coalesced into very large bodies and even supercontinents, in the process generating vast mountain belts, crustal thickening, extensional collapse and exhumation of high-pressure rocks. The formation and break-up of supercontinents (Torsvik 2003) is the most spectacular demonstration of the extremely dynamic nature of our planet, and some evidence points to a periodicity of about 500 Ma in supercontinent formation during Earth history. The cyclicity of supercontinent amalgamation and dispersal has affected both deep and surficial Earth processes and has driven biological evolution and climatic changes.

Norwegian geology provides a virtual textbook for so many of these geological processes. Originally part of the smaller Archaean and Palaeoproterozoic terrane of Fennoscandia, for about the past 1 Ga, the area now represented by Norway formed the eastern margin of Rodinia (Torsvik 2003). From about 550 Ma, Norway formed the western margin of Baltica (Cocks & Torsvik 2002), then the centre of Laurussia, and finally the northwest of Eurasia, where she is today. Baltica was formerly an important continent that is now the fundament for Scandinavia and most of northern Europe eastward to the Urals. Baltica's southwestern margin is defined by the Trans-European Suture Zone (TESZ) whereas the western margin, during the Palaeozoic, probably ran somewhere beneath the offshore Jurassic-Cretaceous Trøndelag Platform that is underlain by a system of Palaeozoic to Early Mesozoic half-grabens that may have originated as a result of late- to post-Caledonian extension (Osmundsen et al. 2002). In the north, Baltica's margin probably ran offshore from Lofoten and continued into the Barents Sea region (Fig. 1). The offshore oceanic lithosphere today can be divided into the extinct Ægir Ridge system (containing the Jan Mayen microcontinent) northwest of the Møre Basin, and the Mohns Ridge system located northwest of the deep Cretaceous Vøring Basin and the Trøndelag Platform (Fig. 1). These two oceanic systems are separated by the Jan Mayen Transfer Zone (JMTZ).

Precambrian to Devonian rocks preserved in mainland Norway, developed in diverse palaeogeographic settings, were ultimately assembled during the severe and deeply penetrating continental collision of Baltica and Laurentia (Roberts & Gee 1985; Torsvik et al. 1996; Torsvik 1998) that resulted in the Scandian Caledonide Orogeny. Continental rifting and sedimentation in the

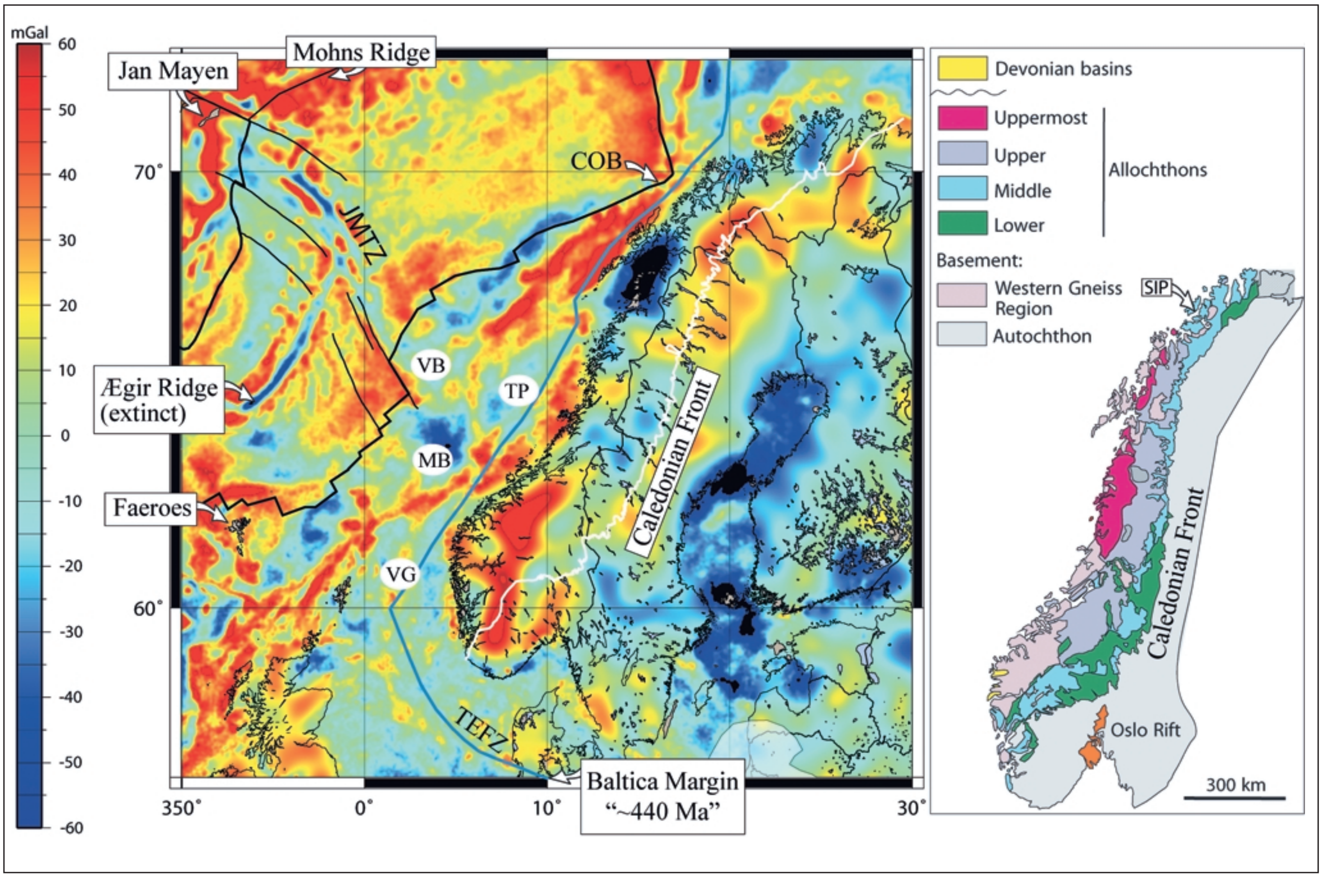

Fig. 1. Left: Free-air gravity map (Smith & Sandwell 1997) for Scandinavia (western Baltica), the Norwegian passive margin and the adjacent oceanic lithosphere. COB=Continent-Ocean Boundary; JMTZ=Jan Mayen Transfer Zone; MB=Møre Basin; TEFZ=Trans-European Fault Zone (Thor Suture at around 440 Ma); TP=Trøndelag Platform; VB=Vøring Basin; VG=Viking Graben. Right: Tectonostratigraphy of the Scandinavian Caledonides (after Corfu et al. 2004 but in original form by Roberts & Gee 1985). SIP=Seiland Igneous Province. The Baltica margin follows Cocks & Torsvik (2005).

Late Palaeozoic and Mesozoic were overtaken by Early Tertiary sea-floor spreading and continental separation from Greenland at about 54 Ma, creating the modern passive margin (Fig. 1). Events in the earliest time frames were responsible for Norway's ore and industrial mineral deposits, whereas deformation, rifting and sedimentation of the Late Palaeozoic and younger eras created and enhanced the Norwegian offshore hydrocarbon resources.

Norway's earliest times

The oldest parts of Norway were formed in the mists of antiquity. During the Precambrian, Baltica was made up of three terranes: Volgo-Uralia, Sarmatia and Fennoscandia, and all of Norway today overlies the Fennoscandian part of the plate. Fennoscandia can herself be divided into two: a northeastern Archaean domain, with rocks dating from 3.5 to 2.7 Ga, and a southwestern Proterozoic zone, with rocks and orogenic belts dating from 2.5 to 1.7 Ga (Bogdanova et al. 2001). To the southwest of the Archaean domain the Proterozoic crust of central Fennoscandia was created soon after 1.9 Ga in a series of orogenic events termed the Svecofennian Orogeny (best exposed in neighbouring Finland). Relatively soon afterwards she collided with the previously-combined Volgo-Uralia and Sarmatia to form Protobaltica. Where Fennoscandia (and subsequently Protobaltica) lay before uniting to form part of the supercontinent of Rodinia is quite unknown. How much Protobaltic crust was subducted in subsequent orogenies is also uncertain.

Later Precambrian reconstructions have, for the last decade, been dominated by the postulate of a Neoproterozoic Supercontinent named Rodinia (e.g., Dalziel 1991; Hoffman 1991; Torsvik et al. 1996; Torsvik 2003). The existence of Rodinia was initially based on a postulated linkage between the presently dispersed c. 1 Ga Grenvillian, Sveconorwegian and Kibaran mobile belts. Laurentia formed the core of this supercontinent (Fig. 2). Norway has traditionally been assumed to face Greenland whilst the Tornquist margin of Baltica faced West Gondwana. However, recent maps show Baltica (Norway) geographically inverted in relation to Laurentia at c. 750 Ma (Hartz & Torsvik 2002; Torsvik

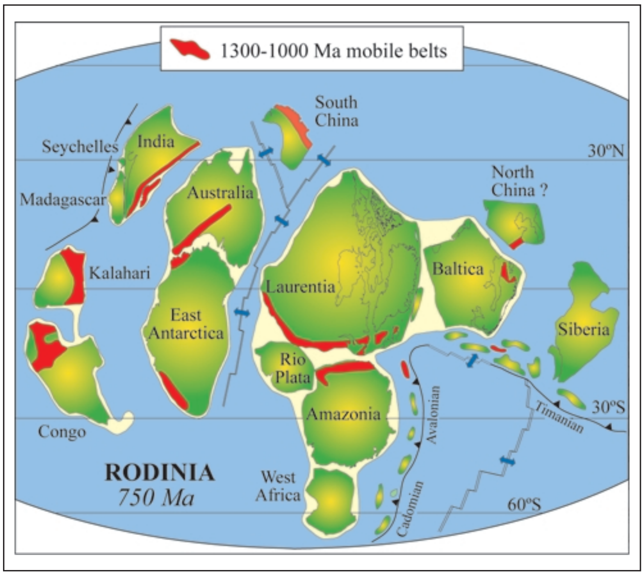

Fig. 2. 750 Ma reconstruction of Rodinia where Baltica and Siberia are geographically inverted and North China is tentatively placed north of Baltica. Continental fragments and magmatic arcs (Avalonian, Cadomian and Timanian/Baikalian) along the southeastern margin of Rodinia were welded on to West Africa, Amazonia, Baltica and Siberia during the Late Precambrian (adapted from Torsvik 2003). At about 750 Ma, and shortly after the break-up of Rodinia. Baltica was still attached to Laurentia and the South American terranes of Rio Plata and Amazonia at that time. The dispositions of the Avalonian/Cadomian, Timanian/Baikalian island arcs are modelled on the peri-Pacific system today.

