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From Wegener until now: the development of our understanding of Earth's Phanerozoic evolution

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ABSTRACT. Since Wegener (1912) proposed that all of the Earth's land areas once formed a single supercontinent that later moved apart (continental drift), our descriptions of the movement and deformation of the Earth's outer layer have evolved into seafloor spreading (1962) and then to plate tectonics by the mid-late 1960s. Results from palaeomagnetic studies in the 1950s were one of the principal reasons why the plate tectonic theory was accepted in the 1960s, and they have proved crucial in the objective positioning of older rocks, some dating from as far back as the Archaean. If we compare Wegener's supercontinent (Pangea) with modern reconstructions, which are based on a much larger database and more disciplines, there are many similarities, but the most striking difference is that we are now able to position Pangea and other continents at their original latitude and longitude. Our knowledge of Pre-Pangean palaeogeography has improved considerably over the past few decades, and has spurred an intensive search for older supercontinents. Many scientists did not accept continental drift for the lack of a mechanism. Ironically, there is still no generally accepted mechanism that explains plate tectonics in the framework of mantle convection, nor is it clear why Earth is the only terrestrial planet with plate tectonics. The presence of water might be a prime factor, but the challenge now is to develop an Earth model that can link plate tectonics with mantle convection through time, and which allows for elements such as deeply subducted slabs and stable thermo-chemical piles at the core-mantle boundary, with plumes rising from their edges.

KEYWORDS: Alfred Wegener, supercontinent, Pangea, continental drift, plate tectonics, palaeogeography, longitude.

1. Introduction

One hundred years ago, Alfred Wegener proposed that all the continents once formed a single supercontinent (Urkontinent), later named Pangaea, which was surrounded by a vast marine area termed the Panthalassa Ocean. Wegener's Pangaea (now more usually spelt Pangea) reconstruction was principally based on the similarity between coastlines on opposite margins of the Atlantic, but he also stressed that Permian and Carboniferous plant and animal fossils from a number of continents, now separated by Oceans, were largely identical. From the distribution of glacial deposits, he also advocated that a continental ice cap must have covered those contiguous southern parts of Pangea in the Late Carboniferous.

Many substantial books and papers (e.g. Oreskes, 1999; Nield, 2007) have described and analysed the history of the origin of Wegener's continental drift theory, its variable (and largely hostile) reception by different scientists, and its subsequent replacement in the 1960s by plate tectonics, and it is not our purpose to repeat that story here more than briefly. The chief aim of the present paper is to review our understanding of Earth's evolution as it has developed and progressed since Wegener's work a hundred years ago, and to outline where we now are on this topic, which is of central relevance not just to Earth scientists but to all humankind.

2. History before plate tectonics

Although the similarity of the opposite continental margins in the Central and South Atlantic had been noticed for centuries, Alfred Wegener (1880-1930) was the first scientist to believe that these two margins had previously been physically united, and to publish diagrams of their postulated original positions and subsequent break-up history. He built on the observations of geologists who had noticed that very similar Permian floras, notably the *Glossopteris* Flora, as well as glacial deposits of Late Carboniferous age, occurred in South America, South Africa, Madagascar, India, eastern Antarctica and Australia but nowhere else, leading him to the conclusion that those southern continents were together in those times. He also postulated for the first time that the continental areas had subsequently moved apart. It was particularly striking that Wegener moved continents from as far away as India (now part of Eurasia) across the substantial Indian Ocean to merge with Africa, Madagascar, East Antarctica and Australia to form parts of Gondwana. He expanded his concept to construct a model which included all of the Earth's land areas into one gigantic supercontinent (Fig. 1a), and that between the Permian and today the continents had split up and drifted across the oceans to their present positions. Wegener was by no means the first to notice the similarities of those southern floras and facies, which had been termed the Gondwanaland (now more usually termed Gondwana) Province many years earlier by Suess (e.g. 1885). However, earlier authors had imagined that the individual fossil sites were in continents which had always been in their present positions, and that the biotas had dispersed through impermanent land bridges which had moved up and down, rather than as a result of the lateral continental movements postulated by Wegener.

A short summary of Wegener's ideas on continental drift was published in 1912 after a lecture on the topic of the Earth's history, but it was not until 1915 that the first edition (in German) of his monumental book emerged in which all his arguments up to that time were collated, although the book was revised through several modifications and additions in new editions over the next twenty years. Wegener's innovative and widely-reproduced reconstructions of the Late Palaeozoic Earth caught the popular imagination, but were accepted by few geologists, largely because no one could perceive any plausible mechanism by which the continents could have moved laterally. Substantial vertical movements, including isostatic readjustments, had been accepted by the geological community as the prime mechanism of mountain building since Lyell's work in the early nineteenth century (1830-33). In addition, there are clearly no physical traces of gigantic thrust faults under the margins of continents, as would be necessary to prove that lateral movements of the continents over the oceans had also occurred. For example, Leake (2011) has shown how J.W. Gregory, one of the foremost and most influential British geologists in the early twentieth century, fairly and amiably reviewed Wegener's continental drift hypothesis at length, but, whilst not rejecting all aspects of it, did not accept it for the lack of a mechanism. Indeed, the theory of continental drift was not accepted as probable fact by a majority of earth scientists until the mid 1960s, and for more than twenty years after that by many workers, particularly in the former Soviet Union, but also in North America.

