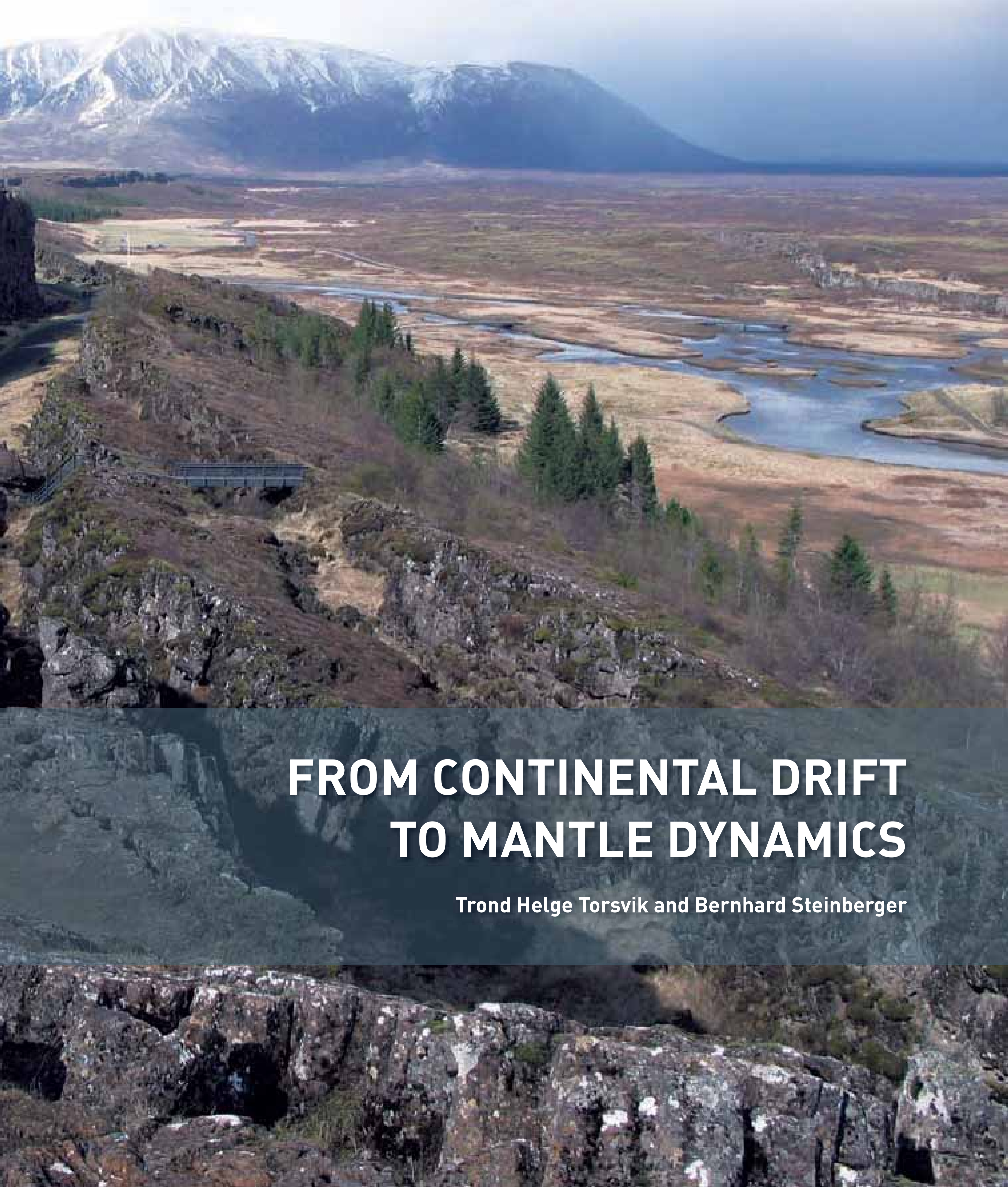
Photo: Terje Wenaas



FROM CONTINENTAL DRIFT TO MANTLE DYNAMICS

Trond Helge Torsvik and Bernhard Steinberger

Our description of movements and deformation of the Earth's outer shell has developed over the course of a century, from the hypothesis of continental drift (ca. 1915), to seafloor spreading (ca. 1962), and more recently to the theory of plate tectonics (ca. 1967). Plate tectonics has had success, both theoretically and practically, and it has formed a scientific framework for many geological disciplines, including within hydrocarbon and mineral exploration. A new revolution is on the way, however, and we postulate here that plate tectonics will become part of a new visionary theory of mantle dynamics.

The article is taken from GEO 8, 2006.

FROM CONTINENTAL DRIFT TO MANTLE DYNAMICS

Trond Helge Torsvik og Bernhard Steinberger

Geological Survey of Norway

THE FIRST REVOLUTION: CONTINENTAL DRIFT

At the beginning of the previous century (1915[1]), Alfred Wegener proposed that the continents originally consisted of a single supercontinent. The supercontinent called Pangea ('all land') was surrounded by the marine area of Panthalassa ('all sea'), which covered the rest of the world (Figure 1a). He believed that, during the Earth's intervening history, Pangea was split into a series of continents through continental drift. At the time, this was a revolutionary theory which rocked the prevailing fundamental assumptions. Back then, all geologists believed that the continents were immobile and had never moved. Wegener partly based his theory on the view that the coastlines of the South Atlantic were extremely similar. He also pointed out that plant and animal fossils from a number of continents during the Permo-Carboniferous Period, such as those from South America and Africa, are almost identical. He argued that it was physically impossible for individual animal organisms to be transported 3000–6000 km from one side of the ocean to the other. Many rock formations are also clearly linked if the two continents are placed next to each other. For example, Wegener pointed to the similarity between the old mountain chain in Great Britain and Scandinavia (the Caledonides) and a corresponding mountain chain in the USA and Canada (the Appalachians). Based on the mapping of older glacial deposits (Figure 2), Wegener was also convinced that a continental ice cap must have covered South America, South Africa, Madagascar, India and the southern parts of Australia around 300 million years ago. He therefore concluded that the continents must have moved in relation to today's South Pole.