2003), thus linking the Proterozoic Timanian/Baikalian, Avalonian and Cadomian arcs to Baltica in a Pacific-type scenario (Fig. 2) (Roberts & Siedlecka 2002). From around 800 to 650 Ma, Avalonian-Cadomian arc activity and accretion of Avalonian and related peri-Gondwanan terranes (e.g. Armorica and Perunica) occurred along the Gondwanan margin (Fig. 2), followed by the onset of the main phase of volcanism at about 630 Ma (Murphy et al. 2000). All these events essentially terminated at around 550 Ma, and Baltica terrane amalgamation was then complete. Central Taimyr had collided with Siberia within the Ægir Sea realm (Fig. 3b).

The disruption of Rodinia, already in progress at 750 Ma, and the subsequent formation of Gondwana were marked by the most spectacular mountain-belt building episode in Earth history. No mountain area as extensive as the Gondwana mountains has been constructed on Earth, before or since (Burke et al. 2004). Gondwana formed by 550 Ma, a vast, newly-assembled continent that stretched from polar to equatorial latitudes. Avalonia, Armorica, Perunica (also known as Bohemia) and many other terranes formed part of Gondwana (Fig. 3a). They were affected by the Avalonian/-Cadomian Orogeny that lasted throughout Vendian time and broadly contemporaneous with the Timanian (~ 610-550 Ma) and Baikalian events in Northwest Russia and Siberia. The latter marks the accretion of Central Taimyr with the Siberian craton between 630 and 570 Ma (Vernikovsky 1997).

One part of Norway which was not part of Baltica was the Svalbard Archipelago. In the Proterozoic (Fig. 2) and in Early Palaeozoic times it formed part of the margins of Laurentia (Gee & Teben'kov 2004), which occupies much of modern North America and Greenland. Laurentian warm-water shelly faunas, well known from the area (Fig. 3b), are completely different from those in Baltica in the Early Ordovician (Cocks & Fortey 1982). Svalbard had a very different history from mainland Norway: it can be divided into four separate small terranes separated by strike-slip faults, all of which were active during the development of the Barentsian Caledonides (Gee 2005). However, Svalbard is not considered further here.

The Scandinavian Caledonides and Laurussia

Our modern understanding of the Scandinavian Caledonides has evolved in several revolutionary stages marked, for example, by classic papers such as Størmer (1967) and the book by Strand & Kulling (1972). In these works, the Caledonides were differentiated into foreland, miogeosynclinal and eugeosynclinal facies, and the various nappes were held to derive from these environments. The next major step in advancing our understanding was the overview of Gee (1975). Gee demonstrated that the nappes had travelled considerable distances to their final sites of emplacement, causing much crustal thickening, and that a number of distinct metamorphic breaks could be identified between overriding nappes and their substrates.

A number of discoveries were made in the late 1970s and early 1980s. The recognition that ophiolites and associated island arcs were represented in Norway (Gale & Roberts 1972, 1974) and constituted important aspects of the stratigraphic/tectonic development (e.g. Sturt 1984) marked a revolutionary conceptual advance in our knowledge of the Scandinavian Caledonides. One should also refer to the tectonostratigraphic subdivision of the Scandinavian Caledonides (Roberts & Gee 1985) in which the rocks are grouped into Autochthon, Parautochthon, and Lower, Middle, Upper and Uppermost Allochthons; providing a logical framework for the nappe complexes (Fig. 1). From the Parautochthon through the lower part of the Upper Allochthon, the nappes all have a bipartite subdivision between basement, recognised as part of Baltica, and cover sequences of Upper Precambrian and Lower Palaeozoic sedimentary rocks. The boundary between the Seve and Köli Nappes of the Upper Allochthon was recognised as

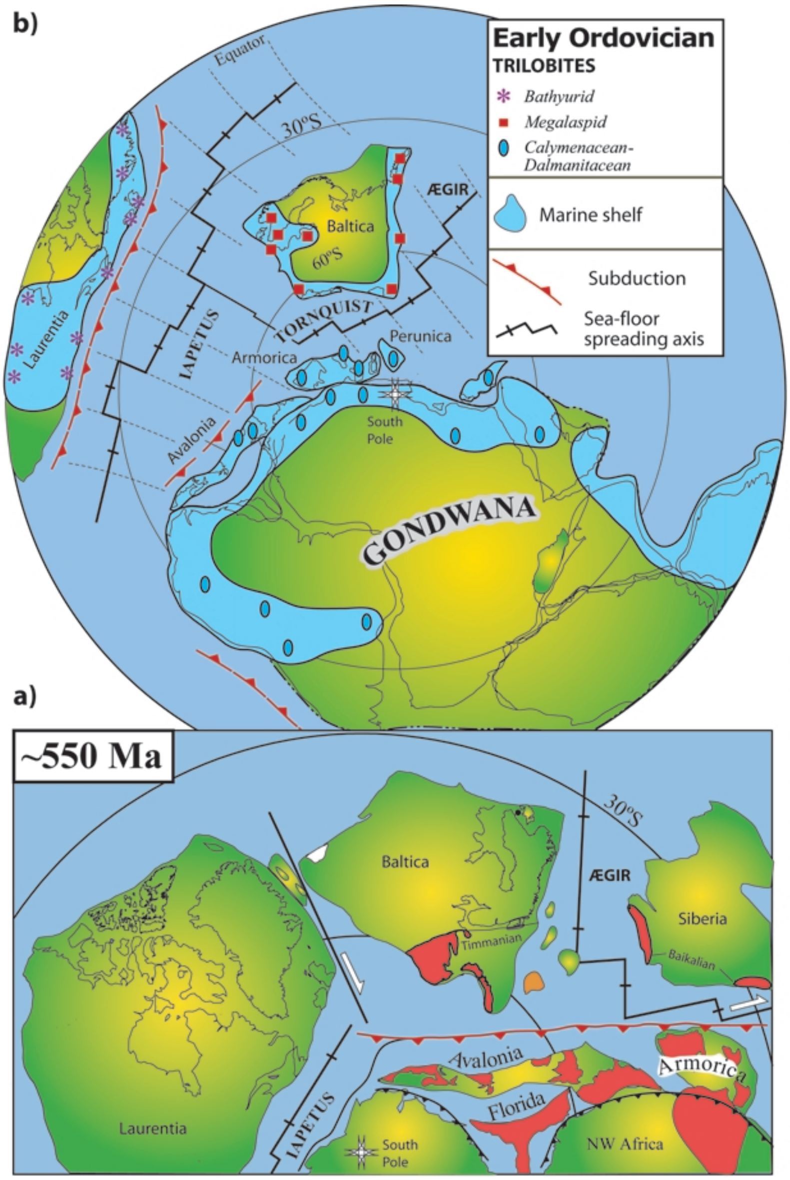

Fig. 3. a) Reconstruction of the Late Vendian (550 Ma). Modified from Hartz & Torsvik (2002) and Rehnström et al. (2002). Shaded areas in red are regions that show evidence of Avalonian-Cadomian-Baikalian-Timanian deformation, terrane amalgamation and magmatism. By 550 Ma, Gondwana was essentially assembled whilst Laurentia had probably started to rift away from South America (Iapetus opening), its position being somewhat uncertain. Also, the amalgamation of northern Baltica terranes was essentially completed and Central Taimyr was accreted to South Taimyr. Baltica and Siberia were separated by the Ægir Sea (Torsvik & Rehnström 2001). Laurentia includes North America, Greenland and the British Isles north of the Iapetus Suture. Baltica includes most of Scandinavia and Russia eastward to the Urals. Avalonia included British Isles/NW Europe south of the Iapetus Suture, Eastern Newfoundland, most of the Maritime Provinces of Canada and parts of the eastern United States. Armorica includes the Armorican Massif of Normandy and Brittany, the Massif Central and the Montagne Noire areas of France, together with parts of the Iberian Peninsula.

b) Early Ordovician reconstruction (470-490 Ma) with the major terranes and some key Arenig-Llanvirn trilobite faunas. The core of Gondwana consisted of Africa, Arabia, Madagascar, Greater India, most of Antarctica, most of Australia, Florida, and most of South America and covered more than 90° of latitude at this time. Gondwana dispersal history commenced with the rifting off of Avalonia at around 465 Ma. Perunica (Bohemia) comprises the area north of the Barrandian basin of Bohemia.

a significant break, the outboard oceanic assemblages (ophiolites and magmatic arcs) first making their appearance in the Köli Nappes. The Uppermost Allochthon comprises exotic elements, including extensive carbonate formations and major batholiths of probable Laurentian affinity (see review in Roberts 2003).

A number of attempts have been made in the direction of describing the development of the Scandinavian Caledonides in a plate tectonic framework. Most of these models, however, adopted a Wilsonian view of the Iapetus Ocean (separating Baltica and Laurentia), relying essentially on a simple opening and closing of oceans along mainly straight and parallel margins. However, more recent literature (Torsvik et al. 1996; Torsvik 1998; Torsvik & Rehnström 2001; Hartz & Torsvik 2002; Cocks & Torsvik 2002; Roberts 2003) shows that, like most convergent margins worldwide, the Caledonide evolution in space and time is not a matter of simple orthogonal tectonics.

