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Excerpt
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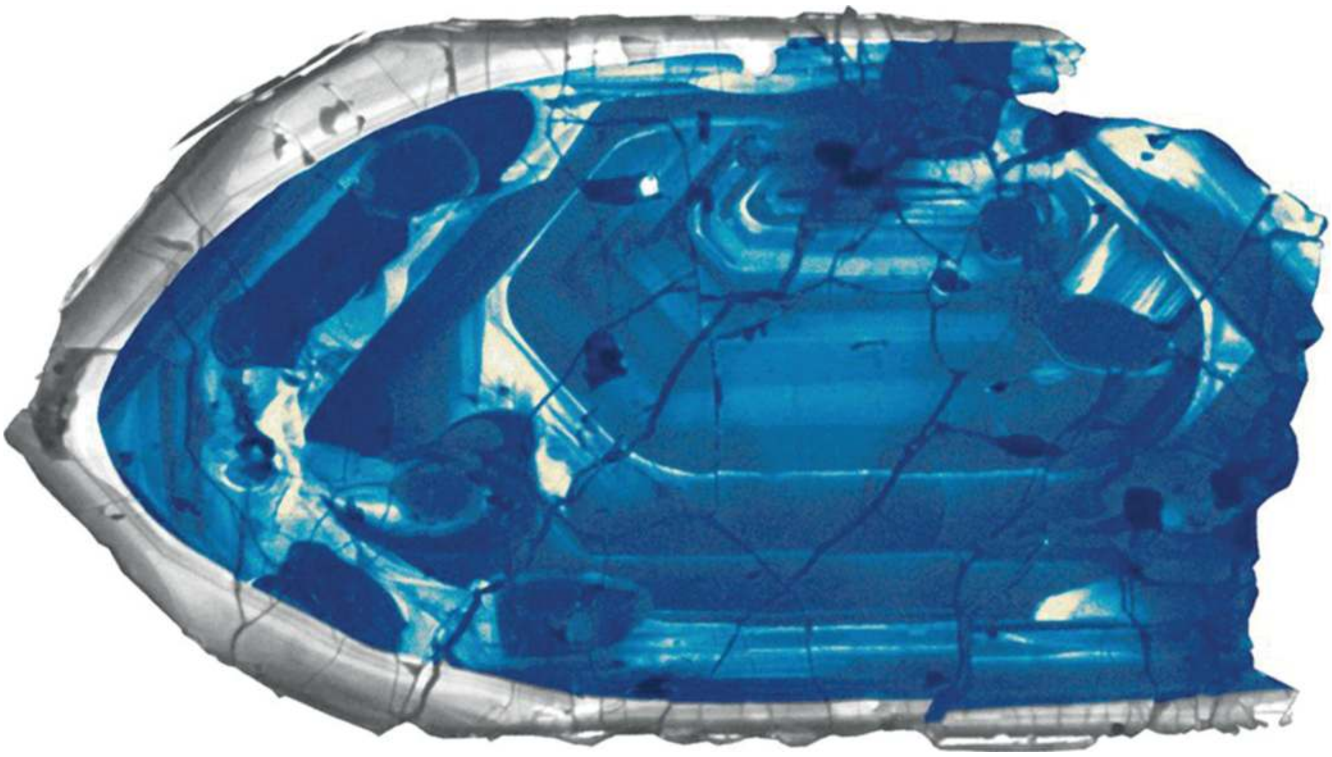
# 1 Introduction



The oldest known zircon on Earth is 4.374 ± 0.006 billion years old. This grain is from the Jack Hills in Western Australia and is about 200 million years younger than the age of the Earth, and is probably a remnant of the oldest continental crust. Credit: John Valley, University of Wisconsin/Nature Geoscience.

When the Earth is viewed from space on a cloudless day, all that can be seen are the edges of lands, seas, and ice caps, all of which can be objectively mapped. From further geophysical exploration, the identities and margins of the oceans and the continental lithosphere which lie beside and below them today can also be discovered. However, how and when all those margins have changed through geological time becomes progressively less easy to discover and also less objective, since an uncertain number of the plates and their included oceanic and continental lithosphere have disappeared by subduction into the Earth's interior. In addition, much of the lithosphere has been distorted through tectonic processes, in many places very heavily.

Our chief aim in writing this book is to interpret, decipher, and describe the complex history of our planet over the most recent half-billion years and the processes through which it has changed, and to compile maps of the distribution of the many tectonic plates through that time, and also show where the lands and seas were situated over that long period. As is usual with narration, we start at the beginning and carry on progressively through time as it elapsed, but the result of that natural sequence is to commence by discussing the periods over which we have the fewest quantitative constraints on Earth's old geography, and thus our geographical reconstructions gradually become more accurate as time continues up to the present day.

The periods into which geological time is divided are shown on the endpapers within this book's covers. The history of the Earth falls naturally into two very unequal divisions: the Precambrian, in which there are no fossils of use in determining the positions of the former continents, and which, including the origin of the planet, is only summarised here in Chapter 4. The Precambrian was followed by the Phanerozoic at 541 million years ago (Ma), and the latter started with the Palaeozoic, from which there is no old *in situ* ocean crust preserved, but this is when the biota was distributed in faunal and floral provinces which are very relevant in assessing oceanic separations in the absence of much useful geophysical data (apart from palaeomagnetism). The boundary between the Palaeozoic and the overlying Mesozoic to the present day was at 252 Ma, after which the ocean-floor magnetic stripes and other useful geophysical data become progressively more abundant and objective, but when the biota, although interesting in its evolutionary development, is again of no primary help in deciphering the palaeogeography. Thus there are separate chapters here for each of the main geological systemic periods from the Cambrian to the Quaternary (Chapters 5 to 15).