In Wegener's reconstruction of the continents 300 million years ago, Africa, Europe and Asia are shown in their current positions, while North and South America are reconstructed through the closure of the Atlantic Ocean (Figure 1a). If we compare this reconstruction with a modern computer-based reconstruction with a much larger database available, we can quite clearly see similarities (Figure 1b). So, what have we actually achieved during the last hundred years or so? The most important difference is that we are now able to position Pangea at its correct latitude using magnetic data. We can therefore directly study how climate-sensitive (latitude-dependent) sedimentary rock types were distributed across the Earth's surface in the past. Around 300–310 million years ago, the South Pole for example was covered by a large ice cap (based on the mapping of glacial deposits), which extended northwards to around 50–45oS. At the same time, the areas around the equator were characterised by coal deposits (tropical wet climate), and salt deposits which largely occur at subtropical latitudes (dry climate).

THE SECOND REVOLUTION: SEAFLOOR SPREADING

The theory of continental drift was not accepted or developed further until the early 1960s. The American geologist Harry Hess was responsible for one of the breakthroughs. In 1962, he published an article in which he proposed the theory of seafloor spreading. In its simplest form, it says that basaltic magma from the mantle flows up beneath the central oceanic spreading ridges, and that old seafloor moves away from the oceanic spreading ridges and is finally returned to the mantle through subduction, where the oceanic plate is pushed

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[1] He gave the very first presentation of his ideas verbally to the German Geological Association in 1912, but it was not until 1915 that he published a book entitled *Die Entstehung der Kontinente und Ozeane (The origin of the continents and the oceans)* in which all the arguments were collated.

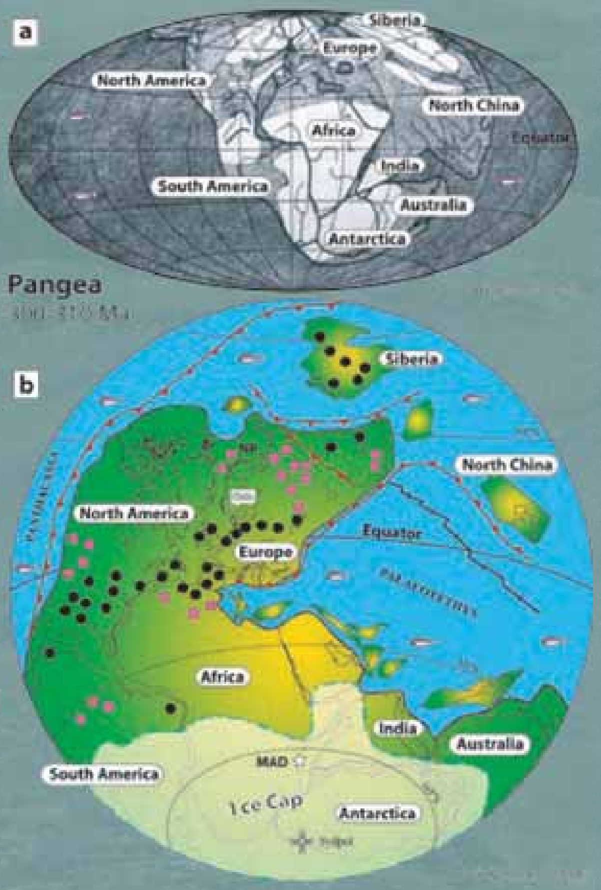


FIGURE 1

(a) Wegener's original reconstruction of Pangea as he believed the supercontinent appeared around 300 million years ago. (b) A modern reconstruction of Pangea as it may have looked 310 million years ago, which also shows salt (pink squares) and coal deposits (black symbols). Southern Pangea was covered by an ice cap at this time. NB = North Cape Basin; MAD = Madagascar.

beneath an overlying plate. One of the reasons why Wegener's continental drift theory was not accepted was because of his assumption that the continents had *ploughed through* the oceanic crust to their current positions, and that he had no proposal for a mechanism for the driving forces behind the movements. In the theory of seafloor spreading, however, the continents sit on top of rigid plates, new oceanic crust is formed along the oceanic spreading ridges, and the new oceanic crust is compensated for along subduction zones elsewhere on the Earth. While the spreading ridges are characterised by high heat flow and shallow earthquakes, the subduction zones are characterised by low heat flow and deep earthquakes. As early as the latter half of the 1950s, it was already known that the seafloor was characterised by linear magnetic anomalies. Yet no one was able to understand the significance of these anomalies until two English geophysicists (Vine & Matthews 1963) realised that the magnetic stripe system, which had been developed parallel to many oceanic spreading ridges, was caused by reversals in the magnetic field (Figure 3). The Earth's magnetic field has its origin in the outer, liquid core and changes direction or polarity (reverses) at irregular intervals. This means that the Magnetic North Pole and South Pole swap over. The Earth's magnetic field has reversed irregularly around every 200,000 years over the past 5 million years. We do not know the reason for these reversals, but it was studies of the seafloor's magnetic field that would become the decisive test to confirm the theory of seafloor spreading.

FIGURE 2

Carboniferous tillite (lithified moraine, deposited by glaciers) from Madagascar. The locality is indicated by a star and MAD in Figure 1. Tillites of Late Carboniferous and Early Permian age are found across the whole of southern Pangea, indicating that a continental ice cap existed at this time.