In the latest Vendian, Baltica and Siberia were separated by the Ægir Sea (Fig. 3a). The Iapetus Ocean between Baltica and Laurentia probably opened at around this time. In the model of Hartz & Torsvik (2002), Iapetus was initiated at a junction between a rift (Laurentia-Gondwana), a right-lateral fault between Laurentia and Baltica and a trench (inverted Baltica/Gondwana). Iapetus probably reached its widest in Late Tremadoc or Early Arenig times (c. 480 Ma) as indicated from different benthic trilobite faunal provinces (Fig. 3b) and palaeomagnetic data (Cocks & Fortey 1982; Cocks & Torsvik 2002). Palaeomagnetic studies, carried out in the early 1990's clearly demonstrated that Baltica was upside-down during the Early Ordovician (Fig. 3b), located at mid-southerly latitudes and separated from

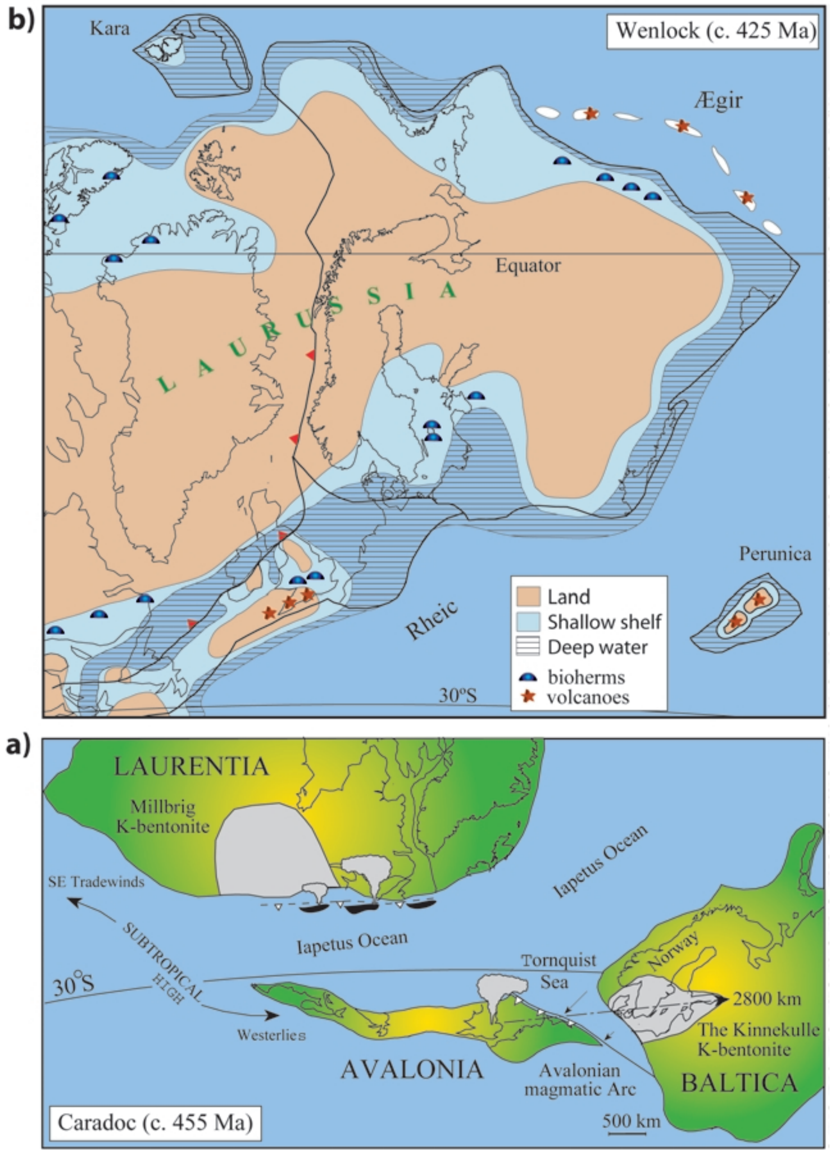

Fig. 4. a) Mid-Caradoc reconstruction of Laurentia, Baltica and Avalonia where the Kinnekulle K-bentonite (Baltica) is linked to the Avalonian magmatic arc (see text). Contemporaneous arc-magmatism along the southeastern margin of Laurentia was probably responsible for the Millbrig K-bentonite (Torsvik & Rehnström 2003).

b) Palaeography of eastern Laurussia in the Middle Silurian (Wenlock, c. 425 Ma), including the Baltica, Avalonia and eastern Laurentia sectors. Adjacent terranes include Perunica and Kara. The Iapetus had closed, and the Rheic Ocean was starting to close. The reconstruction shows land (over some of which was deposited Old Red Sandstone facies), shallower and deeper shelf areas, and oceanic lithosphere. The fringing shallow seas supported spectacular diverse benthic faunas and substantial bioherms such as the reefs of Gotland in Sweden (Cocks & Torsvik 2005).

northwest Gondwana and Laurentia by the Tornquist Sea and the Iapetus Ocean. During the Ordovician, Baltica rotated in a counter-clockwise manner towards its present orientation, and by the Late Ordovician, Norway faced Laurentia for the first time (Figs. 3 and 4).

Rifting between Avalonia and Gondwana was the first breakaway of peri-Gondwana terranes, and Avalonia drifted rapidly northward to gain palaeolatitudes comparable with those of Baltica by the Caradoc (Fig. 4a). Tornquist Sea crust was subducted beneath Avalonia and explosive vents associated with Andean-type magmatism in SE England (Pharaoh et al. 1993) supplied Baltica with gigantic Mid-Caradoc ash-falls (e.g. the Kinnekulle bentonite) controlled by westerly Ordovician winds. Southwest Baltica records an Ashgillian thermal event that is broadly comparable with the Shelveian event in Avalonia (Torsvik & Rehnström 2003). This event is also contemporaneous with Caledonian low-grade metamorphism in the North Sea (Torsvik 1998) and was probably related to the soft oblique Avalonia-Baltica docking at about the Ordovician-Silurian boundary.

By about 420 Ma, Baltica, Avalonia, intervening terranes and Laurentia had all coalesced to form the new superterrane of Laurussia (Fig. 4b). The Scandian orogenic event (Gee 1975) was marked by oblique collision and deep subduction of Baltican crust beneath Laurentia (Andersen et al. 1991; Torsvik et al. 1996; Eide & Torsvik 1996). Large parts of Laurussia were in tropical palaeolatitudes during the Silurian, with the deposition of substantial carbonate deposits. In southern Norway, preserved today in the Oslo Graben (Cocks & Worsley 1993), there were shallow-marine limestones and deeper-water turbidites offshore of them, and these are preserved both onshore and offshore today (Smelror et al. 1997). These areas shallowed up during Wenlock times to be followed by a non-marine 'Old Red Sandstone' facies, the latter indicating the development of molasse-filled basins during upper crustal extension. By the Early Devonian, the Old Red Sandstone facies was developed over a much wider area, extending from central North America to the East Baltic and from the southern Appalachians to Spitsbergen, a distance of over 4,500 km (Friend et al. 2000). In the Oslo region, Old Red Sandstone accumulation (the Ringerike Group) was coeval with Ludlow to Pragian Scandian crustal thickening and later (in Emsian times) with tectonic extension denudation (Gee 2005). However, elsewhere on Baltica the fringing carbonates persisted through all of the Silurian, including the famous reefs of Gotland and Estonia (Fig. 4b).

There has been considerable controversy concerning the nature of the Scandinavian Caledonide orogen. Did it represent one collisional orogeny or was it a polycyclic orogen (reviewed in Roberts 2003) involving several collisions at or close to the leading edge of Baltica? The first, or the more traditional model involves one major collisional event, the Scandian, in Silurian times, and stems mainly from the classic papers of Størmer (1967) and Gee (1975). Early studies from the Seiland Igneous Province in Finnmark (Fig. 1) led directly to the hypothesis of the Late Cambrian-Early Ordovician Finnmarkian Orogeny (e.g., Sturt et al. 1978). However, the nature of the Finnmarkian orogenic event remains a subject of much debate: There has been some agreement that it involved arc/continent collision following subduction, and perhaps involved interaction between Baltica and the Kara Block in the Ægir Sea realm (e.g., Cocks & Torsvik 2002). New and partially unpublished isotope dating studies in northern Norway, however, question the existence of the Finnmarkian orogenic concept and will undoubtedly lead to major modification of our understanding of the Scandinavian Caledonides (Corfu et al. 2004; Roberts et al. 2004).

In addition, two more events have been recognized in the Scandinavian Caledonides, namely the Trondheim (Early Arenig, and about 20 million years younger than the Finnmarkian) and the Taconian (Mid-Late Ordovician) events. Both are linked to arc-accretion related events (Roberts 2003); the Taconic event, represented mostly in the Uppermost Allochthon, is argued to have occurred along the margin of Laurentia but is also contemporaneous with the Shelveian event in southern England and the Avalonia-Baltica docking discussed above.

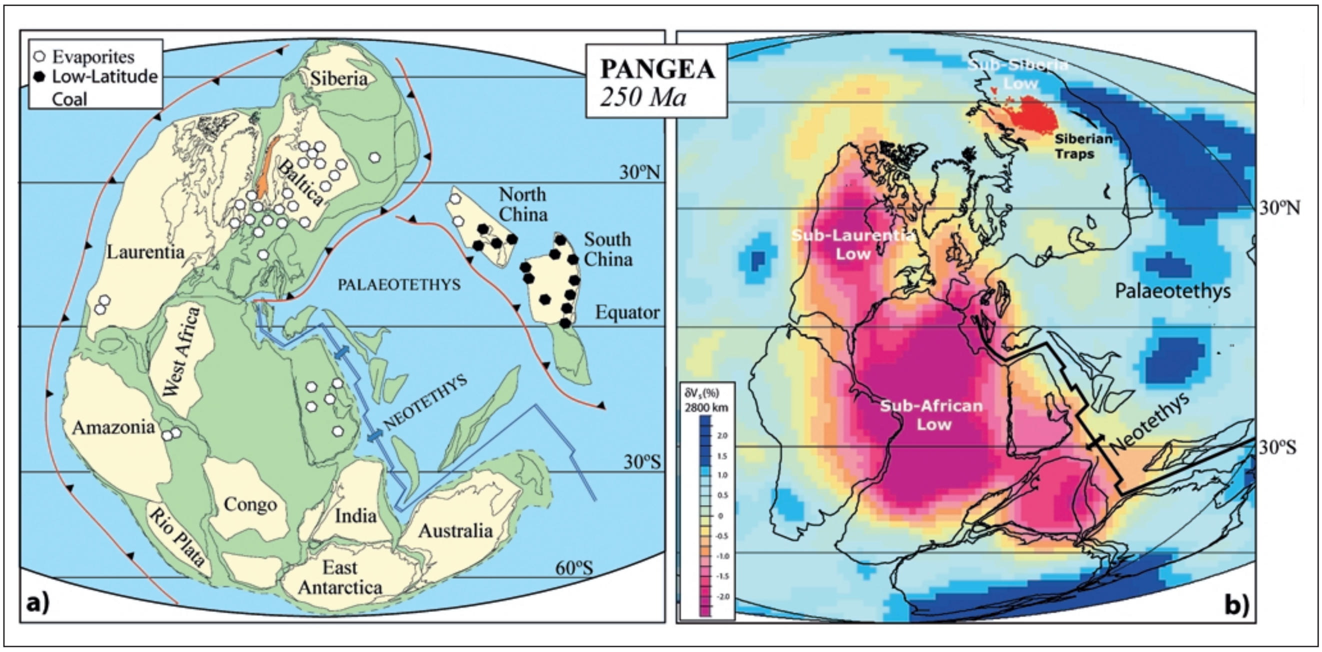

Fig. 5. a) Pangea supercontinent during the Late Permian period (Torsvik 2003; Torsvik & Cocks 2004). The distribution of low-latitude coal deposits (C) and evaporites (E) are indicated. Note that this reconstruction is a Pangea A octupole (15%) reconstruction (Torsvik & Cocks 2004) and differs slightly from the GAD based reconstruction in (b).

