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Evolution of the oceanic and continental crust during Neo Proterozoic and Phanerozoic

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Abstract

In present contribution palaeogeographical maps for the time interval 0.6 Ga BP to present are analyzed in terms of (a) the ratio between continental to oceanic crust areas in order to estimate the speed of continental growth, and (b) the surface motion of continental plates under the influence of global forces of tidal friction and Eötvös force (“pole-fleeing”). It is concluded that the area of the continents during the Phanerozoic was growing and it exhibited a rate $\sim 0.5 \text{ km}^3/\text{yr}$. It is also found that beside the westward oriented tidal frictional forces the Eötvös force can play also a role in tectonical processes. It is shown that the continental plates on average tend to find a position close to the equator during the whole investigated 600 Ma time interval.

Keywords

plate tectonic reconstructions, Phanerozoic, motion of continental plates, tidal friction, “pole-fleeing” force or Eötvös force

Introduction

The geodynamical processes underwent changes during the Neo Proterozoic (Ptz) and Phanerozoic (Pz). In this contribution these processes are analyzed on the one hand in terms of the ratio between continental to oceanic crust areas, global sea level change and on the other hand in terms of displacements of continents.

Problems of Earth evolution

According to Belousova et al., 2010 more than 60% of the recent continental crust was formed before 2.5 Ga. The oldest residuums of the continental crust formed before 4 Ga (Bowring and Housh 1995), the oldest known continent (continent Ur) arose (3.0–2.5) Ga (Rogers and Santosh 2002, 2003), the oldest supercontinent was assembled ~2.7 Ga ago. Therefore plate tectonics at that time, i.e. in the late Archean, was operating (Korenaga, 2008).

Independent kinematical observations indicate a global net westward drift of the lithosphere relative to the mantle (Bostrom 1971 and 2000; Yanick et al. 1991; Crespi et al. 2007; Doglioni et al. 2007). It can be concluded that the plates follow an undulating westward mainstream within a geographical latitudinal zone $\varphi = \pm 60^\circ$ (Riguzzi et al. 2010).

According to Piper (2013a) during the Ptz the continental velocities underwent significant variations between 3 cm/yr and 20 cm/yr, first of all due to changes in magmatic and climatic regimes. From examination of paleogeographical maps we concluded that during the Phanerozoic the typical speed of plates was ~10 cm/yr. A viscosity contrast of 8–10 orders of

magnitude would allow a relative motion of the lithosphere over the asthenosphere due to the long-wavelength perturbations at this rate (Doglioni et al. 2011).

Study of map series of plate tectonic reconstructions for the Phanerozoic

Following Varga et al. (2012) we here continue to analyze the series of paleogeographic maps by Blakey (2010) which are related to maps by Scotese (2004). These maps show the location of continents and the distribution of the main linear components of plate tectonics (spreading centres or ridges and subduction zones) during the last 600 Ma. The map series consists of 20 maps (Figure 1), and present the Earth in Mollweide projection, which is an equal-area (equivalent) mapping (Grafarend and Krumm 2006). The method of digitizing of continental coastlines has been described in detail in Varga et al. 2012.

In Figure 2 the global sea level fluctuations (in m) (according to Hallam (1989)), and calculated by us, with the use of paleogeographic maps by Blakey (2010), relative ocean coverage (in %) are reported.

To assess the uncertainty of continental areas during the Phanerozoic our results were compared with results from a series of maps by Monin and Shiskov (1979). These maps were made also with Mollweide projection but on earlier data base. The comparison shows that the ratio between the areas covered by continental and oceanic crusts do not differ by more than 10 % from those obtained for the recent maps of Blakey (2010) (Table 1).

It should be mentioned, that our interpretation of digitalization of the maps are based on the long-term trend of the investigated paleo-tectonic phenomena; the deviations from the trend, shown by the data in Figure 2 are considered in the present study as random changes.

Area of continental crust and sea level fluctuations during Pz and before

The sea level values of Figure 2 were calculated from the widely used Exxon reconstructions (Haq et al. 1987; Ross and Ross 1988) by averaging the data in a ± 20 Ma window. It is remarkable that according these reconstructions the global eustatic sea level during the Pz was always above the contemporary level.