THE THIRD REVOLUTION: PLATE TECTONICS

Plate tectonics is a revolutionary theory which was formulated during the period 1965 to 1968. It represented an attempt to understand the observable evidence for large-scale movements of the Earth's crust and to explain the theories of continental drift and seafloor spreading. The word 'tectonics' comes from Greek and means 'to build'. Plate tectonics refers to how the Earth's surface is constructed from large and small rigid plates (Figure 4) that move in relation to each other. An important difference from the continental drift theory is that the plates can consist of both continents and seafloor. The American Jason Morgan and the Canadian J. Tuzo Wilson were central figures in the development of plate tectonics (Wilson 1965, 1966; Morgan 1968), but it was the Englishman Dan McKenzie and the American Robert Parker who published the quantitative principles for plate tectonics in an article in Nature in 1967. They demonstrated how the movements of a rigid and non-deformable plate would lead to the constructive, destructive and sideways plate boundaries (see Fact box 1) which can actually be observed on the surface of the Earth. One of the first people to apply the new plate tectonics theory to understanding the development of mountain chains was the British geologist John Dewey (Dewey & Bird 1970). He was one of the first to see the link between the Caledonian mountain chain in Great Britain and Ireland on the one hand and the Appalachians in North America on the other. Plate tectonics is a fascinating story of plates

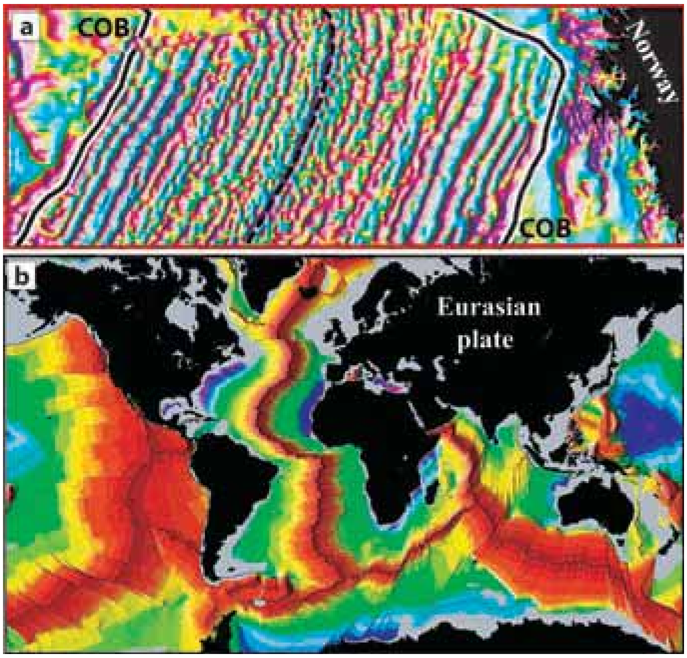


FIGURE 3

(a) Observed (measured) magnetic anomalies parallel to the spreading axis in the Norwegian Sea between Lofoten and Northeast Greenland. The dashed line is the present-day spreading axis. Warm colours (red) indicate magnetic anomalies with normal polarity as today, while colder colours (blue) represent periods with reversed magnetic polarity. COB = Continent-Ocean Boundary. (b) Modelled age of oceanic crust for the entire Earth. Warm (red) colours indicate young seafloor (close to the spreading axis), while cold (blue/violet) colours indicate old oceanic crust. The oldest preserved oceanic crust (around 175 million years old) is found, among other places, in the central Atlantic Ocean (between North America and Northwest Africa) and is linked to the very earliest break-up of the supercontinent Pangea.

that move across the surface of the Earth as a result of processes deep in the mantle. Plates glide apart and create new seafloor or collide and form large mountain chains. Powerful earthquakes and enormous volcanic eruptions close to destructive plate boundaries form part of this story. In areas where the continents are gliding apart, new seafloor is created, as in our part of the world. In the North Atlantic, Scandinavia, which today forms part of the Eurasian plate, is gliding slowly away from both Greenland and North America (the North American plate). Over the plate boundary, we find Iceland, which is one of the world's largest volcanic islands (Figure 4). The photo on pages 22–23 is taken approximately at the plate boundary, with the Eurasian plate to the right and the North American plate to the left. The seafloor spreading between Norway and Greenland began around 54 million years ago. This spreading followed an extended period of continental extension, which forms the basis for sedimentary basins along Norway's continental shelf and its oil and gas deposits.

During the opening of the Atlantic Ocean, the Møre coast was less than 500 km from the east coast of Greenland. Today, the distance between Møre and Greenland is around 1500 km. Approximately 1000 km of new seafloor (equivalent to the distance between Oslo and Alta as the crow flies) have therefore been formed over the past 54 million years. This corresponds to approximately 2 cm per year. It is often said that this is about the rate at which a fingernail grows.

THE ANCIENT DANCE OF THE PLATES

In order to reconstruct the position of the plates through geological time (Fact box 2), we distinguish between *quantitative* and *semi-quantitative* methods (e.g., the distribution of latitude-sensitive/climate-dependent rock types). Magnetic anomalies and fracture zones in the oceanic crust can be used to reconstruct the relative relationship between two or more tectonic plates right back to the Jurassic Period, i.e., about 175 millions back in time. Nowhere on Earth is the oceanic crust older than this (Figure 3b). Another widespread method is the 'hot spot method'. This is an absolute reconstruction method, i.e., we can position a plate in terms of both latitude and longitude, but the method can only be used back as far as the Cretaceous Period (approximately

FACT BOX 1

PLATE TECTONICS

Plate tectonics is a theory which says that the Earth is divided into seven large and several smaller plates which move relative to each other. The Earth's plates, which we also call the lithosphere, vary from 70 to 300 kilometres in thickness.

