Self-subduction of the Pangaean global plate

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One of the most striking and rare occurrences in the Earth's history is the amalgamation of most of the continental lithosphere into one supercontinent. The most recent supercontinent, Pangaea, lasted from 320 to 200 million years ago. Here, we show that after the continental collisions that led to the formation of Pangaea, plate convergence continued in a large, wedge-shaped oceanic tract. We súggest that plate strain at the periphery of the supercontinent eventually resulted in self-subduction of the Pangaean global plate, when the ocean margin of the continent subducted beneath the continental edge at the other end of the same plate. Our scenario results in a stress regime within Pangaea that explains the development of a large fold structure near the apex of the Palaeotethys Ocean, extensive lower crustal heating and continental magmatism at the core of the continent as well as the development of radially arranged continental rifts in more peripheral regions of the plate.

Supercontinent cycles involve the repeated amalgamation and subsequent break-up of continental lithosphere and are a fundamental aspect of the Earth's evolution. Despite its importance, however, the overall geodynamic regime responsible for supercontinent cycles remains poorly understood. The most recent supercontinent, Pangaea, existed from the mid-Carboniferous (about 320 Myr ago) until the Upper Triassic period (about 200 Myr ago) and its assembly and dispersa! profoundly influenced the Earth's recent evolution.

Processes responsible for the initiation of Pangaea rifting, before the onset of Early Jurassic break-up, remain a subject of debate. Several models have been postulated, for example: (1) post 'Variscan-Alleghenian' orogenic collapse2 4, (2) dispersal above a mande superplume[5,6] linked to the effects of supercontinental heat insulation[7] or (3) a combination of different mechanisms [8]. However, all models fail to explain (at least) the three large-scale tectonic phenomena that followed the assembly of Pangaea and set the tectonic framework for its subsequent break-up and dispersa!: (1) the opening of the Neotethys Ocean and the genesis of the Cimmerian ribbon continent[9]-u , (2) the short-lived Early Permian large thermal anomaly that affected most of the interior of Pangaea [12], and which included opening of radial rift basins containing abundant alkalic magmatic rocks, and (3) the development of a continental-scale orocline at the centre of Pangaea (the Cantabrian or Iberian-Armorican arc[13]).

Here, we hypothesize a global-scale geodynamic connection between these phenomena, and propose a kinematic model that accounts for the global tectonic processes that took place immediately after Pangaea assembly[14]. We postulate that, under the appropriate conditions, a non-rigid supercontinental plate can subduct beneath itself (a process hereafter termed 'self-subduction'), leading to rapid changes in stress-strain configurations within its predominantly continental lid. Self-subduction can explain the sudden changes in tectonic regimes that led to Pangaea's break-up and dispersal. We hypothesize that self-subduction was initiated by subduction of a spreading ridge beneath the northern active margin of Palaeotethys, the wedge-shaped oceanic tract within the Pangaean supercontinental plate (Fig. 1). The resulting change in the stress-strain state[13,1]s-17 provides a mechanism for the formation of numerous, mostly extensional (rift-related) or transtensional (pull-apart) basins throughout the Pangaea plate. One such basin evolved into a new ocean, the Neotethys, giving rise to the Cimmerian ribbon continent, which now forms parts of modern Turkey, Iran and Tibet. The ribbon continent rifted from Pangaea, terminating the Pangaean self-subduction process[9 1 20].

The self-subduction model presented here relies on recent advances in the geochronologic (absolute) and stratigraphic timescales around the Upper Pennsylvanian-Permian boundary2 [1]. These advances have been fundamental as they enable, for the first time, the precise correlation of sedimentary, plutonic and metamorphic events that were previously thought to be unrelated and thus assigned to different independent tectonic events.