But what are the stepping stones, which cover many geological and geophysical disciplines, by which we can achieve our aims? After this brief introduction, in Chapter 2 we describe the varied and often independent methods that we have used to reconstruct old lands and seas. In Chapter 3 we list the 268 unit areas among the many making up our planet which are the ones we have used in the construction of our kinematic computer-generated palaeogeographical maps through time, with a very brief sketch of their geological constitutions. Each of those units, which vary in size from large continents to small terranes, can be downloaded digitally from www.earthdynamics.org/earthhistory, together with a digital rotation file and various other files, which can be used by anyone to make their own reconstructions with GPlates (www.gplates.org) for any area and at any given time for the past 540 million years, with no fees involved but acknowledgements requested.

Over the past billion years, our planet's climate has fluctuated wildly between hot and cold temperatures, some so extreme that any life has been scarcely possible. Thus, as well as mentioning those climates during the individual periods in Chapters 4 to 15, the final Chapter 16 brings together the many factors which affect and support the Earth's climate, and also describes how and why that climate has changed so much during the half-billion years and how it has come to be what it is today. Unfortunately, that deeper time perspective appears to be lacking in many modern-day climate scientists and politicians.

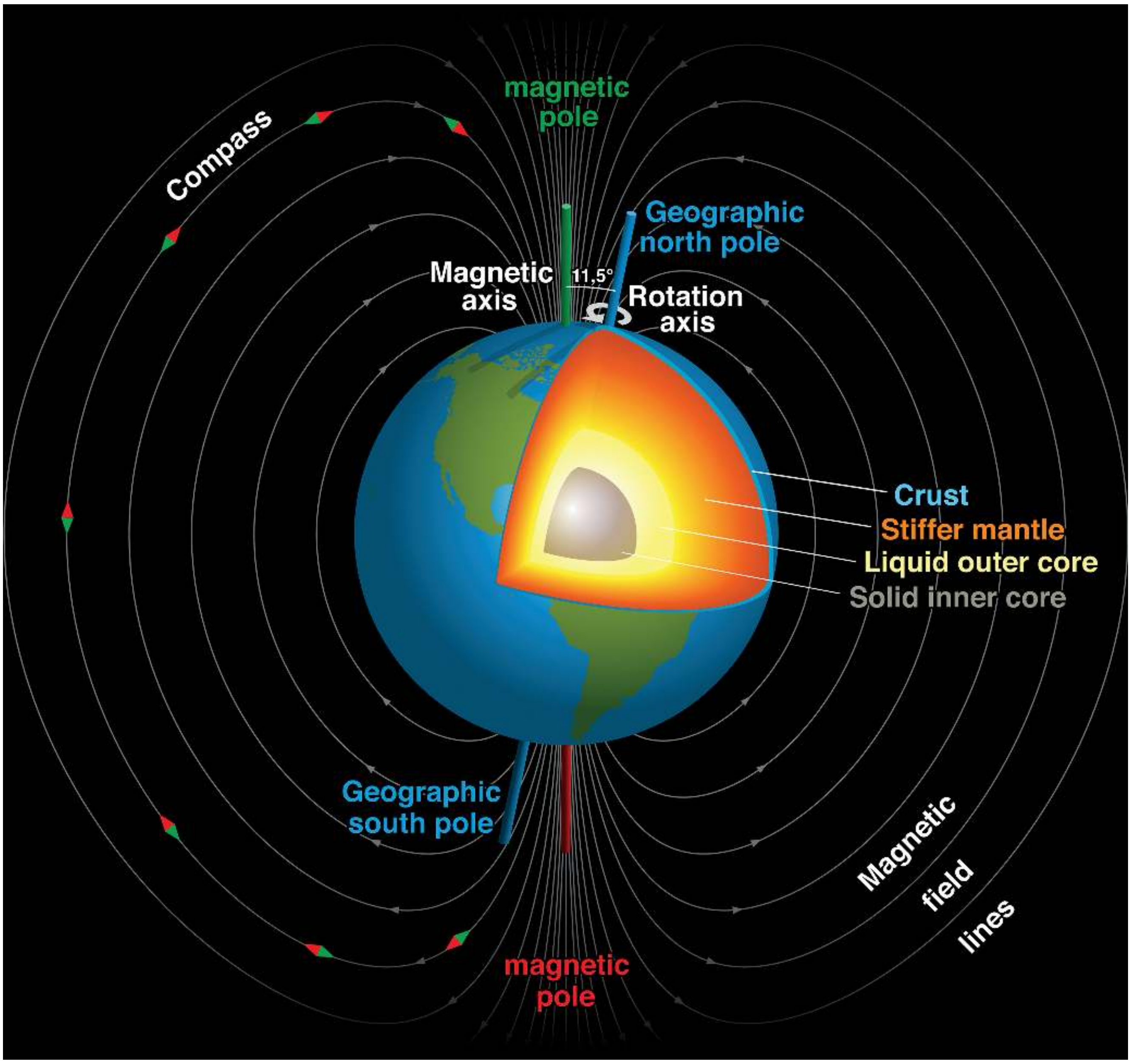
But underlying all that, our book and all of geological thinking depends on knowing how long ago each past event occurred. So that we can comprehend and evaluate the number of years over which the many changes of the Earth's surface and interior have taken place since its origin, and from that the rates of those changes, it is essential to know objectively the amount of time available for their progression. Thus a reliable primary geochronology is critical for underpinning our work.

Since the pioneer work by Arthur Holmes in the early twentieth century, rocks have been dated by radiometric methods, using a great variety of the longer-lived radiogenic isotopes, some of whose half-lives extend over billions of years (Torsvik & Cocks, 2012). The most useful elements have been found to be carbon for the most recent 30,000 years, and a variety of others, including argon–argon ($^{40}Ar/^{39}Ar$) and uranium–lead (U/Pb), for older rocks. All radiometric ages have errors calculated individually, which are given in the original papers, and most are published with dates including proportions within a million years, but, so that this text can flow relatively unimpeded, we have rounded all ages earlier than the Cenozoic (66 Ma) to the nearest one million years, and do not quote the published error ranges here. But, although lacking the objective numbers which have come from geochronology, in much of the Phanerozoic finer time divisions exist through the use of quickly evolving animals and plants from which biozones have been defined, and which have been used in the correlation of rocks. An example of the latter is graptolites in the Silurian, some of whose biozones are less than 100,000 years long, in contrast to the radiometric ages for that period, which are not accurate to within about one-third of a million years.

