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Organization of the tectonic plates in the last 200 Myr

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ABSTRACT

The present tessellation of the Earth's surface into tectonic plates displays a remarkably regular plate size distribution, described by either one (Sornette and Pisarenko, 2003) or two (Bird, 2003) statistically distinct groups, characterised by large and small plate size. A unique distribution implies a hierarchical structure from the largest to the smallest plate. Alternatively, two distributions indicate distinct evolutionary laws for large and small plates, the first tied to mantle flow, the second determined by a hierarchical fragmentation process. We analyse detailed reconstructions of plate boundaries during the last 200 Myr and find that (i) large and small plates display distinct statistical distributions, (ii) the small plates display little organisational change since 60 Ma and (iii) the large plates oscillate between heterogeneous (200–170 Myr and 65–50 Ma) and homogeneous (120–100 Ma) plate tessellations on a timescale of about 100 Myr. Heterogeneous states are reached more rapidly, while the plate configuration decays into homogeneous states following a slower asymptotic curve, suggesting that heterogeneous configurations are excited states while homogeneous tessellations are equilibrium states. We explain this evolution by proposing a model that alternates between bottom- and top-driven Earth dynamics, physically described by fluid-dynamic analogies, the Rayleigh–Benard and Bénard–Marangoni convection, respectively. We discuss the implications for true polar wander (TPW), global kinematic reorganisations (50 and 100 Ma) and the Earth's magnetic field inversion frequency.

1. Introduction

Plate tectonic cycles occur at several timescales, with seismic cycles on the order of hundreds to thousands years, and tectonic cycles of several hundreds of million years for the formation and break-up of supercontinents (Wilson cycle) such as Pangea and Rodinia. Regional plate tectonics is driven by subduction, in which slabs require 5–15 Myr to reach the boundary between the Earth's upper and lower mantle; a time period also required to open back-arc basins (Faccenna et al., 1996; Fukao et al., 2009; Stegman et al., 2010). The intermediate timescale between tens and hundreds of million years is not yet well understood. In this timeframe, apparent polar wander studies and plate reconstructions have identified plate reorganisations at intervals of about 50 Myr (Torsvik et al., 2008a), and sea-level studies have identified cycles at the timescale of 10–100 Myr (Miall, 1990). Yet the geodynamic origin of these observations is still unclear. Here we use a statistical analysis of the tessellation of rigid plates of the Earth's surface in the past to explore the dynamics governing this timescale.

The Pacific plate is the largest tectonic plate on Earth and its boundaries host the majority of subduction zones and earthquakes. The second largest plate, Africa, is at the antipode of the Pacific and is mostly surrounded by mid-ocean ridges. Each of them is located above one of the two low velocity zones at the bottom of the lower mantle, usually associated with a superswell caused by thermal anomaly (Schuberth et al., 2009) or compositional differentiation (van der Hilst and Kárason, 1999). Such a bimodal configuration is illustrated by the Earth's plate tessellation in Fig. 1, based on the dataset in Gurnis et al. (2012), where the grey intensity is proportional to plate size. Combined with another six major plates (Eurasia, Australia, Antarctica, North and South America, and Nazca) these eight large plates cover most of the surface of the Earth. Whether this configuration is coincidental, due to inter-plate stresses or an outcome of the Earth dynamics is topic of research (Anderson, 2002; Grigné et al., 2007; Lowman, 2011; O'Neill et al., 2008, 2009, Zhong et al., 2007).

The remaining plates are one or more orders of magnitude smaller and their size follows a statistical distribution (Pareto Law) which may reflect some sort of fragmentation mechanism (Bird, 2003; Sornette and Pisarenko, 2003). Complex processes such as fragmentation are often revealed by geometrical self-similarity, where a recurring pattern occurs over a wide range of scales. Such a multiscale property is conventionally described by a power-law, a function of the form $S(x) \propto x^{-1/\alpha} = x^{-\beta}$ where S is the observable at

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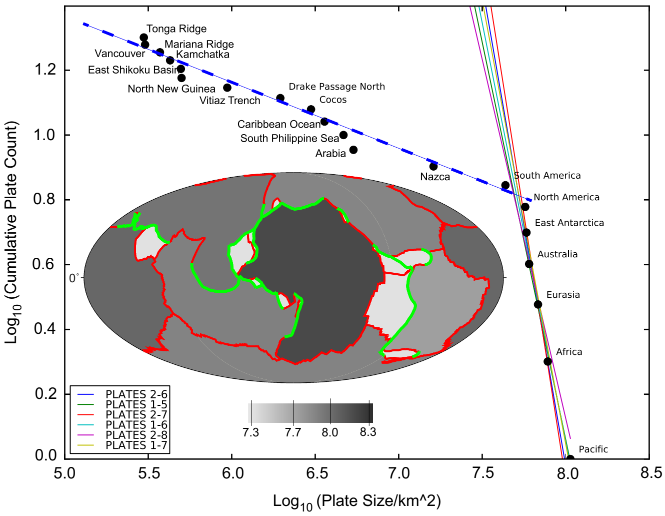

Fig. 1. The planetary map represents the Earth's present tessellation. Grey scale intensity is proportional to the logarithm of plate size. Green boundary lines indicate convergent margins while red lines show the location of spreading boundaries. The map illustrates the polarity of the tectonic system in which the two greatest plates, the African and Pacific, are at the antipodes of one another. The plot represents the logarithm of complementary "cumulative plate count" (Y-axis) vs. the logarithm of the plate size (X-axis) of the 22 plates shown in the global map (data from Gurnis et al. (2012)). The coloured lines are based on 5 fits of overlapping subsets of plates. Two regimes are identifiable: (i) below log(Size)~7.5 the small plates follow a power-law with an exponent α~3–5, (ii) the largest 6–7 plates follow a steeper slope with $\alpha=0.3$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