In order to investigate the trend of the sea level during Pz we used the regression line $P=a \cdot t+b$, where P [m] is the global sea level fluctuation and t [Ma] the time BP. The coefficients a and b are slope and intercept, estimated by least-squares inversion as $\hat{a} = -0.07$ [m/Ma] and $\hat{b} = 121.4$ [m], with estimated standard errors $\hat{\sigma}_{\hat{a}} = \pm 0.1$ [m/Ma]

and $\hat{\sigma}_b = \pm 37.6$ [m]. The question whether the slope estimate \hat{a} reflects a significant trend in the change of global sea level fluctuation has been verified using a statistical hypothesis test (Koch 1999). Assuming identically normally distributed data the test statistics $T := \hat{a}^2 / \hat{\sigma}_a^2 = 0.4$ follows an F-distribution with 17 degrees of freedom. Using a confidence

level of $\alpha=5\%$ the null hypothesis $H_0: a = 0$ is accepted on the basis of the critical value $F_{0.05}(1,17)=4.4$.

Our results (Figure 2), show that during the Phanerozoic, the ratio between the areas covered by continental and oceanic crust underwent a clearly monotonous change. The regression line approximation $P=at+b$ with P [%] being the part of the Earth covered by oceans gives estimates $\hat{a} = -0.011 \pm 0.0025$ [%/Ma] and $\hat{b} = 71.16 \pm 0.85$ [%]. For the reason that the test statistics $T := \hat{a}^2 / \hat{\sigma}_a^2 = 19.3$ is far beyond the critical value $F_{0.05}(1,18)=4.4$ we can conclude a statistically significant growth of the continental crust, which is $\sim 7\%$ of the global surface of the Earth from 600 Ma to present.

The area covered by continental crust has been growing during the Pz by ~ 35 million square kilometres (which is 7% of the 5.1×10^8 km² surface area of the Earth). Large granite plutons become important after 2.6 Ga BP (Condie 2011). If the continental growth factor obtained for the Pz ($\sim 1.1\%$ of the earth surface/100 Ma), what of course is not likely, remains valid also for the Proterozoic and Archean at that time the continental crust occupies 10% of the Earth's surface, and the crust was almost completely mafic ~ 3 Ga. In the same time at present two remaining ancient formations are existing (the Kaapvaal craton in South Africa and the Pilbara craton in Western Australia) with granite-greenstone terranes of Early – Middle Archean and they present area is $\sim 10^7$ km² (Zegers et al. 1998). Probably the size of the early granite plutons was considerably higher 3 billion yr ago.

Motion of continental plates under the influence of global forces

Beside local driving forces (true polar wander, ridge push, slab pull) (Kent, 1997; Tanimoto and Lay, 2000; Turcotte and Schubert 2002) the drift of tectonic plates are highly determined by the global forces connected to axial rotation (Bostrom 1971 and 2000; Yanick et al. 1991; Crespi et al. 2007; Doglioni et al. 2007). The magnitude of these forces, to some extent, decreased with time due to axial despinning of Earth's rotation and due to a decrease in the flattening. The angular speed 500 Ma ago was $\sim 17.25^\circ/\text{h}$ and its recent value is $= 15.00^\circ/\text{h}$. The assumed value of the flattening 500 Ma ago is $f=4.43 \cdot 10^{-3}$ while presently it is $f=3.35 \cdot 10^{-3}$ (Varga 2006).

One of the forces mentioned before is the tidal friction, which produces a westward drift of the continental plates and which is strong enough to serve among the driving mechanisms of plate tectonics (Denis et al.; 2002; Riguzzi et al., 2010). The second force which possibly able to move the plates is the “pole-fleeing” force, caused by the horizontal component of the centrifugal acceleration, due to Earth’s spinning. This force was first mentioned by Eötvös

(1913). Therefore it is often called as “Eötvös force“ also. Caputo (1986), Gasperini (1993) Gasperini and Chierici (1996) have published valuable papers on this topic. They supposed that the tangential acceleration acting along the meridian is due to an anomalous density of the lithosphere “floating” upon a flattened asthenosphere acting as fluid. If the density anomaly is negative, which is typical for the Earth, the force is oriented towards the equator and in case of a positive anomaly towards the poles. In the paper by Goedecke and Ni (1991) “the effective Eötvös tangential basal stress on the lithosphere is equatorward if the lithosphere-asthenosphere boundary is underflattened”. This condition is fulfilled in the case of Earth in the present epoch (Morrow et al., 2012) and it was so probably in the past, too. The common feature of these theories is that they are functions of $\sin 2\theta$ (θ is latitude in case of Caputo (1986) and Gasperini (1993) and colatitude in contribution by Goedecke and Ni (1991)). This means that the Eötvös acceleration is zero at the poles and at the equator, and it has an equator oriented maximum at middle latitudes.