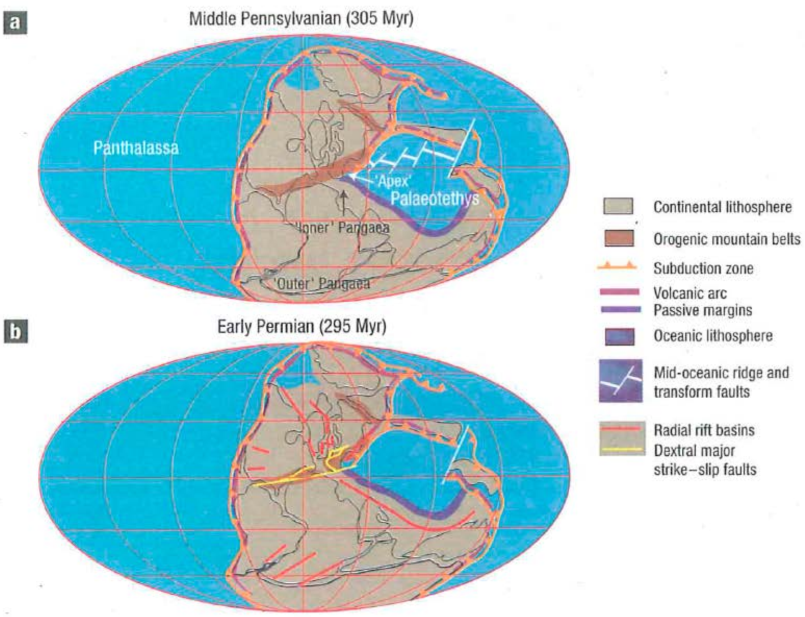

Figure 1 Pangaea configurations during the late Palaeozoic era. a,b, The main geologic features and the relevant geographic references discussed in the text in the Middle Pennsylvanian **(a)** and the Early Permian **(b).** Black lines representing present-day continental coastlines are far reference only. Reconstructions based mostly on refs 12,19,20.

SUPERCONTINENT CONFIGURATION

A supercontinent develops when amalgamating fragments of continental lithosphere are effectively welded together along orogenic sutures into a single large plate. Such a plate is made up almost entirely of continental lithosphere bounded totally[22] or partially'[3] by Andean-type subduction zones However, owing to the irregular shapes of the accreted lithospheric fragments, this plate may also contain large wedge-shaped tracts of oceanic lithosphere attached to the supercontinent that extend into the ocean until bordered by an oceanic ridge (Fig. la).

The Pangaean supercontinent (Fig. la, b) amalgamated during the late Palaeozoic era as a consequence of collisions between Gondwana (Africa, South America, India, Australia and Antarctica), Laurussia (North America and northern Europe) and a set of other terranes with associated subduction-related volcanic areas (Siberia and Kazakhstan). These collisions produced the Variscan-Appalachian (Alleghenian)-Ouachitian [22,24] and the Uralian orogenic belts. Several smaller continental blocks remained around the periphery of Pangaea (for example, North and South China blocks). Pangaea was circular in shape, and it was partially[23] surrounded by subduction zones, and enclosed a large eastward-opening wedge-shaped ocean, (Palaeotethys, Fig. 1). This ocean, which was probably a remnant of the partially closed Rheic and/or Their oceans[9,10], was divided into two plates: (1) a northern plate of oceanic lithosphere boulld to the south by a mid-ocean ridge and to the north by a subduction zone that dipped north beneath northern Pangaea[25,26], and
(2) a much larger plate comprising the southern part of the Palaeotethys and the whole of continental Pangaea (Fig. la). The northern convergent and southern passive margins of Palaeotethys, which both lay within the Pangaean plate, and the Palaeotethyan mid-ocean ridge ali ended together close.. to or in a Euler pole located at the apex of the Palaeotethys Ocean where it pinched out to the west. Consumption of the northern oceanic plate in the Palaeotethys Ocean by northward-directed subduction eventually brought the mid-ocean ridge to the trench. The ensuing ridge subduction is recorded in the Upper Pennsylvanian-Early Permian Meliata rift (as documented in the Hellenides, Greece[25], and the Carpathians[26]). Continued subduction following ridge collision resulted in self-subd uction of Pangaean oceanic lithosphere to the north beneath the northern Pangaean continental lithosphere and the 'slab pull' of the downgoing oceanic lithosphere was responsible for the deformation of continental Pangaea. The period of self-subduction extended from about 300 Myr ago, the age of Meliata rifting, until the Middle Permian (270-265 Myr ago), when the Cimmerian ribbon continent rifted from the northern mal-gin of southern Pangaea, and the geodynamic connection across Palaeotethys was severed at the mid-ocean ridge of the newly formed Neotethys Ocean. The new northern plate created by rifting included, from south to north, the oceanic lithosphere of the northern Neotethys Ocean, the Cimmerian ribbon continent and the remaining Palaeotethys oceanic lithosphere. South of the Neotethys ridge, the oceanic lithosphere of the Neotethys formed part of the Pangaean plate.

