How subduction broke up Pangaea with implications for the supercontinent cycle

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Abstract: Mechanisms that can explain the Mesozoic motion of Pangaea in a palaeomagnetic mantle reference frame may also be able to explain its breakup. Calculations indicate that Pangaea moved along a non-rigid path in the mantle frame between the late Triassic and early Jurassic. The breakup of Pangaea may have happened as a response to this non-rigid motion. Tectonic forces applied to the margins of Pangaea as a consequence of subduction at its peripheries can explain both the motion and deformation of Pangaea with a single mechanism. In contrast, mantle forces applied to the base of Pangaea appear to be inconsistent with the kinematic constraints and do not explain the change in supercontinent motion that accompanied the breakup event. Top-down plate tectonics are inferred to have caused the breakup of Pangaea. Strong coupling between the mantle and lithosphere may not have been the case during the Phanerozoic eon when the Pangean supercontinent formed and subsequently dispersed.

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The mechanisms responsible for plate tectonic change on Earth have been linked to the different stages of the supercontinent cycle (Worsley et al. 1982; Gurnis 1988; Storey 1995; Tackley 2000; Silver & Behn 2008; Li & Zhong 2009; Yoshida & Santosh 2011; Buiter & Torsvik 2014; Nance et al. 2014). Nance et al. (2014) provide a recent review of the hypothesis that bottom-up or mantle-based mechanisms are principally responsible for the breakup of supercontinents, whereas top-down or subduction-based mechanisms are inferred to have governed the dispersal and (re-)amalgamation of supercontinents (Fig. 1). In this hypothesis, the coupling of mantle convection, plumes or superplumes with the overlying lithosphere is thought to have waxed and waned with the formation and dispersal of supercontinents through time. Mantle processes have been strongly implicated in the breakup mechanisms of past supercontinents including Columbia, Rodinia, Pannotia and Pangaea (Nance et al. 2014, Fig. 1).

The purpose of the present study is to re-evaluate the potential roles for both bottom-up and top-down mechanisms for the breakup of Pangaea (Figs 2 & 3). The present study focuses on the analysis of plate motion data (Seton et al. 2012) in a palaeomagnetic mantle reference frame (Torsvik et al. 2012). Boundary conditions calculated here are then compared with basic predictions for mantle-driven and subduction-driven breakup processes as summarized from the results of analogue and numerical modelling studies (Zhong & Gurnis 1993; Li & Zhong 2009; Aitken et al. 2013). The present analysis builds on the previous work of D. F. Keppie (2015) in which only the relative plate motion data were evaluated. D. F. Keppie (2015) demonstrated that the Mesozoic opening of the central Atlantic ocean was balanced by the closure of Palaeo-Tethys and Tethys oceans to the east and not by the closure of Panthalassa. D. F. Keppie (2015) inferred that subduction-based processes were most likely responsible for the breakup of Pangaea because the geometry and timing of events identified in the linked Atlantic–Tethys compensation system appear most simple to explain if the causal forces propagated from the Tethyan domain into the Atlantic domain and not vice versa. The present study tests whether the motions of Pangaea and its daughter plates in a palaeomagnetic reference frame provide a further means to discriminate between subduction-based and mantle-based breakup mechanisms.

Previous work

As (Nance et al. 2014) have recently reviewed the supercontinent cycle, only the main ideas pertinent to Pangaea will be summarized here. Many studies have emphasized potential roles for mantle-based mechanisms, such as convection cells, plumes or superplumes, in the breakup of Pangaea (Doblas et al. 1998; Isozaki 2009; Santosh et al. 2009). Bottom-up plate tectonics are thought to have been prominent during the breakup of supercontinents for the following reasons: (1) oceans close

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during the amalgamation of supercontinents and the subduction zones previously accommodating the closures are annihilated, thus subduction can become minimal or absent (Silver & Behn 2008), or alternatively subduction may move to the periphery of the supercontinent (Murphy & Nance 1991); and (2) geodynamic modelling studies have shown that large amalgamations of continental lithosphere can alter both the mechanical and thermal regimes in the underlying mantle. For example, the areal extent of a supercontinent can exceed a threshold size after which the insulation or thermal barrier supplied by the continental lithosphere is sufficient to trigger changes in the underlying mantle flow (Gurnis 1988; Zhong & Gurnis 1993; Zhong et al. 2007; Li & Zhong 2009; Lenardic et al. 2011; Yoshida 2013). In such cases, the underlying mantle may warm, expand, decrease in density, become buoyant and exert upward and outward tractions on the base of the lithosphere. High volumes of emplaced magmas called Large Igneous Provinces may indicate the influence of upwelling mantle at these extension zones; the inferred melting of mantle at elevated temperatures may support the hypothesis of mantle-driven breakup (Bond et al. 1984; Li et al. 1999; Dalziel et al. 2000; Ernst et al. 2005; Hou et al. 2008; Kouyaté et al. 2013). The Central Atlantic Magmatic Province emplaced during the breakup of Pangaea may be the largest preserved Large Igneous Province in the geological record (Ruiz-Martínez et al. 2012).

