Terra Nova

doi: 10.1111/j.1365-3121.2011.01018.x

Future supercontinent assembled in the northern hemisphere

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ABSTRACT

Continental masses were amalgamated, broken apart and reassembled within supercontinents during different times in Earth history. Here, we attempt to predict the configuration of a potential future supercontinent based on a numerical simulation model of mantle convection. The mantle convection in our model is driven by a density anomaly compiled from a global seismic tomography model. The temporal evolution of a highly viscous continent with an initial present-day configuration is simulated for over 250 Ma. The result reveals that Australia, Eurasia, North America and Africa would gather in the northern hemisphere to form the future supercontinent. On the other hand, Antarctica and South America remain in the present-day position even after 250 Ma from present, and do not join the future supercontinent amalgam. The configuration of the future supercontinent numerically simulated herein is broadly consistent with the hypothetical model of the future supercontinent Amasia speculated from geological correlations.

Terra Nova, 23, 333–338, 2011

Introduction

The convergence of multiple continental fragments carrying ancient cratons together with accreted terranes have created large landmasses on our planet termed as supercontinents (Worsley *et al*., 1984, 1986; Nance *et al*., 1988). Whereas various models have been proposed for the formation and disruption of supercontinents (Condie, 2004; Santosh *et al*., 2009), stochastic and numerical models predict that mantle convection has significant effects on the amalgamation of supercontinents (Zhang *et al*., 2009). Several configurations of supercontinents which shaped the globe during various periods in Earth history have been proposed, including Vaalbara (3.2 Ga), 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) (Rogers and Santosh, 2004). The term Nuna was applied by Hoffman (1989) to describe the Palaeoproterozoic supercontinent, although its reconstruction is based on different criteria, mostly focusing on the amalgam of North American terranes. It should be noted that not all the continental assemblies through Earth's history mentioned above qualify to be defined as supercontinents in terms of their size and well-defined configurations (e.g. Pangea vs. Ur), although relative to the amount of continental lithosphere on the planet in the Archaean, even the early landmasses (e.g. Vaalbara) can be considered as supercontinents. The debates surrounding the definition of supercontinents, including their dynamics and periodicity have been dealt with elsewhere (Yoshida and Santosh, 2011).

The history of supercontinental cycles through time has received considerable attention in the recent years, specifically in relation to the process of crustal growth of the continents, the history of life and major surface environmental changes (Nance *et al*., 1988; Santosh, 2010). Whereas hypothetical models supported by geological correlations have attempted the configurations of past supercontinents, the question of when and where the future supercontinent will form is controversial. A popular concept is that as the Pacific Ocean is shrinking and the Atlantic Ocean is widening, Asia is moving towards America with the western Pacific region defining the frontier of the future supercontinent, dubbed 'Amasia' (Hoffman, 1992, 1999; Maruyama *et al*., 2007), postulated to be assembled after 250 Ma from present. However, if the rapid northward migration of Australia is taken into consideration, this continent could be wedged between Asia and North America within next 70 Ma (Scotese, 2001). The model of the hypothetical supercontinent 'Amasia' faces another more critical problem that the South Pacific large-scale upwelling plume lies central to the path of migration of the Asian continental mass to join America and form the future supercontinent. An alternate concept is that if modern subduction in the Caribbean and Scotia arcs spreads along the Atlantic seaboard, then convergence and destruction of the Atlantic Ocean would result in a supercontinent, termed 'Pangea Ultima' (Scotese, 2000). This hypothesis, however, faces the challenge that if the subduction within the Atlantic realm spreads laterally, the assembly of Pangea Ultima cannot be achieved as postulated, although this model needs to be tested further.

Trubitsyn *et al*. (2008) formulated a three-dimensional (3-D) numerical model to realize the continental drift from present to 100 Ma into the future to predict a configuration of the future supercontinent. The model continents were assumed to be thin 'rigid' (non-deformable) caps that can be drifted by an Euler's solid body equation and arranged in a real distribution of continents on the present day globe. The initial temperature condition of mantle was given by the present mantle flow pattern estimated from a seismic tomography model. Their simulation reveals that after 100 Ma, all the continents would move to the southern hemisphere, with Africa, Eurasia, Australia, Antarctica and South America assembling

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to form a supercontinent around Antarctica. This model also relies on the subduction zones in the western Pacific to effectively 'pull together' the continental fragments.

