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Tectonic speed limits from plate kinematic reconstructions

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A B S T R A C T

The motion of plates and continents on the planet's surface are a manifestation of long-term mantle convection and plate tectonics. Present-day plate velocities provide a snapshot of this ongoing process, and have been used to infer controlling factors on the speeds of plates and continents. However, present-day velocities do not capture plate behaviour over geologically representative periods of time. To address this shortcoming, we use a plate tectonic reconstruction approach to extract time-dependent plate velocities and geometries from which root mean square (RMS) velocities are computed, resulting in a median RMS plate speed of ∼4 cm/yr over 200 Myr. Linking tectonothermal ages of continental lithosphere to the RMS plate velocity analysis, we find that the increasing portions of plate area composed of continental and/or cratonic lithosphere significantly reduces plate speeds. Plates with any cratonic portion have a median RMS velocity of ∼5.8 cm/yr, while plates with more than 25% of cratonic area have a median RMS speed of ∼2.8 cm/yr. The fastest plates (∼8.5 cm/yr RMS speed) have little continental fraction and tend to be bounded by subduction zones, while the slowest plates (∼2.6–2.8 cm/yr RMS speed) have large continental fractions and usually have little to no subducting part of plate perimeter. More generally, oceanic plates tend to move 2–3 times faster than continental plates, consistent with predictions of numerical models of mantle convection. The slower motion of continental plates is compatible with deep keels impinging on asthenospheric flow and increasing shear traction, thus anchoring the plate in the more viscous mantle transition zone. We also find that short-lived (up to ∼10 Myr) rapid accelerations of Africa (∼100 and 65 Ma), North America (∼100 and 55 Ma) and India (∼130, 80 and 65 Ma) appear to be correlated with plume head arrivals as recorded by large igneous province (LIPs) emplacement. By evaluating factors influencing plate speeds over the Mesozoic and Cenozoic, our temporal analysis reveals simple principles that can guide the construction and evaluation of absolute plate motion models for times before the Cretaceous in the absence of hotspot tracks and seafloor spreading histories. Based on the post-Pangea plate motions, one principle that can be applied to pre-Pangea times is that plates with less than ∼50% continental area can reach RMS velocities of ∼20 cm/yr, while plates with more than 50% continental fraction do not exceed RMS velocities of ∼10 cm/yr. Similarly, plates with large portions of continental or cratonic area with RMS velocities exceeding ∼15 cm/yr for more than ∼10 Myr should be considered as potential artefacts requiring further justification of plate driving forces in such scenarios.

1. Introduction

The configuration and motion of plates on Earth's surface is an intrinsic manifestation of plate–mantle coupling and of the evolving heat engine of our planet's interior. The complex interaction of plate boundary forces results in plate motions dictated by the dominance of slab pull and ridge push forces (Forsyth and Uyeda, 1975), as well as the effects of mantle drag (Conrad and Lithgow-Bertelloni, 2006) and radial viscosity contrasts (Phillips and Bunge, 2005). The accurate present-day measurement of plate velocities (Fig. 1A) relies on satellite observations (especially useful for deforming regions), and is supplemented by young oceanic magnetic anomaly identifications and continental Quaternary fault offsets (DeMets et al., 2010; Kreemer et al., 2014). Plate velocities in the geological past rely on well-constrained relative plate motions from magnetic anomaly identifications, as well as plate circuits that link relative plate motions to an absolute reference frame (see Torsvik et al., 2008). However, plate reconstructions using seafloor magnetic anomaly identifications extend only to the time of Pangea, as very little in-situ oceanic lithosphere is preserved from earlier times. To take advantage of the post-Pangea

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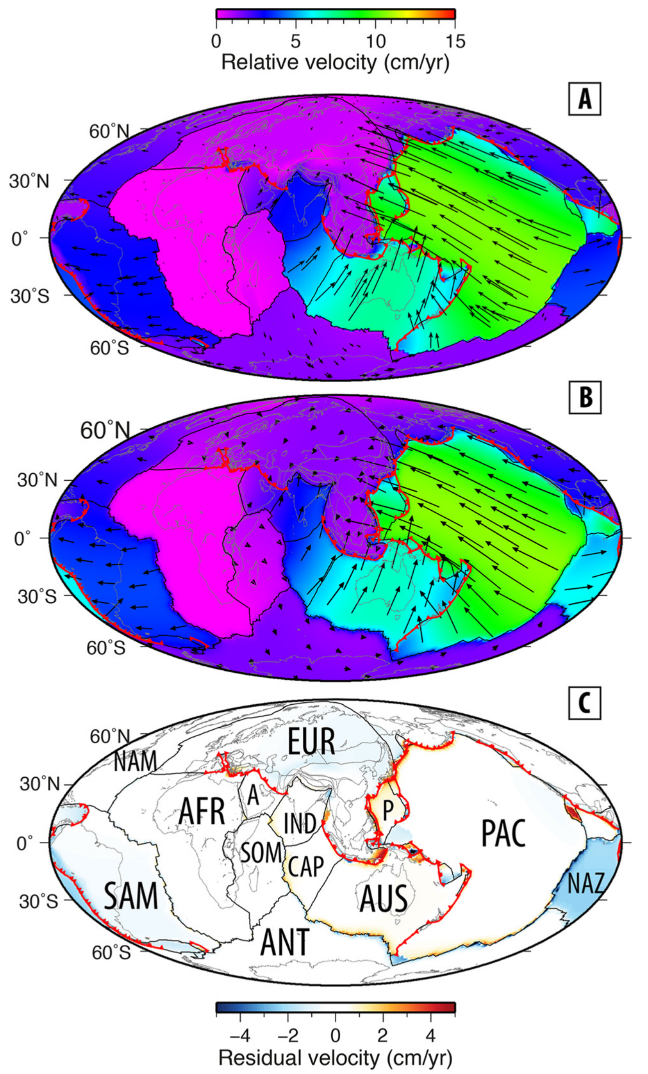