Geodynamic models have shown that subducted lithosphere can accumulate in the transition zone at the base of the upper mantle (Chen & Brudzinski 2001; Hamilton 2007), or at the base of the lower mantle just above the core–mantle boundary (Kendall & Silver 1996; Spasojevic et al. 2010; Sutherland et al. 2010; Tackley 2011). Accumulations of subducted lithosphere at the base of the upper mantle can start to sink rapidly into the deeper mantle in so-called slab avalanche events (Condie 1998; Pyskywec et al. 2003; Capitanio et al. 2009). Slab avalanche events may trigger superplumes in the mantle beneath supercontinents, which may play roles in their amalgamation and breakup (Pyskywec et al. 2003; Nance et al. 2014). Subducted lithosphere that has accumulated above the core–mantle boundary has been inferred from two low-velocity seismic zones interpreted from seismic tomography images of the lower
mantle (Zhao 2004; Burke et al. 2008). These slab graveyards presently underlie the African craton and the Pacific ocean (Zhao 2004), but one may have underlain the central Atlantic region during the breakup of Pangaea (Morra et al. 2013). Slab graveyards can provide an origin of deep mantle plumes as the subducted material is warmed across the core–mantle boundary (Hirose et al. 1999; Lay et al. 2004; Torsvik et al. 2006). Characteristic chemistry of emplaced magmas observed in the terrestrial rock record at the extension zones where supercontinents first began to fail may correspond to a source region that hosts substantial amounts of previously subducted oceanic lithosphere (Senshu et al. 2009; González-Jiménez et al. 2013; Callegaro et al. 2014).

Thus, a variety of thermal and mechanical arguments have been assembled to explain why zones of upwelling mantle may have formed in the regions underlying the terrestrial supercontinents and how these zones of upwelling mantle may have caused the supercontinents to break apart (Nance et al. 2014). However, extensional stresses delivered to supercontinents across subduction zones at the peripheral margins of the supercontinent may have played important roles in the breakup process (Aitken et al. 2013; Buiter & Torsvik 2014). Geodynamic models using realistic physical properties for Earth have not always confirmed the potential for the mantle-driven breakup of supercontinents (Heron & Lowman 2014). In several studies, mantle convection appears to be too vigorous under Earth-like conditions to allow the buildup of thermal anomalies beneath supercontinents at the time scale of the supercontinent cycle (Yoshida 2013; Heron & Lowman 2014). Mantle convection can stabilize in cells beneath the base of the lithosphere instead and not become coupled to the lithosphere, even when the lithosphere hosts a large continent (Moresi & Solomatov 1998).

Top-down plate tectonics are thought to have been prominent subsequent to the breakup of Pangaea (i.e. post-Jurassic time) principally because the axes for seafloor spreading centres of late Mesozoic and Cenozoic age have not been stationary relative to any of the proposed mantle reference frames (e.g. Hamilton 2007). Thus, it has been difficult to link the seafloor spreading centres with driving forces fixed to the mantle frame (Bailey 1977). Analytical and numerical calculations have shown that subduction-based forces, such as slab pull, can contribute a much greater drive for the movement of plates than can rift-based forces, such as ridge push, when mature subduction zones exist in the terrestrial system (Forsyth & Uyeda 1975; Schellart 2004; Meyer & Schellart 2013). For these reasons, top-down plate tectonics are thought to have dominated the dispersal of Pangaea, and by extrapolation to the periods of supercontinent dispersal and (re-)amalgamation (Nance et al. 2014). Nevertheless, plumes may yet be determined to have influenced the motion and deformation of plates during the periods of supercontinent dispersal and amalgamation during the Proterozoic and Phanerozoic eons (Hynes 1990; Burke & Cannon 2013; Conrad et al. 2013; Morra et al. 2013).

Methodology

Data

In this study, three 2012 datasets are used to constrain and reconstruct the past evolution of continental lithosphere since c. 320 Ma: (1) a present-day continent or plate polygon model (Müller et al. 2008; Seton et al. 2012; Morra et al. 2013); (2) a global, rigid plate rotation model for the Phanerozoic evolution of the terrestrial continents (Seton et al. 2012; Morra et al. 2013); and (3) a global, apparent polar wander model for the Phanerozoic evolution of the terrestrial continents (Torsvik et al. 2012). Use of these datasets allows the link between past and present continental configurations to be visualized when the modern polygons are rotated in a rigid fashion (Cox & Hart 1986). The main deficiency with this approach is that rigidly reconstructed modern polygons will overlap or underlap with one another if the rotation model incorporates the past deformation of the reconstructed polygons (Gurnis et al. 2012). Although non-rigid reconstructions are available for the breakup of Pangaea and the subsequent evolution of the terrestrial plates (Gurnis et al. 2012; Seton et al. 2012), non-rigid compilations have yet to be published for the period prior to the breakup of Pangaea. This pre-breakup period is important for the present study; consequently I use the rigid reconstruction of the modern polygons for consistency and simplicity (Seton et al. 2012; Morra et al. 2013). In addition, the rigid reconstruction of the modern polygons is advantageous in the present work because the overlaps and underlaps between adjacent polygons plotted in the reconstructions provide visual cues for the amounts of extension or shortening inferred for these polygons in the underlying rotation model (Fig. 2a).

The >50 modern polygons identified by the Earthbyte group (Seton et al. 2012; Morra et al. 2013) are grouped into five macro-continental aggregate polygons applicable to the Triassic and Jurassic breakup of Pangaea (Fig. 2). The five aggregate polygons are: (1) Neo-Gondwana, which encompasses South America, Africa, India, Australia, Antarctica, and so on; (2) Cimmeria, which includes Iran and adjacent SE Asian blocks; (3) Sinoria,
(a) Pangean Geography