The energy dissipated in the Earth due to tidal friction is $1.2 \cdot 10^{20}$ J/yr (Riguzzi et al., 2010).

Most of this dissipation occurs in the oceans ($0.75 \cdot 10^{20}$ J/yr) and a smaller part in the mantle ($0.42 \cdot 10^{19}$ J/yr). The residual energy ($0.4 \cdot 10^{20}$ J/yr) is sufficient to move the lithospheric plates. On the other hand the energy rate dE/dt for the lateral displacement of a circular plate (with diameter 10^9 cm and thickness 10^7 cm) relative to the viscous mantle $=10^{22}$ Poise ($1P=0.1Pa \cdot s$) with angular (lateral) speed $=1.7^\circ/yr \cdot 10^{-6}$ ($v=2cm/yr$) is $=1.27 \cdot 10^{19}$ J/yr (Riguzzi et al. 2010). Hence it can be concluded that the westward oriented tidal friction can play a significant role in tectonic processes.

What is the relative importance of the tidal despinning versus the “pole-fleeing” forces? This question can be clarified by comparing accelerations generated by these two forces. From Caputo (1986) and Gasperini (1993) it follows that the maximum Eötvös acceleration is $a_E \leq 2 \cdot 10^{-5} m/s^2$. In the same time the lateral acceleration of the tidal bulge can be given as (Gasperini, 1993) $a_T = -2GM_M R d^{-3} \cos \varepsilon \sin \varepsilon$, where G is the gravitational constant ($6.674 \cdot 10^{-11} m^3 kg^{-1} s^{-2}$), M_M the mass of the Moon ($7.348 \cdot 10^{22} kg$), R the radius of the Earth ($6.370 \cdot 10^6$ m), and d the mean distance of the centres of the Earth and Moon ($3.844 \cdot 10^8$ m). The phase delay of the Earth’s bulge ε can be obtained from the time derivative of the Earth-

Moon distance as $\varepsilon=0.5\arcsin(k_2^{-1}\cdot\partial d/\partial t)$, where $k_2=0.29$ is the Love number and $\partial d/\partial t=2.06$ m·s⁻¹ for the Phanerozoic. From this $\varepsilon=-6.8^\circ$ and $a_T\sim 10^{-5}$ m/s² can be calculated for Pz, and therefore it can be concluded that $a_T\sim a_E$.

It was shown earlier that the tidal despinning can influence the plate displacements. Now we try to show the influence of the Eötvös force on the time-dependent location of continents

using the digitized paleogeographical maps. For this purpose the paleogeographical maps were subdivided into zones of 30° latitudinal width where the part of relative global continental coverage (in %) was calculated (Figures 3, 4). It can be seen, that the latitudinal distribution of continents was rather uniform during the last 0.6 Ga. The continents tend to find a position close to equator: the coverage in the area between $\pm 30^\circ$ latitudes is roughly 4 times higher than in the polar regions. The continental distribution is to some extent asymmetrical, it has its maximum at the south latitude 15° (see the average curve of Figure 4). The curves of Figure 3 show secondary phenomena: the continents were slightly shifted to the north in the course of time. This process seems to be fairly clear in mid-latitude zones since 450 Ma.

Discussion

Research results described in previous sections are based on accurate digitizing the paleogeographic maps with the use of a special software described in Varga et al. (2012). Mathematical processing and interpretation of digitized data made possible to investigate some of the features of growth and displacement of continental plates during the Phanerozoic. The evolution of continental crust is one of the questions that remain unresolved in the geosciences. With the tools used here conclusions can be made regarding the magnitude of the growth of continental crust. We draw the inference that the growth of the continents during the Phanerozoic was a continuous process. It had a rate ~ 0.5 km³/yr with an average continental crust total thickness of 40 km. A similar result was obtained by Dhuime et al. (2012) with the use of uranium-lead and hafnium isotopic data. It was mentioned already that Belousova et al. (2010) found that more than 60% of recent continental crust is older than 2.5 Ga. This fact can be consistent with the trend observed by us for Pz only if a slower crust formation is adopted for the period 2.5-0.6 Ga, what can also mean that during the Proterozoic the nature of the tectonic processes differed from those of Phanerozoic as it was concluded by Piper (2013b). Therefore in case of crust formation also the acceleration of geodynamic processes must be assumed close to the end of Ptz, which may be associated with crust forming orogeny of this time (Rino et al., 2008; Griffin et al, 2009).