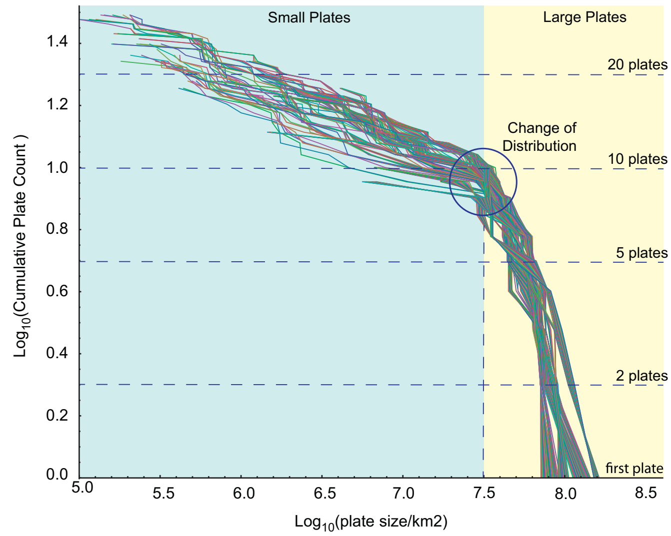

Fig. 2. Plot of the logarithm of the plate size vs. logarithm of complementary "cumulative plate count", as in Fig. 1, for each reconstructed plate tessellation in the past 200 Myr. The number of reconstructed plates (Seton et al., 2012) decreases towards the past from 31 at Present time down to only 10 at 200 Ma (detailed plot in the Supplementary material). The distinction between the large and small plates distributions is observed at any time. The critical plate size at which the distribution changes is about $10^{7.5}$ km^2, slightly less than the square of the Earth radius (6371 km)^2 and Cumulative Plate Count equal to 8..

the scale x and the exponent α (and its inverse β) is a scale-independent coefficient. The simplest way to determine α is by quantifying the slope of the straight line that characterises its log–log representation. Bird (2003) analysed the relationship between *plate area A* and *cumulative plate count N*(A) (the number of plates with area greater than A) for his highly refined database composed of 42 plates, obtaining the best fit $N(A)\propto A^{-1/\alpha}=A^{-\beta}$ with α~4 (β~0.25). In Fig. 1 we perform the same analysis on a different dateset of reconstructed plate boundaries in the past 140 Myr (Gurnis et al., 2012) and obtain a very similar result for the small plates at present time ($\beta_{SP}=0.22$). An even more detailed dataset has been put forward for the last 200 Myr (Seton et al., 2012), showing the same result. We will refer to this most recent dataset in the rest of the paper (Fig. 2).

It has been debated whether the distribution of the largest plates may reflect the same process proposed for the smaller ones (e.g. Bird, 2003; Fig. 19). If they follow a different distribution, this must reflect the complex interaction between surface plate motion and mantle convection. Fig. 1 already suggests that the large plates form a distinct statistical group; however such a small number of data points do not provide sufficient evidence. In effect it has been shown by Sornette and Pisarenko (2003) that a modified Pareto Law, corrected for the finite size of the Earth, would absorb the observed "kink" between the two distributions. In this work we resolve this controversy by analysing the tessellation formed by plate boundaries in the past 200 Myr, showing that the kink is a permanent feature in time, therefore not due to a fluctuation in the statistics as suggested by Sornette and Pisarenko (2003). We employ this result to obtain new insights on the evolution of the Earth's mantle and global tectonics.

2. Analysis of the tectonic reconstructions

Kinematic reconstructions are built upon a wealth of unrelated geological and geophysical data, making a precise quantification of the uncertainties extremely difficult. Stronger constraints exist for the past 100 million of years, for which the finite rotations of the plates are reconstructed using ocean-floor magnetic lineations. A recent estimation of the errors involved in the identification of the timing associated to each isochrone finds no more than few million years (Iaffaldano et al., 2012). The uncertainty associated with the physical location of plate boundaries is greater and reaches one hundred of kilometres (e.g. by multiplying the time uncertainties by the fastest plate velocities: 1 Myr × 10 cm/yr = 100 km). Completely vanished basins cannot be directly identified, but plate boundary inception and cessation can be traced at subduction zones, allowing further constraints on the ancient geometry of the reconstructed plates.

Another source of uncertainty is the true-polar wander (TPW) correction. Before 100 Ma we adopted a TPW correction based on paleomagnetic models (Torsvik et al., 2008a). More details have been published in methodological and review papers (Gurnis et al., 2012; Seton et al., 2012). Although a complete estimation of the errors associated with the reconstruction is not yet possible, we have taken the maximum care in testing the effect of different reconstructions presenting here only the most robust results. We do not interpret the statistics of the small plates earlier than 60 Ma because the number of small plates is too small. For the large plates we analyse only the main statistical features (mean and standard deviation). Any bias in the plate size data is excluded because the boundary model used in this work has been developed totally independently.

2.1. One or two plate size distributions

Fig. 2 shows the relationship between *plate area A* and *cumulative plate count N*(A), as in Fig. 1 for present time, at every million years for the past 200 Myr based on the most recent tectonic reconstruction (Seton et al., 2012). Despite the noise in the data and the uncertainties in the oldest reconstructions, the distribution remains remarkably stable for the past 200 Myr. Furthermore the distinction between large and small plates is always present, at about $\log_{10}(N(A))=0.9$, which corresponds to