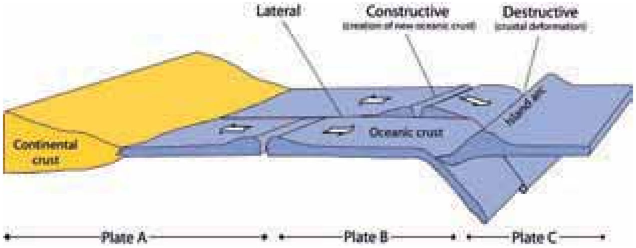
The lithosphere consists of the uppermost mantle and the crust; the outer shell of the Earth. Continental crust (largely granitic in composition) is between 30 and 40 km thick, but under young mountain chains it can be as much as 70–80 km thick. The thickness of the oceanic crust (dominated by basalt) varies from 5 to 10 km. The underside of the lithosphere represents the plates' glide zone where they move over the deep parts of the mantle (the asthenosphere). In plate tectonics theory, a distinction is made between three types of plate boundaries:

(1) Constructive: at oceanic spreading ridges, the plates move apart from each other, and new oceanic crust is formed through molten masses penetrating up from the mantle, solidifying and turning into the rock basalt. The newly formed, hot oceanic crust is light, but as it moves away from the plate boundary it cools and becomes heavier and older. We find such an oceanic spreading ridge along the entire Atlantic Ocean, and it continues northwards into the Norwegian Sea and on into the Arctic Ocean.

(2) Destructive: there are three types of destructive boundary: between an ocean and a continent, between two continents and between two oceans. Along destructive plate boundaries where an ocean is involved, one plate will be forced beneath the other (subduction), causing powerful earthquakes. Where the plate is forced downwards, a deep oceanic trench is formed, where the depth of the sea can exceed 10,000 m. Such boundaries are associated with volcanic activity. The deep oceanic trench south of Java and Sumatra is an example of a subduction zone. Here, the Australian plate is being forced underneath the Eurasian plate.

Along destructive plate boundaries where two continents meet, large mountain chains will be formed. The Himalayas are the best example of such a boundary. Here, the Indian plate is moving northwards and meeting the Eurasian plate. The Caledonian mountain chain that we see the remnants of in Norway today is also the result of a collision between two continents.

(3) Sideways: at this type of plate boundary, two plates move sideways in relation to each other. Over millions of years, the movements can amount to thousands of kilometres. The best known plate boundary of this type is the San Andreas fault in California, where the Pacific Plate is moving northwards relative to the North American plate and causing powerful and destructive earthquakes, including the earthquake off the coast near San Francisco in 1906.



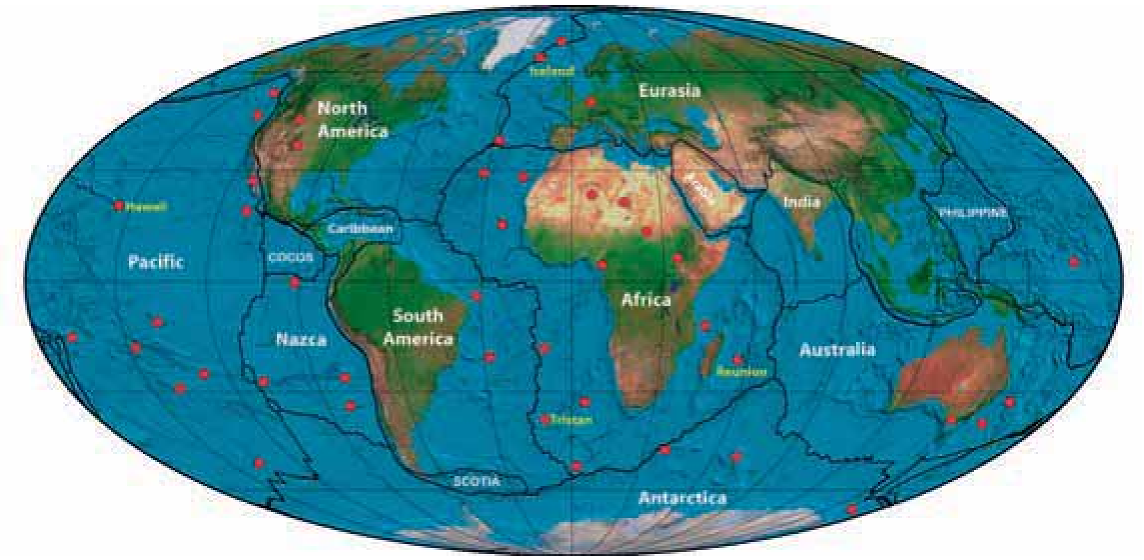


FIGURE 4

The Earth's main plate boundaries (black lines) and the distribution of hot spots (Steinberger 2000) on the surface of the Earth (red circles). Many hot spots are not situated on a plate boundary. This applies to Hawaii (the Pacific plate) and Reunion (the African plate).

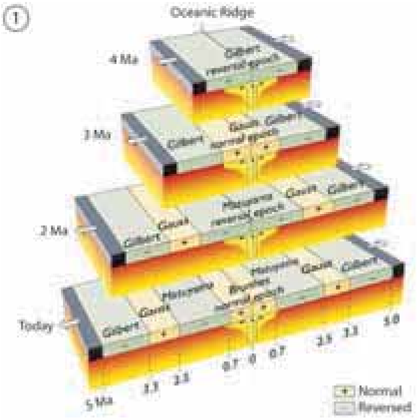
100–130 million years ago), because this is the oldest remaining evidence of a hot spot. Studies of the rocks' magnetism, which we now refer to as 'palaeomagnetism' (Torsvik 2005), were one of the principal reasons why the plate tectonic theory was accepted at the end of the 1960s. By measuring magnetism in a rock, we can find out the latitude at which it was formed. Measuring the magnetisation in Permian lava flows in the Oslo Graben for example shows that Oslo must have been located close to the equator around 300 million years ago (Figure 1b). Magnetism is therefore not just a tool that can be used for navigation in everyday life, by both people and birds, but is one of the primary tools for determining how the plates have moved across the surface of the Earth. Magnetic measurements are actually the only quantitative method for reconstructing what happened to the plates *before* the Jurassic Period.

