Geology

Seafloor spreading evolution in response to continental growth

N. Coltice, T. Rolf and P.J. Tackley

Geology published online 10 January 2014;
doi: 10.1130/G35062.1

Notes

Geology, published online on 10 January 2014 as doi:10.1130/G35062.1

Seafloor spreading evolution in response to continental growth

N. Coltice[1,2], T. Rolf[3], and P.J. Tackley[3]
[1]Laboratoire de Géologie de Lyon, Université Lyon 1, Ecole Normale Supérieure de Lyon, Université de Lyon, 69007 Lyon, France
[2]Institut Universitaire de France, 103, Bd Saint Michel, 75005 Paris, France
[3]Institute of Geophysics, ETH Zurich, 8092 Zurich, Switzerland

ABSTRACT

The growth of the continental crust has shaped the evolution of the Earth from its interior to its fluid envelopes. Continents have played a major role in the evolution of global tectonics through their interaction with mantle convection. The feedback between continents and mantle convection has been studied for the past 25 years, but it is only recently that the dynamic influence of continents on seafloor spreading can be explored thanks to progress in convection modeling. In this work, we investigate how continental size impacts seafloor spreading activity with state-of-the-art three-dimensional spherical convection models. We show that increasing the continental area forces higher production rates of new seafloor with stronger fluctuations. As a consequence, the average age of the seafloor decreases with increasing continental area. This study suggests that mantle heat loss experienced significant fluctuations through continental growth and reinforces the estimate of <10% continental growth since the late Archean.

INTRODUCTION

The nature of seafloor spreading is critical for many aspects of Earth sciences like mantle degassing (Tajika, 1998), sea level (Gaffin, 1987; Flament et al., 2008), ocean chemistry (Berner and Kothavala, 2001), and Earth's cooling (Labrosse and Jaupart, 2007). More than 50 yr of data collection and kinematic reconstruction efforts have led to significant improvements in plate tectonic modeling back to 200 Ma (Pilger, 1982; Kominz, 1984; Rowley and Lottes, 1988; Scotese et al., 1988; Müller et al., 1997; Lithgow-Bertelloni and Richards, 1998; Seton et al., 2012). Models have been proposed for earlier times back to the Paleozoic (Stampfli and Borel, 2002), but such works remain challenging because they are naturally limited by the preservation of very old seafloor. As a consequence, it is very difficult to estimate how seafloor spreading operated in the Paleozoic and Precambrian. Remnants of ancient obduction sequences are suggested, dating back to the late Archean (Kusky et al., 2001) and even to the early Archean (Polat et al., 2002). Geochemical studies have proposed that the Jack Hills (Australia) zircons (more than 4 b.y. old) could be the earliest hints of seafloor spreading (Harrison et al., 2005). Therefore, seafloor spreading could have operated while continents represented a smaller area than today (de Wit, 1998).

Continental growth, along with mantle cooling, is a fundamental process that has shaped Precambrian mantle dynamics. Indeed, the continental area, occupying now around 30% of the surface, may have been as low as 10% in the Mesoarchean (Taylor and McLennan, 1995). The tempo of continental growth is, however, still debated: some models favor massive growth between 2.7 and 2.3 Ga (Taylor and McLennan, 1995), while others propose an earlier growth during the Hadean (Armstrong, 1991).

In this paper, we investigate how the size of continents influences the properties of seafloor spreading using three-dimensional (3-D) spherical convection models with plate-like behavior and continental lithosphere. The calculations presented here show that continental growth enhances seafloor production and the time dependence of spreading. Our study suggests that mantle heat loss experienced significant fluctuations through continental growth and reinforces the estimate of <10% continental growth since the late Archean (Schubert and Reymer, 1985).