(b) Modern Geography
which covers Amuria, North China, South China, Indochina and so on; (4) Eurasia, which covers European and Asian blocks; and (5) Neo-Laurentia, which includes North America, Greenland and Arctic blocks (Fig. 2). The terms Neo-Gondwana, Cimmeria, Eurasia and Neo-Laurentia mostly follow previous practice (e.g. Veevers 2004); however, the term Sinoria is new. In pioneering syntheses, Cimmeria and Sinoria were implicitly included together as responsible for the complex Cimmeride Orogenic System (e.g. Şengör 1984). However, subsequent studies have restricted Cimmeria to those continental blocks responsible for forming the western branch of the original Cimmeride Orogenic System (Stampfli & Borel 2002; Golonka 2007). Sinoria is the term introduced here to identify the aggregate identity of those continental blocks responsible for forming the eastern branch of the original Cimmeride Orogenic Branch. Whereas the collision of Cimmeria with reconstructed southern Eurasia closed the Palaeo-Tethys ocean in the early Jurassic, the collision of Sinoria with reconstructed eastern Eurasia closed the Okhotsk ocean through the late Triassic and Jurassic. Treating the closure of the Palaeo-Tethys and Okhotsk oceans independently follows the views of Van der Voo et al. (1999), in which the Okhotsk Ocean is recognized to have been oriented differently than the Palaeo-Tethys in the geological past. This view departs from ideas in which

Fig. 2. (a) Palaeogeography of Earth at 240 Ma after rotation model of Seton et al. (2012), and (b) present-day polygons for Earth at 0 Ma. The five aggregate continental assemblies of Neo-Laurentia, Neo-Gondwana, Cimmeria, Sinoria, and Eurasia are indicated in different shades of grey. In the present-day reconstruction, the key constituent polygons used to constrain the past motions of the five aggregate continents during the Triassic and Jurassic are indicated with dotted fill patterns.

Fig. 3. (a) Profile view of the conceptual model of mantle-driven, active rifting and the corresponding passive subduction zones depicted in a model of whole mantle circulation with one upper and one lower plate. (b) Profile view of the conceptual model of subduction-driven, passive rifting and the corresponding active subduction zones depicted in a model of whole mantle circulation with one upper and one lower plate and one wholly progressive subduction zone (left-side) and one wholly falling subduction zone (right size).
the Okhotsk Ocean is considered to be a northern segment of the Palaeo-Tethys (Sengör 1984; Zonenshain et al. 1985; Maruyama et al. 1997; Golonka 2007). Sinorian (or SE Chinese) continental blocks appear to have shared the same motion through the Triassic and Jurassic periods in the 2012 Earthbyte compilation, thus justifying the introduction of a single term for their aggregate identity during this time (Seton et al. 2012; Morra et al. 2013).

The following convention is followed in the present work: a subduction zone and its associated orogenic belt is named after the colliding lower plate continent ultimately responsible for the closure of the associated ocean. Thus, a Sinoride Orogenic System is associated with closure of the Okhotsk ocean, which gave rise to the collision of Sinoria with Eurasia; the Cimmeride Orogenic System is associated with closure of the Palaeo-Tethys ocean, which gave rise to the collision of Cimmeria with Eurasia; and, the Indide (or Himalayan) Orogenic System is associated with closure of the Tethys Ocean, which gave rise to the collision of Cimmeria with Eurasia; and, the Indide (or Himalayan) Orogenic System is associated with closure of the Tethys Ocean, which gave rise to the collision of India with Cimmeria/Eurasia (Fig. 2a). The present-day map (Fig. 2b) identifies the individual blocks whose rotation tables are used to constrain the motion of the five aggregate macro-continental polygons (rotation data from Seton et al. 2012). Specifically, motions during the Triassic and Jurassic are constrained as follows: (1) Neo-Gondwana with the rotations of South Africa; (2) Cimmeria with the rotations of Iran; (3) Sinoria with the rotations of Amuria; (4) Eurasia with the rotations of Europe; and (5) Neo-Laurentia with the rotations of North America (Seton et al. 2012; Morra et al. 2013). This approach simplifies the analysis herein, although it neglects details in the block motions internal to each of the aggregate continental assemblies. The palaeomagnetic mantle reference frame used in the present study is derived from the recently computed apparent polar wander master path for Pangaea (Torsvik et al. 2012), as discussed in detail elsewhere (J. D. Keppie & D. F. Keppie 2014).

**Terminology**

The main technical ideas used in this paper include: (1) the concept of a first-order (rigid-plate motion) tectonic reference frame (D. F. Keppie 2014a); (2) the classic distinction of two end-member types of subduction with respect to a mantle reference frame (Fig. 3; Wilson & Burke 1972); (3) the classic concepts of active v. passive rifting and the complementary concepts of passive v. active subduction respectively (Fig. 3); (4) the concepts of meridional or axial symmetry v. zonal or equatorial symmetry in the description of rifts and subduction zones (Fig. 4); and (5) a distinction between the concepts of stage poles and net stage poles. These concepts are defined next.

Flow paths for rigid-plate motion follow small circle arcs centred about the stationary rotation pole that governs the rigid motion between two plates for a given stage of Earth history (Cox & Hart 1986). Rigid-plate motion is called first-order tectonic motion here in order to discriminate it from higher-order tectonic motions in which lithosphere moves non-rigidly (F. Keppie 2013; D. F. Keppie 2014b). A first-order tectonic reference frame is the spherical coordinate system of longitude and latitude lines defined according to the location of the rotation axis that constrains the relative plate or plate–mantle motion of interest (Fig. 4; D. F. Keppie 2014b). The familiar geographic terms of longitude, latitude, equator and north/south pole are used in analogous fashion for tectonic reference frames (Fig. 4). The word **tectonic** is used to distinguish these terms from **geographic** terms (e.g.

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**Fig. 4.** Plan view of a passive rift associated with a stationary and progressive subduction zone depicted in a model of whole mantle circulation with one stationary plate and one moving plate. The passive rift is plotted so that it is both meridionally or axially symmetrical about the (moving) rift axis and zonally or latitudinally symmetrical about the equator of the governing tectonic reference frame. The north and south tectonic poles governing the opening of the passive rift are shown with implied strike-slip connections between the ends of the passive rift and the corresponding ends of the compensatory subduction zone included as well.
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tectonic longitude and tectonic latitude). Boundaries of convergence or divergence between two adjacent plates trend parallel to lines of tectonic longitude. Boundaries of strike-slip shear between two adjacent plates tend parallel to the lines of tectonic latitude (D. F. Keppie 2014a).