However, including the study by Trubitsyn *et al.* (2008), most of the numerical attempts so far have assumed the continent/supercontinent to be rigid or non-deformable bodies mainly because of the limitations in the numerical simulations, as well as the simplification of models (see review by Yoshida and Santosh, 2011). In this study, we use a preliminary, but more robust numerical model which enables us to treat the evolution of deformable, mobile continental lithosphere both in space and time (Yoshida, 2010), and attempt to answer the question of when and where the future supercontinent might form.

Model description

The details of model description for mantle convection and continent are described in Supporting Information.

The temperature (T)-, phase (Γ)-, composition (C)-dependent rheology is considered in the mantle. The dimensionless viscosity form used is given by;

$$\eta = \Delta\eta(\Gamma)\Delta\eta_{\mathrm{cont}}(C) \cdot \left(\frac{2E}{T - T_{\mathrm{top}} + \Delta T} - \frac{2E}{0.5 + \Delta T}\right), \quad (1)$$

where T_{top} is the temperature at the top surface (=0.1092), ΔT is the temperature difference across the mantle (=1), E is the dimensionless activation energy that controls the viscosity contrast across the mantle and set to be $\ln(10^3)$ = 6.91 so as to set the viscosities at the top and bottom surfaces to be 10^2 and 10^{-1}, respectively. The viscosity contrast between the continent and surrounding mantle $\Delta\eta_{\mathrm{cont}}(C)$ is fixed at 10^2 or 10^3 in the continent if C = 1 and 1 in the mantle if C = 0. The value of $\Delta\eta(\Gamma)$ is fixed at 1 in the olivine-spinel phase and 30 in the post-spinel phase.

The initial temperature field, $T_{\mathrm{init}}(r, \theta, \phi)$, is obtained from a compositionally homogeneous convection model with no continental material ('free convection') that reaches well-developed, statistically steady state (Fig. 1) and mainly from a seismic tomography model. The initial state of temperature field is given by

$$T_{\mathrm{init}}(r, \theta, \varphi) = T_{\mathrm{conv}}(r) + \delta T_{\mathrm{seis}}(\theta, \varphi), \quad (2)$$

where $T_{\mathrm{conv}}(r)$ is the laterally averaged temperature of free convection (Fig. 1c) and $\delta T_{\mathrm{seis}}(\theta, \phi)$ is the lateral temperature anomaly determined by seismic tomography models, named 'smean' and 'pmean' models (Becker and Boschi, 2002) (see Supporting Information) and the regionalized upper mantle seismic model based on seismicity in the upper mantle, named 'RUM' model (Gudmundsson and Sambridge, 1998).

Following Karato (2008), the seismic velocity anomaly $\delta V_{\mathrm{S,P}}$ is converted into the temperature anomaly δT_{seis} applying the following relationship (see Supporting Information):

$$\delta T_{\mathrm{seis}} = A^{-1}_{V_{\mathrm{S,P}}T}\,\delta V_{\mathrm{S,P}}, \quad (3)$$

where $A_{V_{\mathrm{S,P}}T}$ is the temperature derivative of seismic wave velocity as a function of radius; $A_{V_{\mathrm{S,P}}T} \equiv \partial \ln V_{\mathrm{S,P}}/\partial T$, which is determined by mineral physics (Karato, 2008). The depth profile of $A_{V_{\mathrm{S,P}}T}$ used in our model is shown in Fig. 2a (see Supporting Information). The calculated δT_{seis} for smean and pmean models are illustrated in Fig. 2b and c, respectively. The smean and pmean models are adapted in the regions under 350 km depth. The RUM model, which represents the configuration of subducting slabs, is adapted in the regions above 660 km depth. The lateral temperature anomaly of subducting slabs in the upper mantle is herein fixed at −500 K.