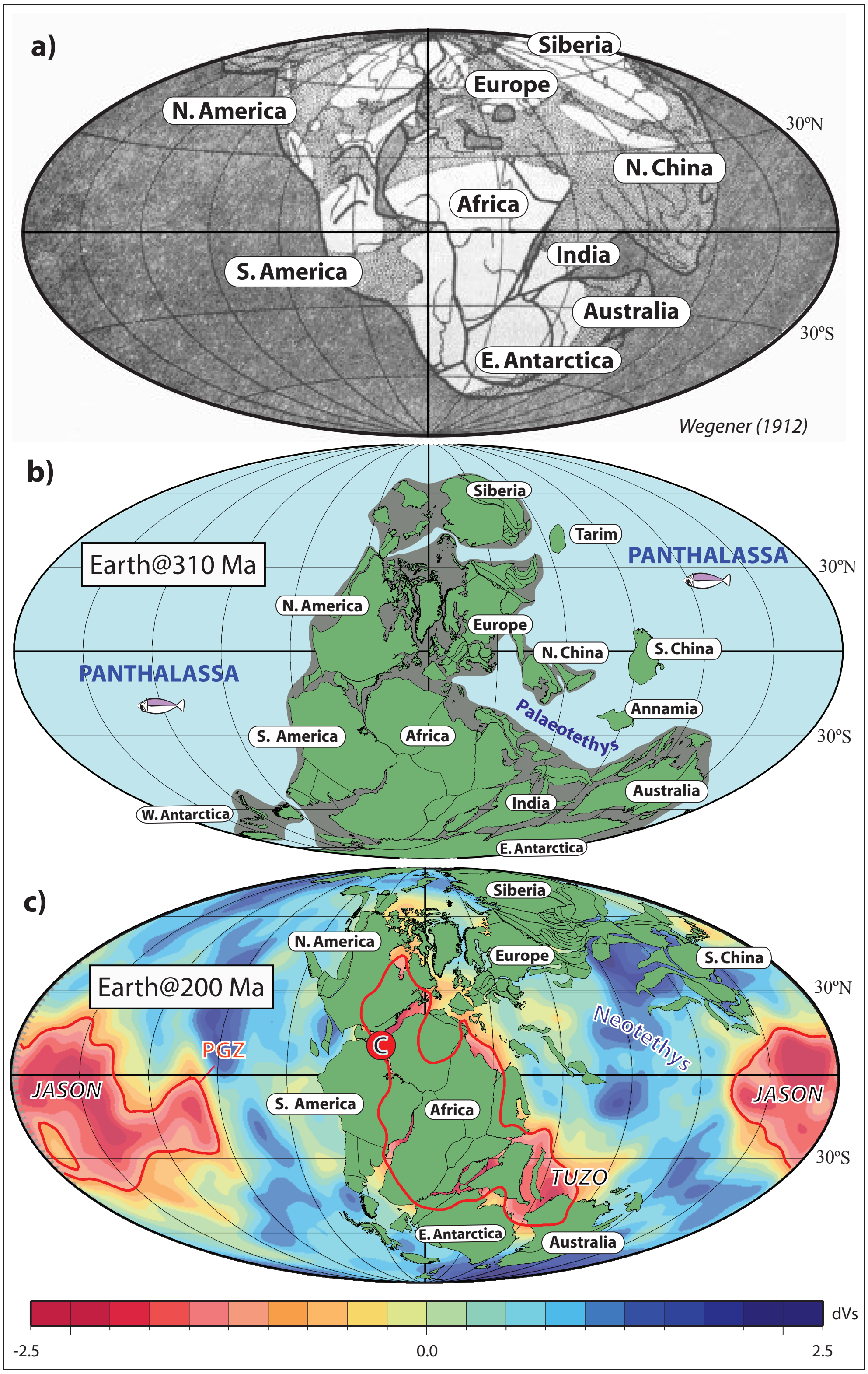

Figure 1: Sequence of reconstructions that witness 100 years of progress since Wegener. **(a)** Wegener's (1912) relative reconstruction of Pangea (Africa and Europe kept fixed) with ice caps (white areas) as it may have looked in the Late Carboniferous (according to the present geological time scale at around 310 Ma). **(b)** modern reconstruction of the continental blocks (Torsvik et al. 2012) at the same age, but reconstructed to both its latitude and longitude with palaeomagnetic data using the 'zero longitude' approximation for Africa. **(c)** The Earth at Triassic-Jurassic boundary times at 200 Ma during the breakup of Pangea (based on Ruiz-Martínez et al., 2012). PGZ are the Plume Generation Zones (near the thick red lines) at the margins of the two Large Low Shear Velocity Provinces at the core-mantle boundary named 'Tuzo' (beneath Africa) and 'Jason' (beneath the Pacific) from which mantle plumes originate. The PGZ sources LIPs, kimberlites and many hotspots, and we show the estimated eruption centre for the Central Atlantic Magmatic Province (red circle marked C) at 200 Ma. The palaeomagnetically true polar wander corrected reconstruction is draped on the SMEAN tomographic model (Becker & Boschi, 2002). Blue regions (faster than average shear-wave velocities) represent the subduction graveyards for the past 300 Myrs. Shear-wave velocity anomalies (dVs) are in percentage (see scale bar).

The age of the Earth has been the topic of much debate for many hundreds of years. It was first scientifically calculated from extrapolating cumulative sedimentation rates, for example in glacial varves. Influential early nineteenth century scientists, including Hutton, Lyell and Darwin, had estimated ages exceeding 300 Myr to allow time for successive fossil faunas and floras to become established and eventually replaced by others. However, those estimates were revised sharply downwards when Kelvin (1863), one of the foremost physicists of his day, calculated that the Earth could be as young as 25 Myr old, based on the assumption that the Earth had solidified from a molten state. But radioactivity was not known in Kelvin's day, and was first recognised only subsequently by Bequerel (1896).

The discovery of radioactivity also led subsequently to the identification of radioactive isotopes, such as lead and uranium, with very long decay rates which could in turn provide dates for the rocks in which those individual elements with long-lived isotopes are found. Arthur Holmes was one of the first geologists to measure the isotopes from old rocks, and he created the first radiometric time scale, and concluded in 1913 that the Earth was more than 1600 million years old, many times older than almost all previous estimates. It is not clear exactly what figure Wegener imagined to be correct for the Earth's age in 1912 when he proposed his continental drift theory, but the very large amount of time required for drift to have taken place across significant distances (thousands of km) must have been in his mind.

An outstanding exception to most scientists' refusal to accept continental drift was the same Arthur Holmes who had generated the radiometric time scale, and who postulated in 1931

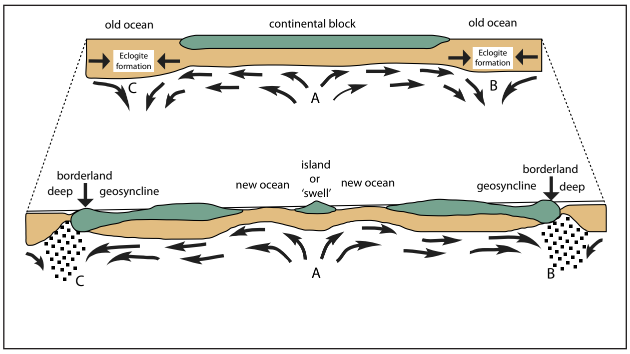

Figure 2: Arthur Holmes' concept of convection zones in the mantle which flow from upwelling under the mid-ocean (Zone A) and then laterally to downwelling at Zones B and C (redrawn from Holmes, 1931).

that 'lateral flowage' in the crust could be caused by convection currents which would be necessary to dissipate the radiogenic heat generated in the Earth's mantle. However, the existence and extent of mid-ocean ridges were quite unknown at that time, so Holmes could only schematically depict the convection currents (Fig. 2) as being the driving force behind the breakup of a theoretical (unidentified) continent into two pieces, with 'new ocean' between the two, and the new ocean itself divided by a central island or 'swell'.

3. Plate tectonics

As detailed in the section on palaeomagnetism below, in 1956, Keith Runcorn discovered key differences between the European and North American polar wander paths. This was the first independent geophysical evidence that the continents had moved ('continental drift' sensu Wegener).