b) Pangea A reconstruction (GAD-based). The present 'sub-African' slow velocity zone near the core-mantle-boundary was probably situated beneath parts of Laurentia and was centered below the supercontinent. The Siberian Traps (251 Ma) also overlie hotter (?) deep mantle. Continents are draped on shear-wave velocity anomalies near the core mantle boundary (Becker Boschi 2002). The distribution of the Siberian Traps is outlined in red shading (after Burke & Torsvik 2004).

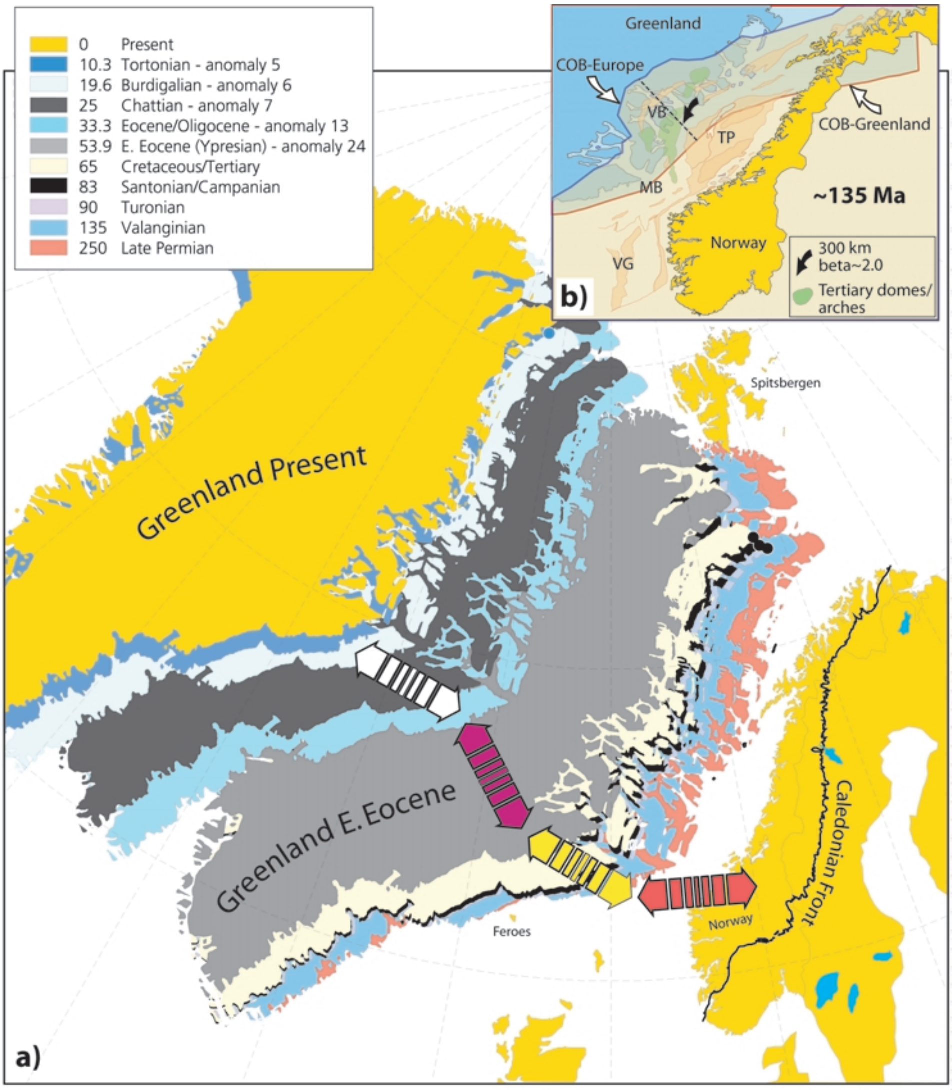

Fig. 6. (a) Relative reconstruction (Europe fixed) showing the progressive separation (pre-drift and sea-floor spreading) between Greenland and Scandinavia (adapted from Mosar et al. 2002). (b) Relative reconstruction (Norway fixed) at around 135 Ma showing the COB overlap at this time (see text), notably across the Mid-Norwegian margin (300 km with β ≥2). On the Norwegian shelf we also show some basins, highs and domes (many younger than the reconstruction) pointing to the overlap with the East Greenland margin. VB=Vøring Basin; TP=Trøndelag Platform; MB=Møre Basin; VG=Viking Graben.

Pangea Assembly

In the Carboniferous, starting at about 330 Ma, Gondwana merged with Laurussia and intervening terranes to form the supercontinent of Pangea (Van der Voo & Torsvik 2001; Torsvik & Van der Voo 2002; Torsvik & Cocks 2004). The Variscan belts of Europe became part of a belt that stretched from the Caucasus to the Appalachian and Ouachita mountains (Matte 2001). The Palaeotethys Ocean, an embayment in eastern Pangea, separated the northern from the southern parts of today's European collage during the later Palaeozoic (Fig. 5a). The Late Carboniferous and Early Permian were marked by a significant glacial episode which lasted as long as 50 Ma, but also witnessed the formation of the most extensive coal deposits of the Phanerozoic which are very well represented in Europe. These subsequently became the source for one of Earth's highest reserves of natural gas. Although there are no glacial deposits known from the Late Permian, and the climate was extraordinarily arid, it is noteworthy that low-latitude coal deposits are lacking within Pangea (indicating an arid equator). Conversely, a wet equator is indicated for terranes in the eastern Palaeotethys (South and North China) that were not part of Pangea at this time.

In the Late Permian, Pangea was at her climax. However, minor fragmentation of Pangea had already begun as new oceanic crust was forming the Neotethys Ocean along the eastern margin of Pangea (Stampfli & Borel 2002; Torsvik & Cocks 2004). The existence of a single large landmass and intense magmatism (~251 Ma Siberian Traps and the Emeishan Traps of South China) created climatic and atmospheric conditions that culminated in the Earth's largest known extinction event near the Permo-Triassic boundary. Consequently, good hydrocarbon source rocks are rare until the Mid Jurassic and onwards (e.g. Upper Jurassic black shales with excellent source potential along the

Norwegian margin; Brekke et al. 2001), when animal evolution once again flourished, and the break-up of the Pangea supercontinent had developed new shelf and habitat areas.

In the deep Earth, the long-term shielding effect of the Pangea supercontinent over large parts of the underlying mantle probably caused an increase in mantle temperatures and spawned continental doming in the interior of the supercontinent. Heterogeneities near the core-mantle boundary (CMB) observed today under parts of Africa may be the residual effect of supercontinent insulation (Fig. 5b), protecting the Pangea mantle from subduction and cooling (Burke & Torsvik 2004).

Norway's latest story

Since the Late Palaeozoic, and directly linked to the break-up of Pangea, the Norwegian continental shelf experienced multi-phase rifting (e.g., Brekke et al 2001, Mosar et al. 2002), culminating in the separation of Greenland and Norway and the formation of the Northeast Atlantic Ocean in the Early Tertiary at Anomaly 24 time (~54 Ma). From the Late Permian to the Early Cretaceous, the stretching direction between the present-day Norwegian shelf and East Greenland was orientated east-west, oblique to the present coastline (Fig. 6a). During the Late Cretaceous, the rifting direction changed to a more northwest-southeast orientation, more perpendicular to Norway's present coastline. Plate reconstructions based on Torsvik et al. (2001a) suggest that the main phase of post-Pangea pre-drift extension on the Norwegian-Greenland passive margins took place during the Cretaceous (Fig. 7). This extension can be quantified by the amount of continent-ocean boundary (COB) overlap, but the precise location of the COB and an appropriate plate model are critical requirements for these estimates. In addition, the COB is not a distinct boundary but rather a transition zone, some tens of kilometres wide between true continental and true oceanic crust. Across the Mid-Norwegian shelf to East Greenland, the COB overlap was about 300 km in the Early Cretaceous (Fig. 6b), amounting to a plate tectonic-scale stretching factor (β) of at least 2. During the latest Cretaceous and earliest Tertiary (~69-56 Ma) the extension rate amounted to ~1 cm/yr. Total extension during this time interval was in the order of 150 km (Fig. 7).

Sea-floor spreading between Greenland and Europe commenced in the Early Tertiary (~54 Ma), post-dating and partly coinciding with vast igneous activity in the UK, Ireland, the Faeroes, Greenland and the West Greenland-Baffin corridor (e.g., Saunders et al. 1997; Skogseid et al. 2000; Torsvik et al. 2001b). Full spreading velocities for the NE Atlantic were ~4 cm/yr during break-up, declining to a minimum of 1.4 cm/yr at Anomaly 13 (~33 Ma). A velocity recovery of approximately 2 cm/yr has followed during the past 20 million years. There is notable misfit (gap) between the southwest Greenland COB and the Eurasian COB (Mosar et al. 2002) at the assumed time of break-up. This implies either that 1) the COB is not properly identified, 2) the plate fit is inaccurate, 3) break-up started a few million years earlier in this sector of the NE Atlantic, or 4) some combination of the above.