The present-day continental distribution used in this study is compiled

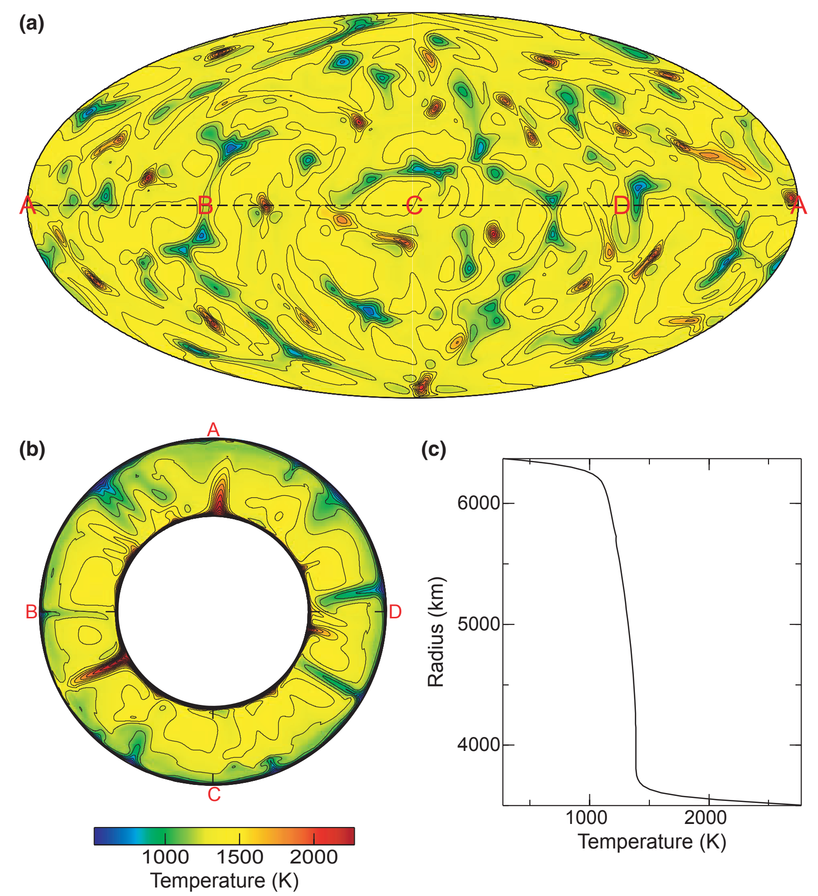

Fig. 1 Snapshot of the initial temperature field from a compositionally homogeneous convection model with no continental material ('free convection') that reaches well-developed, statistically steady state. (a) The temperature at the mid-mantle (1433 km) depth. (b) A cross-section of mantle along the path A–B–C–D–A shown in (a). (c) Depth profile of the laterally averaged temperature in the mantle.

