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A synopsis of recent conceptual models on supercontinent tectonics in relation to mantle dynamics, life evolution and surface environment

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A R T I C L E I N F O

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A B S T R A C T

A synthesis of some of the recent conceptual models suggests that mantle dynamics exerted a significant control on the assembly and breakup of supercontinents through the history of the Earth. During the amalgamation of continental fragments, the subducted oceanic lithosphere of intervening oceans either moves down to the deep mantle or gets horizontally flattened as stagnant slabs in the mantle transition zone. Blobs of these stagnant slabs sink down into the deep mantle and accumulate as slab graveyards at the core–mantle boundary. The recycled oceanic lithosphere at the core–mantle boundary is thought to contribute potential fuel for generating superplumes which rise from the core–mantle interface to the uppermost mantle, penetrating the mantle transition zone and eventually giving rise to hot spots. Multiple subduction zones promote the rapid amalgamation of continental fragments into supercontinents and also act as major zones of material flux into the deep mantle transporting substantial volume of trench sediments and arc crust through sediment subduction and tectonic erosion. Due to buoyancy, the subducted TTG (tonalite-trondhjemite-granite) material is stacked in the mid mantle region and may not sink down to deeper levels. Thus, continents and supercontinents can be speculated to occur as three layers: on the surface of the globe, at the mid mantle region and on the core–mantle boundary, with material transfer on a whole earth scale controlled by plate, plume and 'anti-plate' tectonics. Whereas mantle tomography opens windows into the deep Earth, the imbricated remnants of 'ocean plate stratigraphy' preserved in accretionary orogens constitute useful geological tools to study subduction-accretion-collision history, particularly in relation to the assembly of older supercontinents on the surface of the globe. The dynamics of supercontinents also impact the origin and extinction of life as well as surface environmental changes. Large scale flow of material and energy through mantle downwelling and upwelling associated with supercontinent assembly and breakup is thought to affect the Earth's dynamo which would lead to catastrophic environmental changes, sometimes even triggering mass extinction. When a rising plume impinges the base of a supercontinent, the resultant continental rifting, formation of large igneous provinces and volcanic emissions might lead to the initiation of a plume winter, the aftermath of which would be mass extinction and long-term oceanic anoxia. Supercontinent tectonics in relation to mantle dynamics thus provides a key to evaluate the history of evolution and destruction of the continental crust, to understand the history of life, and to trace the major surface environmental changes of our planet.

1. Introduction

Supercontinents are large landmasses formed by the convergence of multiple continental fragments carrying ancient cratons, together with accreted terranes. The early ca. 2 billion year history of the Earth was dominated by island arcs in the oceanic environment, in the absence of any large continental masses. Arc–arc collision and formation of composite arcs led to the development of embryonic continents which subsequently amalgamated to form larger continents. The first coherent supercontinent is thought to have been assembled by around 2.0 Ga, although it was much smaller in size as compared to that of some of the younger supercontinents. The configuration of supercontinents and pseudo-supercontinents which shaped the globe during various periods in Earth history as generally discussed in literature are the hypothetical assembly Ur (3.0 Ga), Kenorland (2.7–2.5 Ga), Columbia (1.8–1.9 Ga), Rodinia (1.1 Ga), Gondwana (0.54 Ga) and Pangea (0.25 Ga) (e.g. Rogers and Santosh, 2004 and references therein). Several other configurations such as Valbaara (3.2 Ga), Pannotia (0.7 Ga), among others, have also been postulated. The history of growth, evolution and dispersion of supercontinents on the globe through time has received considerable attention in the

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recent years, particularly with respect to the impact of the assembly and dispersion of continental fragments on mantle dynamics, surface processes and life evolution (for a recent compilation, see Santosh and Zhao, 2009, and papers therein). Stochastic models predict that mantle convection has significant effects on the amalgamation of supercontinents (Zhang et al., 2009a,b). According to these models, a moderately strong lithosphere and lower mantle relative to upper mantle with high mantle convection leads to the assembly of continental blocks within a supercontinent in about 250 million years. However, for models with intrinsically small-scale mantle flows, even when continental blocks merge to form a supercontinent, the assembly times are too long. The rates of movement of continents to form a supercontinent assembly depend on various factors including mantle temperature anomalies and polar motion. The development of double-sided or multiple subduction zones have been postulated to be one of the key factors that promote the rapid assembly of continental fragments into supercontinents (e.g. Maruyama et al., 2007; Santosh et al., 2009a). Some workers identify a crescent-shaped symmetry in the accretion of continental crust into supercontinents (e.g. Piper, 2010-a). By analogy with Phanerozoic Pangaea and the present-day geoid, the interpretation offered is that this symmetry resulted from large-scale, presumably whole mantle, convection systems driving the continental crust towards regions of minimum gravitational potential.