The resolving capabilities of databases used for aims of present research allowed statistically significant determination of the linear trends of sea level and growth of the continental crust

from 600 Ma to present. It was found that there is no established linear trend in global sea level fluctuation but a significant growth of the continental crust was detected for the whole Phanerozoic. This result can be important in the light of the present studies of subduction of continental lithosphere reported recently in many papers (e.g. Motaghi et al., 2014; Zhang et al., 2014). At the same time an antiphase correlation can be seen between the sea level

variation and relative area covered by oceanic crust, starting from about 200 Ma to present (Figure 2). This negative correlation can be very interesting for interpretation of the tectonic processes acting at plate boundaries. Unfortunately with the use of our current databases this phenomenon can not be justified yet. Authors' intention is the examination of this issue in the near future with the use of more detailed databases.

In the second part of our study the surface motion of continental plates was investigated under the influence of global forces. These forces determined by the axial spin of our planet are tidal friction and the pole-fleeing force. They are – contrary to geological forces – of external origin, their magnitude is more or less monotonously diminished in the Earth's history due to a decrease in rotational speed. The tidal despinning generates a westward drift whose contribution to geodynamical processes is recognizable (Crespi et al. 2007; Doglioni 2007, 2008, 2011). It was shown earlier by (Riguzzi et al. 2010) that the magnitude of the residual tidal energy is significant among driving forces which move the lithospheric plates. A comparison of accelerations generated by the tidal friction and by the Eötvös force shows that these two values are equal. At first glance, these two values are low for a principal driving force of plate tectonics. The extent of this effect, however, should not be judged without knowing the decoupling between crust and mantle. Doglioni et al. (2011) have shown that with the right model of [lithosphere-asthenosphere viscosity contrast and decoupling](#), the impact of westward drift may become significant in the tectonic processes. At the same time it can be assumed that the Eötvös force also played a role in keeping the overwhelming part of the continents far away from the poles throughout Pz. Over the whole studied 0.6 Ga time interval the area of continents was four times greater in the latitudinal zone than in the polar regions (Figure 4). This phenomenon was complicated by a northward movement of continents (Figure 3) since about 450 million yr which still waiting for its explanation.

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| Time BP | Area covered by oceanic crust in % | |
|---------|------------------------------------|-------------------------|
| | Blakey, 2010 | Monin and Shiskov, 1979 |
| 560 | 71 | 73 |
| 470 | 70 | 72 |
| 380 | 69 | 72 |
| 335 | 69 | 72 |
| 280 | 68 | 67 |
| 205 | 67 | 72 |
| 148 | 63 | 59 |
| 90 | 66 | 60 |
| 0 | 67.9 | 70.5 |

Table 1. Comparison of map series compiled by Blakey (2010) and Monin and Shiskov (1979) for the Phanerozoic in case of relative area covered by oceanic crust (see also Varga et al. 2012).

Figure captions

Figure 1. Paleogeographic maps for the late Proterozoic and Phanerozoic (Blakey 2010)

(1. Late Precambrian, 600 Ma BP; 2. Early Cambrian, 550 Ma BP; Middle Cambrian, 510 Ma BP; Early Ordovician, 480 Ma BP; Late Ordovician, 450 Ma BP; Middle Silurian, 430 Ma BP; Early Devonian, 400 Ma BP; Late Devonian, 370 Ma BP; Early Mississippian, 340 Ma BP; Late Pennsylvanian, 300 Ma BP; Early Permian, 270 Ma BP; Late Triassic 220 Ma BP; Early Jurassic, 200 Ma BP; Middle Jurassic, 160 Ma BP; Late Jurassic, 150 Ma BP; Late Cretaceous, 80 Ma BP; Late Eocene, 40 Ma BP; Early Miocene, 20 Ma BP; Present Epoch).

Figure 2. Relative oceanic crust coverage (Varga et al. 2012) and global sea level fluctuations (Hallam 1989) from 600 Ma to present.

Figure 3. Temporal variation (in %) of areas occupied by continental crust in different latitudinal zones.