Opening of the NE Atlantic took place at three interconnected ridges: Reykjanes, Ægir and Mohns (Fig. 7). An important change in seafloor spreading occurred with the abandoning of the Ægir Ridge system shortly before Anomaly 13 (~ 35 Ma) when the Reykjanes Ridge propagated north and west of Jan Mayen (the Kolbeinsey Ridge). Jan Mayen rotated away from Greenland in an anticlockwise manner and shortly after Anomaly 13, the Ægir ridge became extinct, and the Kolbeinsey Ridge became well developed along the western margin of Jan Mayen. From 30 Ma and onwards Jan Mayen became part of the Eurasian plate. Seafloor spreading in the Labrador Sea had ceased by this time and Greenland became part of the North American plate once again.

The North Atlantic Igneous Province (NAIP) is one of several Large Igneous Provinces (LIPs) that have erupted on the Earth's surface (Eldholm & Coffin 2002). Burke & Torsvik (2004) have recently shown that almost all LIPs of the past 200 My, when reconstructed to the time of their eruption, become concentrated radially above areas of the CMB occupied by the slower parts of the D" zone (the lowest 300-400 km of the mantle). They attribute the generation of LIPs to hotter material that left the D" zone episodically in thermally buoyant mantle plumes that rose to the base of the lithosphere. Because NAIP rocks extend over vast areas, not all of these outcrops can mark the site of the eruption of the Iceland plume. Many must represent material that has propagated horizontally within the asthenosphere from the original plume eruption site (e.g. Marzoli et al. 1999), and into weakened crust, existing rifts or interacted with the spreading ridge (Ito et al. 2003). A sloping base exists near spreading ridges, and if the spreading ridge is less than a few hundred kilometres away from the hotspot (Ito et al. 2003), volcanic eruption will occur at the ridge rather than directly above the plume.

At present, the estimated location of the Iceland hotspot (64.4°N, 341.9°E in Fig. 8a) overlies a shear-wave velocity anomaly of ~-0.5% at the CMB. The Iceland plume does not have a hotspot track and past locations can only be estimated from a fixed Indo-Atlantic hotspot frame (Müller et al. 1993) accounting for Labrador rifting and spreading, or a mantle reference frame

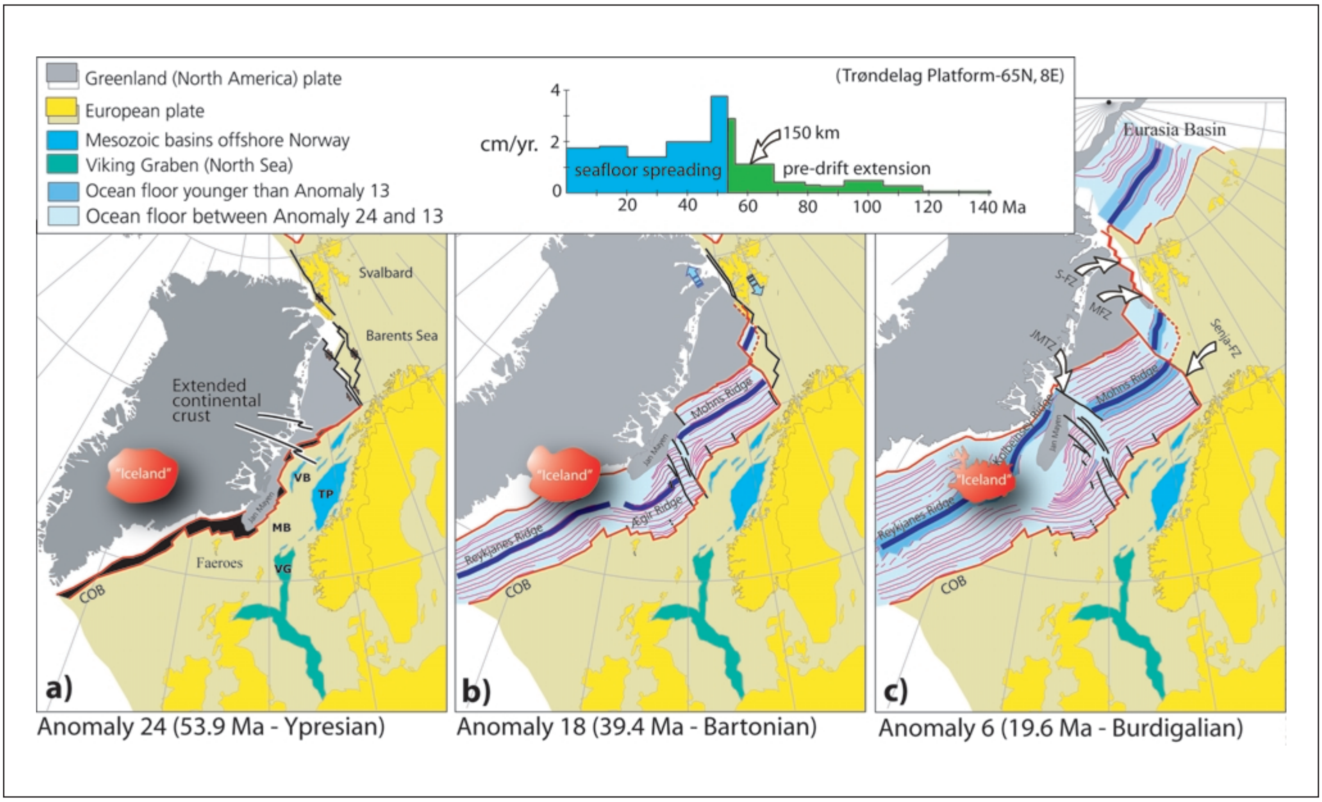

Fig. 7. (a) Reconstruction at Anomaly 24 time, shortly before the onset of seafloor spreading. The COB gap between Greenland and Europe is shown in black and discussed in the text. (b) Reconstruction at Anomaly 18 time. At this time the convergence of Greenland and Svalbard was at its climax and a transpressive regime governed the structural development in Svalbard and NE Greenland. (c) Reconstruction at Anomaly 6 time. New ocean floor developed between the Svalbard and Greenland conjugate margins and the Jan Mayen microcontinent in the process of drifting away from Greenland. All reconstructions are relative to a fixed Europe and adapted from Mosar et al. (2002). The right-hand diagram in the legend box shows the full pre-drift (shaded green) and spreading (blue shading) velocities calculated for a location on the Mid-Norwegian shelf (Trøndelag Platform: 65°N, 60°E), and based on the plate-tectonic model II of Torsvik et al. (2001a). VB=Vøring Basin; TP=Trøndelag Platform; MB=Møre Basin; VG=Viking Graben; JMTZ=Jan Mayen Transform Zone; MFZ = Molloy Fault Zone; S-FZ = Spitsbergen Fault Zone; COB=Continent Ocean Boundary.

(Steinberger 2004) in which the motion of the Iceland plume in a convecting mantle is considered (Fig. 8a). The latter approach, computed from the SMEAN tomographic model (Becker & Boschi 2002) with a plume initiation age of 80 Ma, is not very different from a fixed Indo-Atlantic reference frame, but generally indicates a westward motion of the hotspot of ~ 200 km over the past 60 Ma. If mantle reference frames are correct to a first approximation, continents can be reconstructed in an 'absolute' sense, and the velocity field for the plates can be calculated (Fig. 8b). In the Late Cretaceous and the Early Tertiary all plates in the North Atlantic realm were mostly drifting NW or NNW (Torsvik et al. 2001b), but at different relative speeds, with the opening of the Labrador Sea and the NE Atlantic occurring simultaneously. After Anomaly 13, North America and Greenland show similarly NW-directed movements (seafloor spreading ceased in the Labrador Sea) whilst Eurasia (with Jan Mayen, which had rifted off Greenland to join Europe) changed to a NE course (Fig. 8b) compatible with the present motion of Europe. Northwestward movement of Greenland during most of the Tertiary (Fig. 8b) was the important factor in positioning the Iceland plume at the leading edge of Greenland at around 40 Ma, and with focussed and well-dated magmatism in East Greenland almost directly above the estimated plume location at that time. The NE plate motion shift for Eurasia is comparable to that of Africa, indicating stronger coupling between Africa and Eurasia, or alternatively is linked with the positioning of the Iceland plume below the spreading ridge, leading to increased local upwelling below the ridge at around 20-30 million years ago, or a combination of these two causes.

Since the opening of the northeast Atlantic at around 54 Ma, Norway has been relatively quiescent. However, she has been uplifted during the Tertiary, and undergone extensive isostatic adjustment during the past 3 million years. Glaciations and regional uplifts have caused deep erosion of the mainland area and the Barents Sea shelf as well as deposition of sediments along the Norwegian-Greenland Sea (Brekke et al. 2001).