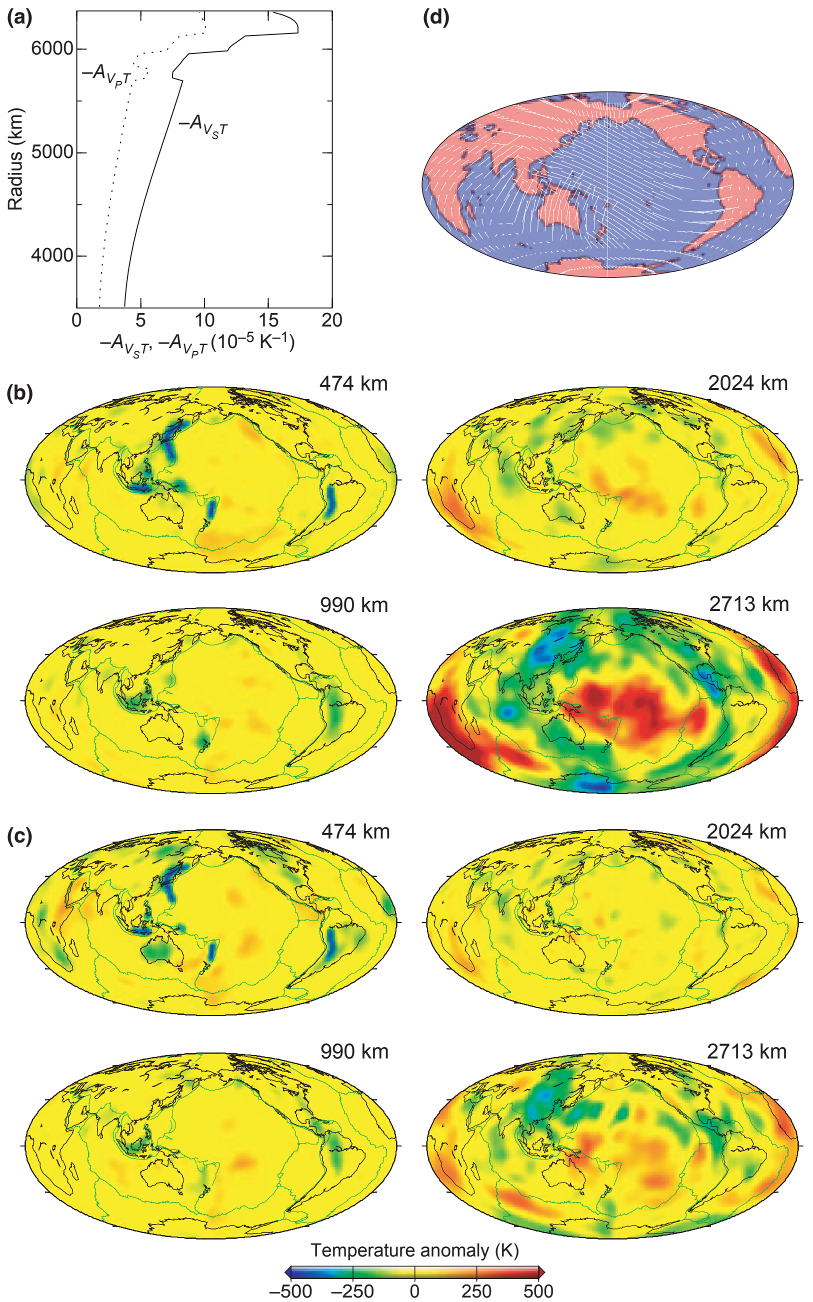

Fig. 2 (a) Depth profile of the temperature derivatives of seismic wave velocity, $A_{V_{S,P}T}$, compiled from the data given by Karato (2008). (b, c) The temperature anomaly at each depth compiled from the (b) 'smean' and (c) 'pmean' seismic tomography models (Becker and Boschi, 2002), which is adapted in the regions under 350 km depth. The RUM model (Gudmundsson and Sambridge, 1998), which represents the configuration of subducting slabs, is adapted in the regions above 660 km depth. The lateral temperature anomaly of subducting slabs in the upper mantle is herein fixed at −500 K. (d) The present-day continental configuration imposed in the simulation model. White arrows show the plate motions imposed for the first stage (≤5 Ma) of simulation.

from the ETOPO1 model (Amante and Eakins, 2009). The continents initially cover ~35% of the total surface and have a uniform thickness of 250 km (see Supporting Information). Following the previous work (Yoshida, 2010), the time integration of the advection of compositionally different continental materials (*C*-field) with zero chemical diffusion is performed by a tracer particle method (see Supporting Information). The continent is instantaneously set on the mantle convection model with the initial temperature field, $T_{\mathrm{init}}(r, \theta, \phi)$. To give plate-scale flow around the surface boundary, the present-day plate motion (Argus and Gordon, 1991) is imposed for the first stage of the simulation (for 5 Ma) as the velocity boundary condition (Fig. 2d) instead of the free-slip condition. The run continues for over 250 Ma.

Result

In the present study, we test four potential scenarios with different tomography models (i.e. smean and pmean) and different viscosity of continents, that is, $\Delta\eta_{\mathrm{cont}}(C)$ (Table 1). The pattern and magnitude of temperature anomaly between smean and pmean models is quite different (Fig. 2b,c), which allows us to study the model sensitivity to the obtained result. Furthermore, the previous study showed that the viscosity of continents significantly depends on the behaviour of the continental movement (Zhang *et al.*, 2009; Yoshida, 2010). This also allows us to study the model sensitivity to the obtained result.

We first show the result for Model S2 with the smean-based initial condition and $\Delta\eta_{\mathrm{cont}}(C)$ of 10^2. Figure 3 illustrates the temporal evolution of continental distribution (left panel) and the temperature anomaly of the mantle (right panel). The four selected time stages at 33, 90, 139 and 250 Ma are shown. The continents start to move on the start of the simulation at 0 Ma. The most interesting result obtained in our study is that Australia moves northwards at a high speed; an outcome of extrapolating the current rapid northward movement. Ultimately, Australia, Eurasia, North America and Africa gather in the northern hemisphere to form a future supercontinent. Conversely, Antarctica and South America remain in their present-day position even after 250 Ma and are not assembled in the future supercontinent, primarily because of the two large-scale upwelling plumes beneath the present-day South

Table 1 Model studied.