CONVECTION MODELS WITH CONTINENTS AND SEAFLOOR SPREADING

The numerical models employed in this study are 3-D spherical convection models built on successive generations of software that started with the Cartesian models of Tackley (2000) incorporating pseudo-plasticity, before being extended to spherical geometry (van Heck and Tackley, 2008). They now include a basic model of continental lithosphere (Yoshida, 2010; Rolf and Tackley, 2011), modeled as thick and buoyant rafts, being 100 times more viscous than oceanic lithosphere. In this study, we computed numerical solutions in spherical geometry with a spherical cap–shaped continent covering 10%, 30%, 50%, or 70% of the surface (both of the latter percentages are probably higher than ever existed on Earth) and without any continent. The numerical models used here are technically similar to those in Rolf et al. (2012) and Coltice et al. (2012), with a resolution reaching 40 km vertically in the top boundary layer. This resolution appears relatively crude because 1 km resolution needs to be reached to resolve present-day Earth plate boundaries (Gurnis et al., 2004), but the rheology employed here produces broad and diffuse plate boundaries that are resolved here (a computation with 30% continent and improved resolution of 30 km reproduced the results). Although the presented models are state of the art and converge toward tectonic models (Coltice et al., 2013), improvements in rheology and resolution are required for a direct comparison with the Earth. Also, the Rayleigh number of our models (based on the temperature drop over the surface boundary layer) is 10^6, 10–100 times lower than expected for the Earth. Therefore, time in the numerical solutions is scaled such that the model with 30% continents has a present-day Earth's transit time of 85 m.y., as described in Gurnis and Davies (1986). The models are purely internally heated; a uniform, time-independent internal heating rate of ~3×10^{-12} W kg^{-1} is used to obtain a 1300 K drop over the lithosphere for 30% continental area with our parameters. In a previous study, no significant differences in the following results were observed for the problem addressed here when 14% of basal heat flow was introduced with multiple continents covering 30% of the surface (Coltice et al., 2012).

The models presented are >3-b.y.-long convection solutions at statistical steady state, so they can be used to obtain a statistical description of the production rate of new seafloor and average seafloor age for a given configuration of continental area. The area-age distribution of the seafloor in the models is computed by converting heat flow into age assuming a half-space cooling model, following the approach of Labrosse and Jaupart (2007) as used previously in Coltice et al. (2012).

RESULTS

We studied the evolution of the area-age distribution of the seafloor in models with a continent covering 10%, 30%, 50%, and 70% of the surface of the model, and in a model with 0% continental area. The snapshots in Figure 1 were chosen to represent area-age distributions closest to box-shaped in order to make a comparison between the models. The proportion of the seafloor is the same for any given age until it eventually drops down for the maximum age. Such a distribution is expected in a case of steady-state convection without a continent: cold instabilities start to sink once a critical age is reached, corresponding to the maximum age, and no younger subduction is expected. However, mantle convection is not steady-state and continents impose a geometrical constraint on surface tectonics. Hence, over the course of a