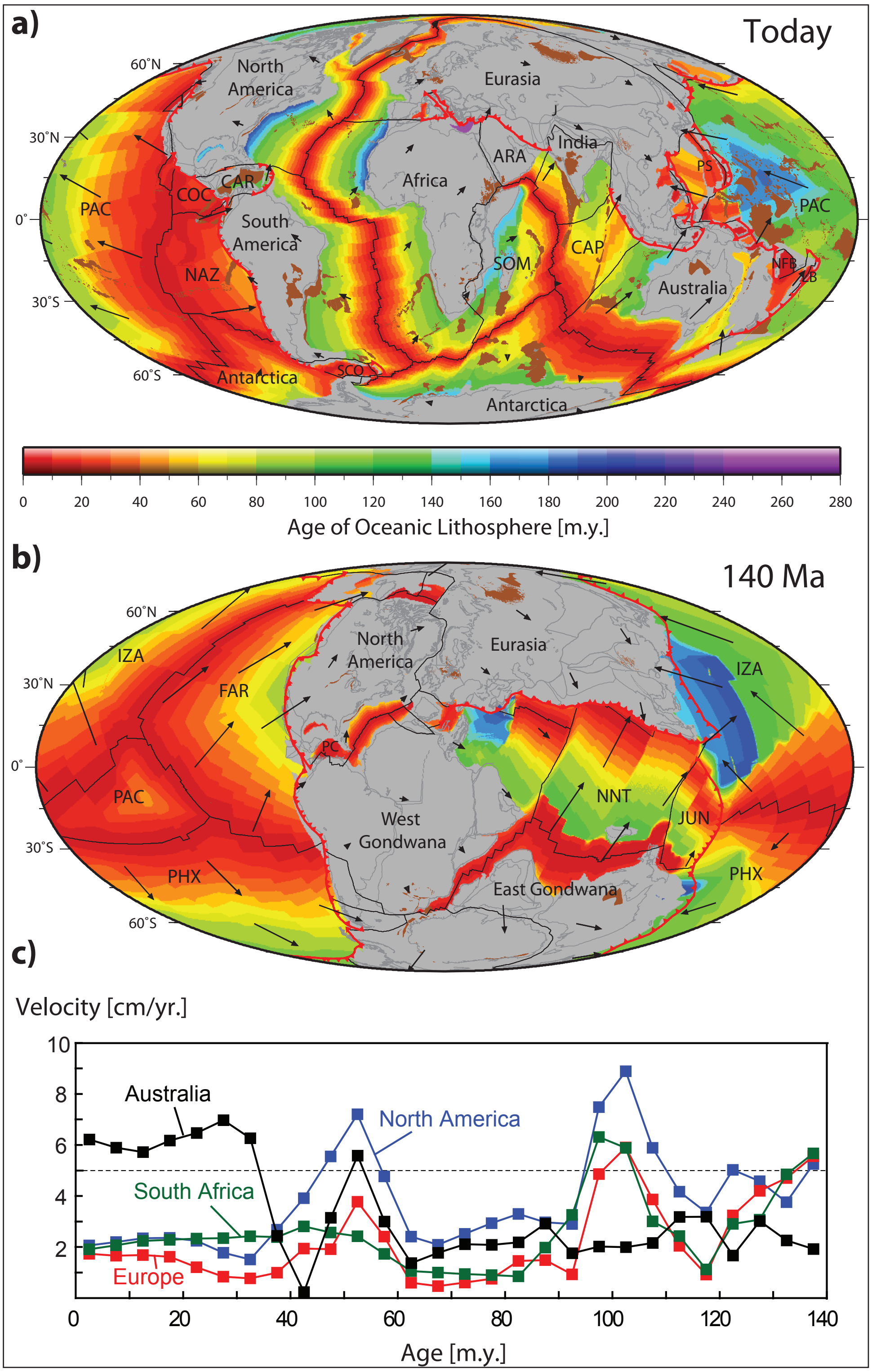

Figure 3: (a) The modern Earth, and **(b)** Early Cretaceous reconstruction (140 Ma) with age of oceanic lithosphere. Red tagged lines are subduction zones; black lines are mid-ocean ridges and transform faults. Brown polygons are products of plume-related LIP volcanism. Absolute plate velocity vectors are denoted as black arrows and based on a hybrid reference frame, i.e. true polar wander corrected palaeomagnetic data at 140 Ma (Torsvik et al., 2008b; Steinberger & Torsvik, 2008) and an Indo-Atlantic mantle reference frame for modern Earth (O'Neil et al., 2005). Ages of oceanic lithosphere as in a). Plate abbreviations: ARA, Arabia; CAP, Capricorn; CAR, Caribbean; COC, Cocos; EB, Ellice Basin; FAR, Farallon; IZA, Izanagi; JUN, Junction; NAZ, Nazca; NFB, North Fiji Basin; NNT, North Neo-Tethys; PAC, Pacific; PC, Proto Caribbean; PHX, Phoenix; PS, Philippine Sea; SCO, Scotia Sea; SOM, Somalia. Redrawn from Seton et al. (2012). **(c)** Mean plate velocities calculated for Australia (part of East Gondwana in 3b), South Africa (West Gondwana), North America and Europe (part of Eurasia). Same hybrid reference model used to construct Fig. 3b.

Mostly through US Navy activities during and in the years after the Second World War, the floors of the oceans were mapped and their contours charted comprehensively for the first time, and thus the amazing extent and size of the mid-ocean ridges, which consist largely of basaltic volcanic rocks, became known. As a result of that new knowledge, Harry Hess (1962) made a breakthrough when he proposed the theory of seafloor spreading, which states that magma from the mantle flows up in linear spreading centres beneath the mid-oceanic ridges, and that consequently the existing ocean floor (Figs 3a,b) is pushed laterally away from the spreading ridges to make space for the accommodation of the new basalts. That new material thus enlarges the margins of the two areas (now termed plates) on both sides of each ridge. Since the Earth has probably always been essentially the same size, the enlargement of a plate through extrusion of new basalt at one margin is compensated for, usually at the opposite margin, by the plate's reduction when crustal material is finally returned to the mantle through subduction, in which one plate is pushed beneath its neighbour. One of the chief reasons why Wegener's continental drift theory had not been accepted by most geoscientists was because of his conclusion that the continents had 'ploughed through' the oceanic crust to their current positions, which was clearly wrong. After the concept of seafloor spreading was established and accepted, the continents could be seen to be sitting relatively passively on top of the rigid lithosphere, which was divided into mobile plates which could move laterally. The most significant difference between the original continental drift theory and plate tectonics is that each plate may consist of both continents and ocean floor, rather than continents alone.

Even in the latter half of the 1950s, it was known that at least parts of the sea floor were characterised by magnetic anomalies arranged in a linear pattern. Yet no one was able to understand that pattern and the significance of those anomalies until Vine & Matthews (1963) realised that the magnetic stripes which are developed subparallel to the oceanic spreading ridges had been caused by numerous reversals in the Earth's magnetic field. The geomagnetic field has its origin in the outer and liquid part of Earth's core, and it reverses polarity at irregular intervals, roughly every 200,000 years on average over the past 5 million years. The exact causes of those reversals and superchrons (when the field does not reverse for tens of millions of years) are still debated (Biggin et al., 2012), but the switch in magnetic attraction from the North to the South Pole and back again has created the same mirror pattern of alternating magnetic stripes seen in sea floor basalts on both sides of the ocean spreading ridges, a pattern whose recognition and understanding decisively confirmed the theory of seafloor spreading.

That appreciation of the significance of sea floor spreading from mid-ocean ridges was an essential stepping stone in the development of the wider theory of Plate Tectonics, which was largely formulated during the period 1965 to 1968. This theory has become the unifying paradigm for earth scientists in a comparable way as evolution was for biologists nearly a century earlier. However, unlike Darwin's theory of evolution, no one person initially defined plate tectonics, which was developed by an international spectrum of various scientists with differing backgrounds, largely in North America, Britain and France. Plate tectonics defines how the Earth's surface is constructed from large and small rigid plates (Fig. 3a) that move in relation to each other, and it explains the observable evidence for large-scale lateral movements of the Earth's crust (including continental drift) and seafloor spreading. 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. But, particularly since powerful earthquakes and enormous volcanic eruptions occur close to destructive plate boundaries, it also became progressively clearer that the reason why crustal plates move across the surface of the Earth is due to processes deep in the underlying mantle.

J. Tuzo Wilson (1965, 1966) and Morgan (1968) were pioneer figures in the development of plate tectonics, and McKenzie & Parker (1967) provided the quantitative principles to support it. They and others demonstrated how the differing movement patterns of the relatively rigid plates lead to the varied types of constantly-evolving plate boundaries seen on the surface of the Earth, which are constructive at the ocean ridges, destructive at subduction zones, and bounded at other margins by lateral strike-slip fault movements. Subsequently, Dewey (1969) and Dewey & Bird (1970) applied the new theory to understanding the origins and development of mountain chains, in particular by demonstrating the link between the Caledonian mountains in Great Britain and Ireland on the one hand, and the Appalachians of North America on the other.

Wilson (1966) deduced that there must have been a proto-Atlantic Ocean prior to the Late Palaeozoic assembly of the supercontinent Pangea, and that the ocean must have closed before the Carboniferous and later re-opened to form the present-day Atlantic Ocean. Such movements were dubbed 'Wilson Cycle' tectonics by Kevin Burke (e.g., Burke & Dewey, 1974), and for the first time, plate tectonic processes were understood to have been operating before the time of Pangea. Wilson was well into his 50's when he made his most important scientific contributions, and, before the classic 1966 paper, had already suggested that hotspots such as Hawaii could have been sourced by mantle plumes (Wilson, 1963), and also identified the key part played by the third and hitherto unidentified type of plate boundary (transform faults) needed for the development of realistic models to underpin reconstructions of old geographies (Wilson, 1965).

4. Developments since plate tectonics

The initial studies which first demonstrated and then confirmed the reality of plate tectonics were understandably confined to younger rocks of Mesozoic to Recent ages until the paper by Wilson (1966). The first concerted effort to decipher the positions of the terranes in older times came with a Cambridge symposium in 1971, whose results were published in Hughes (1973), in which many stratigraphers put their previously-gathered individual palaeontological and sedimentological data on to new global maps constructed from palaeomagnetic data. Those tentative initial reconstructions were soon much modified as a result. For example, Cocks & McKerrow (1973) had shown Silurian faunas and facies plotted on the Cambridge Symposium maps, but their conclusions became largely outdated and were quickly replaced by fresh reconstructions (partly based on better and more focussed palaeomagnetic data) for the same Silurian period by Ziegler et al. (1977). Another milestone symposium for Palaeozoic palaeogeographical studies was held in Oxford in 1988 (where THT was a young post-doctorate scientist) and the results were published in McKerrow & Scotese (1990).