LARGE-SCALE TECTONIC FEATURES OF UPPER PENNSYLVANIAN-LOWER PERMIAN PANGAEA

Many of the enigmatic aspects of the Upper Pennsylvanian-Ea rly Permian thermal . and tectonic evolution of Pangaea can be explained by processes that occurred during or immediately following self-subduction of the Pangaean plate. Upper Pennsylvanian-Lower Permian rift basins are widespread in Pangaea, and, with few exceptions, record intense igneous activity[12] that started at the Carboniferous-Permian boundary (about 300 Myr ago) and terminated abruptly at the end of the Lower Permian (about 270 M,yr ago; timescale of Gradstein *et al.*[21]). The magmatism and its related thermal anomaly are recognized worldwide but are best documented in western Europe, including the Alps[12]. This thermal-tectonic event has, in the past, been linked to the collapse of the Alleghenian-Variscan-Ouachita belt[4]. However, by the Upper Pennsylvanian, the main Variscan architecture, including modifications attributable to its complete orogenic collapse, was already well established [3]. The magmatism and rifting have also been attributed to a superplume event3[3], but geochemical data from Lower Permian volcanic rocks in the northern European realm argue against the involvement of a mantle plume[34,35] and mantle melting could be related to lithospheric stretching and necking at a boundary with thicker lithosphere[36]. The restricted age of igneous activity (between 305 and 280 Myr ago) mandates a short-lived thermal pulse, which is also incompatible with a superplume event[37].

A further manifestation of this intense tectonothermal event is the almost ubiquitous presence of a Late Carboniferous-Permian unconformity in widely separated basins throughout Pangaea[38, 39]. In most of these basins there is also a hiatus, or paraconformity, at the Lower-Middle Permian boundary. We propose that both unconformities reflect global changes in the tectonic stress-strain pattern in Pangaea related to initiation and subsequent termination of self-subduction of the Pangaean plate.

UPPER PENNSYLVANIAN-LOWER PERMIAN LITHOSPHERIC FEATURES

Lithospheric-scale structures that developed in Pangaea during the Upper Pennsylvanian-Lower Permian can be subdivided according to their kinematic history and location (Fig. 1). The nature and distribution of these structures reflect an abrupt change in the supercontinent's stress-strain state and are best explained as recording the onset of Pangaean self-subduction. For convenience, we first discuss structures in the interior of Pangaea (adjacent to the 'apex' of the Palaeotethys Ocean) and then those in outer Pangaea (Fig. la).