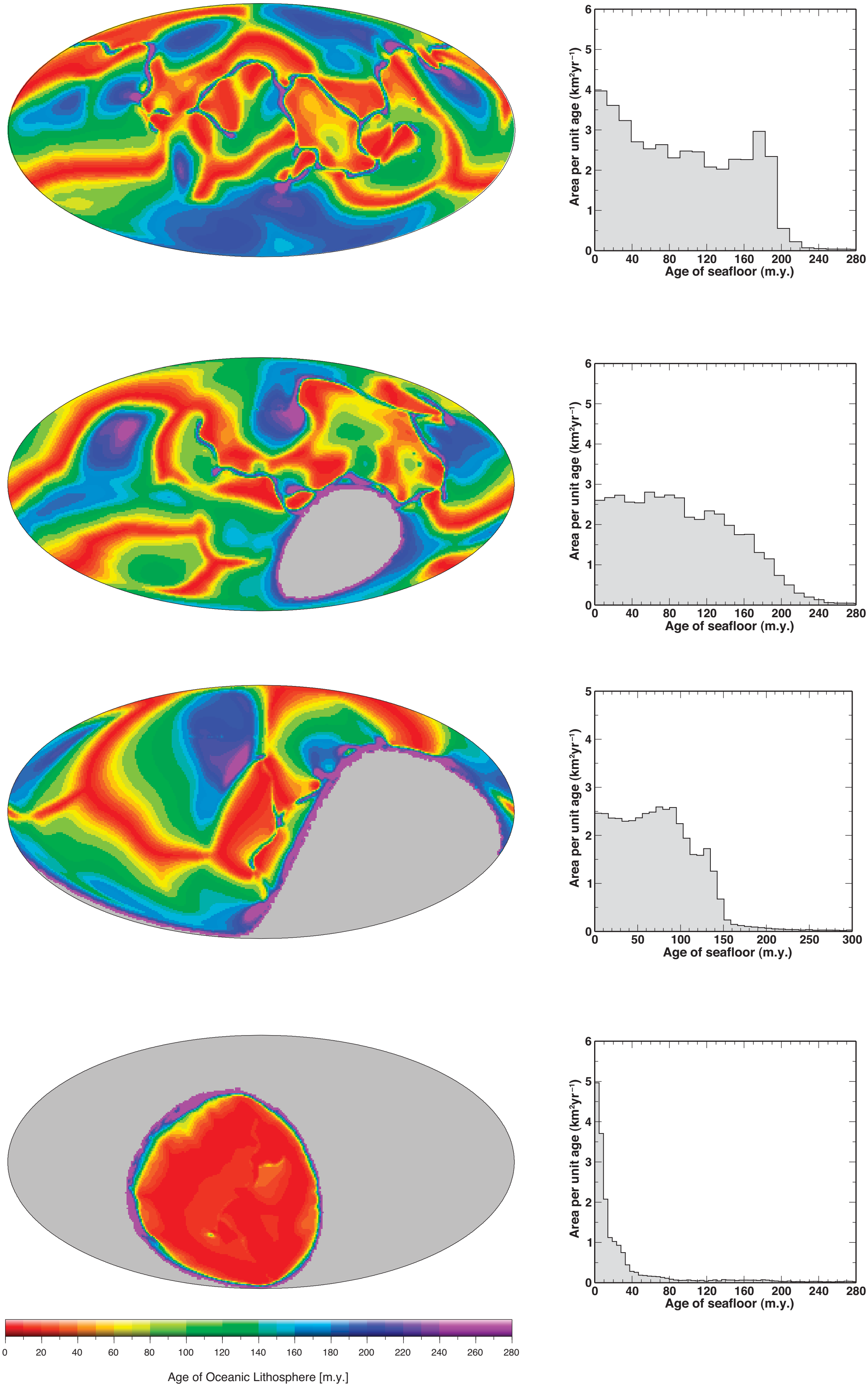

Figure 1. Snapshots of convection solutions with increasing continent size (in gray) increasing from top to bottom (0%, 10%, 30%, and 70% of surface). Left column represents seafloor age maps, and right column represents corresponding area-age distributions.

calculation, the area-age distribution is mostly linearly to exponentially decreasing once a continent is present in our calculations (Coltice et al., 2012, 2013). The seafloor age maps, concordantly with the area-age distributions, show that younger seafloor ages dominate the system when continental area is increased. The time series of the seafloor production rate for the 50% continent case displays a long episode of periodicity, during which the seafloor production rate varies between the highest and lowest values, that other models do not show. This peculiar feature may be caused by the specific continental configuration, representing a spherical harmonic of degree one, which also corresponds to the dominant wavelength of convection with plate-like behavior and a large continent (Zhong et al., 2007; Rolf et al., 2012).