The overall time scale on which our work depends is inside the endpapers of this book, where the dates for the bases of the major time units are shown, most of which have now been standardised by the International Union of Geological Sciences (IUGS) Commission on Stratigraphy (Cohen et al., 2013).

It has been difficult to know how many references should best be cited. Many textbooks are frustrating in their relative lack, or sometimes even complete absence, of references, whilst research papers usually include at least one reference to support every fresh statement, and often far too many more, particularly to papers written by friends of the authors. This has led us to compromise, and we apologise both to current workers for the omission of precise citation of much invaluable work, and also to those earlier scientists on whose shoulders we all stand, particularly since we have tended to refer to summary articles in many places here, rather than to the many papers which underpin those works.

# 2 Methods for Locating Old Continents and Terranes




From the vantage point of geological time, the Earth is best seen as a giant heat engine. The decay of radioactive nuclides in the deep interior provides energy for its most fundamental dynamical processes: convection in both the liquid outer core and the stiffer (solid) but slowly deforming mantle. Under the influence of the Earth's rotation, the electrically conductive outer core generates the Earth's magnetic field. This field shelters us from cosmogenic radiation, modulates atmospheric escape, and provides guidance for many migratory species. The Earth's ancient magnetic field provided one of the fundamental markers used to document the motion of the continents and evolution of the Earth. Changes in ancient magnetic polarity at irregular intervals are recorded in the surface rock record, and over some fifty years such palaeomagnetic data have been used to create the geomagnetic time scale, to firmly document sea-floor spreading, to validate plate tectonics, and to reconstruct vanished supercontinents. The magnetic poles differ from the geographical poles because the magnetic axis is inclined relative to the geographical (rotation) axis (today ~11.5°). The magnetic axis, however, is rotating slowly around the geographical axis and, over a period of a few thousand years, the averaged magnetic poles have corresponded reasonably well with the geographical poles. Credit: Furian/Shutterstock.

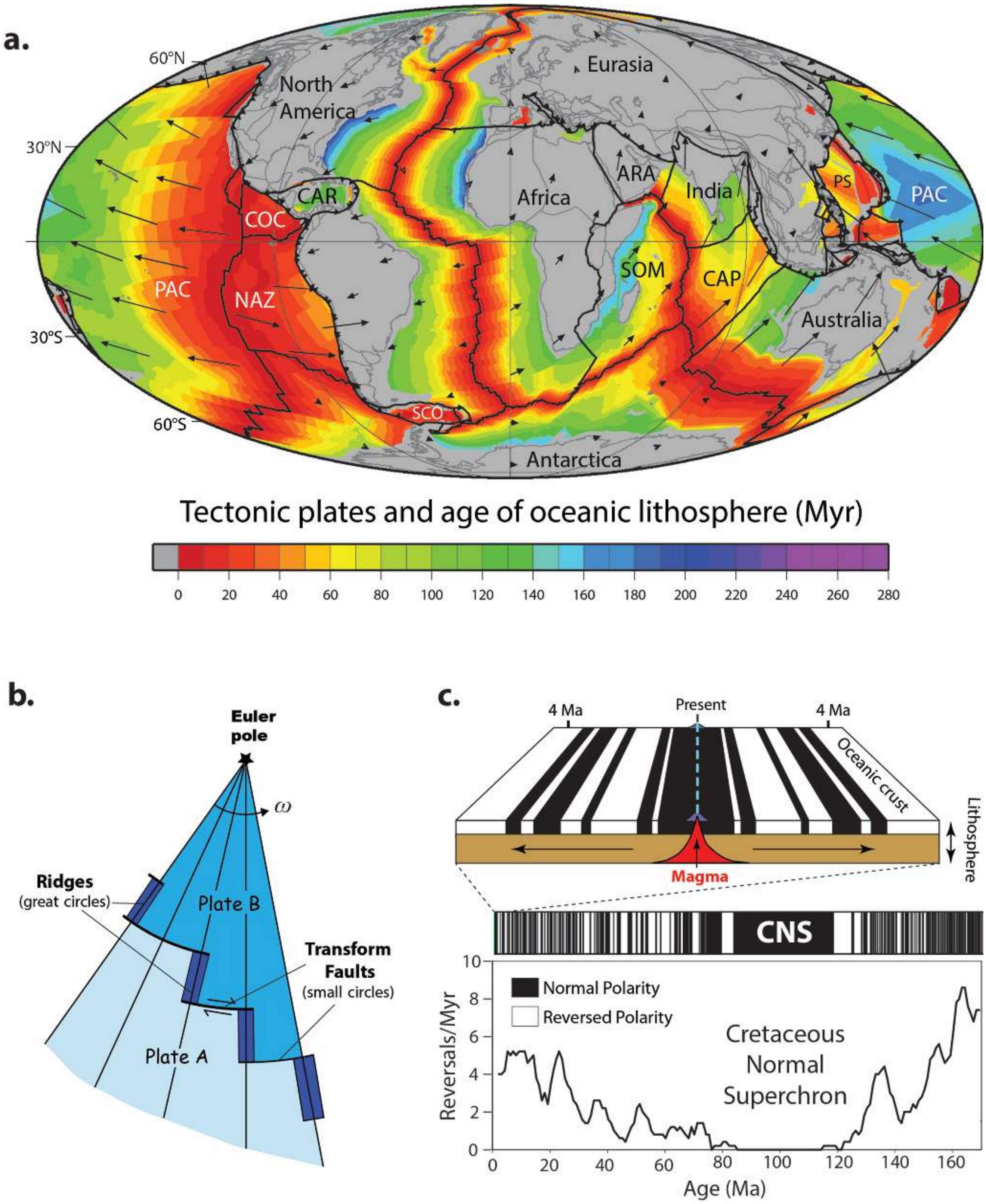



**Fig. 2.1** (a) Present-day distribution of tectonic plates. Base map shows the modelled age of oceanic crust; warm (red) colours indicate young sea floor (close to the spreading axis), while cold (blue/violet) colours indicate old oceanic crust. The oldest preserved oceanic crust (possibly 195 million years old: Early Jurassic) is found, among other places, in the Central Atlantic between North America