The negative buoyancy of a lower plate or slab can produce two end-member types of subduction when viewed relative to the mantle reference frame (Wilson & Burke 1972). Common terminology in use links these end-members with type examples where: (1) Andean-type subduction indicates subduction in which a moving lower plate under-thrusts a stationary upper plate; and (2) Marianas-type subduction indicates subduction in which a moving upper plate over-rides a stationary lower plate. Further, the term subduction rollback appears to be used synonymously with Marianas-type subduction because the position of the hinge/trench zone is thought to migrate backwards (or towards the lower plate) as a stationary lower plate is overridden. This classic terminology is quite limiting, however, for more nuanced treatments of subduction evolution. Therefore, I introduce new terms for this classic distinction next.

I use the terms: (1) progressive subduction to indicate subduction in which a moving lower plate under-thrusts a stationary upper plate; and (2) falling subduction to indicate subduction in which a moving upper plate over-rides a stationary lower plate. I further suggest using the terms hinge or trench retreat, instead of subduction rollback, to refer to the backwards relative movement of the hinge or trench location in the context of falling subduction. The concepts of falling subduction and hinge or trench retreat should not be viewed as synonymous because these phenomena may not be coupled. Slabs can fall into the mantle such that the dip of the slab increases with time even as the hinge/trench location remains in a constant position relative to the mantle.

The new terms have the following advantages when compared with the old. First, the type of subduction that takes place at a given zone may evolve in time. Gurnis & Hager (1988) showed that young subduction zones tend to express Marianas-type or falling slab behaviour whereas older subduction zones tend to express Andean-type or progressive slab behaviour. It would appear that this evolution in behaviour is true even for the type examples of the Marianas and Andean subduction zones (Gurnis & Hager 1988; Seton et al. 2012). The new terms eliminate the awkward semantic link between the two types of subduction and the specific natural examples that accommodated both types to different degrees at different times. Second, Manea & Gurnis (2007) showed that slab dip can change depending on the rheology of material immediately above a descending slab; critically it may steepen or shallow through time. The new terminology makes it easier to speak about the time-evolving character of subduction zones. This is because the terms progressive subduction and falling subduction can be contrasted with opposing behaviour. Progressive subduction can be viewed as opposite to regressive subduction, which would indicate the slowing or reversal in motion of a previously advancing lower plate. Likewise, falling subduction can be viewed as opposite to rising subduction, which would indicate the shallowing or lift of a previously sinking lower plate. This paper lays the framework for testing some of these different possibilities in future studies of Pangaea breakup and so I introduce these new terms here.

Active rifting refers to rifting caused by mantle processes that directly underly the rift zone and push the rifting lithosphere apart (Fig. 3a), whereas passive rifting refers to rifting caused by tectonic forces delivered at peripheral subduction zones that act to pull the rifted lithosphere apart (Fig. 3b) (Fried 1967; Turcotte & Emerman 1983). Active rifting is compensated for by passive subduction, in which a lower plate is pushed under an upper plate as a consequence of the active rifting (Fig. 3). Passive rifting arises as compensation for active subduction in which a lower plate is pulled under an upper plate owing to its own negative buoyancy (Fig. 3).

The terms meridional symmetry or axial symmetry are used to identify rifts or shortening zones that are symmetrical about a central line of tectonic longitude (Fig. 4). Seafloor spreading centres are typically meridionally asymmetrical and subduction zones are typically meridionally asymmetrical in classic treatments of plate tectonic theory (McKenzie & Morgan 1969). The terms zonal symmetry and equatorial symmetry are used to identify rift (or shortening) zones that are symmetrical in a latitudinal sense about the tectonic equator corresponding to the relative stage pole (Fig. 4).

The terms stage pole and net stage pole are used as follows. A stage pole corresponds to a finite rotation inferred to have governed the exact motion between two plates for a given interval of time based on geological data. A net stage pole corresponds to finite rotations calculated from a global plate rotation model for an arbitrary interval of time. Thus, a net stage pole many not correspond to an exact relative plate motion, but instead represents an average of the component motions for the time interval used to make the stage calculation.

Mechanical models

In this study, two end-member mechanical regimes are tested for a contribution to the breakup of
Pangaea: (1) the mantle-based, bottom-up mechanical regime (e.g. Bercovici 2003; Dziewonski et al. 2010; Nance et al. 2014), and (2) the subduction-based, top-down mechanical regime (e.g. Anderson 2001; Hamilton 2007; Aitken et al. 2013).

The tested regimes are conceptual and correspond to abstract simplifications of corresponding mechanisms described in the analytical, numerical and analogue modelling literature. Superplumes, plumes or stable mantle convection cells are seen as default mantle-driven breakup mechanisms. The test of mantle-based mechanisms made here assumes that the driving forces are stationary in the mantle frame and are capable of delivering upward- and outward-directed forces to the overlying lithosphere that could be pushed apart (Fig. 3a). Falling slabs are seen as the likely subduction-driven breakup mechanism for Pangaea. This is because Africa was relatively stationary during the Jurassic in a palaeomagnetic reference frame and the Tethyan subduction zones linked to Atlantic rifting dipped under southern Eurasia (Dewey et al. 1973; Şengör 1984; Scotese 1991; Van der Voo et al. 1999; D. F. Keppie 2015). Progressive subduction may have become important as well as the breakup progressed. The test of subduction-based mechanisms made here assumes that slabs can progress or fall into the mantle and this could pull adjacent lithosphere inwards and downwards above the subduction zone (Fig. 3b).