As shown in Figure 1, the production rates of new seafloor are similar in the different snapshots and lower than average. However, in most cases this production rate is dependent on the continental area as shown in Figure 2. Indeed, it increases linearly with continental area, and the standard deviation of the production rates also increases proportionally (Fig. 3). The fluctuations of seafloor spreading are hence enhanced by increasing continental lithosphere and favor linearly decreasing to exponentially decaying area-age distributions.

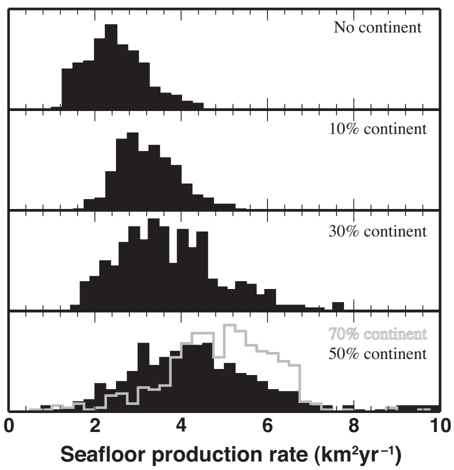

Figure 2. Distributions of production rate of new seafloor corresponding to presented time-dependent convection models.

As a consequence, the average age of ocean basins in our models decreases linearly with increasing continental area (Fig. 3). The average age obtained with 30% continental cover is 63 Ma, consistently close to that of the Earth at 62 Ma (Müller et al., 1997). In this case, the average seafloor age reaches a maximum of 80 Ma and a minimum of 43 Ma. The case with 50% continental cover differs from the others, probably because of the peculiar regularity of the flow

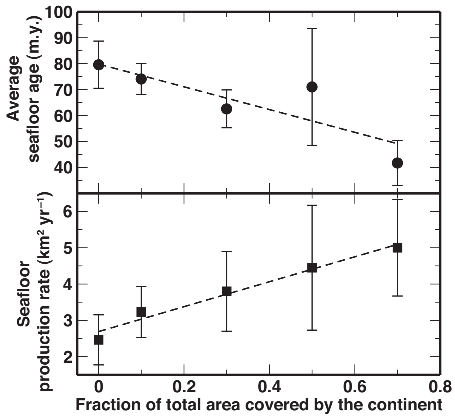

Figure 3. Average production rate of new seafloor and mean seafloor age as a function of surface fraction covered by continents.

as already described above, but we think it is an outcome of this unique configuration.

DISCUSSION AND CONCLUSIONS

The models show that increasing the continental area results in higher production rate of new seafloor. Continental lithosphere represents a thick conductive lid, hence the growth of the continents reduces the area over which the mantle can efficiently cool. As a consequence, the oceanic heat flow per unit of area and the production rate of new seafloor are higher for a smaller oceanic area for a given amount of heat sources. The area-age distribution is thus increasingly dominated by young seafloor ages as continents grow, the average age of ocean basins decreasing accordingly.

The calculations presented here confirm spreading rate can vary by a factor of two as in recent tectonic and convection models (see discussion and references in Coltice et al., 2013). They also suggest that continental growth enhances the time dependence of seafloor spreading. Moresi and Solomatov (1998) already mentioned a stronger time dependence of convection when continental lithosphere is present. Time dependence of the production rate has a large impact on the consumption of seafloor (Becker et al., 2009), hence the area-age distribution changes notably with time from a box shape with reduced spreading to a decay shape with substantial spreading (Coltice et al., 2012).

Our models have limitations as discussed earlier, but we are confident our results will hold with improved treatment of shear localization in the future because predictions of these models already converge toward plate tectonic models (Coltice et al., 2013). Previous studies show that the multiplicity of continents does not affect the average seafloor production rate by more than 10%, but reduces by at least 30% the magnitude of the fluctuations (Coltice et al., 2012). Future work on the roles of multiple continents, layered viscosity, continental area evolution, core heating, and the existence of deep chemical heterogeneities will refine this first attempt to characterize seafloor spreading through continental growth.