Compressional lithospheric features. In the core of Pangaea, class to the apex of the Palaeotethys Ocean, is the Cantabrian or Iberian-Armorican are, which is interpreted as an orocline [12]. Orocline formation resulted from a marked change in regional stress directions that caused a portian of the almost linear Variscan-Appalachian- Ouachita orogenic belt to buclde nearly 180º around a vertical axis[13]. The orocline is especially tight in the Cantabrian Zone of the western European Variscan orogen. Within its core, orocline development was accommodated by shortening of the upper crust (Fig. 2), whereas shortening at deeper levels produced an unstable thickened lithospheric root. This root subsequently delaminated giving way to asthenospheric upwelling and heat influx into the crust, thereby providing an explanation for the voluminous Late Variscan, about 300-280 Myr ago, magmatism in the region affected by oroclinal development3°.4°. This tectonothermal event re-equilibrated the lower crust near the apex of the Palaeotethyan Ocean[41].4[2].

Transtensional lithospheric features. Upper Pennsylvanian-Lower Permian transtensional lithospheric-scale structures in the inner part of Pangaea consist almost exclusively of dextral continental strike-slip faults[43].4[4] that lie just outside the Iberian-Armorican orocline core (farther from the Palaeotethys Ocean apex, Figs 1b and 2). Most of the fault traces are curved parallel to the orocline, suggesting accommodation of vertical axis rotations by flexural slip. The less curved faults transect the southern limit of the Iberian-Armorican orocline and probably compensated for buckling in a fold-hinge fault fashion. Restoration of slip along these latter structures brings the Variscan belt into continuity with the Moroccan and North American Variscan-Appalachian belts[45] (Figs l and 2). Many of these faults, which are hypothesized to affect the entire líthosphere4[6], are transtensional, and produced spatially and genetically related Upper Pennsylvanian-Lower Permian basins filled wíth continental sedimentary and alkaline volcanic rocks[47].

Extensional lithospheric-scale structures. Numerous Lower Permian rift basins that contain abundant volcanic rocks are distributed in a radial pattern throughout outer Pangaea and are focused on the apex of the Palaeotethys (Fig. 1b). One example is the Oslo Rift, which consists of at least three majar segments formed during dextral wrench faulting[48]. Its broadly north-south orientation was in part controlled by pre-existing lithospheric structures-'[6].4[9]. The mode of rupturing may also have been affected by the concurrent development of significant rifts in the ancestral North Atlantic Ocean and Barents Sea[50]. The distribution of radial rifts is consistent with tangential longitudinal stretching of outer Pangaea, coeval with shortening in the inner are of inner Pangaea. All of these structures developed during the brief interval of Pangaean self-subduction (Fig. 2).

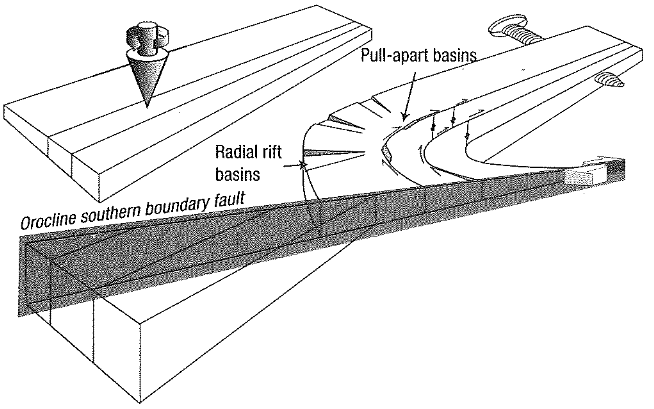

Figure 2 Conceptual model showing lithospheric buckling around a vertical axis. Schematic diagram showing the relation between (1) orocline bending, (2) strike-slip dextral faulting and related transtensional basins and (3) radial basin formation in the aftermath of the Variscan-Appalachian orogenic event. Far clarity, no lithospheric thickness changes are shown, although they are likely to have occurred[27].