For the mantle-based mechanisms, active rift zones are predicted to be both meridionally and zonally symmetrical (Fig. 4) and the start of active extension and rifting is expected to pre-date the start of compensatory passive subduction. For the slab-based mechanisms, passive rift zones are predicted to be either meridionally symmetrical and moving in a mantle reference frame, or stationary and meridionally asymmetrical (Fig. 3b). Passive rifting is expected to span a zonal range of latitude that is equivalent to the zone spanned by the causal active subduction zone. Zonal symmetry is not expected for passive rifts. The start of active shortening and subduction is expected to pre-date the start of the compensatory passive extension and rifting. Active progressive subduction is predicted to produce passive rifting in the lower plate, whereas active falling subduction is predicted to produce passive rifting in the upper plate (Fig. 3b).

These predictions are consequences of assuming the conservation of area over the surface of Earth (Hallam 1984).

**Evaluation methods**

**Mantle-based mechanism.** The potential influence of a mantle-based mechanism in the breakup of Pangaea is evaluated using a set of palaeogeographic reconstructions for Pangaea and its daughters from 275 to 100 Ma in 25 Ma increments, on which are plotted a possible breakup-causing point of mantle upwelling in the palaeomagnetic mantle reference frame (red dot in Fig. 5a–h). The chosen upwelling location is one that would have lain underneath the central Atlantic region near the Carolinas of the USA at c. 203 Ma. This reconstruction series provides a qualitative view for how Pangaea moved relative to the underlying mantle and relative to one possible location for the top of a mantle convection cell, plume or superplume. The initial reconstruction series also provides a reference for the general breakup of Pangaea and its daughter plates in a familiar projection scheme (Dewey & Bird 1970).

The locations of two net stage poles are calculated for the periods of time from 200 to 180 Ma and from 180 to 160 Ma (Fig. 6). These net stage poles correspond to the divergence of North America from Africa across the central Atlantic during the early breakup of Pangaea. The initial extension age for the breakup of Pangaea is inferred to be 203 Ma (Seton et al. 2012). However, a 200 Ma start age for the initial rifting is adopted here and this choice does not introduce significant differences to the relative motion calculations. The terrestrial palaeogeography is reconstructed for the end age of each stage in projections about the net stage pole locations with Neo-Gondwana held stationary (Fig. 6). These projections allow the identification of the net meridional and zonal symmetry of the central Atlantic rift during each corresponding stage.

The meridional symmetry of rifting across the central Atlantic rift can be inferred for successive points along the rift trace. For each point, a velocity triangle is constructed for the relative net motions of adjacent elements in the Neo-Laurentia/Neo-Gondwana/mantle plate circuit (McKenzie & Morgan 1969). The sides of the velocity triangles correspond to small circle arc segments taken about the net stage rotation axes for each successive pair in the tectonic circuit. In Figure 6, the poles and arcs: (1) for the net stage motion between Neo-Laurentia and Neo-Gondwana are given in yellow; (2) for the net stage motion between Neo-Laurentia and the mantle are given in orange; and (3) for the net stage motion between Neo-Gondwana and the mantle are given in blue. The central Atlantic rift is meridionally symmetrical above a stationary position in the mantle reference frame, if a line of tectonic longitude (i.e. a straight line radial from the projection centre) both bisects the Neo-Laurentia/Neo-Gondwana arc (arc plotted in yellow) and is coincident with the relative motion of the underlying mantle reference frame (the vertex of the triangle formed where the orange and blue arcs intersect). The zonal span and symmetry
of the central Atlantic rift can be estimated directly by noting the tectonic latitudes of the central Atlantic rift axis at its western (Caribbean) and eastern (Atlantic Canadian) limits (Fig. 6). The tectonic latitudes for the rift ends give the boundaries for the zone of tectonic latitude spanned by the rift zone as a whole (Fig. 4).

**Subduction-based mechanism.** The potential influence of subduction-based mechanisms in the breakup of Pangaea is evaluated using a set of palaeogeographic reconstructions for Pangaea and its daughters from 230 to 150 Ma in 10 Ma increments in a series of successive tectonic reference frames (Fig. 7a–i). The tectonic reference frame used in each figure is centred on the stage rotation axis for the motion of Neo-Gondwana (or Pangaea prior to breakup) relative to the mantle for the 20 Ma time interval preceding the reconstruction age. For each reconstruction, the palaeogeography of the whole Earth is shown using two adjacent, complementary hemisphere projections. Left projections show the palaeogeography of Earth for the hemisphere of tectonic latitude centred on the first surface-piercing point of the tectonic axis. Right projections show the same palaeogeography for the opposite hemisphere of tectonic latitude centred on the opposite surface-piercing point of the tectonic axis. Net motions can be inferred directly from these reconstructions because the palaeogeography of Earth is plotted both for the start ages (red polygons) and the end ages (green polygons) of the corresponding stages.

The motion of Neo-Gondwana (and Pangaea prior to breakup) relative to the mantle is parallel to the circular lines of latitude in these reconstructions. Neo-Gondwana moves in a clockwise fashion in the left projections and counter-clockwise in the right projections. Neo-Gondwana thus moves upwards through the edges and downwards through the middle parts of the two hemisphere projections when viewed together. Continents are reconstructed with arbitrary amounts of rotation about the tectonic stage poles so that the leading margin of Pangaea lay in the middle parts of the paired projections. Thus, the leading margin of Pangaea is presented as moving down through the middle parts of the reconstructions shown in Figure 7a–i. Hypothetical subduction zones that could have been associated with the leading margins of Pangaea are coloured to allow their distinction. Subduction responsible for the closing Okhotsk and Arctic Panthalassa oceans is given in dark blue, that for the closing of the Palaeo-Tethys ocean in blue and that for the closing of the Tethys ocean in cyan.