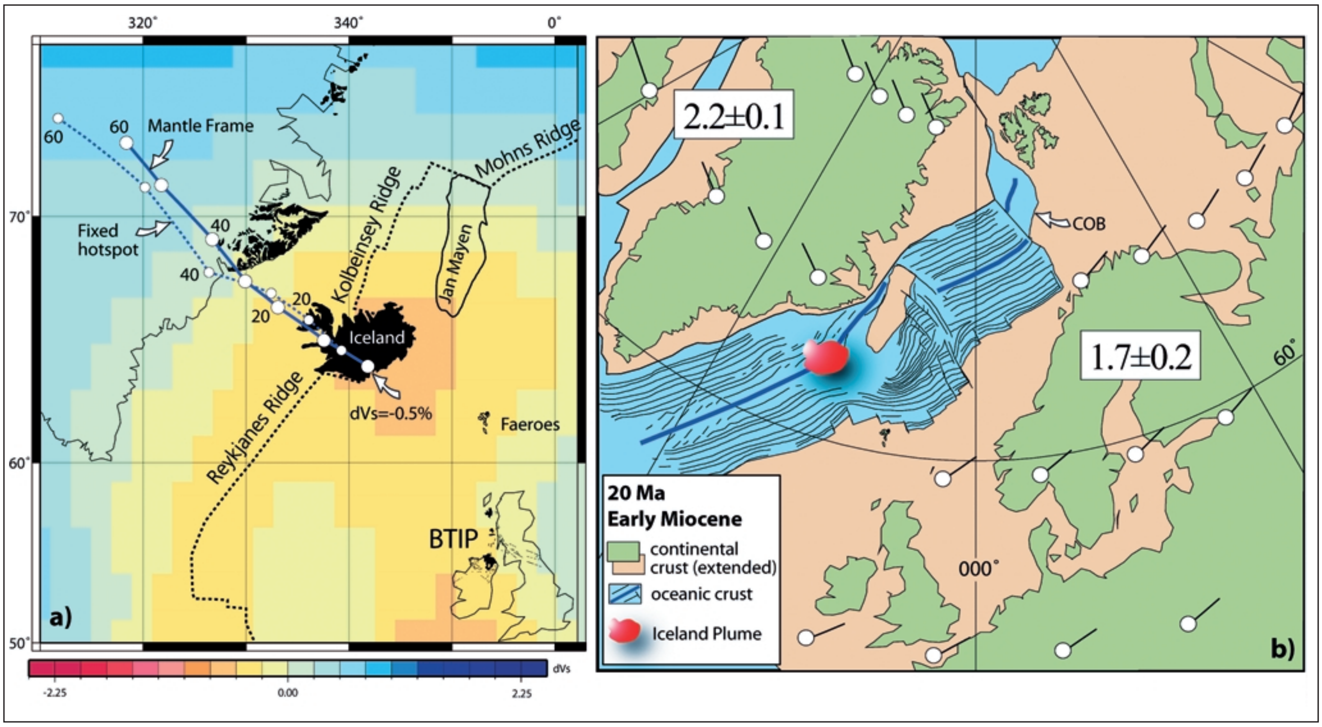

Fig. 8. a) Map showing SE Greenland, the British Isles, Faeroes and Iceland with onshore volcanic outcrops and current spreading ridges draped on the SMEAN shear-wave tomography model of Becker & Boschi (2002) near the core mantle boundary (CMB). The Iceland hotspot today overlies a shear-wave (δVs) anomaly of –0.5% at the CMB. The two estimated hotspot tracks are based on a fixed hotspot frame and a mantle frame that attempts to account for an advecting plume in the convecting mantle (see text for details). BTIP=British Igneous Province. (b) Example of a ~ 20 Ma plate reconstruction, similar to Fig. 7c, but using a mantle frame where the continents can be modelled in an 'absolute' sense. Greenland together with North America is drifting NW with a mean velocity of 2.2 cm/yr. whilst Europe is drifting NE at a speed of 1.7 cm/yr. The reconstruction shows the 20→10 Ma velocity fields and mean plate velocities calculated for a 10 x 10° grid for the entire North American and Eurasian plates.

Norway's drift story - Finale

In contrast to hotspot/mantle frames, palaeomagnetic data can be used throughout Earth history, but they only constrain latitude and the amount of angular rotation. We can therefore position continents at any longitude we wish by using other geological constraints such as the fossil record (e.g. Fig. 3b). Apparent polar wander (APW) paths represent a convenient way of summarising palaeomagnetic data. In the running mean method palaeomagnetic poles are assigned absolute ages, a time window is selected (e.g., 20 m.y. used in Fig. 9), and then all palaeomagnetic poles with ages falling within the time window are averaged. Figure 9 is the APW path used to reconstruct Norway (Baltica) in Phanerozoic space and time (Fig. 10). The early part of this APW path is based purely on Baltica data (mostly from Sweden) before the Silurian since Baltica was an independent continent. For later times, Baltican data are combined with Laurentian data (Scotland/North America). Finally, all globally available data from 330 Ma onwards are rotated to Norwegian (European) co-ordinates (Table 1), based on data selection and relative fits detailed in Torsvik & Van der Voo (2002) and on work in progress.

The drift history for Norway can be constructed with relatively high confidence since the Cambrian, whilst the older history is more patchy and poorly understood. For the times when Norway was part of the Rodinia supercontinent there exist essentially three undisputed data-sets: (1) Sveconorwegian poles (~ 970-1100 Ma) suggesting low-to-subtropical latitudes for Baltica, (2) the ~ 850-900 Ma Hunnedalen dykes (850 Ma) and the Egersund anorthosites (880-900 Ma uplift magnetizations) in SW Norway indicating high latitudes, and (3) 700-800 Ma sedimentary poles from Northern Norway and Russia that demonstrate equatorial latitudes. During and after Rodinia break-up, Baltica returned to high latitudes (~ 616 Ma). Thus, Norway is known to have experienced a rather tortuous Neoproterozoic and Vendian drift history.

Neoproterozoic (Vendian) glacial deposits are recorded on many continents, some evidently deposited at low latitudes and thereby suggesting that Earth was affected by global glaciation events (e.g., Hoffman & Schrag 2002). In Norway, the Moelv Tillite in the southeast and its correlative the Varangerian Mortensnes Formation in the far north (Fig. 10) are poorly dated. However, U/Pb dating of detrital zircons now constrain the

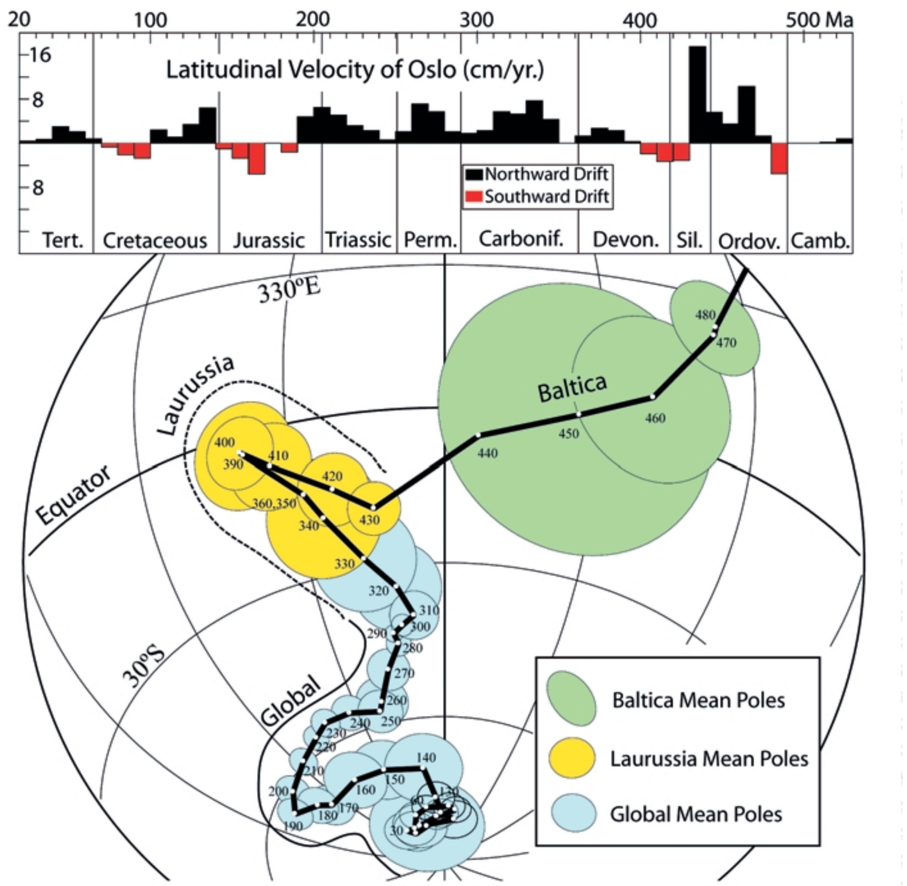

Fig. 9. Lower diagram: Apparent polar wander path (APW) for Norway (Baltica)(cf. text and Table 1). Running mean poles are shown with A95 confidence circles and mean poles older than 480 Ma (on the opposite hemisphere) are listed in Table 1. Top diagram: Latitudinal velocities for Oslo (based on APW path below).

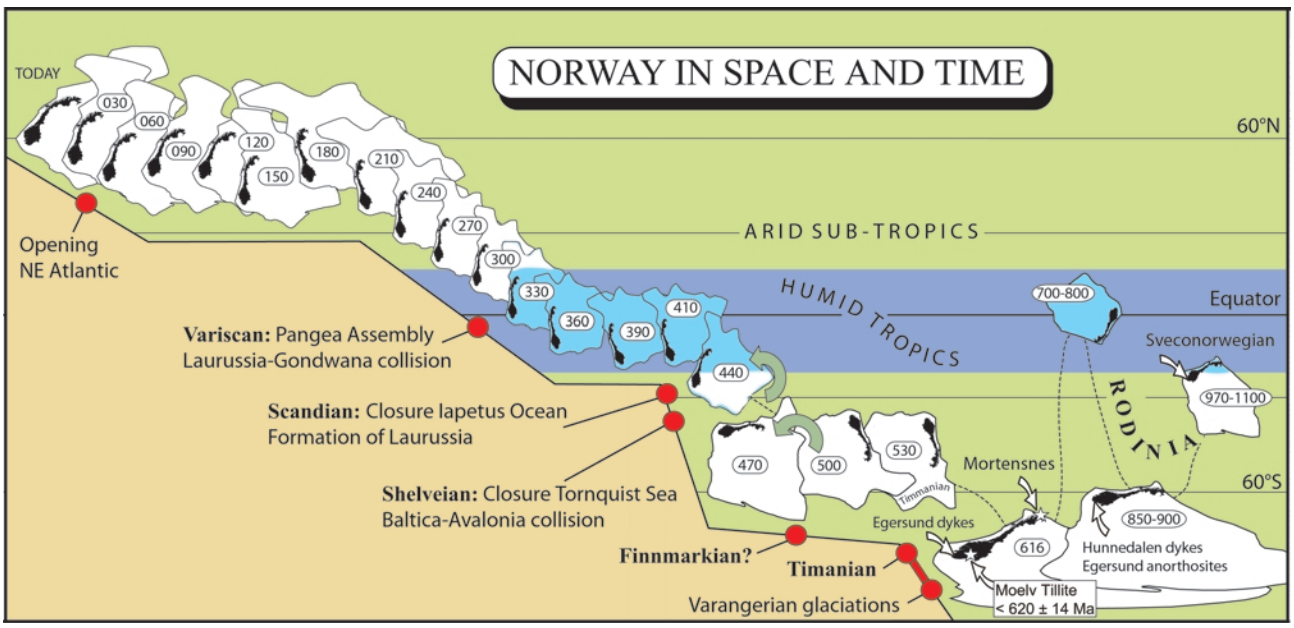

Fig. 10. The drift history for Norway (Baltica) based on the APW path in Figure 9.

Table 1.