Pangea never included all the continents at any one time, although it reached its maximum size during latest Palaeozoic and early Mesozoic times. The most important amalgamation phase was at about 320 Ma, during the Late Carboniferous, when Gondwana, Laurussia and intervening terranes collided, and in the process produced the Alleghenian-Hercynian Orogenic Belt (Matte, 2001; Torsvik & Cocks, 2004). However, well before the end of the Palaeozoic, in mid-Permian times, many former peri-Gondwanan terranes started to separate from the north-eastern Gondwana margin, causing the opening of the Neotethys Ocean between the two (e.g., Şengör et al., 1984; Stampfli & Borel, 2002). One of the most important phases in the Mesozoic breakup of Pangea started shortly after 200 Ma, near the Triassic-Jurassic boundary (Fig. 1c), when the central Atlantic Ocean began to form (Labails et al., 2010). Not by coincidence (as originally suggested by Burke & Dewey, 1973, and confirmed by Courtillot et al., 1999), the region of central Atlantic breakup (Fig.1c) occurred shortly after a massive episode of volcanism and Large Igneous Province (LIP) formation (Central Atlantic Magmatic Province, 200 Ma), a situation similar to many other examples world-wide events, including the South Atlantic (Parana-Etendeka, 134 Ma) where peak LIP activity also preceded break-up by around 5-7 Myr.

From the reconstructions compiled over the past thirty years, we can directly appreciate how climate-sensitive (latitude-dependent) sedimentary rock facies, including the varying extents of polar ice-caps, have been distributed across the Earth's surface; for example, in the Late Ordovician and Carboniferous-Permian

(Torsvik & Cocks, 2004; 2011). From that knowledge, models of past climates have been constructed. Recently-developed techniques also now allow us to determine the palaeolongitude of Pangea for the first time, which palaeomagnetism does not reveal. Those techniques (Section 6) have linked the distribution of both LIPs and kimberlites at the Earth's surface (Burke & Torsvik, 2004; Torsvik et al., 2008a; 2010) to specific plume-generation zones at the core-mantle boundary (Burke et al., 2008); as well as fitting former active margins to subducted slab remnants in the mantle (van der Meer et al., 2010), by direct comparison of mantle heterogeneities to the surface of the Earth.

5. The varied subdisciplines which underpin current understanding of palaeo-geography

Both quantitative and semi-quantitative methods have been and are used to assess the changing positions of each plate through time. Analysis of magnetic anomaly stripes and fracture zones on the ocean floors are the best for reconstructing the progressing relative relationship between adjacent plates (Figs 3a,b), but nowhere on Earth is the *in-situ* oceanic crust older than the Jurassic. Another quantitative and absolute method involves charting the changes in hotspot location (volcanic seamounts) as the host plate moves over a fixed (Morgan, 1972, Müller et al., 1993) or semi-stationary (Steinberger & O'Connell, 1998; Steinberger et al., 2004) plume site (which caused the hotspot) at the core-mantle boundary. However, there are relatively few hotspot tracks, only two older than 84 Ma, and the oldest remaining identifiable hotspot, Tristan (South Atlantic), is only of Cretaceous age (134 Ma). Thus for reconstructions for times before the Jurassic (magnetic anomalies) or Cretaceous (hotspot tracks), other methods must be used, which are led by analysis of palaeomagnetic data, and supplemented by the less quantitative understanding of old faunas, floras, and certain types of sediments, all of which are now reviewed here. Underlying all plausible palaeogeographical reconstructions must be realistic plate speeds and believable kinematic continuity in both the immediately preceding and also the immediately succeeding maps in any one period.

5.1. Palaeomagnetism

Palaeomagnetism is the study of the Earth's magnetic field through time as preserved in the remnant magnetism of rocks, and has been and remains the chief quantitative tool in deciphering palaeogeography. Results from palaeomagnetic studies were one of the principal reasons why the plate tectonic theory was accepted in the 1960s, and they have proved crucial in the objective positioning of older rocks. Through palaeomagnetic measurements, the latitude at which the rocks were originally deposited and their subsequent rotation can be deduced.

The discovery that some minerals (e.g., magnetite), at the time of their formation (when igneous rocks solidify), can become magnetized parallel to the Earth's magnetic field had already been made in the 19th century. In 1906 Bernard Brunhes made the amazing discovery that some rocks are magnetised in quite different orientation to the present-day magnetic field, which led him to propose that the Earth's magnetic field had reversed its polarity in the past.

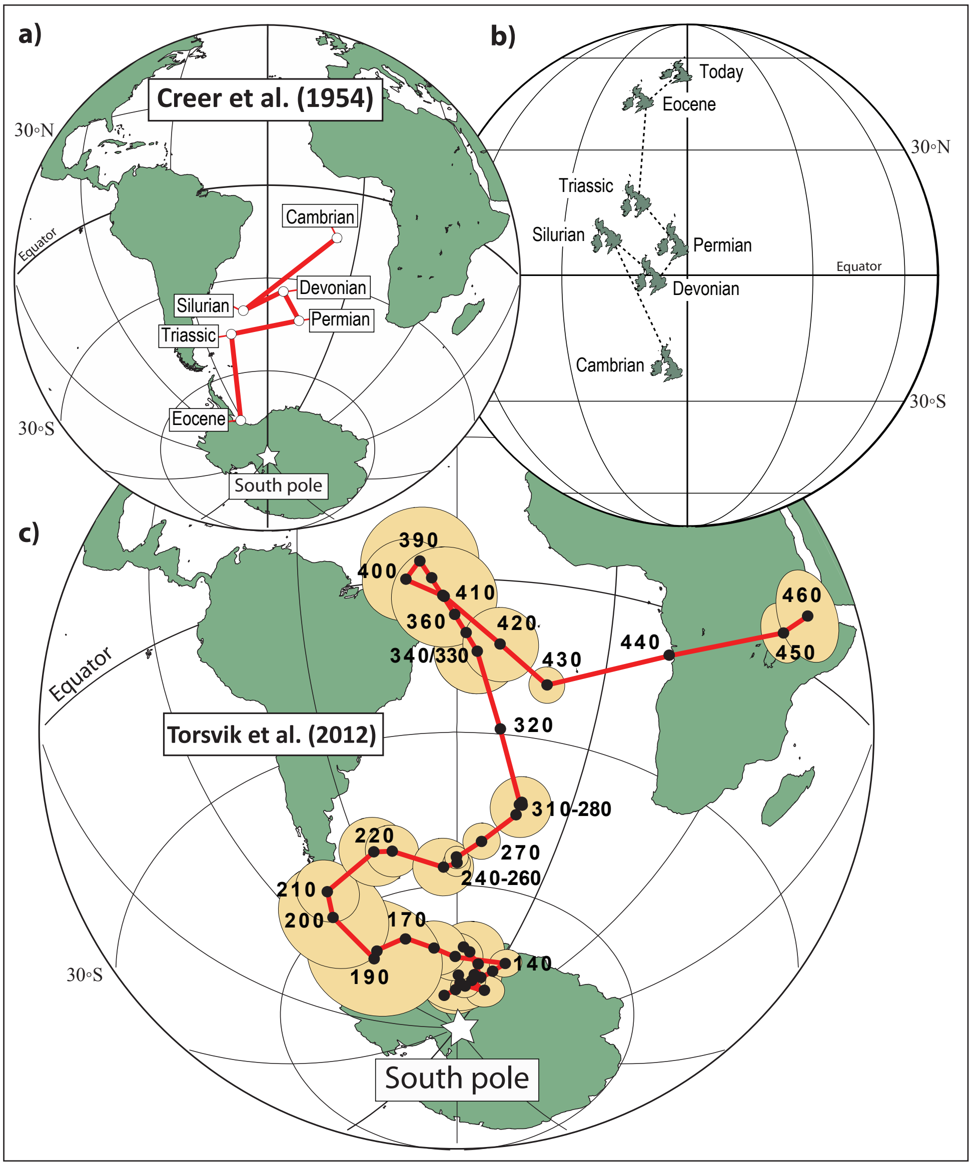

Figure 4: Successive development of the palaeomagnetically-derived position of Britain; **(a)** redrafted from the original results of Creer at al. (1954) as an APWP, **(b)** showing the successive positions of the British Isles at different times according to the results from Creer et al. (1954); **(c)** Apparent polar wander path (APWP) for Baltica/Stable Europe and that includes poles from Britain after 430 Ma. The APWP is a running mean path shown in 10 Myr intervals and with 95% confidence ovals (after Torsvik et al., 2012).