The two net stage poles from Figure 7 are then re-used to show the balance between central Atlantic opening and peripheral ocean closure in the tectonic reference frames governing North America–Africa divergence between 200 and 180 Ma (Fig. 8) and 180–160 Ma (Fig. 9). This approach has been explained elsewhere (D. F. Keppie 2015). Briefly, net strain estimates for each of the main plate boundaries are constructed for each stage and superimposed on the palaeogeography. Reconstructions of strain are limited here to the 60° of tectonic latitude about the net stage axis. Net strain estimates are constructed by taking a line of tectonic longitude and rotating it about the net stage pole location by the finite amount inferred for the given stage. The resulting polygons provide a simplified picture of the strain predicted for the given margin over the given stage period. Segments of the 30° tectonic latitude line are rotated with the motion of the corresponding intersecting plate as well to show how much lithosphere moved into or out of the plotted area during the stage period. Net flow of lithosphere into or out of the plotted area must ultimately be balanced by shortening or extension outside the plotted area, but investigation of this deformation is outside the scope of the present study.

Several reconstruction conventions have been adopted here. Plotted reconstruction series increment in 10 and 25 Ma time steps. Net stage poles used to constrain successive stage reconstructions are calculated using a constant stage interval of 20 Ma, however. The use of 20 Ma for the calculation of net stage poles represents a compromise between: (1) a stage period of sufficient brevity that it approximates geologically instantaneous relative motion; and (2) a stage period of sufficient duration that the net finite motions can be easily visualized. Various choices of stage period were tested in the preparation of this paper and 20 Ma identified as an adequate compromise between these two priorities. The main conclusions are not dependent on the exact stage size used. Reconstruction plots are labelled with a header that includes the base reconstruction age and the tectonic element held stationary in brackets. The palaeomagnetic mantle reference frame is called the Pangaea Pole.

**Results**

The palaeogeographic reconstructions in Figure 5a–h show how Pangaea moved with respect to a possible breakup-causing mantle upwelling before, during and after its breakup. Pangaea moved principally to the north in a palaeomagnetic mantle reference frame prior to the start of breakup between c. 280 and 203 Ma. A zone of mantle upwelling would have appeared to track to the south under North America. After c. 203 Ma, a zone of mantle upwelling would have appeared to track to the SW roughly parallel to the trace of the central
Fig. 5. Palaeogeography of Earth from 275 to 100 Ma plotted in 25 Ma time-steps with a palaeomagnetic mantle reference frame (i.e. Pangaea Pole) held stationary after Seton et al. (2012) and Torsvik et al. (2012). Potential position of a zone of mantle upwelling that would have been located beneath the central Atlantic rift zone in the latest Triassic is plotted as a red dot. Continental blocks are shaded according to the conventions of Figure 2.
Atlantic rift. After c. 160 Ma, a zone of mantle upwelling would have appeared mostly fixed to the NW margin of NW Africa.

Figure 6 provides an analysis of the kinematic boundary conditions governing the breakup of Pangaea from c. 200 to 160 Ma. Reconstructions are plotted in stereographic projections of the tectonic reference frames corresponding to Neo-Laurentia/Neo-Gondwana relative motion in the 200–180 Ma stage (Fig. 6, top) and in the subsequent 180–160 Ma stage (Fig. 6, bottom) with Neo-Gondwana held stationary. Figure 6 shows that the early extension in the central Atlantic took place about relative stage poles located in reconstructed southern Europe (Ruiz-Martinez et al. 2012; D. F. Keppie 2015). Velocity closure triangles for the Neo-Laurentia/Neo-Gondwana/mantle circuit are superimposed on the reconstructions in Figure 6 for selected points near Nova Scotia, Carolina and Texas. These velocity closure triangles allow assessment of the symmetry of central Atlantic rifting.

The calculated velocity closure triangles prove that the central Atlantic did not extend or open in a meridionally symmetrical fashion above a stationary position in the mantle. This is because lines of tectonic longitude cannot be constructed that both bisect the Neo-Laurentia and Neo-Gondwana relative motion (corresponding to the yellow edge in the closure triangles) and coincide with the relative motion of the mantle under these points (corresponding to the velocity vertex where the orange and blue edges intersect). For the 200–180 Ma stage, both Neo-Laurentian and Neo-Gondwanan margins of the central Atlantic rift zone continued to move NE over the mantle at all of the selected points (Fig. 6, top). For the 180–160 Ma stage, only the velocity closure(s) for position(s) near offshore Carolina correspond to meridional symmetry (Fig. 6, bottom). However, this symmetry is not retained to the NE or SW along the central Atlantic rift trace. The local motion of Neo-Gondwana and the mantle were similar at the Caribbean end of the central Atlantic rift (for position(s) near offshore Texas), whereas the local motions of Neo-Laurentia and the mantle were similar at the Canadian end of the central Atlantic rift (for position(s) near offshore Nova Scotia).

The calculated locations of relative Neo-Gondwana/Neo-Laurentia stage poles also indicate that the central Atlantic rift also was not zonally symmetrical (D. F. Keppie 2015). This is explicit in Figure 6 because most of the trace of the central Atlantic (and proto-Caribbean) rift zone lies polewards of the 30° lines of tectonic latitude for both the 200–180 and 180–160 Ma stages. A feature fixed to the mantle frame under the central Atlantic could not have been equatorial or zonally centred with respect to the rift breakup of Pangaea.