Over the last century, our portrayal of the movement and deformation of the Earth's outer layer evolved from the hypothesis of Continental Drift (1912) into Sea-Floor Spreading (1962) and then to the paradigm of Plate Tectonics (1967). The word 'tectonics' comes from Greek and means 'to build', and plate tectonics is as fundamentally unifying to the Earth Sciences as Darwin's (1859) Theory of Evolution is to the Life Sciences. Most of this book describes how the geography of the Earth has changed over geological time. However, this chapter sets out the various methods by which the positions of old continents can be deduced, most of them completely independent from each other. It is important to bear in mind that the geographical areas (Chapter 3) in older times shown on our reconstructions (Chapters 4–15) rarely reflect the real shape of those continents at those individual times in the past, since their margins have been much changed by subsequent tectonic events.

Plate reconstructions at successive intervals in geological time are the result of a reiterative process using a wealth of methods. The relative positions of continents are commonly determined from ocean-floor magnetic anomalies (since the Jurassic) and fracture-zone geometries, analysis of continent–ocean boundaries, palaeomagnetic poles, and other geological and geophysical data. Continents and terranes are then reconstructed to their ancient positions on the globe using hotspot trails (since the Cretaceous) or palaeomagnetic data, and by identifying and discriminating between the distributions of various fauna and flora in their various provinces at different times. These biological distributions can indicate if terranes with similar biota were close to one another or were separate. The distribution of key sediments, such as glacial deposits, coal, and evaporites, can also be useful, but they are largely latitudinally determined rather than terrane-specific.

## Plates and Plumes

Plate tectonics describes how the Earth's lithosphere (the crust and upper mantle) is constructed from a dozen large and many smaller rigid blocks that move in relation to each other (Fig. 2.1a). It is a captivating story of oceanic and thicker continental plates that move across the Earth's surface, and how they glide apart forming new oceanic crust (divergent plate boundaries), collide to form mountain belts (convergent boundaries), or move sideways in relation to each other (transform boundaries). The motions of rigid plates can be described by Euler rotations (Fig. 2.1b). Plate velocities range from about 1 to 15 cm/yr, and earthquakes and volcanic eruptions close to the plate boundaries are key elements of the plate tectonic paradigm. Under the influence of the Earth's rotation, the electrically conductive outer core generates the Earth's magnetic field. The history of that ancient magnetic field provides one of the fundamental clues used to document the motion of the continents and evolution of the Earth. Changes in ancient magnetic polarity at irregular intervals are recorded in the surface rock record, and those palaeomagnetic data have been used to create the geomagnetic time scale (Fig. 2.1c).

Hotspots can be referred to as volcanism unrelated to plate boundaries and rifts, and many intra-plate hotspots such as the one beneath Hawaii (Wilson, 1963) have been suggested to overlie plumes that originated at the core–mantle boundary. A few hotspots also lie at the ends of plume trails (chains of volcanic islands) which are connected to large igneous provinces (LIPs), e.g. the Tristan (Paraná–Etendeka) and Reunion (Deccan) hotspots. The Hawaii Hotspot was probably also linked to a starting LIP, which was long subducted (Chapters 13 and 14), whilst the New England Hotspot lies at the end of a plume trail that was connected with Jurassic kimberlite volcanism in continental north-eastern America. Many hotspots are clearly intra-plate (e.g. in the Pacific and Africa, Fig. 2.2a) and therefore unrelated to plate tectonics, but some are located on or near a plate tectonic boundary.

The lowermost mantle is characterised by two large heterogeneities where shear-wave velocities are up to three per cent slower than in the surrounding mantle. Those thermochemical piles are near antipodal and equatorially centred

**Fig. 2.1** (*cont.*) and North-West Africa, and linked to the very earliest breakup of the supercontinent of Pangea. Red lines denote subduction zones, black lines denote mid-ocean ridges and transform faults. Plate motions (moving hotspot frame) are shown as black arrows. ARA, Arabia; CAP, Capricorn; CAR, Caribbean; COC, Cocus; NAZ, Nazca; PAC, Pacific; PS, Philippine Sea; SCO, Scotia; SOM, Somalia (data from EARTHBYTE). (b) On a sphere the relationship between two plates (A and B in this example) is described by a rotation (Euler) pole (latitude, longitude, and angle) and the relative speed ($\omega$) is commonly expressed in °/Myr. Spreading ridges define great circles, while ocean fracture zones (transform faults) define small circles. (c) Cartoon illustrating the formation of magnetic anomalies at a mid-ocean ridge and the marine magnetic anomaly polarity record and reversal frequency (10 Myr running mean based on data in Biggin et al., 2012). Reversal frequency peaked in the Jurassic (~150–170 Ma), but the most extreme geomagnetic behaviour was in the Cretaceous Normal Superchron (CNS) from 121 to 84 Ma (Late Jurassic to Mid–Late Cretaceous), when the field was of single polarity for almost 40 Myr. Two older Phanerozoic superchrons have also been suggested: the Permian–Carboniferous Kiaman Reverse Superchron (~265–310 Ma) and an Ordovician Reversed Superchron between about 460 and 490 Ma.