The assembly and dispersal of supercontinents could lead to two types of true polar wander (TPW), driven either by a well developed hot upwelling axis that creates a stable maximum moment of inertia, or by the homogenization of mantle thermal structure following continent dispersal that leads to destabilization of the principal axis and possible large magnitude polar wander (Phillips et al., 2009). Evans (2003) illustrated a simplified concept of true polar wander (TPW) in the context of plate tectonics linking the geodynamo, the equatorial bulge and the climate zones. This model suggests that the rotation axis is constant and that mantle convection associated with plate tectonics incorporates rising and sinking density anomalies. Due to viscosity, these vertical motions deform the upper and lower boundaries as well as any of the internal discontinuities of the mantle. TPW turns the entire mantle, driving the upwellings to the equator, and the downwellings to the poles. The outer core-derived geomagnetic field remains aligned with the spin axis, as does the equatorial bulge and climatic zonation. Continents ride in unison on top of the migrating mantle. The birth of a superplume and the eruption of flood basalts can trigger a change. Maruyama and Santosh (2008) proposed an alternate model to explain the TPW invoking a quasi-polar dynamo. The present day Earth has a dipole dynamo flow with minor non-dipole components, although this need not have been the case in the past. The dynamo flow is strongly influenced by the high-speed rotation of the Earth, but is also controlled by the thermal structure on the core–mantle boundary (CMB). The presence of a cold slab graveyard accumulated at the bottom of the mantle through prolonged subduction generates equatorial downflow in the outer core which could enhance the non-dipole dynamo component. According to this interpretation, the apparent polar wander is a probable result of the non-dipole flow. When the equatorial downflow weakens, the system returns to the original bi-polar dynamo. Thus, the 'switch-on' and 'switch-off' mechanism can explain the onset and disappearance of the 'Snowball Earth' with additional input by strong cosmic showers.

The mechanisms by which once stabilized supercontinents break apart have also been investigated in several recent works. The assembly of supercontinents impact mantle flow fields significantly, affecting the distribution of subduction, upwelling plumes and lower mantle chemical heterogeneities. These would contribute to voluminous volcanism that is often associated with the breakup of supercontinents, as recently modeled based on the thermal and dynamic impact of supercontinents on Earth-like mobile-lid convecting systems (O'Neill et al., 2009). On the other hand, some workers consider that the stagnant-lid convection probably did not occur because massive heat transfer necessitated vigorous mantle overturn in the early hot Earth (Ernst, 2009). In this case, the bottom-up mantle convection, including voluminous plume ascent, efficiently rid the planet of heat, with the intensity decreasing over time. An increasingly negative buoyancy of the cooler oceanic lithosphere was achieved in the younger Earth during the Proterozoic-Phanerozoic. Supercontinent assemblies might have witnessed density instabilities of thickening oceanic plates dominated by overturn of the suboceanic mantle as cold, top-down convection. The bottom-up versus top-down tectonics generated by hot asthenospheric upwelling versus lithospheric foundering and asthenospheric return flow changed gradually over geologic time in response to planetary thermal relaxation (Ernst, 2009). These studies, among several other recent investigations, mark the importance of Solid Earth processes in controlling the dynamics of formation and disruption of supercontinents.

This paper offers an overview of some of the recent conceptual models on supercontinent assembly and dispersal, how the supercontinent tectonics might be related to mantle dynamics, and how it might have impacted on the evolution of life and climate. These topics cover various interdisciplinary areas on which different schools of thought have contributed substantially. However, the present work is only a synoptic overview of some of the selected works, and does not claim to be a comprehensive review.

2. Slab graveyards and supercontinent history

Seismic tomography has considerably advanced our knowledge on the structure of the Earth's crust and underlying mantle (e.g. Grand, 2002; Fukao et al., 2001, 2009; Zhao, 2004, 2009). Several studies have demonstrated that subducted slabs penetrate the mantle transition zone and go directly into the lower mantle such as in the case of Mariana, Central America, Tonga-Kermadec and Hellenica (e.g. Spakman et al., 1993; Grand et al., 1997; van der Hilst et al., 1997; Bijwaard et al., 1998; Gorbatov and Kennett, 2003). From an extensive synthesis of tomographic models of deeply subducted slabs around the circum-Pacific region, Fukao et al. (2001) concluded that subducted slabs tend to be horizontally flattened at various depths in the mantle below 400 km, referred to as stagnant slabs. Subsequent studies identified stagnant slabs of the Mediterranean lithosphere in the mantle transition zone under southern Europe (e.g. Marone et al., 2004), the Cocos-Farallon plate under southern Mexico (Gorbatov and Fukao, 2005), and the remnant flattened slab of the Farallon plate under southern North America (e.g. Schmid et al., 2002), among those in other regions. The stagnant slabs have been defined as subducted oceanic lithosphere sub-horizontally deflected above, across, or below the 660 km discontinuity and has now been widely recognized to occur beneath subduction zones around the circum-Pacific and in the Mediterranean.

Zhao (2004) synthesized a P-wave tomographic image for the Western Pacific region, along a transect covering Beijing to Tokyo, where about 1200 km-long stagnant slabs are seen floating in the mantle boundary layer (MBL). The image shows the presence of a high P-wave velocity anomaly close to the bottom of the mantle and immediately above the core–mantle boundary (CMB) which has been interpreted as a 'slab graveyard' (Fig. 1a). The general paucity of high velocity anomalies in the depth range of 660–2000 km is also notable. Maruyama et al. (2007, 2009) correlated this feature to catastrophic collapse of stagnant slabs at the MBL at around 30 Ma ago, because the stagnant slabs in the depth range 410–660 km that extend over 2000 km from the Japan trench to the region under-