THE HYPOTHESIS

The genesis of supercontinental-scale structures formed early during the Pangaea's lifespan can be accounted for with a simple model of self-subduction of the oceanic portian of a superplate. Self-subduction produced a marked change in stress-strain patterns affecting the entire Pangaean plate (Fig. 3). Once the Palaeotethyan mid-ocean ridge was subducted[25, 26] (Fig. 3a,b), the oceanic (Palaeotethyan lithosphere) part of the Pangaean plate began to self-subduct beneath the Laurussian portian of the Pangaean supercontinent along the northern margin of the Palaeotethys Ocean. Continuity of the subducting oceanic portian of the superplate with the passive margin along its trailing edge[18] (the northern Gondwanan margin of Pangaea) meant that the subduction-related slab pull was transmitted into continental Pangaea. The result was a complete shift in the stress regime within the Pangaean plate.

In general, the mechanical response of the Pangaean continental lithosphere is in agreement with the principles of tangential-longitudinal strain[40], which imply shortening in the inner are and coeval extension in the outer are during rigid-body rotation (Figs 2 and 3d). The Euler pole of rotation was located adjacent to present-day Iberia at the apex of the Tethyan oceanic domain. Shortening in the inner are was accommodated by rotation around a vertical axis and buckling of the crust to generate the Iberian-Armorican orocline. Concomitant lithospheric delamination in the subcontinental mantle lithosphere provided a mechanism to facilitate oroclinal bending and accounts for the