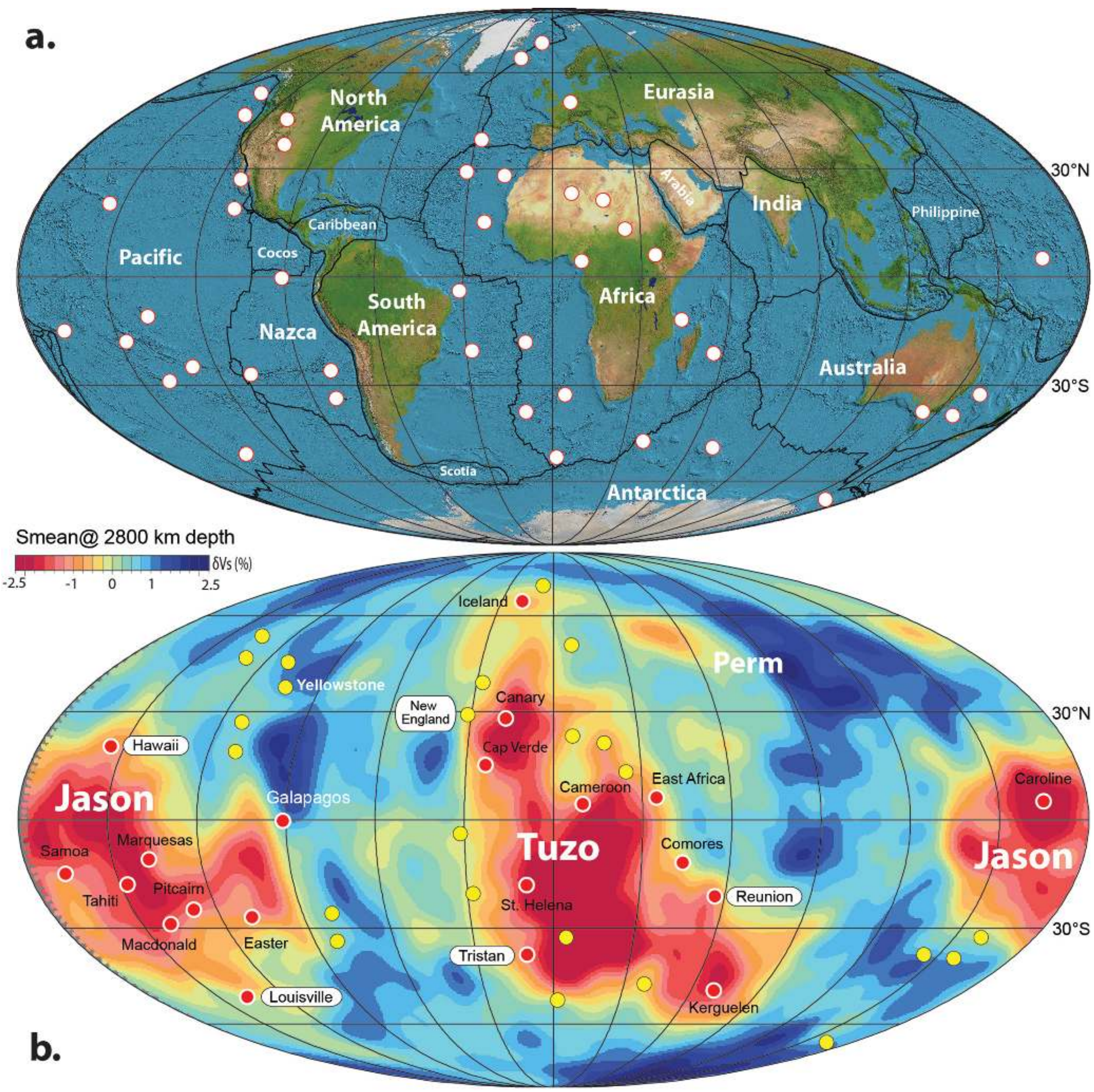



Fig. 2.2 (a) Main plate boundaries (black thick lines) and the distribution of hotspots (red circles with white filling; Steinberger, 2000) draped on a global map of topography and bathymetry. In plate tectonic theory, volcanism, deformation, and earthquakes should be confined mainly to regions near the plate boundaries. However, many hotspots are found within the plates (e.g. Pacific and African plates) which are not readily explained by plate tectonic processes. (b) Plot of hotspots as in (a) but draped on the SMEAN shear-wave velocity anomaly model at 2,800 km depth (Becker & Boschi, 2002). Velocity anomalies ($\delta V_s$) in percentage and red denote regions with low velocity. The lower mantle is characterised by two main zones of low shear-wave velocities, mainly beneath Africa (Tuzo) and the Pacific (Jason). In addition, a smaller one named Perm (which may alternatively be part of Tuzo) is located beneath Siberia. Many hotspots appear to overlie regions of slower than average shear-wave velocities (notably those associated with Tuzo) but there are clear exceptions (e.g. Yellowstone in North America). Those hotspots, thought to be sourced by deep plumes from the core–mantle boundary (primary and clearly resolved plumes in French & Romanowicz, 2015), are shown as white circles with red filling, whilst others of unknown origin are shown as yellow dots.