SCANDINAVIA IS BORN

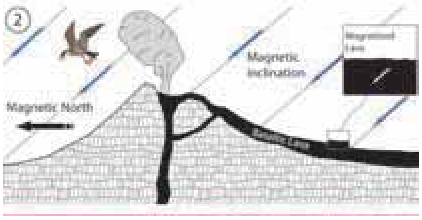
Scandinavia is today part of the Eurasian plate (Figure 4), which extends from Svalbard to Spain in the Atlantic Ocean area, right across to the Himalayas (where it collides with the Indian plate) and the Pacific Ocean. In Norway, large earthquakes or destructive volcanic eruptions do not affect us. This is because we live a long way from any plate boundaries. However, if you think that today's geological processes are a little boring, they were most definitely not boring in the early history of the Earth. For a long period in the Palaeozoic, Scandinavia formed part of a fairly small continental plate called Baltica (Figure 5a). Baltica was separated from other continents by large marine areas, including the Iapetus Ocean between Baltica and Laurentia (North America, Greenland, Scotland and northern Ireland) and the Tornquist Sea between Baltica and Avalonia (the southern areas of England/Ireland and parts of Western Europe). The distribution between continents and marine areas also played a role in the development of life on Earth. We can clearly see this in the Early Ordovician in that trilobites from Scandinavia (Baltica) are different from those that are found in North America and Africa (Figure 5a). During the Ordovician Period (Figure 5b), the Tornquist oceanic crust was pushed underneath the small continent of Avalonia (subduction), resulting in the formation of a chain of large volcanoes in England (around 455 million years old). These volcanoes were probably the reason why the whole of southern Scandinavia (including Oslo) was covered by a thick ash layer (up to 2 m), which extended as far east as St. Petersburg in Russia. We find

FACT BOX 2

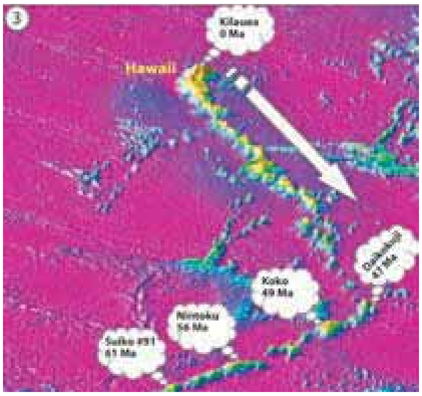
QUANTITATIVE METHODS FOR PLATE RECONSTRUCTION



Magnetic anomalies: magnetic anomalies are the result of the formation of new oceanic crust at the same time as the Earth's magnetic field changes direction (polarity). This results in the formation of a striped magnetic pattern with normal and reversed polarity. This striped pattern, together with fracture zones, is used to reconstruct marine areas—these are relative reconstructions and give no indication of the latitude of the continents. Early in the last century, Frenchman Bernard Brunhes was the first to discover that some rocks were magnetised in the opposite direction to the present day magnetic field, and the Earth's current normal polarity (for approximately the last 700,000 years) is therefore named after him (the Brunhes Normal Polarity Epoch).



Palaeomagnetism: virtually all rocks that are formed on the Earth contain small magnetic minerals, which tell us the latitude that a continent was at when the rock was formed. Magnetic minerals are non-magnetic at high temperatures, normally over 600°C, but during a volcanic eruption, when the lava solidifies and cools below this temperature, small magnets will be locked into the lava. The orientation of these magnets is determined by where on the Earth the volcanic eruption occurred. This is because the angle of slope (the inclination) of the Earth's magnetic field varies with latitude. At the equator, the inclination is equal to zero; in the Oslo area the inclination is around 75° and at the magnetic north pole it points directly downwards and is 90° (Torsvik 2005).



Hot spot tracks: reconstructions using hot spot tracks are based on the assumption that hot spots are relatively stable in the Earth's mantle. Volcanic activity associated with a hot spot can exist for between a couple of million years to over a hundred million years. When a plate moves over a hot spot, volcanic islands are formed in a line. Hawaii (here viewed from the northwest) is an example of this. The arrow indicates the direction of movement of the Pacific plate. By dating the volcanic islands, it is possible to reconstruct a plate in latitude and longitude. Around 47 million years ago, a dramatic change occurred in the direction of the hot spot track.