The distribution of seafloor ages is fundamental for modeling heat flow or continental freeboard. When the production of new seafloor is high and the area-age distribution features a decay with increasing age, both heat flow and sea level are high. Our results corroborate the work of Labrosse and Jaupart (2007), suggesting that strong heat flow fluctuations and the changing shape of area-age distributions have to be taken into account when modeling the small changes of heat loss through the Precambrian (Herzberg et al., 2010).

Continental freeboard has been modeled as resulting mainly from the competition between two processes (Schubert and Reymer, 1985; Galer, 1991; Flament et al., 2008): continental growth reduces the size of oceanic basins and hence promotes flooding, in contrast to mantle cooling which deepens ocean basins. The hypothesis of a constant freeboard since the late Archean (Eriksson, 1999; Miller et al., 2005) has been used to constrain crustal growth to a limited amount during this period, so as to compensate for the deepening of ocean basins subsequent to mantle cooling (Schubert and Reymer, 1985). Our results show that the effect of continental growth on seafloor spreading further prevents ocean basin deepening because younger seafloor is favored when continental area increases. For a present-day continental area, switching from a box-shape area-age distribution to a linearly decreasing area-age distribution corresponds to ~400 m of sea-level rise (Labrosse and Jaupart, 2007), which is equivalent to a growth of continents from 70% to 100% of their present-day volume (Galer, 1991). Hence, our study strongly reinforces the estimate of <10% continental growth since the late Archean (Schubert and Reymer, 1985). Progressive emergence of continental landmasses throughout the Archean (Eriksson et al., 2006; Flament et al., 2008; Pons et al., 2011; Arndt and Nisbet, 2012) suggests that continental growth occurred early within the Earth's history.

ACKNOWLEDGMENTS

We thank Carolina Lithgow-Bertelloni and two anonymous reviewers for their fruitful comments, as well as the journal editor James Spotila, for constructive advice that improved the manuscript. This research has received funding from Institut Universitaire de France and Crystal2Plate, a FP-7 funded Marie Curie Action under grant agreement number PITN-GA-2008-215353. Calculations were performed on MONTE ROSA, the high-performance computing cluster of the Swiss National Supercomputing Centre (CSCS), under project ID s272.

REFERENCES CITED

Armstrong, R., 1991, The persistent myth of crustal growth: Australian Journal of Earth Sciences, v. 38, p. 613–630, doi:10.1080/08120099108727995.

Arndt, N.T., and Nisbet, E.G., 2012, Processes on the young Earth and the habitats of early life: Annual Review of Earth and Planetary Sciences, v. 40, p. 521–549, doi:10.1146/annurev-earth-042711-105316.

Becker, T., Conrad, C., Buffett, B., and Müller, R., 2009, Past and present seafloor age distributions and the temporal evolution of plate tectonic heat transport: Earth and Planetary Science Letters, v. 278, p. 233–242, doi:10.1016/j.epsl.2008.12.007.

Berner, R., and Kothavala, Z., 2001, GEOCARB III: A revised model of atmospheric CO_2 over Phanerozoic time: American Journal of Science, v. 301, p. 182–204, doi:10.2475/ajs.301.2.182.

Coltice, N., Rolf, T., Tackley, P., and Labrosse, S., 2012, Dynamic causes of the relation between area and age of the ocean floor: Science, v. 336, p. 335–338, doi:10.1126/science.1219120.

Coltice, N., Seton, M., Rolf, T., Müller, R.D., and Tackley, P.J., 2013, Convergence of tectonic reconstructions and mantle convection models for significant fluctuations in seafloor spreading: Earth and Planetary Science Letters, v. 383, p. 92–100, doi:10.1016/j.epsl.2013.09.032.

de Wit, M.J., 1998, On Archean granites, greenstones, cratons and tectonics: Does the evidence demand a verdict?: Precambrian Research, v. 91, p. 181–226, doi:10.1016/S0301-9268(98)00043-6.