Figure 4. Areas (in %) of latitudinal zones covered by continental crust in different epochs of Late Proterozoic and Phanerozoic and the average distribution.

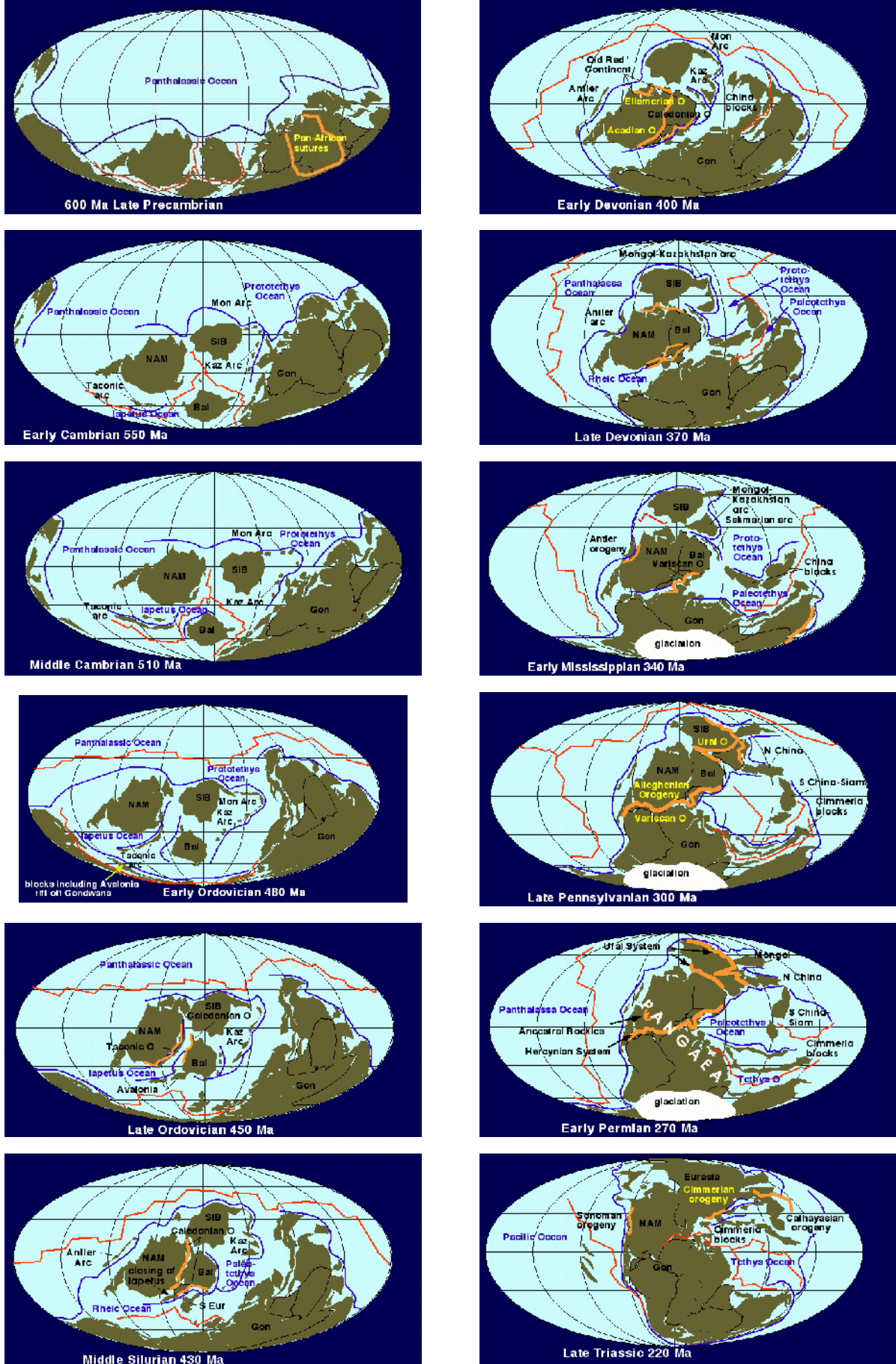


Figure 1.