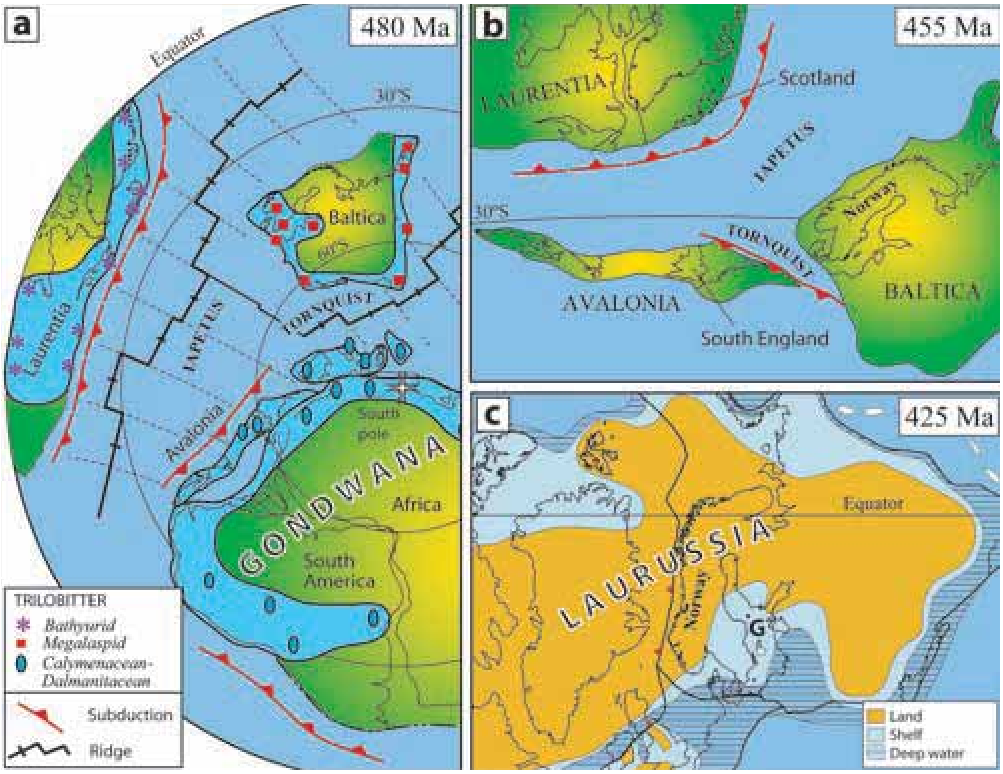


FIGURE 5

(a) Early Ordovician (480 million years) reconstruction based on palaeomagnetic data for various plates which existed at this time, e.g., Gondwana, Baltica, Laurentia and some plates which no longer exist along the margin of Gondwana (such as Avalonia). Gondwana extended from the South Pole (Africa) to the equator (such as Australia, which is not shown on this figure), Baltica was located at intermediate southerly latitudes (separated by the Tornquist Sea), while Laurentia was located close to the equator. The Iapetus Ocean (approximately 5000 km wide) and the Tornquist Sea (approximately 1100 km wide) were at their widest at this time. This is probably the reason why trilobites from Laurentia (bathyurid) and Gondwana are so different from those which belonged to Baltica (Torsvik 2005). (b) Late Ordovician (455 million years) reconstruction of Laurentia, Baltica and Avalonia. The Iapetus Ocean shrank as the oceanic crust between Laurentia and Baltica was pushed underneath Laurentia (Torsvik & Cocks 2005). (c) Silurian (425 million years) reconstruction, in which Baltica and Avalonia have collided with Laurentia and thereby formed Laurussia. The Iapetus Ocean is now closed.

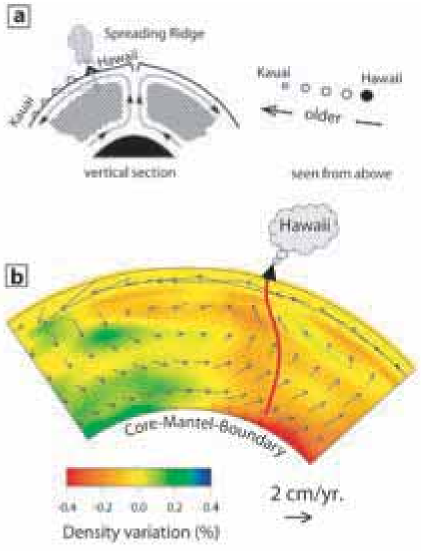


FIGURE 6

(a) J. Tuzo Wilson's original drawing (1963) in which he developed the hot spot theory. He argued that the volcanic island chain of Hawaii was the result of the Pacific plate moving over a deep stationary thermal plume in the mantle. (b) More recent research shows that hot spots are probably not stationary, as a result of convection in the mantle. This figure shows currents (arrows) in the mantle (N–S profile under Hawaii) and the way in which this affects the thermal plume beneath Hawaii (red line) on its way from the transition between the mantle and core (Steinberger 2000, Steinberger et al. 2004).