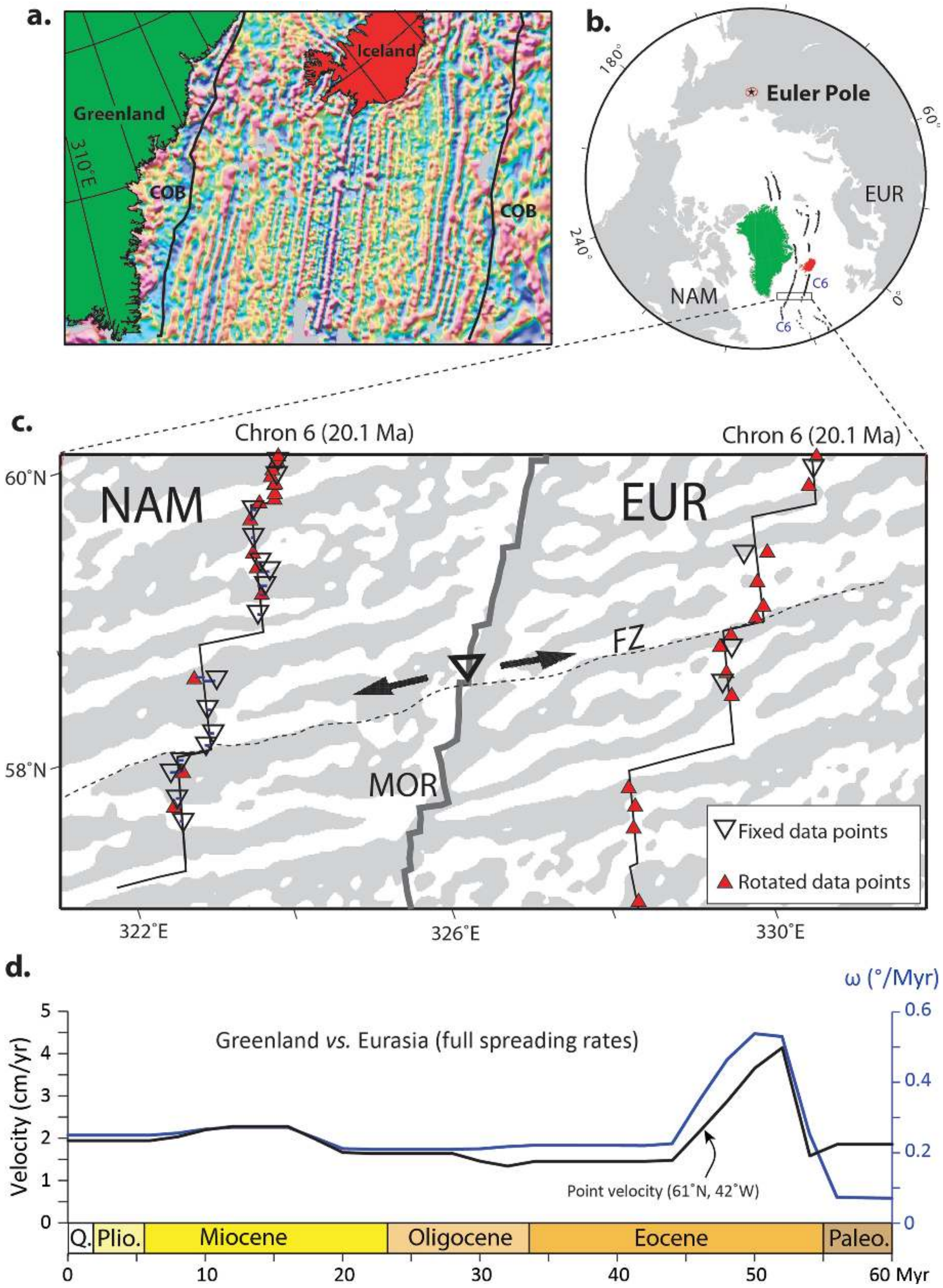



**Fig. 2.3** (a) Magnetic anomaly grid of the north-east Atlantic south of Iceland. The thick black lines are Continent–Ocean Boundary transitions (COBs). (b) Example of marine magnetic anomaly interpretations (700 data points of Chron 6, C6) and resulting Euler pole (EP) (black star) and uncertainty ellipse (red contour around EP; enlarged three times so as to be visible on the map) for relative motion between

(Fig. 2.2b), and are termed large low shear-wave velocity provinces (LLSVPs) (Garnero et al., 2007) or more simply 'Tuzo' (beneath Africa) and 'Jason' (beneath the Pacific) by Burke (2011). Courtillot et al. (2003) and Ritsema and Allen (2003) concluded that only eight hotspots (Afar, Easter Island, Hawaii, Iceland, Louisville, Réunion, Samoa, and Tristan) potentially had a deep plume origin. Montelli et al. (2006) added three extra hotspots (Azores, Canary, and Tahiti) to those of deep origin, and Torsvik et al. (2006) pointed out that all hotspots of potential deep origin plot on or very near the margins of Tuzo or Jason. In a recent study using full-wave tomography, French and Romanowicz (2015) identified 20 primary or clearly resolved plumes (Fig. 2.2b) that all overlie Tuzo and Jason.

## Relative Positions of Continents and Ocean Floor Magnetic Stripes

As long ago as the 1950s, scientists noticed the regular pattern of positive and negative magnetic anomalies across the ocean floors (Fig. 2.3a), and it was realised subsequently that the lines of those magnetic anomalies are arranged in sub-parallel stripes on both sides of each of the mid-ocean ridges (Vine & Matthews, 1963). That was explained by the realisation that, as magma is erupted at the mid-ocean ridges, it flows laterally and displaces the rock erupted previously. That causes the ocean floor to spread out relatively symmetrically from both sides of the spreading ridges (Figs. 2.1a and 2.3a). When the magma cools to form rock, magnetic minerals in the oceanic crust acquire a magnetisation aligned with the Earth's magnetic field (Fig. 2.9). That magnetisation in the rock reflects the polarity of the magnetic field (Fig. 2.1c), which has reversed from north to south and back again at irregular intervals many times in the past. The Late Jurassic witnessed high reversal frequencies but in the Cretaceous the field was of a single normal polarity lasting for almost 40 Myr (Cretaceous Normal Superchron, ~84–121 Ma), and thus no magnetic stripes exist for that time interval. On average, there has been a reversal every 200,000 years (five reversals per million years) during the past 10 Myr.

The matching of magnetic anomalies and fracture zones of the same age, corresponding to patterns of palaeo-ridge (great-circle) and palaeo-transform (small-circle) segments at any particular reconstruction time (Fig. 2.1b), is used to determine the relative motions between tectonic plates (Fig. 2.3b and c). The Hellinger (1981) method is most commonly used to derive best-fit rotations (Euler poles) from conjugate magnetic anomalies and fracture zone data (Fig. 2.3c), which are in turn used to derive spreading velocities between two plates. Figure 2.3 shows gridded magnetic anomalies in the north-east Atlantic from Iceland and southwards, with an example of fitting magnetic anomalies and fracture zones at around Chron 6 time (20.1 Ma) along the Reykjanes Ridge. Applying this method to all the identified Chrons in the north-east Atlantic (Gaina et al., 2002) one can calculate the relative speed back to the initial opening of the north-east Atlantic at around 54 Ma. Velocities peaked during the Early Eocene opening stage (about 0.5°/Myr or 4 cm/yr for a location along the southern Greenland margin), but otherwise have been quite stable at around 0.2°/Myr or 2 cm/yr. Spreading velocities are often reported as half-spreading rates in the literature; the values calculated in Fig. 2.3d are full spreading rates and the Reykjanes Ridge, and the other ridges in the north-east Atlantic and the high Arctic, are considered as slow to ultra-slow spreading ridges.