Palaeomagnetic results are most commonly expressed in terms of palaeomagnetic poles. In turn, those palaeopoles can be used to construct apparent polar wander paths (APWPs) for individual continents. In this way, instead of charting the motion of a continent while holding the rotation axis fixed, the motion of the north or South Pole relative to a fixed continent can be visualized. The motion of continents relative to the Earth's spin axis may be either due to the drift of individual continents or to the rotation of the entire Earth relative to its spin axis — the latter is true polar wander (TPW). Creer, Irving and Runcorn, all at Cambridge, England, were the first to publish an APWP for 'Europe' as early as 1954, based on Precambrian to Eocene palaeomagnetic poles from Britain. Those poles (plotted as south poles in Fig. 4a) all differ markedly from the present-day pole, and the authors were faced with two possible explanations; firstly, that the pole itself has moved (TPW), or, secondly, that Britain/Europe (Fig. 4b) have moved ('continental drift').

Creer et al. (1954) initially interpreted their results as 'a slow change in the axis of rotation of the earth with respect to its surface', in other words TPW, which is caused by redistribution of density heterogeneities within the mantle and corresponding changes in the planetary moment of inertia (e.g., Goldreich & Toomre, 1969; Steinberger & Torsvik, 2010). Two years later, however, Runcorn (1956) published an APWP for North America and that allowed him to compare the European and North American paths for the first time. He noted that they were broadly similar in shape, but some 30° apart in longitude, which he interpreted to be due to the opening of the modern Atlantic; thereby establishing the first independent geophysical evidence that the continents had indeed drifted away from each other.

Many APWPs have since been published for Europe (e.g. Van der Voo, 1990, 1993: Torsvik et al., 1996, 2012 and references therein), and in contrast to the initial compilation of merely five Palaeozoic-Mesozoic poles from Britain (Creer et al., 1954), the most recent Phanerozoic APWPs (Fig. 4c) are based on several hundred reliable palaeomagnetic poles. Due to that surge of fresh data, the APWPs have changed dramatically over the past six decades, partly also due to improved analytical methods and instrumentation, but also because of our progressively greater understanding of Pre-Pangean palaeogeography. For example, Creer et al. (1954) also included a Precambrian pole from the Torridonian Sandstone in northern Scotland in their compilation (not shown in Fig. 4a), but we now know that, in the Precambrian, Scotland was part of a different continent, Laurentia (which also includes North America and Greenland). In contrast, in the Cambrian, Southern England was part of the Avalonia sector of north-western Gondwana (Cocks and Fortey, 1982; Torsvik & Trench, 1991), and thus not representative of 'Europe' (whose parts today include several old continents). Of all the compiled poles of Creer et al. (1954), only the Permian pole (based on the ~290 Ma Exeter lavas) resembles more modern 'European' compilations (Fig. 4). Nonetheless, their observations, even though now known to be partly faulty, that the 'axis of the dipole field diverges considerably from the present geographical axis' have had a fundamental and long-lasting impact, and for more than fifty years since then palaeomagnetic data have been used to create the geomagnetic time scale, to document seafloor spreading, to validate plate tectonics, and to reconstruct vanished supercontinents and smaller terranes.

5.2. Biological distributions.

Faunal and floral provinces have been identified in various parts of the globe for at least three hundred years, but of course the reasons underlying their distributions remained partly hidden until the movements of continents had become understood. Modern provinces are chiefly caused by differences in climates and temperature, which are in turn linked broadly to latitude; but also by the (in)ability of the biota to get across physical barriers, chiefly land (in the case of marine life) and seas (for terrestrial plants and animals). The identification of various faunal and floral groupings useful for palaeogeographical studies is particularly important during the Palaeozoic (Fig. 5b), which is after life became very diversified, but before more quantitative methods (such as unravelling the old ocean-floor magnetic stripe patterns) can be used. However, provinces and faunal links recognised, particularly before about 1980, often reflected the views of individuals or teams working within very narrow time frames, with apparently little thought for the provincial situation just before or just after. Comparably, many palaeontologists have only considered the often limited animal or plant groups with which they are familiar, and have thus identified provinces which are not widely significant, since they reflect only a minority of the biota present.

Wilson had recognised in 1966 that the faunal distribution known on both sides of the present-day Atlantic Ocean are best explained by the existence of an Early Palaeozoic Proto-Atlantic Ocean (Fig. 5a) before the Atlantic opened in the Mesozoic. However, it has since been realised from both palaeomagnetic and faunal data that his Proto-Atlantic Ocean consisted of several oceans; the main Proto-Atlantic Ocean (subsequently renamed Iapetus Ocean by Harland and Gayer, 1972), a smaller Tornquist Sea (Figs 5b, 7) that separated Avalonia from Baltica (Cocks & Fortey, 1982), and the Rheic Ocean (McKerrow & Ziegler, 1972), which separated terranes such as Avalonia from Gondwana. The Iapetus Ocean started to form in the Late Precambrian, and the Rheic Ocean first opened at Cambrian-Ordovician boundary times at about 490 Ma (Fig. 6), when Avalonia separated from Gondwana (Cocks & Torsvik, 2002). Avalonia existed only separately during the Ordovician before merging with Baltica near Ordovician-Silurian boundary time at 440 Ma, closing the Tornquist Ocean in between them

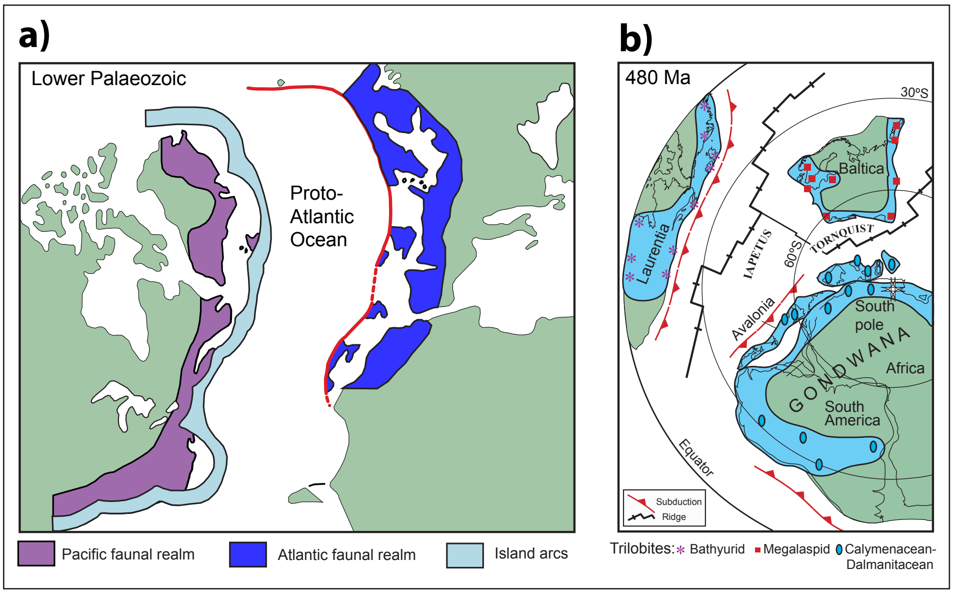

Figure 5: Lower Palaeozoic reconstructions of today's North Atlantic area; **(a)** redrawn from the first reconstruction by Wilson (1966); **(b)** redrawn from Torsvik et al. (1996) and including the distribution of key provincial trilobite sites originally plotted in Cocks & Fortey (1982).