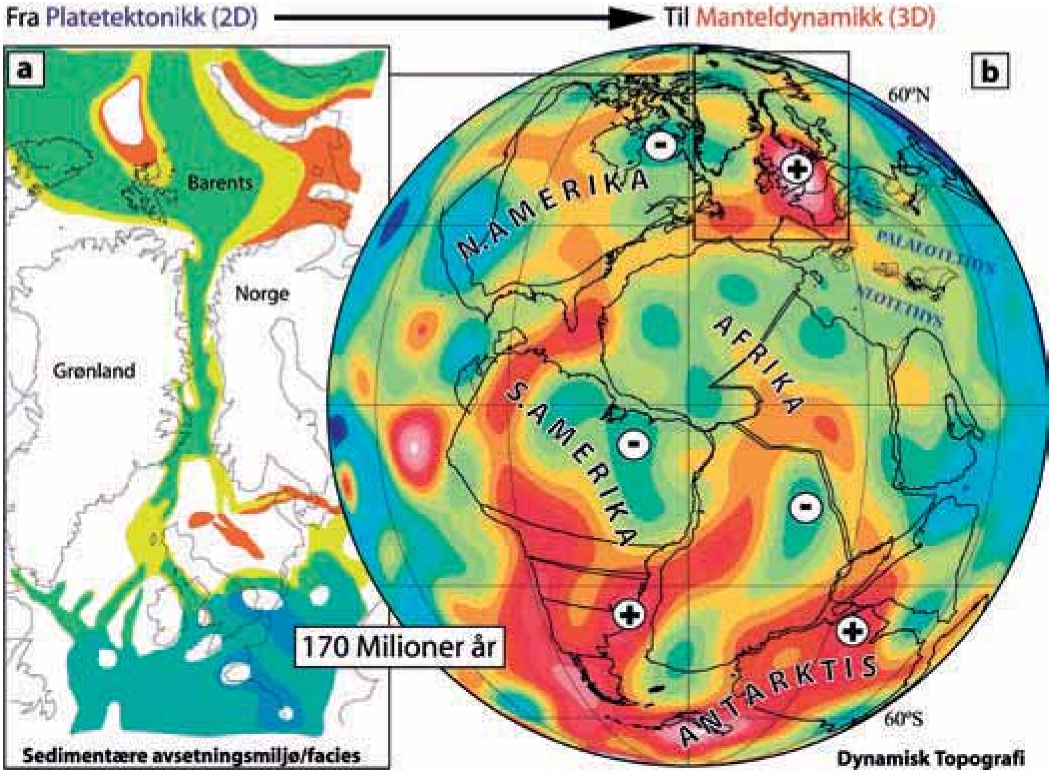


FIGURE 7

(a) Plate reconstruction of the North Atlantic and the Barents Sea in the Middle Jurassic (170 million years ago), which also shows sedimentary deposition environments (Torsvik et al. 2002). (b) Global reconstruction in which we have also calculated the dynamic topography based on mantle tomography (seismic images) and a new absolute reference frame developed by the authors of the article. Dynamic topography may become important for the petroleum industry, as it gives information on the areas of the continents which were below (blue colours, -) or above (red/white colours, +) sea level. Changes over time can tell us about uplift and sinking rates, which in turn can be used to predict sedimentary deposition rates. It will, however, be a long time before dynamic topography calculations for such a long way back in time as the Jurassic Period can be considered credible.

these ash layers as thin layers of clay (bentonite) interbedded with Ordovician limestones. Baltica and Avalonia collided around 440 million years ago (Early Silurian), but this was a 'soft' collision and cannot be compared with the collision between Baltica and Laurentia around 425 million years ago (Middle Silurian). The latter collision (Figure 5c) resulted in the formation of the Caledonian mountain chain, which extended from the east coast of North America via the British Isles, Scandinavia and Greenland, and as far north as Svalbard. During the Silurian, parts of the Baltic plate (Western Norway) were forced down underneath Laurentia (Greenland) to great depths, perhaps 100 km. At the same time, rocks (nappes) were pushed over Norway, and many of the rocks we have in Norway today, such as the metamorphosed gneisses in Western Norway, are a direct result of this latter collision. The nappes contain rocks from Baltica, metamorphosed basalts from the former Iapetus Ocean, and rocks from Laurentia. The mountain chain has since been eroded down, but we can see the remains of the mountain chain along the entire coast of Norway as a result of subsequent land uplift and erosion. During the Silurian Period, Southern Norway was situated at southerly latitudes and Tromsø was close to the equator. The climate was therefore far more pleasant than it is today.

THE FOURTH REVOLUTION: MANTLE DYNAMICS

Convection in the underlying mantle is generally accepted as the fundamental cause of plate movements. The geometry of the mantle currents is, however, poorly understood, and there is still no generally accepted mechanism that can explain the forces that drive the plates. Hot spots and enormous volcanic provinces that we find in certain parts of the world can also not be explained with the aid of plate tectonics. A new revolution is on the way, however. At the Centre for Geodynamics at the Geological Survey of Norway, plate tectonics is being integrated into a new theory for mantle dynamics. In contrast to plate tectonics, where simple kinematic models explain plate movements and deformation, mantle dynamics attempts to develop a complete three-dimensional geodynamic model. To achieve this, we are using many geological methods: plate kinematics, geodesy, mantle convection modelling, seismic images of the Earth (seismic tomography), petrology and mineral physics. We believe that our work on mantle dynamics will lead to a theory that covers the entire Earth, from crust to core, in which plate movements, both horizontal and vertical, are linked to deeper processes