Eriksson, P.G., 1999, Sea level changes and the continental freeboard concept: General principles and application to the Precambrian: Precambrian Research, v. 97, p. 143–154, doi:10.1016/S0301-9268(99)00029-7.

Eriksson, P.G., Mazumder, R., Catuneanu, O., Bumby, A.J. and Ountsché, I.B., 2006, Precambrian continental freeboard and geological evolution: A time perspective: Earth-Science Reviews, v. 79, p. 165–204, doi:10.1016/j.earscirev.2006.07.001.

Flament, N., Coltice, N., and Rey, P., 2008, A case for late-Archaean continental emergence from thermal evolution models and hypsometry: Earth and Planetary Science Letters, v. 275, p. 326–336, doi:10.1016/j.epsl.2008.08.029.

Gaffin, S., 1987, Ridge volume dependence on sea-floor generation rate and inversion using long-term sea-level change: American Journal of Science, v. 287, p. 596–611, doi:10.2475/ajs.287.6.596.

Galer, S., 1991, Interrelationships between continental freeboard, tectonics and mantle temperature: Earth and Planetary Science Letters, v. 105, p. 214–228, doi:10.1016/0012-821X(91)90132-2.

Gurnis, M., and Davies, G.F., 1986, Mixing in numerical models of mantle convection incorporating plate kinematics: Journal of Geophysical Research, v. 91, p. 6375–6395, doi:10.1029/JB091iB06p06375.

Gurnis, M., Hall, C., and Lavier, L., 2004, Evolving force balance during incipient subduction: Geochemistry Geophysics Geosystems, v. 5, Q07001, doi:10.1029/2003GC000681.

Harrison, T., Blichert-Toft, J., Müller, W., Albarede, F., Holden, P., and Mojzsis, S., 2005, Heterogeneous Hadean hafnium: Evidence of continental crust at 4.4 to 4.5 Ga: Science, v. 310, p. 1947–1950, doi:10.1126/science.1117926.

Herzberg, C., Condie, K., and Korenaga, J., 2010, Thermal history of the Earth and its petrological expression: Earth and Planetary Science Letters, v. 292, p. 79–88, doi:10.1016/j.epsl.2010.01.022.

Kominz, M., 1984, Oceanic ridge volumes and sea-level change: An error analysis, *in* Schlee, J.S., ed., Interregional unconformities and hydrocarbon accumulation: American Association of Petroleum Geologists Memoir 36, p. 109–127.

Kusky, T.M., Li, J.H., and Tucker, R.D., 2001, The Archean Dongwanzi ophiolite complex, North China craton: 2.505-billion-year-old oceanic crust and mantle: Science, v. 292, p. 1142–1145, doi:10.1126/science.1059426.

Labrosse, S., and Jaupart, C., 2007, Thermal evolution of the Earth: Secular changes and fluctuations of plate characteristics: Earth and Planetary Science Letters, v. 260, p. 465–481, doi:10.1016/j.epsl.2007.05.046.

Lithgow-Bertelloni, C., and Richards, M.A., 1998, The dynamics of Cenozoic and Mesozoic plate motions: Reviews of Geophysics, v. 36, p. 27–78, doi:10.1029/97RG02282.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, p. 1293–1298, doi:10.1126/science.1116412.

Moresi, L., and Solomatov, V., 1998, Mantle convection with a brittle lithosphere: Thoughts on the global tectonic styles of the Earth and Venus: Geophysical Journal International, v. 133, p. 669–682, doi:10.1046/j.1365-246X.1998.00521.x.

Müller, R., Roest, W., Royer, J., Gahagan, L., and Sclater, J., 1997, Digital isochrons of the world's ocean floor: Journal of Geophysical Research, v. 102, p. 3211–3214, doi:10.1029/96JB01781.