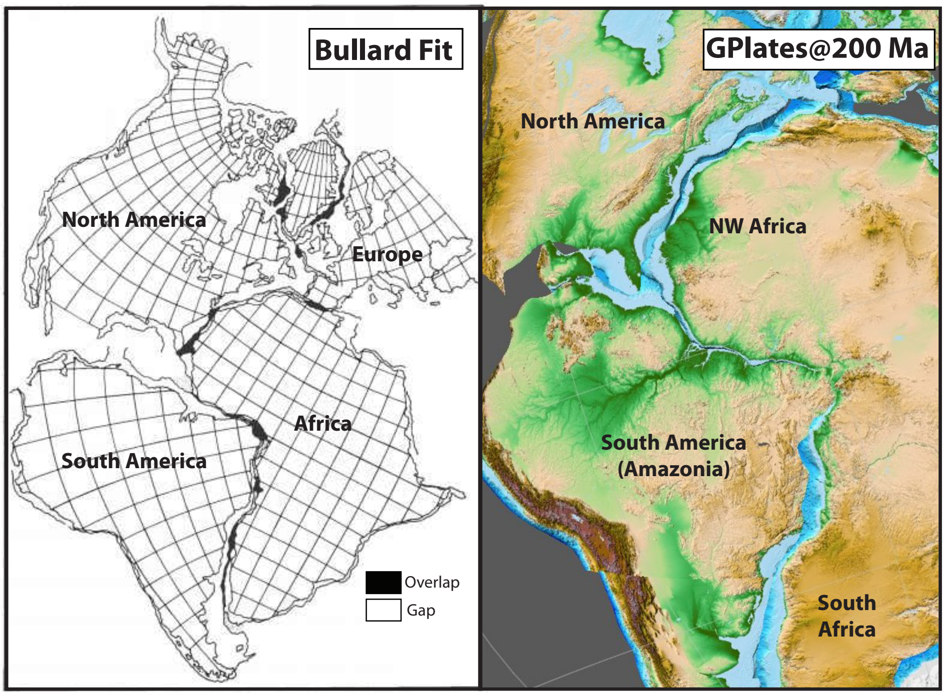

Figure 6: (a) The first computer-based reconstruction fitting the continents around the Atlantic Ocean (redrawn from Bullard et al., 1965). **(b)** 200 Ma reconstruction in GPlates demonstrating the rotation ability of raster data (in this case exemplified by present day topography and bathymetry).

(Torsvik & Rehnström, 2003). The movement of the united Baltica and Avalonia towards Laurentia closed the Iapetus Ocean soon afterwards at around 430-420 Ma (Torsvik et al. 1996), forming Laurussia (Fig. 7) in a collision that caused the Appalachian and Caledonian Orogens. The Rheic Ocean closed in the Late Carboniferous, during the main Pangea growth phase, which created the Alleghenian (in North America) and the Hercynian/Variscan (in Europe) orogenic belts. It is interesting to note that, in Wilson's (1966) classic paper, which was the first to postulate drift prior to the Carboniferous, the only supporting evidence which is not now superseded comes from the Cambrian fossil trilobites which link Newfoundland and Wales across the present-day intervening Atlantic Ocean.

5.3. Other indicators of geography

Other semi-quantitative or qualitative methods, for example the distribution of latitude-sensitive and climate-dependent rock types, have also proved useful in deciphering old geographies, and they, like fossils, can also have the advantage of being derived from data gleaned from rocks which have suffered from much tectonic activity, in contrast to palaeomagnetism.

The distribution of past climates have always been of great interest, and many new palaeoclimatic maps have been generated which reflect the changing continental arrangements as understood since the arrival of plate tectonic reconstructions. Witzke (1990) was one of the first to do so for the Palaeozoic in a series of maps covering North America and Europe from the Cambrian to the Permian.

Carbonate build-ups, often termed bioherms or reefs, are widespread throughout Phanerozoic rocks. However, they were largely laid down within tropical latitudes, and thus their distribution in ancient times can be a useful check on the signals derived from palaeontological and other data. Comparably, evaporites are most usually found in belts on either side of the palaeo-equator (subtropics), and so they restrain reconstructions which might show them at high latitudes. Conversely, coal deposits are confined to the equator (wet conditions) or the northerly or southerly wet-belts at intermediate to high palaeolatitudes (Torsvik & Cocks 2004).

The recognition of glacial deposits has been important in placing continents since Wegener's original work. Much direct evidence of glaciers, such as eskers and drumlins are rarely preserved in rocks older than the Pleistocene, but magnificent glacial striated pavements are known from various Precambrian glacial episodes, as well as those in North Africa caused by the latest Ordovician (Hirnantian) glaciation, and in India and elsewhere from the lengthy glaciation which lasted from the Middle Carboniferous to the Early Permian. In addition, glacial tillites are well represented in rocks of many ages, as well as dropstones deposited by icebergs. However, the latter must be treated with caution since, for example, the cold Labrador Current on the eastern side of Canada today can carry icebergs well down into temperate latitudes.

It is notable that all those sedimentary deposits mentioned above only reflect latitudinal bands, and since this is also the chief output from palaeomagnetic data, sedimentary distribution seldom plays a prime part in generating reconstructions of ancient times. Only the analysis of faunal provinces could produce palaeolongitudinal implications for the Pre-Cretaceous until the 'zero-longitudinal motion' approximation for Africa (Burke & Torsvik, 2004) and the new work derived from the 'messages' from the core-mantle boundary (Section 6).

5.4. Technological innovations in plate tectonic and numerical modelling

Sequential plate reconstructions enable analysis and interpretation of biological, geological, palaeoclimatic and palaeogeographic data in time and space. One of the first attempts to reconstruct the Atlantic bordering continents (e.g., North and South America, Africa and Europe) using a computer, was Bullard et al. (1965). Their model (dubbed the Bullard fit) juxtaposed the continents by minimizing misfits, gaps or overlaps, of the ~900m contour on the continental shelves (Fig. 6a). In the modern day, rotation (Euler) poles for pre-breakup fits (relative fits) are more commonly determined from matching continent-ocean boundaries from adjacent margins, palaeomagnetic poles, or a combination of these data sets. Bullard et al. (1965) also treated South America and Africa as two rigid blocks, which leads to unrealistically large overlap and gaps. Following the work of Nürnberg & Müller (1991), both blocks are now divided into tectonic domains, and in the model of Torsvik et al. (2009) South America and Africa were divided into four and five blocks respectively (Figs 1b,c) that were reshuffled into their present geometry from Mid Jurassic to Late Cretaceous time.

Since the first computer-fitted Pangea reconstruction by Bullard et al. (1965), there has been an astounding development in computing power. The past decades has seen the development of many plate tectonic reconstruction tools (e.g., PLATES: University of Texas at Austin, http://www.ig.utexas.edu/research/projects/plates; PALEOMAP: Chris Scotese, http://www.scotese.com/;GMAP: Torsvik and Smethurst, 1999; PaleoMac: Cogne,