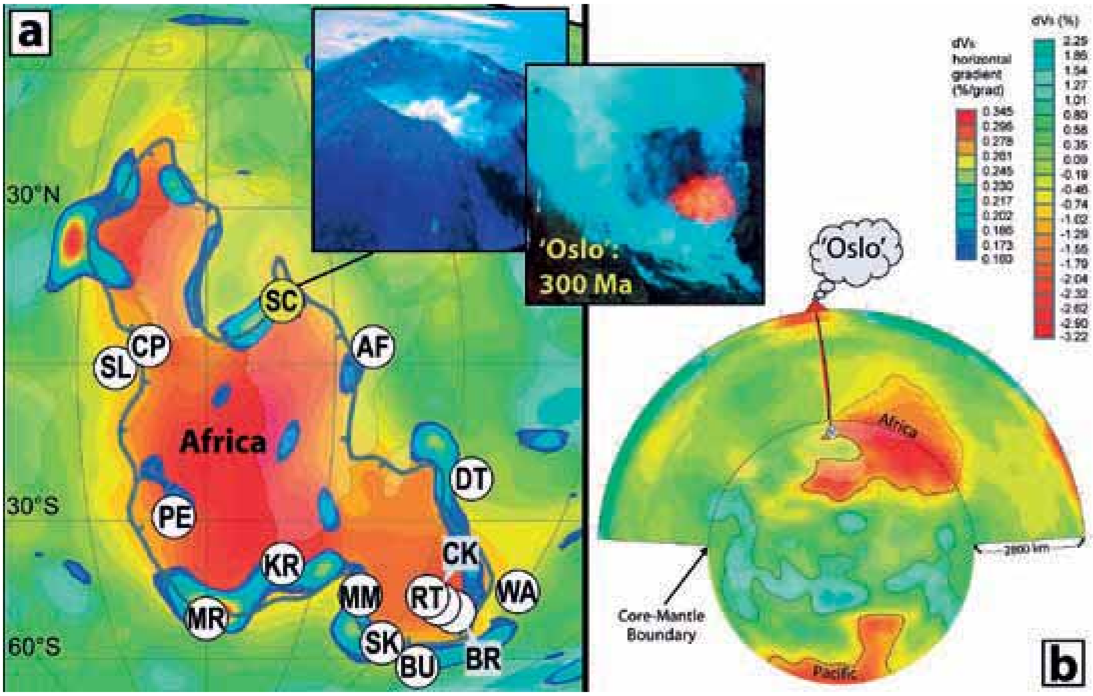


FIGURE 8

(a) Reconstruction of large volcanic provinces for the last 300 million years in the Atlantic/Indian region compared with seismic anomalies (s-waves) close to the mantle/core transition (2800 km). These seismic anomalies have existed for several hundred millions, perhaps billions, of years. It can be clearly seen that there is a strong tendency for such provinces to be located over the margin of the African low-velocity area (red colours) and often close to large horizontal gradients close to the –1% contour (thick grey line). Velocity anomalies (dVs) are expressed as a percentage. The blue colour represents areas with high seismic velocity, and red low velocities. Horizontal gradients are shown as (%dVs/degree) when they exceed 0.16. SC = Skagerrak thermal plume (Torsvik et al. 2008). (b) Seismic tomography close to the mantle/core boundary as in (a) but also showing parts of the antipodean Pacific low-velocity anomaly and a tomographic cross-section through the Earth. The African low-velocity anomaly extends high up into the mantle (to a depth of about 1500 km) and the authors claim that the Oslo Rift and its volcanism around 300 million years ago was a result of a long journey (about 10–20 million years), which began with a thermal plume from the mantle/core boundary. Modified from Torsvik et al. (2006).

inside the Earth. This is entirely essential in order to understand the forces that move the plates on the surface of the Earth, and phenomena such as hot spots and large volcanic provinces. Below we present some examples of attempts to integrate surface observations with processes in the Earth's interior.

A GLOBAL REFERENCE FRAME

Plate movements are linked to processes in the deep interior of the Earth through complex and enigmatic causal relationships. A definite prerequisite for developing a mathematical-physical relationship model is the development of an absolute reference frame that describes the plate movements quantitatively through geological time. Magnetic anomalies and fracture zones in the oceanic crust (Figure 3) are used for detailed relative reconstructions between the plates, but only the hot spot method and palaeomagnetism can relate the plates to the underlying mantle and the Earth's axis of rotation. The hot spot method can be used for the last 130 million years, and in mathematical terms is an absolute method where every point on the Earth can be positioned with the correct longitude and latitude in geological time. There is however increasing evidence to suggest that volcanic chains, which can be found along the island chain of Hawaii for example (Figure 6a and Fact box 2), have not moved over a stationary thermal plume in the mantle, but that currents in the mantle affect the thermal plume (Figure 6b). Stationary hot spot reference frames must therefore be replaced by mantle reference frames, in which corrections must be made for the movement of the thermal plumes in a circulating mantle. Absolute reconstructions prior to the Cretaceous Period will therefore be problematic. Only the palaeomagnetic method can be used for this. This method basically only gives the latitude and rotation of a plate, but using a simple method developed by the authors (Torsvik et al. 2006), where we make the assumption that the African plate is the most stable (has moved least in terms of distance), we have developed a hybrid geomodel for absolute plate movements over the last 300 million years. This method was used for the reconstructions in Figures 7 and 8.

MANTLE CURRENTS AFFECT THE SURFACE OF THE EARTH

The topography of the Earth is controlled by density variations (isostatic topography) close to the surface of the Earth, and by the dynamic response of the surface as a result of currents in the Earth's mantle (dynamic topography). An important challenge in the modelling of mantle currents is the calculation of large-scale uplift and sinking of the surface of the Earth over geological time (Figure 7). Dynamic topography influences which areas are above or below sea level, and thereby also where sediments and related natural resources are formed. A two-dimensional plate tectonic reconstruction of the North Atlantic shows the distribution of sedimentary facies, while the three-dimensional mantle dynamic reconstruction combines the position of the plates with calculations of dynamic topography (the vertical dimension). In this example (Figure 7), the calculated dynamic topography for the North Sea area coincides with uplift, which resulted in restricted communication between the Arctic (the Barents Sea) and the Tethys Sea in the area of the present day Mediterranean. Modelling of dynamic topography will be a central element in the major new European project 'TOPO–EUROPE', which particularly focuses on the link between processes deep in the Earth, surface processes and the development of continental topography.

A JOURNEY FROM THE INTERIOR OF THE EARTH

Over the past 20 years, seismic tomography has led to a breakthrough in the detailed mapping of the deep mantle. It is now possible to study relationships between phenomena such as hot spots and large volcanic provinces and seismic structures in the mantle. Close to the transition between the mantle and the core at a depth of 2800 km, we are now able to demonstrate two large seismic low-velocity regions, which we believe are hotter areas. These remarkable 'red' antipodean regions (i.e., approximately 180° from each other) under Africa (Figure 8) and the Pacific Ocean, respectively, are separated by 'blue' high-velocity regions. The high-velocity zones coincide with virtually all destructive plate boundaries, and they can be considered as a graveyard for lithosphere that has been transported right down to the transition between mantle and core. Several of the global mass extinctions have been linked to catastrophic volcanism and enormous volcanic provinces. One example is volcanism in Siberia around 252 million years ago, at the transition between the Permian and the Triassic, which coincides with the largest mass extinction ever. Melting in the upper mantle causes volcanism, but whether the heat and the material that is involved originate from the deep mantle (thermal plumes), or whether they are simply the result of stretching in the lithosphere, is a controversial point. We believe that the large volcanic provinces are best interpreted as periodic thermal plumes originating in the transition between the mantle and core (Torsvik et al. 2006). Our justification for this view is that when the large volcanic provinces are reconstructed at the surface of the Earth, they are almost always located above the margins of the two low-velocity areas. An example of this is volcanism in the Oslo area around 300 million years ago. The thermal column was centred on Skagerrak, and we find volcanism of the same age in Scotland, England, the North Sea, Skåne and Germany. When the thermal plume under Skagerrak (marked 'SC' in Figure 8) and the Oslo area is reconstructed, we see a clear relationship with mantle tomography. Around 300 million years ago, Oslo was situated at 12°N–16°E (equivalent to Chad in present day Africa), directly over the margin of the African low-velocity belt. In other words, a long journey from the Earth's interior, which resulted in the Earth's crust fracturing from Skagerrak to Hamar causing earthquakes and large-scale volcanism.

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