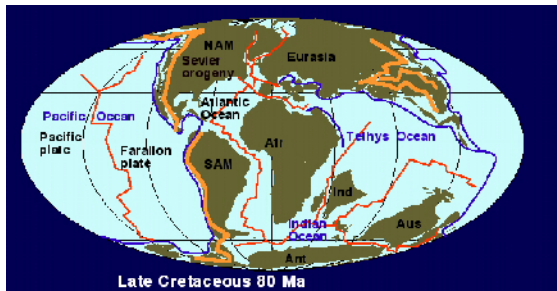
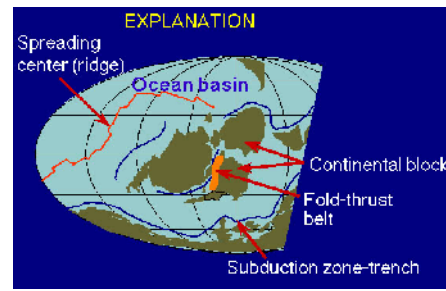
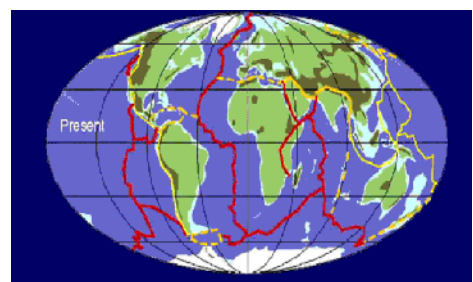
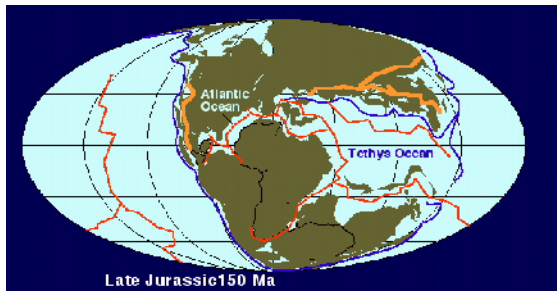
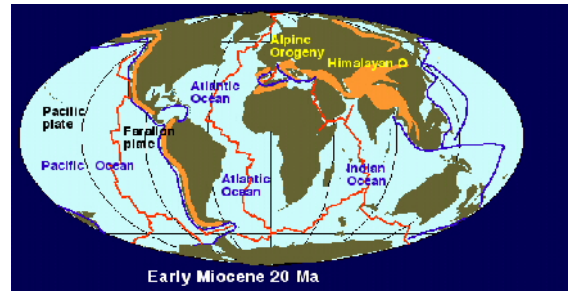
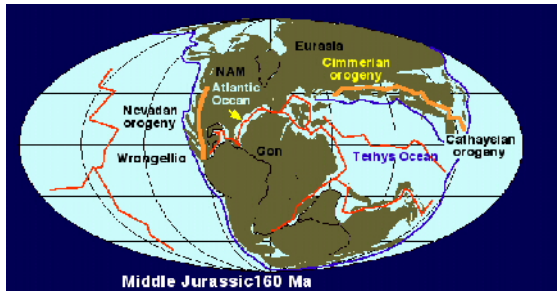
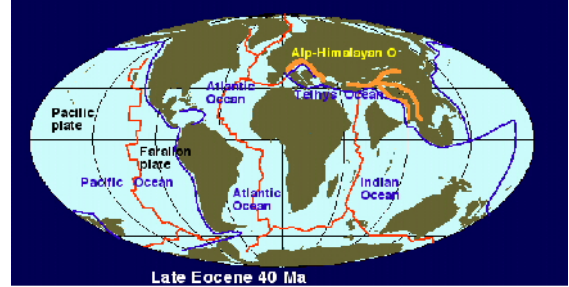
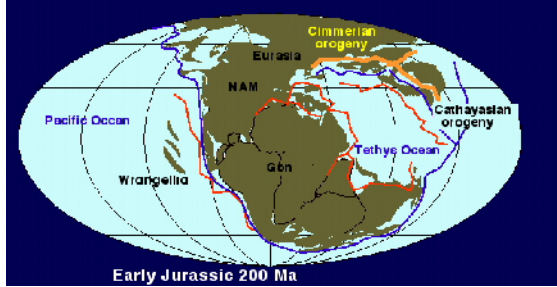


Figure 1. (Continuation)