## Absolute Plate Reconstructions Using Hotspot Tracks

After Wilson (1963) suggested that linear chains of seamounts and volcanoes are caused by hotspots, Morgan (1971) proposed that hotspots may be caused by mantle plumes up-welling from the lower mantle, and constructed the first hotspot reference frame. In that and later models

**Fig. 2.3** (*cont.*) North America (NAM) and Eurasia (EUR). (c) Detailed image shows a subset of the Chron 6 (20.1 Ma) interpretation in the North Atlantic and illustrates Hellinger's (1981) criterion of fit. Fixed data points are represented by inverted triangles; rotated data points are red triangles. The background shows the vertical gradients of free air gravity that allow identification of fracture zones (FZ) and offsets between spreading segments. Great circles were fitted for data points in each individual spreading segment. For a given rotation the measure of fit represents the sum of squares of the weighted distances (short blue line segments perpendicular to the great circle segment shown as an example on the NAM isochron). The thick grey line shows the present-day mid-ocean ridge (MOR); the arrows indicate the direction of spreading on NAM and EUR plates (simplified from Torsvik et al., 2008b). (d) Relative velocity between the Greenland and Eurasian Plates expressed in °/Myr ($\omega$, blue curve) and cm/yr (black curve) for a point in southern Greenland (61° N, 42° W). Those velocities are calculated from Euler poles determined by the Hellinger (1981) method detailed in Gaina et al. (2002). Sea-floor spreading between Greenland and Eurasia started at around 54 Ma, but before then there was a period of Late Cretaceous–Paleocene pre-drift extension, and therefore velocities are not zero before breakup. Velocities are calculated over a 5 Myr window and shown at 2 Myr intervals. Paleo., Paleocene; Plio., Pliocene; Q., Quaternary.

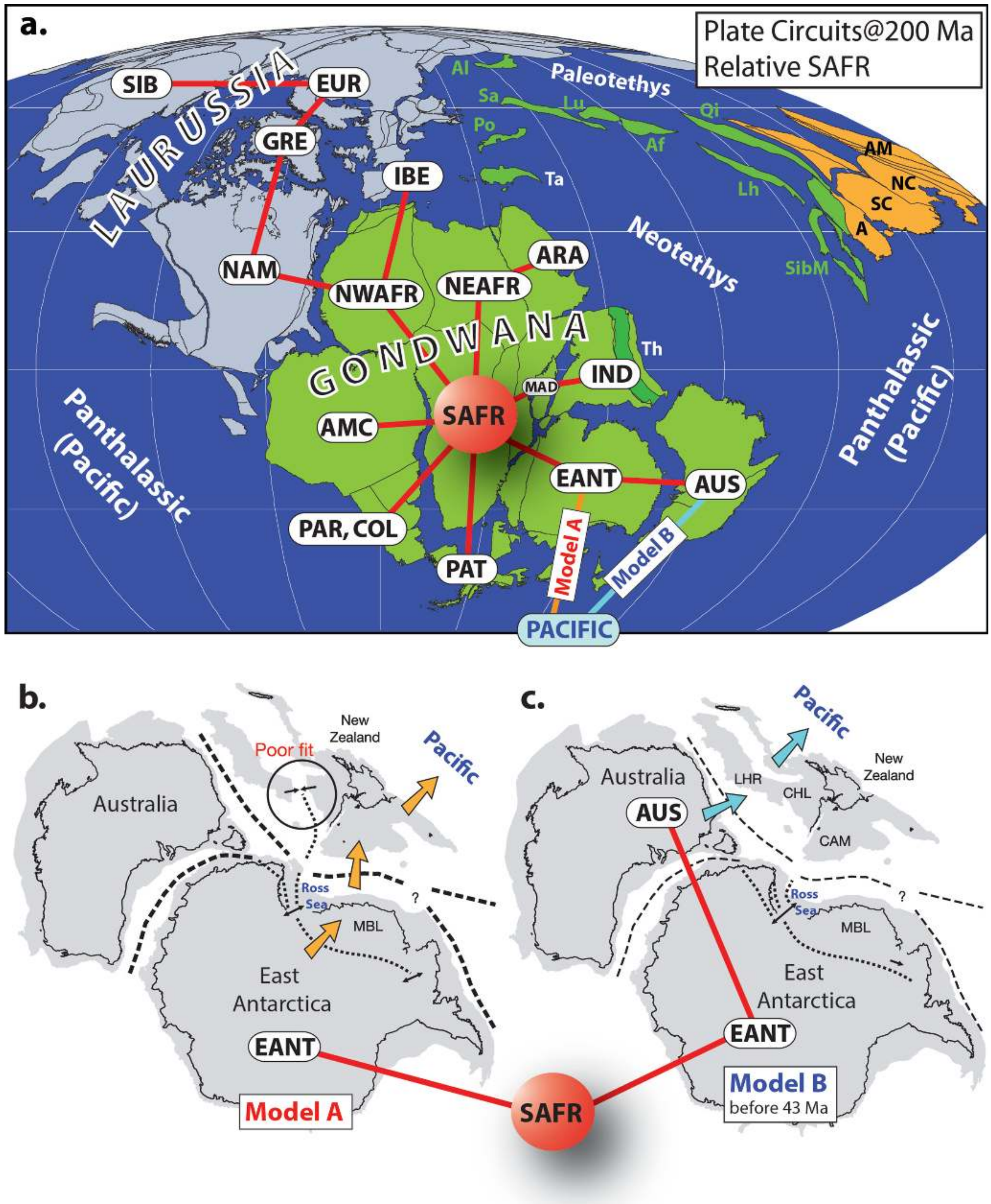



**Fig. 2.4** (a) When building global plate motion models before the Cretaceous it is important to choose a plate as an initial reference that has undergone a small amount of longitudinal movement. Africa is the ideal candidate because it has remained extremely stable for the past 200 Myr, having mostly been surrounded by spreading centres since the Jurassic. Africa has the added advantage of being nearly in the

(e.g. Müller et al., 1993), plumes remained fixed relative to each other over long periods of time (fixed hotspot hypothesis). However, there is abundant evidence that hotspots are moving relative to each other; for example, the fixed Pacific and African hotspot reference frames do not agree with each other (Fig. 2.5a), and there is sound palaeomagnetic evidence (Tarduno et al., 2009) that the Hawaii Plume underwent considerable southward drift in Late Cretaceous to Paleogene times (Fig. 2.7). Fixed hotspot reference frames must therefore (at least before 40 Ma) be replaced by a mantle (moving hotspot) frame in which motions of hotspots in a convecting mantle are assumed (Steinberger et al., 2004).