The palaeogeographic reconstructions in Figure 7a–i show how Pangaea moved with respect to retreating Eurasian margins in the palaeomagnetic mantle reference frame between 230 and 150 Ma. These reconstructions show the change in position of the continental lithosphere from the start time of a given 20 Ma stage of Earth history (red-bounded polygons) to the end time of the same stage (green-bounded polygons). These reconstructions show that the margins of Pangaea would have accommodated trench retreat along the Okhotsk and Arctic Panthalassa margins of Eurasia during the Triassic and along the Palaeo-Tethys and Tethys margins of Eurasia during the Jurassic. This change in the locus where trench retreat is inferred corresponds to changes in the relative location of the Neo-Gondwana/mantle stage poles. Neo-Gondwana (and Pangaea previously) was moving along a non-rigid path when the breakup occurred and continued to move towards the retreating margins of Eurasia throughout the Jurassic. Neo-Laurentia, Eurasia and Neo-Gondwana were all over-riding the Tethyan slabs during this time. Neo-Laurentia and Eurasia were advancing towards Tethys at a faster rate than Neo-Gondwana when the breakup started. Sinoria and Cimmeria microplates collided with the eastern and southern margins of Eurasia during this time (Figs 5–9).

Figures 8 and 9 display the compensatory relationship between closure of the Tethyan domain...
and the early opening of the central Atlantic (D. F. Keppie 2015). The balance between Tethyan closure and early Atlantic opening is evident because the relative rotation pole governing Tethyan closure lay in almost the same location as the relative rotation pole governing the early Atlantic opening. For the 200–180 Ma stage, final closure of Palaeo-Tethys compensated for the opening of the central Atlantic (Fig. 8), whereas for the 180–160 Ma stage, initial closure of Tethys compensated for the further opening of the central Atlantic (Fig. 9). The zonal symmetry of Palaeo-Tethyan/Tethyan closure was also almost exactly conjugate to the zonal symmetry of the early Central Atlantic in both stages, albeit about stage poles in slightly different locations (Figs 8 & 9). The zone of tectonic latitude spanned by the central Atlantic rift between its western Caribbean and eastern Canadian ends was almost equivalent to the zone of tectonic latitude spanned by the closing Palaeo-Tethys and Tethys domains between their eastern Iranian and western Alpine limits, respectively.

Discussion

Figures 5–9 illustrate and quantify the breakup of Pangaea and the correlative opening of the central Atlantic from different perspectives. These perspectives inform whether the breakup of Pangaea can be linked to slab-based (Hynes 1990) or mantle-based (Dalziel et al. 2000) driving mechanisms.

One observation is that Neo-Laurentia and Eurasia extended and broke away from Neo-Gondwana in the latest Triassic and early Jurassic, even as Neo-Gondwana continued to follow Neo-Laurentia and Eurasia towards the retreating margins of Eurasia (Hynes 1990; Figs 5a–h & 7a–i). The motion of Neo-Gondwana followed a non-rigid path through the period when breakup took place (Fig. 7a–i). There are two end-member ways that such non-rigid motion could have been accommodated at the surface of Earth: (1) all plate boundaries for Pangaea could have changed in the style and amount of deformation required to accommodate the different movements of a rigid supercontinent; or (2) the supercontinent could have deformed to accommodate the non-rigid motion. The second scenario appears likely because we have inferred the breakup of Pangaea from the geological record (Seton et al. 2012).

Slabs falling into the mantle at different rates through time under the different margins of Pangaea provide a direct mechanism that could influence the motion of Pangaea as a whole in a mantle reference frame. A hypothetical evolution in the way slabs fell through time at the margins of the supercontinent could explain why pull forces acting on Pangaea evolved through time as well. This hypothetical evolution in pull forces could explain why Pangaea moved in a non-rigid path and ultimately broke up. In this scenario, the rise of asthenosphere and emplacement of a large igneous province linked to a breakup event would post-date the onset of non-rigid motion and thinning of the continental lithosphere. Central Atlantic Magmatic Province emplacement has been inferred to post-date the onset of extensional rifting in the case of the central Atlantic (McHone 2000), which would be consistent with tectonic processes driving the breakup of Pangaea.

In the mantle-driven scenario, however, a zone of mantle upwelling beneath central Pangaea could explain the breakup but would not appear to provide an explanation for the change in the motion of the supercontinent. Additional processes may need to be included to model the full evolution of the lithosphere during this period of Earth history. Mantle-driven breakup models need to address why the central Atlantic rift was neither stationary nor symmetrical in the mantle frame and why Pangaean lithosphere as a whole continued to move in the same general direction during breakup as well.