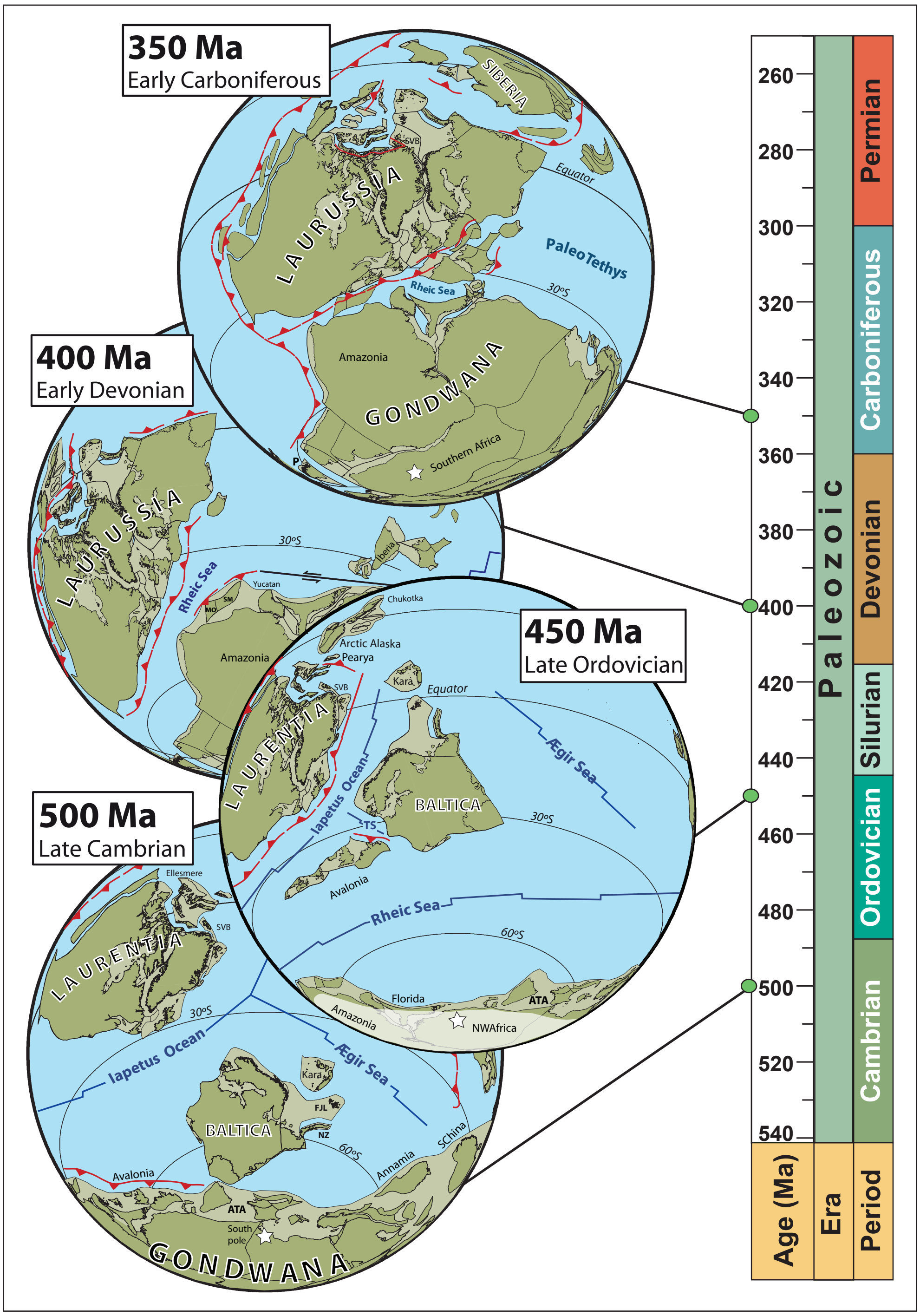

Figure 7: Development of continental positioning through the Palaeozoic from about 500 Ma to 350 Ma. Reconstructions based on Cocks & Torsvik (2002), Torsvik & Cocks (2004) and Torsvik et al. (2012). Red tagged lines are subduction zones whilst blue lines (tentative) are spreading ridges and transforms. Timescale after Gradstein et al. (2004). TS, Tornquist Sea; ATA, Armorican Terrane Assembly; SVB, Svalbard; NZ, Novaya Zemlya; FJL, Franz Josef Land.

2003; PLACA: Matias et al., 2005; and Pplates: Smith et al., 2007). GPlates (www.gplates.org) is the latest generation of software for interactive visualization and modelling of plate tectonics (Boyden et al., 2011), offering a novel combination of interactive plate tectonic reconstructions, geographic information system (GIS) functionality and raster data visualization through geological time (Figs. 1c, 3, 6b).

Since Wegener we can now with ease calculate both relative and absolute (Fig. 3) plate speeds. Absolute velocities for continental plates are typically below 5 cm/yr. (Fig. 3c) and very much slower than those estimated by Wegener. Plate velocities calculated from plate models now serve as important boundary conditions for lithosphere modelling, and plate reconstructions in GPlates (Fig. 3b) with continuously closing plates (Gurnis et al., 2012) are now routinely ported as crucial input constraints to sophisticated subduction and mantle modelling software.

A future aim is to develop digital databases and complementary software that link plate reconstructions, numerical models (climate, lithosphere and mantle) and the Earth's interior (seismic tomography) in a *single* application. Linking plate tectonic (lithospheric) processes to the mantle is challenging, but is now becoming feasible due to better constraints on deriving ancient longitudes before the Cretaceous, much improved seismic tomographic images of the underlying mantle, and better understanding of the dynamics of true polar wander. Dramatic improvements in computational capacity and numerical methods that efficiently model mantle flow (while incorporating surface tectonics and subduction) have emerged (e.g. Stadler et al., 2010). In the near future, massive parallel simulations will allow us to combine detailed plate reconstructions with real-time convection modelling at high resolution.

6. Connecting Earth's ancient surface to its interior: the importance of Longitude

Wegener's reconstructions are relative in the sense that Africa and Eurasia are kept fixed and all other continental elements were (hand) drawn relative to these (Fig. 1a). In our time, ancient continents can be reconstructed using ocean floor magnetic anomalies and fracture zones (also a relative method), by using

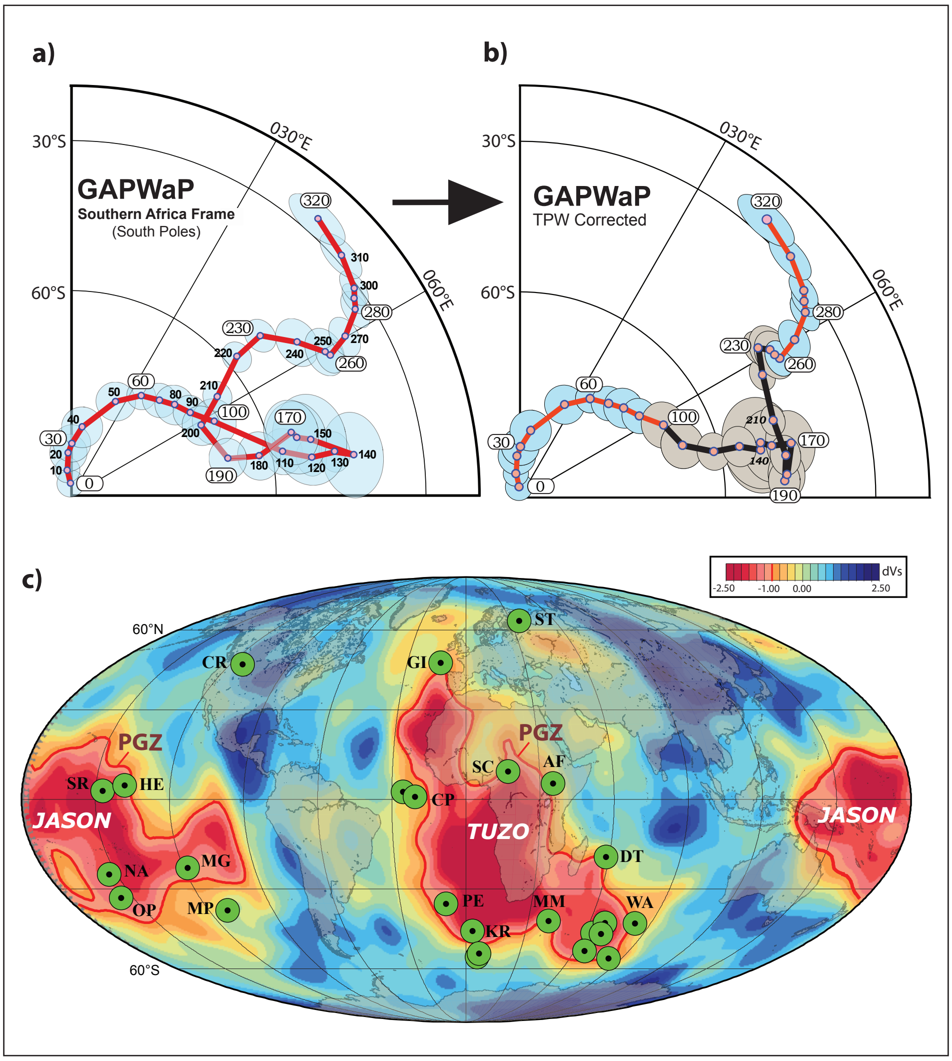

Figure 8: (a) Global APWP (GAPWaP) shown as South Poles in Southern Africa co-ordinates. A running mean path (10 Myr intervals) and shown with 95% confidence ovals. **(b)** GAPWaP corrected for four prominent phases of true polar wander between 250 and 100 Ma (black lines with grey confidence ovals), redrawn from Torsvik et al. (2012). **(c)** Reconstructed LIP centers (black dots with green circles) based on the plate motion reference frame of Torsvik et al. (2008b). Most LIP centers of the past 300 My lie near vertically above the plume generation zones (PGZs) at the time of their eruption. The one percent low velocity contour (red line) in the lowermost layer (2800 km depth) of the SMEAN tomography model (Becker & Boschi, 2002) approximates the PGZs. LIP abbreviations sorted by increasing age (from 15 to 300 Ma): CR, Columbia River Basalts; AF, Afar Flood Basalts; GI, North Atlantic Igneous Province; DT, Deccan Traps; MM, Madagascar; WA, Wallaby; HE, Hess Rise (Pacific); NA, Nauru Basin (Pacific); OP, Ontong Java Plateau (Pacific); MP, Manihiki Plateau (Pacific), PE, Parana-Etendeka, MG, Magellan Rise (Pacific); SR, Shatsky Rise (Pacific); KR, Karroo Basin; CP, Central Atlantic Magmatic Province; ST, Siberian Traps; SC, Skagerrak Centred LIP. Modified from Torsvik et al. (2010).