Model name	Tomography model	$\Delta\eta_{cont}(C)$	Figure
Model S2	smean	10^2	3
Model P2	pmean	10^2	4
Model S3	smean	10^3	S1 (Supporting Information)
Model P3	pmean	10^3	S2 (Supporting Information)

Pacific and South Africa that lie along the path between these continents and the future supercontinent. These two large-scale upwellings almost remain stable for 250 Ma (see white arrows in right panel).

We next show the result for Model P2 with pmean-based initial condition and $\Delta\eta_{cont}(C)$ of 10^2 in Fig. 4. The four selected time stages at 31, 88, 129 and 248 Ma are shown. It is clear that the overall movement of the continents in Model P2 does not show any significant change from that in Model S2. Thus, Australia, Eurasia, North America and Africa gather in the northern hemisphere to form a future supercontinent, and the two large-scale upwelling plumes beneath the present-day South Pacific and Africa remain almost stable for 250 Ma. This result implies that the future continental movements numerically predicted herein do not depend on the initial condition of the temperature field based on the tomography model, even though the magnitude and pattern of temperature anomaly in the mantle interior is quite different between smean and pmean models (Fig. 2b,c).

Discussion and conclusions

Our study suggests that the African and South Pacific large-scale upwelling plumes will remain stable for the next few hundred million years, as they seem to have done over the last 500 Ma (Torsvik *et al*., 2010). Torsvik *et al*. (2010) suggested that the margins of large low-shear-wave-velocity provinces, stable for at least 200 Ma and possibly for 540 Ma, seem to have controlled the eruption of most Phanerozioc kimberlites. On the other hand, Zhong *et al*. (2007) argued that Pangea was assembled above a major downwelling, and following its assembly, a sub-Pangea upwelling associated with the African large-scale upwelling plume developed relatively fast (*c*. 50 Ma) as mantle return flow in response to circum-Pangea subduction. If this numerical model is correct, the African large-scale upwelling plumes would not have existed prior to Pangea, and this would mean that the Earth alternates between degree 1 and degree 2 convections. Zhang *et al*. (2010) recently suggested that the mantle in the African hemisphere before the assembly of Pangea was characterized by a cold downwelling structure resulting from plate conver-