Slab-driven models (e.g. Hynes 1990; Stampfl & Borel 2002; Collins 2003) are potentially simpler than mantle-driven models for explaining the breakup of Pangaea because slab-driven models provide a single explanation for both the motion...
Fig. 7. Continued.
Fig. 7. Continued.
Fig. 8. Palaeogeography of Earth at 180 Ma is plotted in the stereographic projection of the tectonic reference frame governing the net clockwise rotation of Neo-Laurentia away from Neo-Gondwana during the 20 Ma stage period immediately preceding the reconstruction age with Neo-Gondwana held stationary. Continental blocks are depicted with the conventions of Figure 2. The deformation balance within the surface area spanned by the 60° of tectonic longitude about the central governing stage rotation pole is shown. The earliest extension in the central Atlantic region is shown to be balanced by the final closure of the Palaeo-Tethys Ocean between western Cimmeria (i.e. Iran) and Eurasia. The western margin of North America is shown to be parallel to lines of tectonic latitude during this stage; subduction along the western margin of North America could not have been compensatory for any of the initial extension in the Atlantic domain. Stage rotation poles governing the central Atlantic extension and the palaeo-Tethys closure lie in reconstructed southern Europe (i.e. Iberia), which precludes a direct connection of a propagating rift between the Atlantic and Alpine or Tethyn realms. Instead, the Atlantic and Alpine/Tethyn realms could have been connected via a sinistral strike-slip zone that curved along the southern margin of Europe and the northern margin of Africa (D. F. Keppie 2015). The earliest extension in the central Atlantic region is shown to share a similar zonal symmetry between the 30 and 80 lines of tectonic latitude about a stage pole similar to that governing the final closure of the palaeo-Tethys.
Fig. 9. Palaeogeography of Earth at 160 Ma is plotted in the stereographic projection of the tectonic reference frame governing the net clockwise rotation of Neo-Laurentia away from Neo-Gondwana during the 20 Ma stage period immediately preceding the reconstruction age with Neo-Gondwana held stationary. Continental blocks are depicted with the conventions of Figure 2. The deformation balance within the surface area spanned by the 60° of tectonic longitude about the central governing stage rotation pole is shown. The rift-to-drift extension in the central Atlantic region is shown to be balanced by early closure of the Tethys Ocean between Neo-Gondwana and Eurasia. The western margin of North America is shown to be roughly parallel to lines of tectonic latitude during this stage; subduction along the western margin of North America could not have been compensatory for much of the mid-Jurassic extension in the Atlantic domain similar to the situation shown in Figure 8.
and deformation of Pangaea in the mantle frame. A switch in the locus of trench retreat, from being along the northern Eurasian margin during the Triassic to being along the southern Eurasian margin during the Jurassic, may have caused the breakup of Pangaea based on the calculations reported here. This switch would have depended on the evolving negative buoyancies of the Arctic Panthalassan/Okhotskian and Tethyan slabs with respect to each other and the regions of mantle accommodating the descending slabs. Parameters such as slab age, upper mantle temperature and lower mantle strength might be expected to modify the buoyancy of the different slabs through time. This could be tested in future studies.

Another observation is that the diachronous collisions of Sinoria and Cimmeria with Eurasia took place through the period of time when Pangaea broke apart. The closure of the intervening oceans probably involved the loss of subduction and any associated tectonic forces at the corresponding margins. Loss of subduction-derived forces along particular segments of Pangaea may have led to changes in the motion of Pangaea as well. If an Okhotskian slab (dipping under the eastern margin of Pangaea) was continuous with the Arctic Panthalassan slab (dipping under the northern margin of Pangaea), then the closure of the Okhotsk Ocean between Eurasia and Sinoria could have lessened the tectonic forces delivered to Pangaea owing to subduction along its northern margins. The collision of Sinoria (and to a lesser extent Cimmeria) with Eurasia could have been responsible for diverting Pangaea into a non-rigid motion that triggered the failure of the supercontinent.

The balance evident between the early opening of the Atlantic domain and the closure of the Palaeo-Tethyan and Tethyan domains provides further context (Figs 8 & 9; D. F. Keppie 2015). The fact that this balance is best revealed in the relative plate frames rather than in the mantle frame supports the hypothesis of a subduction-based breakup mechanism. The mechanical links appear to be independent of the mantle frame and may indicate that the mantle played a subordinate role in the breakup. The opening of the Atlantic domain and the closure of the Tethyan domains not only share almost the same governing relative stage rotations, but deformation along these boundaries also spans the same zone of tectonic latitude. This link between the geometry of a pre-existing subduction zone (i.e. Palaeo-Tethys/Tethys) and a new rift (i.e. central Atlantic) is most likely if subduction drove rifting.

Neo-Gondwana and Neo-Laurentia may have rifted apart across the central Atlantic owing to partial exploitation of suture zones preserved from their earlier amalgamation in the late Palaeozoic.

Fig. 10. The supercontinent cycle showing the time spans for which the inferred Columbia, Rodinia, Pannotia and Pangaea supercontinents existed at the surface of Earth (Nance et al. 2014). The hypothesis that the driving mechanisms of plate tectonics might have been governed by top-down plate tectonics throughout all stages of the supercontinent cycle is portrayed (blue).
PAST SUPERCONTINENT CYCLES COULD HAVE BEEN GOVERNING A KEY ROLE PLAYED BY TOP-DOWN PROCESSES IN THE BREAKUP OF PANGAEA. BY ANALOGY WITH PANGAEA, IT SEEMS POSSIBLE TO HYPOTHESIZE THAT ALL PHASES OF SUBDUCTION-BASED MECHANISMS FOR THE BREAKUP OF PANGAEA BETWEEN 625 MA AND 555 MA: NEW EVIDENCE AND IMPLICATIONS FOR CONTINENTAL BREAK-UP ALONG SUTURES? HOW SUBDUCTION BROKE UP PANGEA

Conclusions

This paper shows that a mechanism able to explain the non-rigid motion of Pangaea through the Triassic and Jurassic periods is sufficient to explain its initial breakup. An expected influence from falling slabs under the Arctic Panthalassan margin of Eurasia in the Triassic and under the Tethyan margins of Eurasia in the Jurassic provides the simplest hypothesis for this mechanism. The approximately synchronous collisions of Sinoria and Cimmeria with Eurasia in the latest Triassic and early Jurassic may have triggered the changes in the motion of Pangaea and its subsequent failure. This study supports the view that slab-driven mechanisms provide the simplest explanation of the available constraints (D. F. Keppie 2015). Mantle-driven breakup mechanisms, by contrast, are inconsistent with some of the kinematic data, are unnecessary to explain the deformation of the supercontinent, and do not readily explain the non-rigid path followed by Pangaea before, during and after its breakup.

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