Pilger, R.H., 1982, The origin of hotspot traces: Evidence from eastern Australia: Journal of Geophysical Research, v. 87, p. 1825–1834, doi:10.1029/JB087iB03p01825.

Polat, A., Hofmann, A., and Rosing, M.T., 2002, Boninite-like volcanic rocks in the 3.7–3.8 Ga Isua greenstone belt, West Greenland: Geochemical evidence for intra-oceanic subduction zone processes in the early Earth: Chemical Geology, v. 184, p. 231–254, doi:10.1016/S0009-2541(01)00363-1.

Pons, M.L., Quitté, G., Fujii, T., Rosing, M.T., Reynard, B., Moynier, F., Douchet, C., and Albarède, F., 2011, Early Archean serpentine mud volcanoes at Isua, Greenland, as a niche for early life: Proceedings of the National Academy of Sciences of the United States of America, v. 108, p. 17,639–17,643, doi:10.1073/pnas.1108061108.

Rolf, T., and Tackley, P., 2011, Focussing of stress by continents in 3D spherical mantle convection with self-consistent plate tectonics: Geophysical Research Letters, v. 38, L18301, doi:10.1029/2011GL048677.

Rolf, T., Coltice, N., and Tackley, P.J., 2012, Linking continental drift, plate tectonics and the thermal state of the Earth's mantle: Earth and Planetary Science Letters, v. 351, p. 134–146, doi:10.1016/j.epsl.2012.07.011.

Rowley, D.B., and Lottes, A.L., 1988, Plate-kinematic reconstructions of the North Atlantic and Arctic: Late Jurassic to present: Tectonophysics, v. 155, p. 73–120, doi:10.1016/0040-1951(88)90261-2.

Schubert, G., and Reymer, A., 1985, Continental volume and freeboard through geological time: Nature, v. 316, p. 336–339, doi:10.1038/316336a0.

Scotese, C.R., Gahagan, L.M., and Larson, R.L., 1988, Plate tectonic reconstructions of the Cretaceous and Cenozoic ocean basins: Tectonophysics, v. 155, p. 27–48, doi:10.1016/0040-1951(88)90259-4.

Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., and Chandler, M., 2012, Global continental and ocean basin reconstructions since 200 Ma: Earth-Science Reviews, v. 113, p. 212–270, doi:10.1016/j.earscirev.2012.03.002.

Stampfli, G.M., and Borel, G.D., 2002, A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons: Earth and Planetary Science Letters, v. 196, p. 17–33, doi:10.1016/S0012-821X(01)00588-X.

Tackley, P., 2000, Mantle convection and plate tectonics: Toward an integrated physical and chemical theory: Science, v. 288, p. 2002–2007, doi:10.1126/science.288.5473.2002.

Tajika, E., 1998, Climate change during the last 150 million years: Reconstruction from a carbon cycle model: Earth and Planetary Science Letters, v. 160, p. 695–707, doi:10.1016/S0012-821X(98)00121-6.

Taylor, S.R., and McLennan, S.M., 1995, The geochemical evolution of the continental crust: Reviews of Geophysics, v. 33, p. 241–265, doi:10.1029/95RG00262.

van Heck, H., and Tackley, P., 2008, Planforms of self-consistently generated plates in 3D spherical geometry: Geophysical Research Letters, v. 35, L19312, doi:10.1029/2008GL035190.

Yoshida, M., 2010, Temporal evolution of the stress state in a supercontinent during mantle reorganization: Geophysical Journal International, v. 180, p. 1–22, doi:10.1111/j.1365-246X.2009.04399.x.

Zhong, S., Zhang, N., Li, Z., and Roberts, J., 2007, Supercontinent cycles, true polar wander, and very long-wavelength mantle convection: Earth and Planetary Science Letters, v. 261, p. 551–564, doi:10.1016/j.epsl.2007.07.049.

Manuscript received 27 August 2013
Revised manuscript received 26 November 2013
Manuscript accepted 3 December 2013

Printed in USA