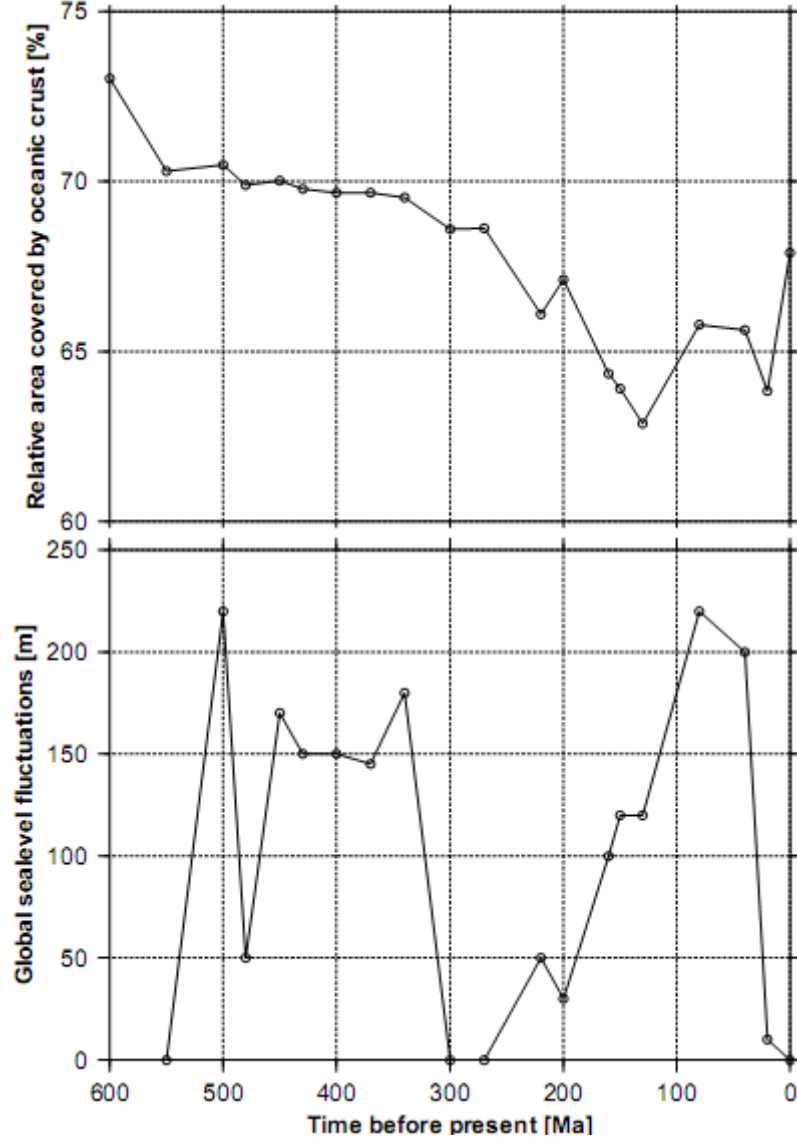


Figure 2.