Hotspot reference frame reconstructions are absolute in the sense that they constrain the ancient positions of continents (described by latitudes, longitudes, and orientations). There are three key elements that define a moving hotspot reference frame: (i) relative plate reconstructions (Fig. 2.4), (ii) the ages and geometries of hotspot tracks (Figs. 2.5 and 2.6), and (iii) the motions of mantle plumes that rely on backward advection of present mantle density structures. Incorporating data from hotspot tracks formed on different plates into a common reference frame requires estimates of relative plate motion. That is achieved by reconstructing coeval locations from all the tracks that are present at a certain age relative to a selected 'anchor' plate, which is most commonly South Africa (Unit 701, Chapter 3). A global absolute plate motion model is therefore made in such a way that all the tracks were on the southern African Plate (using plate circuits, Fig. 2.4) and then averaged to define a global moving hotspot reference frame (GMHRF).

The GMHRF of Steinberger et al. (2004) was based on four hotspot tracks, two in the Pacific (Hawaiian and Louisville), one in the South Atlantic (Tristan), and the fourth in the Indian Ocean (Réunion). All those hotspots probably initiated as LIPs (catastrophic melting of the upper mantle) at around 125–120 Ma (Ontong Java: Louisville), 134 Ma (Paraná–Etendeka: Tristan), and 65 Ma (Deccan: Réunion). Indo-Atlantic Plate circuits are quite robust but relating the Pacific Plate to the Indo-Atlantic system is not straightforward. The Steinberger et al. (2004) model of hotspot motion predicted a southward motion (up to a few cm/year) of the Hawaii Hotspot, and in combination with a plate motion chain that connects Africa and the Pacific via East Antarctica and Marie Byrd Land (West Antarctica) allowed a fit of hotspot tracks globally for times after the age of the Hawaiian–Emperor bend. In this model, no motion occurred between East Antarctica and Marie Byrd Land prior to 43.8 Ma (model A in Fig. 2.4b). Before 43.8 Ma, an east–west misfit between predicted and observed Hawaiian hotspot tracks remains (Fig. 2.5a). Steinberger et al. (2004) thus explored alternative plate circuits linking Africa and the Pacific via East Antarctica–Australia–Lord Howe Rise in older times (Model B, Fig. 2.4c), and with this model they were able to achieve a reasonable fit to hotspot tracks globally back to around 65 Ma. Prior to that, a notable misfit between predicted and observed Hawaiian tracks remains (Fig. 2.5a).

The GMHRF of Torsvik et al. (2008b) also used the model B plate motion chain of Steinberger et al. (2004), but relative plate motions are slightly different and the South Africa *versus* East Antarctica and Australia *versus* Lord Howe Rise rotations were smoothed. The transition between models A and B was also smoothed. By doing that, at 75 Ma (Campanian), the difference between observed and predicted

**Fig. 2.4** (*cont.*) centre of the plate circuit tree, thus limiting error propagation. Abbreviations in our 200 Myr reconstruction keeping Africa fixed: SIB, Siberia; EUR, Europe; GRE, Greenland; NAM, North America; IBE, Iberia; NWAFR, North-West Africa; NEAFR, North-East Africa; SAFR, South Africa; AMC, Amazonia Craton; PAR, COL, Paraná, Colorado sub-plates; PAT, Patagonia sub-plate; IND, India; ARA, Arabia; MAD, Madagascar; EANT, East Antarctica; AUS, Australia; Th, Tethyan Himalaya. Once peri-Gondwanan terranes (dark greenish) and not part of Pangea include Ta (Taurides, Turkey), Po (Pontides, Turkey), Sa (Sanand, Iran), Lu (Lut, Iran), Al (Alborz, Iran), Af (Afghanistan), Qi (Qiantang, North Tibet), Lh (Lhasa, South Tibet) and SibM (Sibumasu). China block not part of Pangea (separated from Asia by the Mongol–Okhotsk Ocean) includes A (Annamia), SC (South China), NC (North China), and AM (Amuria, Central Mongolia). We also show two different relative plate circuit models between Indo-Atlantic (Africa) and Pacific hotspots before the Middle Eocene (Chron 20, 43 Ma). After Chron 20, models A and B follow the same plate motion chain through East Antarctica and Marie Byrd Land. The models were originally named model 1 and 2 (Steinberger et al., 2004). (b) and (c) Late Cretaceous (Maastrichtian) South Pacific reconstructions, the standard model A and the alternative plate chain model B, which link Africa and the Pacific via East Antarctica, Australia, and the Lord Howe Rise (LHR). For the South-West Pacific Plate motion chain, model B predicts intra-Antarctic motion prior to 43.8 Ma with extension in the Ross Sea area, whereas model A does not involve movements between East and West Antarctica before 43.8 Ma. The large arrows show paths of plate motion chains, thick stippled lines are divergent plate boundaries with sea-floor spreading, and dotted lines are conditional intra-continental plate boundaries necessary to accommodate the two different plate circuit models. The standard model A demonstrates a New Zealand misfit whilst model B requires about 300 km extension in the Ross Sea. CHL, Challenger Plateau; CAM, Campbell Plateau; MBL, Marie Byrd Land.