Age±10 Ma	A95 (°)	N	Pole Latitude	Pole Longitude	Euler Latitude	Euler Angle
10	9.96	17	-82.06	337.42	67.42	7.94
20	3.8	27	-82.57	319	49	7.43
30	3.98	23	-81.24	313.59	43.59	8.76
40	3.64	20	-81.6	322.68	52.68	8.4
50	2.9	28	-79.31	332.41	62.41	10.69
60	2.57	36	-78.27	344.4	74.4	11.73
70	2.82	32	-78.32	3.93	93.93	11.68
80	2.72	34	-78.92	10.02	100.02	11.08
90	2.78	32	-80.43	351.79	81.79	9.57
100	4.72	11	-81.55	329.78	59.78	8.45
110	4	16	-81.01	10.93	100.93	8.99
120	3	24	-79.74	356.69	86.69	10.26
130	3.29	17	-76.47	353.59	83.59	13.53
140	7.07	9	-70.2	348.74	78.74	19.8
150	6.02	16	-68.58	328.94	58.94	21.42
160	5.73	14	-67.82	313.22	43.22	22.18
170	4.09	23	-68.29	294.37	24.37	21.71
180	3.66	27	-66.36	289.93	19.93	23.64
190	3.15	29	-63.66	280.35	10.35	26.34
200	3.17	32	-61.54	289	19	28.46
210	2.62	29	-59.37	302.05	32.05	30.63
220	2.41	30	-57.36	312.04	42.04	32.64
230	2.73	29	-55.83	317.91	47.91	34.17
240	3.44	32	-55.95	327.1	57.1	34.05
250	4.21	35	-57.45	337.37	67.37	32.55
260	4.91	26	-55.73	338.9	68.9	34.27
270	4.08	28	-49.83	343.43	73.43	40.17
280	2.39	57	-45.12	347.58	77.58	44.88
290	1.69	67	-43.03	346.71	76.71	46.97
300	2.14	36	-41.65	349.2	79.2	48.35
310	4.71	20	-39.92	352.39	82.39	50.08
320	8.63	10	-34.2	348.85	78.85	55.8
330	10.08	8	-28.12	342.39	72.39	61.88
340	11.39	5	-19.12	335.22	65.22	70.88
350		1	-14	332	62	76
360		1	-14	332	62	76
390	9.94	5	-3.81	321.27	51.27	86.19
400	6.68	7	-3.15	320.62	50.62	86.85
410	8.13	11	-7.19	326.21	56.21	82.81
420	6.98	16	-14.08	337.87	67.87	75.92
430	5.14	11	-18.75	345.69	75.69	71.25
440		1	-5.3	6.5	96.5	84.7
450	26.47	3	0.93	25.26	295.26	-90.93
460	15.53	3	7.38	39.23	309.23	-97.38
470	7.56	6	22.44	52.14	322.14	-112.44
480	8.45	5	24.13	52.81	322.81	-114.13
490		1	52	111	21	-142
500		1	52	111	21	-142
510		1	52	111	21	-142
530		1	58.4	122.5	32.5	-148.4

Phanerozoic running mean APW path (south poles) for Baltica (globally from 330 Ma and onwards) and Euler rotation data (Euler longitude is zero for all times) in European co-ordinates. A95=95% confidence circle; N=Number of poles.

deposition of the Moelv Tillite to younger than 620 ± 14 Ma (Bingen et al. 2005). Palaeomagnetic data from the 616 Ma Egersund dykes (Walderhaug & Torsvik, in preparation) demonstrate that Baltica was located at high latitudes during the Varangerian glaciation. These data do not rule out the postulate of a global glaciation (the so-called Snowball Earth), but reject an explanation in terms of changes in Earth's obliquity since such an explanation precludes high-latitude glaciations. The Varangerian glaciation was probably broadly contemporaneous with Vendian magmatism, metamorphism and tectonic activity (c. 630-550 Ma) in the Timan-Pechora-Rybachi-Varanger region, i.e. the Timanian orogenic event, a period of documented arc/continent along the northeastern margin of Baltica (Gee et al. 2000; Roberts & Siedlecka 2002; Rehnström et al. 2002; Roberts & Olovyanishnikov 2004).

In the Early Palaeozoic, Norway was located at intermediate to high southerly latitudes and rotated almost 180° compared to her present orientation. Late Cambrian and Ordovician times were marked by pronounced counter-clockwise rotation with northward drift during mid Ordovician to mid Silurian times. This culminated with a minor episode of southward movement (Fig. 9) after collision with Laurentia and the formation of Laurussia. Norway was located within the tropics from Late Ordovician to Late Carboniferous times and then drifted northwards into its present location (Fig. 9). Latitudinal velocities for Norway (Oslo) generally indicate velocities below 8 cm/yr. except for a velocity burst (16 cm/yr.) in the Early Silurian, and hence just prior to the Laurentia-Baltica collision.

Sedimentary facies and their contained faunas clearly reflect Baltica's drift history. In the Cambrian and early Ordovician, when Baltica was at relatively high southerly palaeolatitudes, the characteristic benthic brachiopod and trilobite faunas were not very diverse (Cocks & Fortey 1982). Carbonates, when present (rare), were of high-latitude temperate type (Jaanusson 1973). Baltica was apparently at its farthest distance from the other major terranes near the beginning of the Ordovician (Fig. 3b) and thus there were many endemic forms, even at the family level, such as the brachiopod *Lycophoria*. However, as the Ordovician progressed, the diversity increased as Baltica moved towards the palaeoequator. Also, the proportion of endemic brachiopod and trilobite genera decreased as immigrants from neighbouring terranes were able to migrate across the Iapetus and Tornquist Oceans as they narrowed (Cocks & Fortey 1998). In addition, from Caradoc times onwards, the sedimentary facies also reflects warmer climes, culminating in the substantial reefs seen in the Ashgill and even more widely in the Silurian (Fig. 4b).

From Late Devonian to Early Jurassic times, Norway was drifting systematically northwards with an average speed of 4 cm/yr. (Figs. 9 & 10). This northward drift is clearly documented in the sedimentary facies in the Barents Sea realm, where tropical Lower Carboniferous depositions changed to subtropical carbonates and evaporites (Nordkapp Basin with salt deposits at 20-23°N) by the Late Carboniferous (e.g., Roberts et al. 2003). During the Late Permian, southern Norway and the North Sea region entered the subtropics, evidenced by the Zechstein salt deposits (~260 Ma) that were mostly confined to latitudes between 18 and 27°N (arid climate).

Norway's general northward drift during the last 600 million years witnesses a history from a southerly arctic climate, through equatorial and sub-tropical climates (Late Ordovician through the Triassic), to the present stage of a temperate-to-arctic climate in the northern hemisphere. The drift history was associated with large rotations of Norway, and northward drift was periodically interrupted by short phases of southerly drift.

Acknowledgements: This paper is an overview gleaned from many papers that involved co-operation and discussions with Torgeir B. Andersen, Lewis D. Ashwal, Bernard Bingen, Kevin Burke, Fernando Corfu, Elizabeth A. Eide, Richard Fortey, Ebbe H. Hartz, Joe G. Meert, Jon Mosar, Manoj Pandit, Tim F. Redfield, Emma F. Rehnström, Donald M. Ramsay, David Roberts, R. James Roberts, Mark A. Smethurst, Bernhard Steinberger, Allan Trench, Harald J. Walderhaug, Rob Van der Voo and not least, the late Brian A. Sturt and W. Stuart McKerrow (Mac). We dedicate this paper to the memories of Brian and Mac and their outstanding contributions to Caledonide evolution and Palaeozoic palaeogeography.

References

Andersen, T. B., Jamtveit, B., Dewey, J. F. & Swensson, E. 1991: Subduction and eduction of continental crust: major mechanisms during continent–continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides. *Terra Nova 3*, 303–310.

Bogdanova, S., Gorbatschev, R., Stephenson, R.A. & Guterch, A. (eds.) 2001: Eurobridge: Palaeoproterozoic accretion of Fennoscandia and Sarmatia. *Tectonophysics 339*, 1-237.

Burke, K., MacGregor-Duncan, D. S. & Cameron, N.R. 2004: Africa's petroleum systems; four tectonic "aces" in the past 600 million years. *In* Arthur, T., MacGregor-Duncan, S. & Cameron, N.R. (eds.), *Petroleum geology of Africa; new themes and developing technologies.* Geological Society London Special Publications 207, 21-60.

Burke, K. & Torsvik, T.H. 2004: Derivation of large igneous provinces of the past 200 million years from long-term heterogeneities in the deep mantle. *Earth and Planetary Science Letters 227*, 531-538.

Becker, T.W & Boschi, L. 2002: A comparison of tomographic and geodynamic mantle models. *Geochemistry, Geophysics, Geosystems 3*, 2001GC000168.

Bingen, B., Griffin, W.L., Torsvik, T.H. & Saeed, A. 2005. Timing of Late Neoproterozoic glaciation on Baltica constrained by detrital zircon geochronology in the Hedmark Group, Southeast Norway. *Terra Nova* (in review)

Brekke, H., Sjulstad, H.I., Magnus, C. & Williams R.W. 2001: Sedimentary environments offshore Norway – an overview. *In* Martinsen, O.J. & Dreyer, T. (eds.), *Sedimentary Environments Offshore Norway – Palaeozoic to Recent.* Norwegian Petroleum Society special publication 10, 7-37.

Cocks, L.R.M. & Fortey, R.A. 1982: Faunal evidence for oceanic separations in the Palaeozoic of Britain. *Journal of the Geological Society London 139*, 465-478.

Cocks, L.R.M. & Fortey, R.A. 1998: The Lower Palaeozoic margins of Baltica. *Geologiske Föreningens i Stockholm Förhandlinger 120*, 173-179.

Cocks, L.R.M. & Torsvik, T.H. 2002: Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. *Journal of the Geological Society London 159*, 631-644.

Cocks, L.R.M. & Torsvik, T.H. 2005: Baltica: the gain and loss of a terrane's identity. *Earth-Science Reviews* (in press).

Cocks, L.R.M. & Worsley, D. 1993: Late Llandovery and early Wenlock stratigraphy and ecology in the Oslo Region, Norway. *Bulletin of the Natural History Museum (Geology) 49*: 31–46.