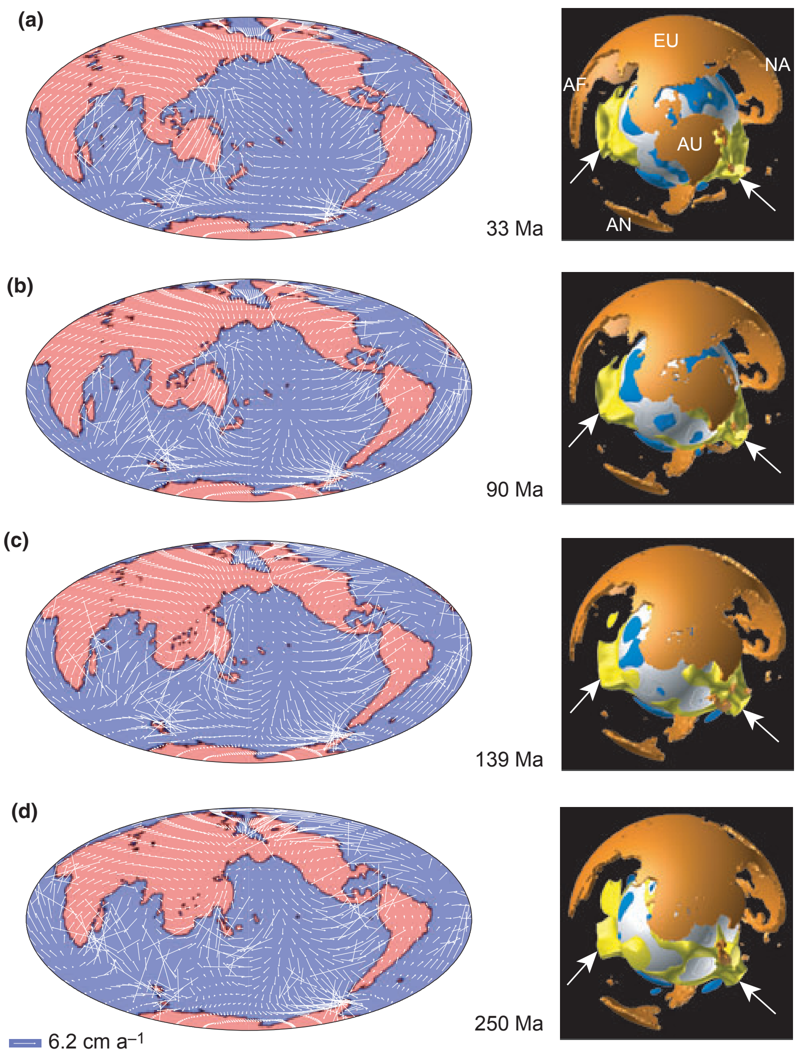

Fig. 3 Temporal evolution of deformable continents at (a) 33 Ma, (b) 90 Ma, (c) 139 Ma and (d) 250 Ma for Model S2 with the smean-based initial condition and the viscosity contrast between the continent and surrounding mantle [$\Delta\eta_{cont}(C)$] of 10^2. Left panel: White arrows show the flow field at the surface of mantle. Australia, Eurasia, North America and Africa gather in the northern hemisphere to form the future supercontinent. On the other hand, Antarctica and South America remain in their present-day position even after 250 Ma and are not assembled in the future supercontinent. Right panel: 3-D views of the temperature anomaly and the position of the continents. Blue and yellow isosurfaces indicate temperature anomalies (i.e. temperature deviations from the lateral mean at each radius) of −200 and +300 K, respectively. Brown colour indicates the position of the continent (AU, Australia; EU, Eurasia; AF, Africa; NA, North America; AN, Antarctica). The white arrows show the positions of the two large-scale upwelling plumes beneath the present-day Africa and South Pacific. The isosurfaces of the temperature field at depths of < 660 km are omitted for clarity. The white spherical surface shows the bottom of the model mantle.