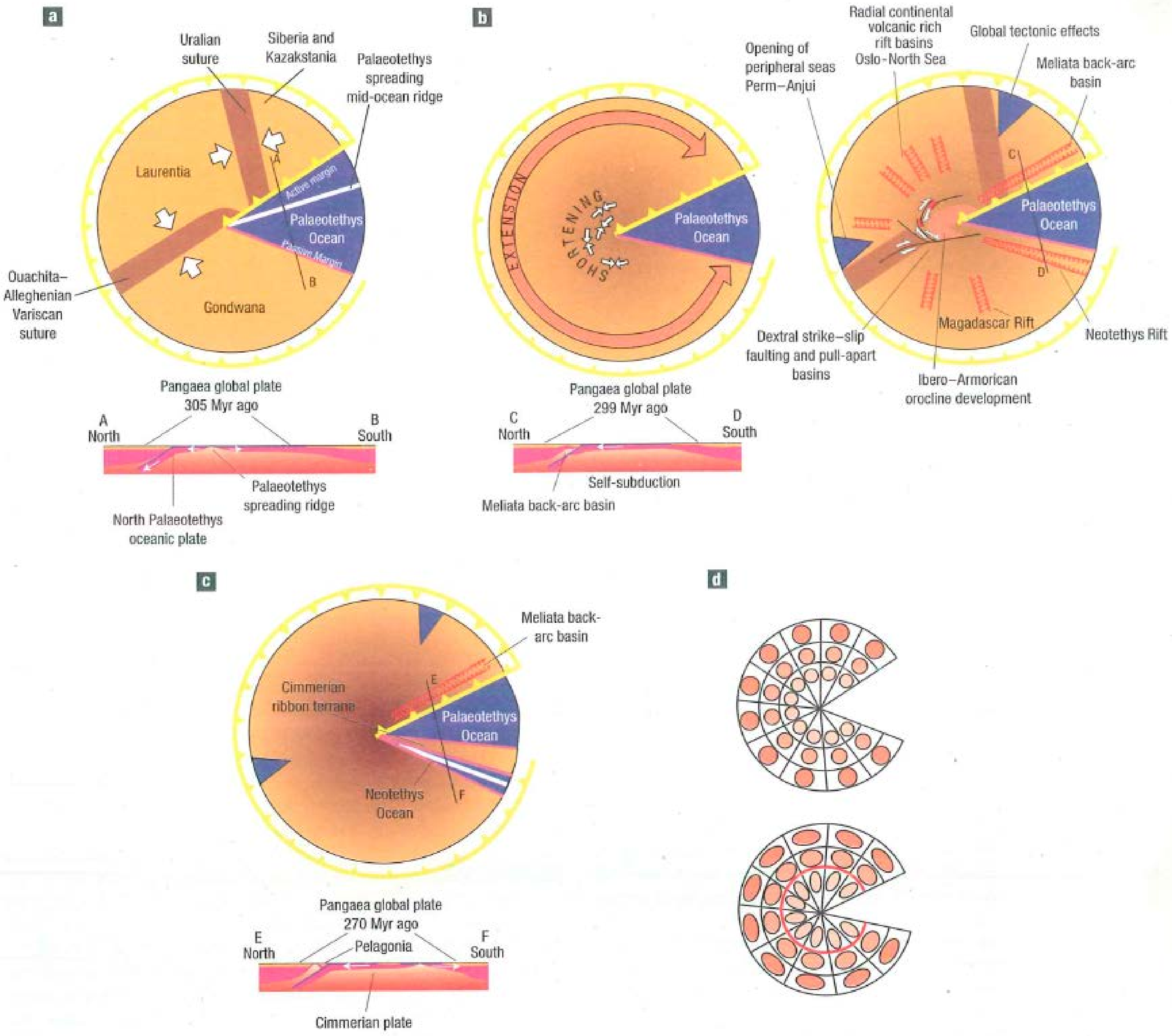

Figure 3 Self-subduction model and geological effects in Pangaea. Schematic diagrams showing simplified Pangaea reconstructions and schematic lithospheric cross-sections through Palaeo- and Neothethys oceans far the middle Pennsylvanian al 305 Myr ago **(a),** the Carboniferous-Permian boundary al 299 Myr ago **(b)** and the Roadian age al 270 Myr ago (e). White arrows in **a,b** represent! main components of horizontal shortening and extension. **d,** Strain distribution in a tangential longitudinal strain model (red line = neutral surface).

voluminous, but short-lived plutonic and volcanic activity in the vicinity of the orocline. Near the neutral fibre of the lithospheric oroclinal buckle fold, deformation produced lithospheric-scale dextral faults and transtensional, mostly continental, basins accompanied by widespread mantle-related volcanism (for example, German late Palaeozoic basins). In the outer are, particularly in northern Pangaea, radial rift zones were generated in response to extensional strain. Continental extension along the outer periphery of the Pangaean plate is interpreted to have played a significant role in the development of triangular-shaped basins such as the Perm and Anjui[8] basins of North Arnerica and Siberia (Fig. 3b) respectively.

Slab pull eventually resulted in total failure of the Pangaean continental lithosphere along the radial rift that evolved into the Neotethys Ocean. Self-subduction ended with the formation of the Neotethys mid-ocean ridge. The new ridge separated continental Pangaea from the subducting slab, terminating the transmission of slab pull into the continent, and ending self-subduction-related deformation. The rifting event split the Pangaea superplate into two plates, including the still subducting Palaeotethyan oceanic lithosphere in which the Cimmerian ribbon continent was embedded[9] (Fig. 3c). This geodynamic change is recorded as a widespread unconformity in all Permian continental basins. Self-subduction left a legacy, as structures generated during the period of self-subduction subsequently became the loci of continental rifts that facilitated Pangaea break-up.

In summary, we describe the hitherto unrecognized tectonic process of self-subduction. Self-subduction can occur during the lifespan of a supercontinent, profoundly influencing its evolution and subsequent break-up. For Pangaea, this process provides a unified explanation for a variety of enigmatic lithospheric-scale features that characterize the supercontinent. Self-subduction also offers insights into the processes that shape the evolution of supercontinents, as well as providing an extra mechanism that may play a significant role in supercontinental evolution and break-up. The consistency of our model also demonstrates the importance of having an accurate geologic timescale for the Carboniferous-Permian boundary [21]. It was the recently updated timescale [21] that enabled us to recognize the synchronicity and diachronism of specific tectonic, stratigraphic and magmatic events that critically underpin the global relationships pivotal to our model.

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Author contributions

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