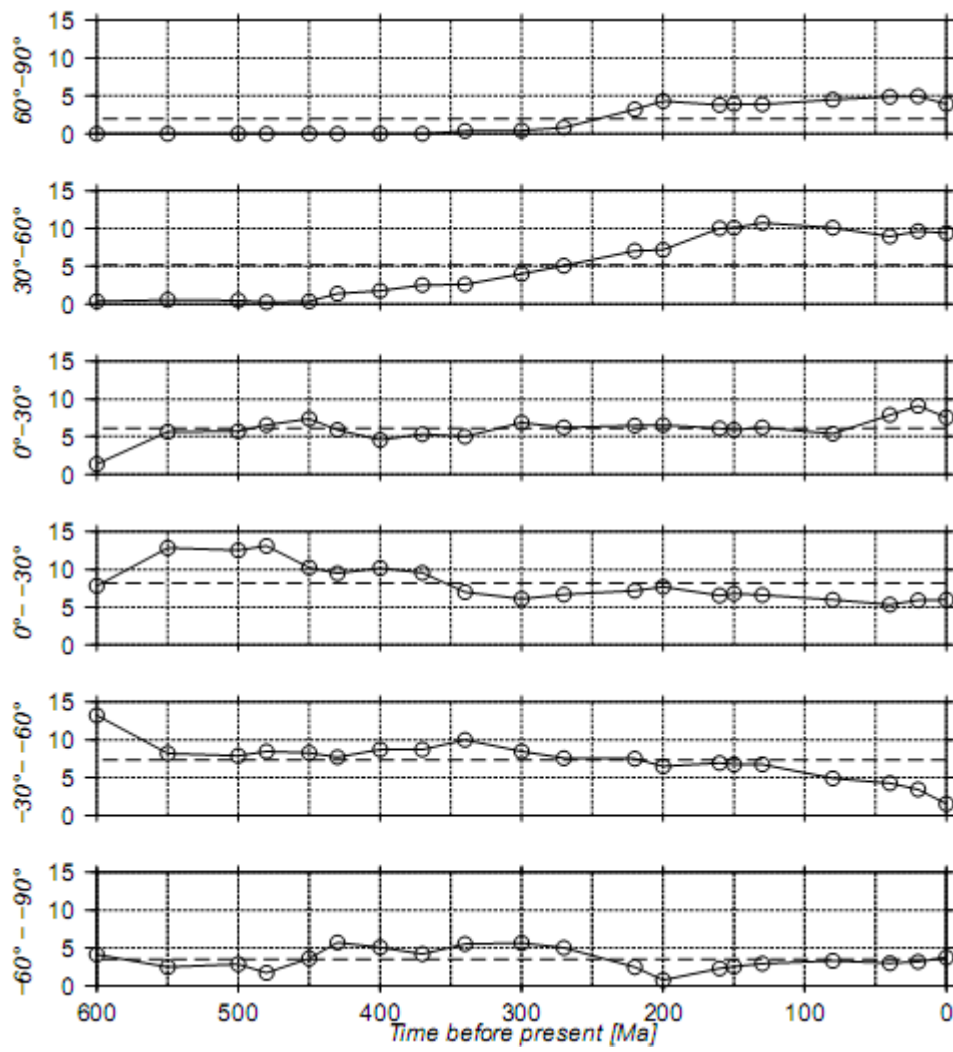


Figure 3.

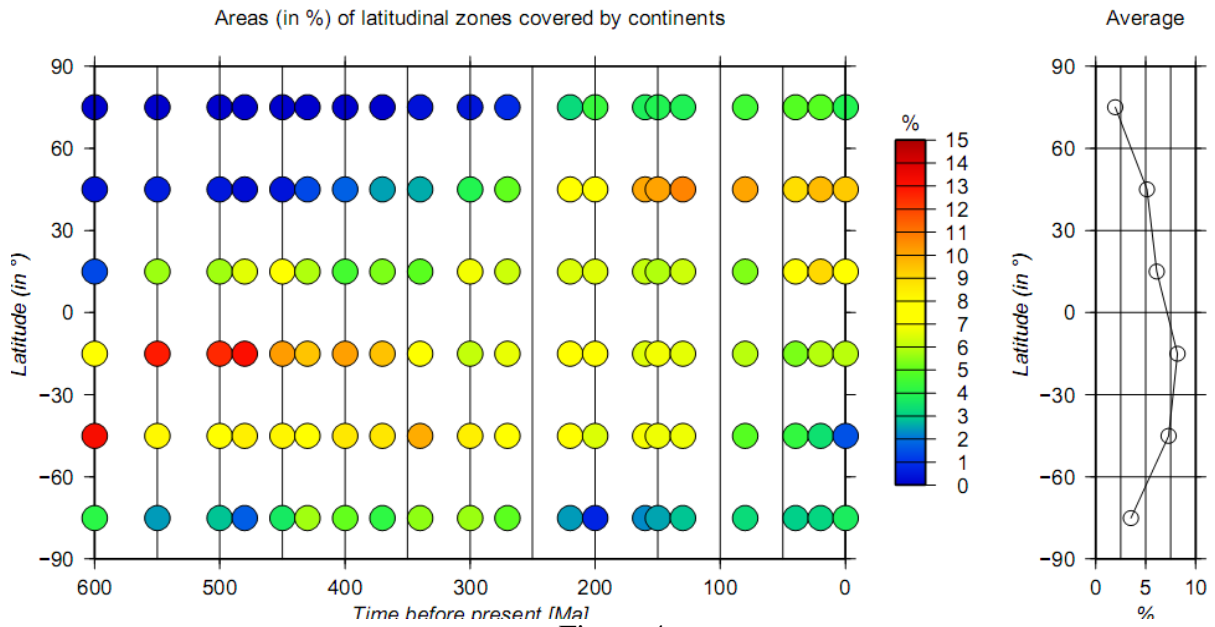


Figure 4.