Corfu F., Roberts R.J., Torsvik T.H., Andersen T.B., Ramsay D.M. & Ashwal L.D. 2004: Crustal processing: The Finnmarkian orogen reassessed. *Geochimica et Cosmochimica Acta 68*, 624.

Dalziel, I.W.D. 1991: Pacific margins of Laurenatia and East Antarctica-Australia as a conjugate rift pair – Evidence and implications for an Eocambrian supercontinent. *Geology 19*, 598-601.

Eide, E.A. & Torsvik, T.H. 1996: Paleozoic Supercontinent assembly, Mantle flushing and genesis of the Kiaman Superchron. *Earth and Planetary Science Letters 144*, 389-402

Eldholm, O. & Coffin, M.F. 2000: Large Igneous Provinces and Plate Tectonics. *In* Richards, M.A., Gordon, R.G. & van der Hilst R.D. (eds.), *The History and Dynamics of Global Plate Motions.* American Geophysical Union, Washington, 309-326.

Friend, P.F., Williams, B.P.J., Ford, M. & Williams, E.A. 2000: Kinematics and dynamics of Old Red Sandstone basins. *Geological Society of London Special Publications 180*, 29-60.

Gale, G.H. & Roberts, D. 1972: Palaeogeographical implications of greenstone petrochemistry in the southern Norwegian Caledonides. *Nature 238*, 60-61.

Gale, G.H. & Roberts, D. 1974: Trace element geochemistry of Norwegian Lower Palaeozoic basic volcanics and its tectonic implications. *Earth and Plantary Science Letters 22*, 380-390.

Gee, D.G. 1975: A tectonic model for the central part of the Scandinavian Caledonides. *American Journal of Science 275*, 468-515.

Gee, D.G. 2005: Scandinavian Caledonides (with Greenland). *In* Selley, R.C., Cocks, L.R.M. & Plimer, I.R. (eds), *Encyclopedia of Geology.* Elsevier, Amsterdam (in press).

Gee, D.G. & Teben'kov, A.M., 2004. Svalbard: a fragment of the Laurentian margin. *Geological Society London Memoirs 30*, 191-206.

Gee, D.G., Beliakova, L., Dovshikova, E., Larionov, A. & Pease, V. 2000: Vendian intrusions in the basement beneath the Pechora Basin, northeastern Baltica. *Polarforschung 68*, 161–170.

Hartz, E.H. & Torsvik, T.H. 2002: Baltica upside-down: A new plate-tectonic model for Rodinia and the Iapetus Ocean. *Geology 30*, 255-258.

Hoffman, P.F. 1991: Did the breakout of Laurentia turn Gondwanaland inside-out? *Science 252*, 1409-1412.

Hoffman P. F. & Schrag D. P. 2002: The snowball Earth hypothesis: testing the limits of global change. *Terra Nova 14*, 129–155.

Ito, G., Lin, J. & Graham, D. 2003: Observational and theoretical studies of the dynamics of mantle plume-mid-ocean ridge interaction. *Reviews of Geophysics 41*, doi:10.1029/2002RG000117.

Jaanusson, V. 1973: Aspects of carbonate sedimentation in the Ordovician of Baltoscandia. *Lethaia 6*, 11-34.

Marzoli, A., Renne, P.R., Piccirilo, E.M., Ernesto, M., Bellieni, G. & De Min, A. 1999: Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province. *Science 284*, 616-618.

Matte, P. 2001: The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: a review. *Terra Nova 13*, 122-128.

Mosar, J., Torsvik, T.H. & the BAT team 2002: Opening of the Norwegian and Greenland Seas: Plate tectonics in Mid Norway since the Late Permian. *In* Eide, E.A. (coord.), *BATLAS – Mid Norway plate* *reconstruction atlas with global and Atlantic perspectives*. Geological Survey of Norway, 48-59.

Murphy, J. B., Stachan, R. A., Nance; R. D., Parker, K. D. & Fowler; M. B. 2000: Proto-Avalonia: A 1.2-1.0 Ga tectonothermal event and constraints for the evolution of Rodinia. *Geology 28*, 1071-1073.

Müller, R.D., Royer, J.-Y. & Lawver, L.A. 1993: Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks. *Geology 16*, 275-278.

Osmundsen P.T., Sommaruga A., Skilbrei J.R. & Olesen O. 2002: Deep structure of the Mid Norway rifted margin. *Norwegian Journal of Geology 82*, 205-224.

Pharaoh, T.C., Brewer, T.S. & Webb, P.C. 1993: Subduction-related magmatism of late Ordovician age in eastern England. *Geological Magazine 130*, 647-656.

Rehnström, E.F., Corfu, F. & Torsvik, T.H. 2002: Evidence of a Late Precambrian (637 Ma) Deformational Event in the Caledonides of Northern Sweden. *Journal of Geology 110*, 591-601.

Roberts, D. 2003: The Scandinavian Caledonides: event chronology, palaeogeographic setting and likely modern analogues. *Tectonophysics 365*, 283-299.

Roberts, D. & Gee, D.G. 1985: An introduction to the structure of the Scandinavian Caledonides. *In* Gee, D.G. & Sturt, B.A. (eds.), *The Caledonide Orogen — Scandinavia and Related Areas*. Chichester, John Wiley and Sons, 55-68.

Roberts, D. & Siedlecka, A. 2002: Timanian orogenic deformation along the northeastern margin of Baltica, Northwest Russia and Northeast Norway, and Avalonian–Cadomian connections. *Tectonophysics 352*, 169-184.

Roberts, D. & Olovyanishnikov, V., 2004. Structural and tectonic development of the Timanide orogen. *Geological Society London Memoirs 30*, 47-57.

Roberts, R.J., Torsvik, T.H., Andersen, T.B. & Rehnström, E.F. 2003: The Early Carboniferous Magerøy Dykes, Northern Norway: Palaeomagnetism and Palaeogeography. *Geological Magazine 140*, 443-451.

Roberts R.J., Corfu F., Ashwal L.D., Torsvik T.H. & Ramsay D.M., 2004: The Seiland Igneous Province: Provenance and geodynamic significance. *Geochimica et Cosmochimica Acta 68*, 594.

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J. & Kent, R.W. 1997: The North Atlantic Igneous province. In Mahoney, J.J. & Coffin, M.F. (eds.): *Large Igneous Provinces*. Geophysical Monograph, 100, American Geophysical Union, Washington D.C., 45-93.

Skogseid, J., Planke, S., Faleide, J. I., Pedersen, T., Eldholm, O. & Neverdal, F. 2000: NE Atlantic continental rifting and volcanic margin formation. *Geological Society of London Special Publication 167*, 295-326.

Smelror, M., Cocks, L.R.M., Mørk, A., Neuman, B.E.E. & Nakrem, H.A. 1997: Upper Ordovician – Lower Silurian strata and biota from offshore South Norway. *Norsk Geologisk Tidsskrift 77*, 251-268.

Smith, W.H.F. & Sandwell, D.T. 1997: Global sea floor topography from satellite altimetry and ship depth soundings. *Science 277*, 1956-1962.

Steinberger, B., Sutherland, R. & O'Connell, R.J. 2004: Prediction of Emperor-Hawaii seamount locations from a revised model of plate motion and mantle flow. *Nature 430*, 167-173.

Stampfli, G.M. & Borel, G.D. 2002: A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters 196*, 17-33.

Strand, T. & Kulling, O. 1972: *Scandinavian Caledonides*. Wiley-Intersci., 302 pp.

Sturt, B.A. 1984: The accretion of ophiolitic terrains in the Scandinavian Caledonides. *Geologie en Mijnbouw 63*, 201-212.

Sturt, B.A., Pringle, I.R. & Ramsay, D.M. 1978: The Finnmarkian phase of the Caledonian Orogeny. *Journal Geological Society London 135*, 547-610.

Størmer, L. 1967: Some aspects of the Caledonian geosyncline and foreland west of the Baltic Shield. *Q. Journal of the Geological Society London 123*, 183-214.

Torsvik, T.H. 1998: Palaeozoic Palaeogeography: A North Atlantic viewpoint. *Geologiske Föreningens i Stockholm Förhandlinger 120*, 109-118.

Torsvik, T.H. 2003: The Rodinia Jigsaw Puzzle. *Science 300*, 1379-1381.

Torsvik, T.H. & Trench, A. 1991: The Ordovician history of the Iapetus Ocean in Britain: New palaeomagnetic constraints. *Journal of the Geological Society London 148*, 423-425.

Torsvik, T.H. & Rehnström, E.F. 2001: Cambrian palaeomagnetic data from Baltica: Implications for true polar wander and Cambrian palaeogeography. *Journal of the Geological Society London 158*, 321-329.

Torsvik, T.H. & Rehnström, E.F. 2003: The Tornquist Sea and Baltica-Avalonia docking. *Tectonophysics 362*, 67-82.

Torsvik, T.H. & Cocks, L.R.M. 2004: Earth geography from 400 to 250 million years: a palaeomagnetic, faunal and facies review. *Journal Geological Society London 161*, 555-572

Torsvik, T.H. & Van der Voo, R. 2002: Refining Gondwana and Pangea Palaeogeography: Estimates of Phanerozoic (octupole) non-dipole fields. *Geophysical Journal International 151*, 771-794.

Torsvik, T.H., Mosar, J. & Eide, E.A. 2001b: Cretaceous-Tertiary Geodynamics: A North Atlantic exercise. *Geophysical Journal International 146*, 850-867.

Torsvik, T.H., Van der Voo, R., Meert, J.G., Mosar, J. & Walderhaug, H.J. 2001a: Reconstructions of the continents around the North Atlantic at about the 60th parallel. *Earth and Planetary Science Letters 187*, 55-69.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A. & Walderhaug. H.J. 1996: Continental break-up and collision in the Neoproterozoic and Palaeozoic: A tale of Baltica and Laurentia. *Earth-Science Reviews 40*, 229-258.

Vernikovsky, V. A. 1997: Neoproterozoic and Late Palaeozoic Taimyr Orogenic and Ophiolitic Belts, North Asia: A Review and Models for their formation. *Proceedings 30th International Geological Congress 7*, 121–138.

Van der Voo, R. & Torsvik, T.H. 2001: Evidence for Permian and Mesozoic Non-dipole Fields Provides an Explanation for the Pangea Reconstruction Problems. *Earth Planetary Science Letters 187*, 71-81.