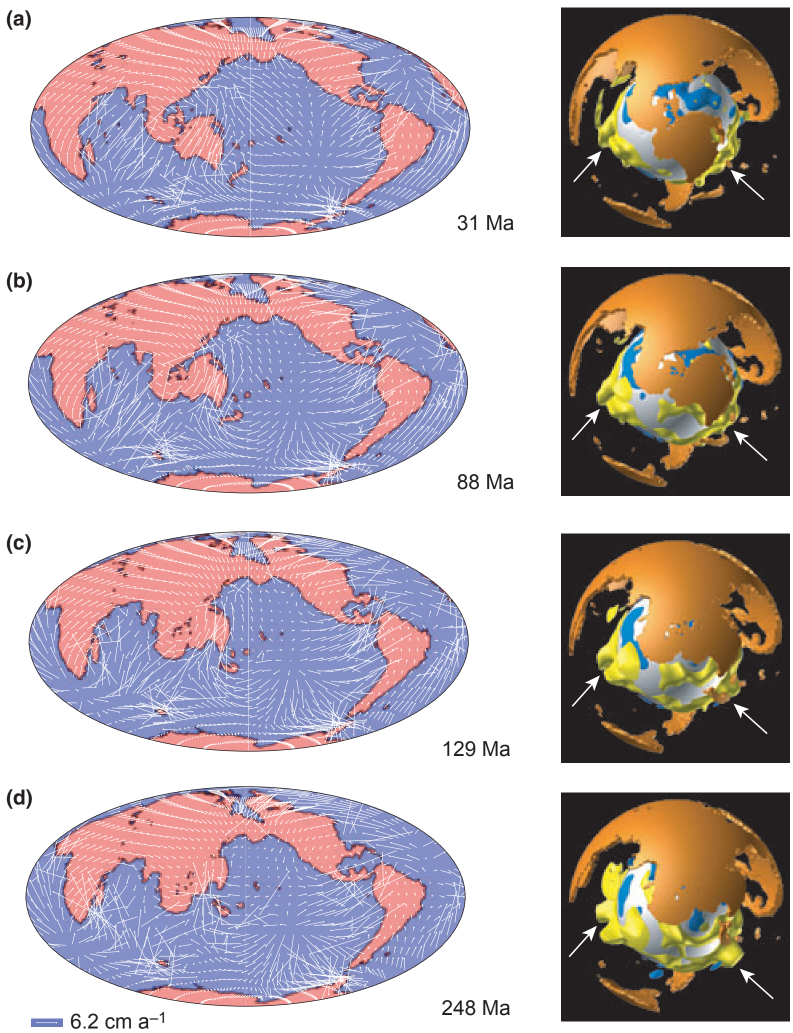

Fig. 4 Temporal evolution of deformable continents at (a) 31 Ma, (b) 88 Ma, (c) 129 Ma and (d) 248 Ma for Model P2 with the pmean-based initial condition and $\Delta\eta_{\mathrm{cont}}(C)$ of 10^2. See Fig. 3 for details.

gence between Gondwana and Laurussia, and therefore it is unlikely that the bulk of the African 'superplume' structure formed before *c*. 230 Ma. They concluded that the plate motion during last 120 Ma played an important role in generating the African superplume.

There are several other suggestions for the long-term stability of the two superplumes. The Pacific superplume was suggested to have formed *c*. 700 Ma ago during the breakup of Rodinia supercontinent and has remained largely unchanged since then (Maruyama, 1994; Maruyama *et al*., 1997, 2007; Condie, 2003), as inferred from evidence for long-lived subduction zones along the continental margins surrounding the Palaeo-Pacific (Li and Powell, 2001; Scotese, 2001; Collins, 2003). On the other hand, the African superplume might have been located beneath the supercontinent Pangea that existed between 330 and 180 Ma. It has been proposed that the African superplume formed during Pangea time as a result of thermal insulating effects from Pangea and that, the superplume may eventually have caused the breakup of Pangea (Anderson, 1982). Recognizing that most of the large igneous provinces generated in the past 300 Ma erupted near the edges of the Africa and Pacific superplumes, Torsvik *et al.* (2006, 2008) suggested that the African and Pacific superplumes and the degree 2 mantle structure probably existed for the last 300 Ma [see review by Zhang *et al.* (2010) for details].

The mechanisms of assembly and dispersal of supercontinents on the Earth have drawn considerable attention in the recent years with various configurations of the past continental amalgams derived from geological jigsaw puzzles. Although some attempts have been made to configure the future supercontinent, these studies were largely speculative or were pivoted on simplified parameters and models. Our study provides the first attempt based on a preliminary, although robust numerical simulation model involving deformable, mobile continental lithosphere and their time-dependent evolution.

Tectonic models that emphasize the role of double-sided (as in the western Pacific region, see Maruyama *et al.*, 2007) or multiple subduction as potential zones to pull together dispersed continental fragments are significant and offer clues to the amalgamation of supercontinents. Although the configuration of a future supercontinent numerically simulated herein is broadly consistent with a hypothetical future supercontinent Amasia predicted from geological correlations, the speculated configuration of Amasia is not fully realized in our numerical simulations, inhibited by large-scale upwellings along the path of migration of some of the continents. Thus, according to our model, the next supercontinent to be assembled at around 250 Ma into the future would comprise an amalgam of Australia, Eurasia, North America and Africa lying in the northern hemisphere of our planet.

Acknowledgements

We thank J. Brendan Murphy, an anonymous referee, and the associate editor for their thoughtful comments, which helped to improve the manuscript. Some of the figures were produced using the Generic Mapping Tools (GMT) of Wessel and Smith (1998). The calculations presented were performed on the supercomputer facilities (SGI Altix 4700) at JAMSTEC. M.Y. was supported by a Grant-in-Aid (Nos. 20740260, 23340132) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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Received 4 November 2010; revised version accepted 19 July 2011

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Model parameters used.

Figure S1. Temporal evolution of deformable continents at (a) 32 Ma, (b) 84 Ma, (c) 140 Ma, and (d) 243 Ma for Model S3 with the smean-based initial condition and $\Delta\eta_{\mathrm{cont}}$ (C) of 10^3. See Fig. 3 for details.

Figure S2. Temporal evolution of deformable continents at (a) 31 Ma, (b) 76 Ma, (c) 130 Ma, and (d) 244 Ma for Model P3 with the pmean-based initial condition and $\Delta\eta_{\mathrm{cont}}$ (C) of 10^3. See Fig. 3 for details.

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