palaeomagnetic data or by using hotspot trails. However, hotspot-based reference frames cannot be used prior to the Cretaceous. That leaves palaeomagnetism — which cannot determine *longitude* — as the only current quantitative means of positioning objects on the globe before the Cretaceous. However, by choosing a reference continent that has moved the least longitudinally (Africa), longitudinal uncertainty can be minimized. The analytical trick is to rotate all palaeomagnetic poles to Africa (based on relative fits) and calculate a global APW path (GAPWaP, Fig. 8a) in African co-ordinates, which serves as the basis for subsequent global reconstructions. This method is referred to as the "zero-longitudinal motion" approximation for Africa (Burke & Torsvik, 2004; Torsvik et al., 2006, 2008a).

The past decade has also seen the dawn of so-called hybrid reference frames, which combine different frames for different time periods. The first of these (Torsvik et al., 2008b) was based on a mantle reference (moving hotspot) frame for the past 100 Ma, and, before that, a reference frame derived from the African GAPWaP and making the assumption that Africa has not moved in longitude. Choosing Africa as a reference plate that has remained stationary (or quasi-stationary) with respect to longitude only works back to Pangea's assembly, because most relative plate circuits are reasonably well-known from that time, except for terranes or continents not belonging to Pangea, such as North China, South China and Annamia (Fig. 1b). The latter terranes did not join Laurasia (Eurasia) before the Late Jurassic, or perhaps early Cretaceous, and thus well after the main Pangea break-up.

APWPs record a signal from two sources of absolute motion, i.e. motion of lithospheric plates relative to the Earth's mantle ("continental drift") and the rotation of the entire solid Earth with respect to the spin axis (TPW). Creer et al. (1954) argued for TPW to explain their first APWP for Britain/Europe (Fig. 2a). Two years later, Runcorn (1956) favoured 'continental drift', but a combination of both is more likely.

Attempts to link Earth's ancient surface (using palaeomagnetic data) to its interior requires that TPW is accounted for (Fig. 8b). Fortunately, the net cumulative effect of TPW through time (at least since the Late Palaeozoic) is small (Steinberger & Torsvik, 2008; Torsvik et al., 2012), and thus at many time periods TPW-corrected or not corrected reconstructions are quite similar.

The lowermost mantle is characterized by two large heterogeneities where shear-wave velocities are a few percent lower than the average mantle. Those thermo-chemical piles at the core-mantle boundary are near antipodal and equatorially centred (Fig. 8c), and were named Large Low Shear wave Velocity Provinces (LLSVPs) by Garnero et al. (2007). The two were named 'Tuzo' (beneath Africa) and 'Jason' (beneath the Pacific) by Burke (2011), honouring the ground-breaking work of Tuzo Wilson and Jason Morgan. By reconstructing LIPs of the past 300 Myr (Figs 8c, 1c) it has become evident over the past decade that most originated from plumes at the edges of the LLSVPs, the plume generation zones (PGZs) of Burke et al. (2008). Intermittent or continuous upward fluxes of hot and buoyant material from the PGZs are not only related to the emplacement of LIPs (Fig. 8c), but also to most kimberlites (Torsvik et al., 2010) and many hotspot volcanoes, such as Hawaii (Pacific Ocean) and Réunion (Indian Ocean).

The correlation of reconstructed eruption sites of LIPs indicates long-term (at least 300 Myr) stability of the LLSVPs. But how and why plumes develop from their margins (Tan et al., 2011; Steinberger & Torsvik, 2012), and whether the two LLSVPs (fertile or primordial mantle reservoirs) have remained in the same places before Pangea, and perhaps throughout Earth's history, are debated (Zhong et al., 2007; Torsvik et al., 2010; Dziewonski et al., 2010). The remarkable correlation, however, between surface and mantle features provides a new way of reconstructing the original positions of LIP and kimberlite sites. If LLSVPs have remained in the same places before Pangea as today, we can restore continental *longitudes* so that their contained LIPs and kimberlites are vertically above the Pacific or African PGZ. This is the PGZ *longitude* method of Torsvik et al. (2008a), and, combined with palaeolatitude and rotation constraints derived from palaeomagnetic data, can potentially lead to 'absolute' reconstructions back to the dawn of the previous supercontinent, Rodinia (Dalziel, 1997; Weil et al., 1998; Torsvik, 2003; Li et al., 2008), at around 1.1 Ga.

7. Conclusions

If we compare Wegener's continental reconstruction (Fig.1a) with a modern reconstruction (Fig. 1b), which is based on a much larger database, there are many similarities. So, what have we achieved during the last hundred years? At around 310 million years ago, the South Pole was indeed covered by continents, which were overlain by a large ice cap extending northwards up to about 45°S. However, Wegener's original concept was conveyed in a hand-drawn sketch with few objective contents apart from the fit across the Atlantic. The driving mechanisms to support his innovative ideas were quite unknown. In mighty contrast, we can now generate objective maps in which all the continental units have been placed accurately as to their palaeolatitude and rotation (using palaeomagnetic data), and in an absolute sense using hotspot frames (since the Cretaceous) or the 'zero-longitudinal motion' approximation for Africa (Burke & Torsvik, 2004) in order to also constrain longitudes from palaeomagnetic data. Different geometric configurations for Pangea have been postulated by palaeomagnetists over the past decades, but a Pangea configuration not very different from Wegener (1915) and Bullard et al. (1965) remains our favourite (Domeier et al., 2012).

We now know that Pangea did not include all the major continental land masses at any one time, as summarised above. In addition, although scientists such as Wegener had realised that the Earth is quite old, they were thinking in terms of a maximum total of a few hundred million years, rather than the 4.55 Ga we know today through the development of accurate radiometric dating.

Thus, in the same way Wegener used his placement of continents in progressively changing positions to understand the distributions of the Permian floras and Carboniferous glacial deposits, we are now in a position to see where the various land areas, sedimentary belts and faunal and floral provinces have been situated around the globe throughout the Palaeozoic, as well as during Mesozoic and later times. We can also plot the successive climates with much more confidence, since their patterns owe much to the evolving configurations of land and sea. These fundamental revolutions in earth sciences have taken place during our lifetimes, and have been an incredibly stimulating and perhaps unrepeatable experience. But the current surge for a new theory that explains plate tectonics in the framework of both mantle convection and plumes, may advance the next revolution in earth sciences.

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Abbreviations

Apparent polar wander (APW): Apparent motion of the Earth's spin axis (pole) relative to a plate. It represents a convenient way of summarizing paleomagnetic data for a continent instead of producing paleogeographic maps at each geological period.

Global apparent polar wander path (GAPWaP): Apparent polar wander paths from many continents rotated through plate motion chains to one common reference plate and combined into a global paleomagnetic path.

Large igneous provinces (LIPs): Large surface expressions in the form of igneous rocks, overwhelmingly of basaltic affinity, and with catastrophically rapid dissipation of large quantities of internal heat.

Large low-shear-velocity provinces (LLSVP): Two large and stable regions (thermo-chemical piles) at the base of the mantle with shear wave velocities several percent lower than average. The African and Pacific LLSVPs are ca. 180° apart with most of their mass in their bottom 200-400 km.

Plume Generation Zone (PGZ): Narrow loci of intermittent or continuous upward fluxes of hot and buoyant material (mantle plumes) from the core-mantle boundary at the margins of LLSVPs. This flux appears to be related to the emplacement of large igneous provinces, hotspot volcanoes and kimberlites. The 1% low velocity contour in the lowermost layer of the SMEAN tomography model (red line in Fig. 8c) is a reasonable proxy for the PGZs.

True polar wander (TPW): Rotation of the entire Earth with respect to the spin axis.

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