Fig. 1. A) Geologically-current velocities from GPS stations, Quaternary fault offset rates and youngest magnetic anomaly identifications in the oceans from GSRM-v2.1 (Kreemer et al., 2014) B) compared to the present-day plate velocities predicted by the Seton et al. (2012) plate motion model with Africa (Nubia) fixed with plate boundaries (subduction zones: teethed lines, mid oceanic ridges/transforms: black lines), C) The residual (A–B) plate velocities highlight the differences resulting from the assumption of plate rigidity in the plate reconstruction (B), as well as artefacts near plate boundaries arising from slightly different plate boundary geometries. In addition, the Nazca (NAZ) and Philippine Sea (P) plates are up to 2 cm/yr different than the geologically current plate velocities. Major plate abbreviations: A, Arabian; ANT, Antarctic; AUS, Australian; CAP, Capricorn; EUR, Eurasian; IND, Indian; NAM, North American; NAZ, Nazca; SAM, South American; P, Philippine Sea; SOM, Somalian.

seafloor spreading record, we use a plate reconstruction approach to evaluate factors affecting the speed of plate motions, including the effects of continents, cratons, subduction zones and plume head arrivals in the Mesozoic and Cenozoic. Although ridge push is an important plate boundary force, it is largely secondary to the dominant slab pull (Forsyth and Uyeda, 1975), and for this reason we do not investigate the role of effective ridge lengths in this study.

We harness decades of data collection and identification of seafloor magnetic anomalies, and their incorporation into global plate reconstructions (Seton et al., 2012) that capture plate motions and plate boundary evolution. We test the findings of Stoddard and Abbott (1996) that Archean lithosphere impedes plate motions, while Proterozoic lithosphere promotes higher plate velocities in a time-dependent plate reconstruction context. Using the global plate reconstruction approach, we are able to extract statistics for the last 200 Myr, increasing the sample size from a handful of plates at present-day to 85 distinct plates over the post-Pangea timeframe, resulting in a total 3952 samples of plate behaviour. Our results not only have first-order implications for our understanding of plate tectonics, but can guide the construction and evaluation of pre-Pangea plate motion models (e.g., Domeier and Torsvik, 2014) for which no in-situ oceanic lithosphere is preserved, thus requiring the creation of synthetic plates from geological proxies.

1.1. Plate velocities from plate reconstructions

A number of key studies have investigated the factors affecting plate velocities, including the modulating effects of plate, continental and cratonic areas (Gordon and Jurdy, 1986; Solomon et al., 1977; Stoddard and Abbott, 1996). These early studies were limited by the sample size of plate speed measurements – for example, present-day plate velocities from eight plates (Australia was deemed an outlier) were analysed by Stoddard and Abbott (1996) who suggested that deep Archean keels result in slower-moving plates while conversely suggesting that Proterozoic lithosphere likely had a positive feedback on plate velocities.

The general approach of using present-day data alone would be sufficient assuming that the instantaneous plate configurations and velocities are representative of Phanerozoic and older plate tectonics. It is therefore essential to incorporate post-Pangea plate tectonic reconstructions to capture plate behaviour over a geologically representative period of time that is constrained largely by seafloor spreading histories. Solomon et al. (1977) pioneered such an approach, and analysed global plate velocities for the present-day and a single plate reconstruction at 55 Ma, which captured the very fast northward motion of India towards Eurasia. The convergence between India and Eurasia is ∼5 cm/yr at present, while at ∼55 Ma was up to 19 cm/yr (Zahirovic et al., 2012), highlighting the contrast between recent and past plate velocities. A similar approach with increased temporal resolution using six stages bounded by 56, 48, 43, 25, 10 and 0 Ma was incorporated by Gordon and Jurdy (1986), whose results suggested that oceanic plates move faster than continental plates.

Similarly, Schult and Gordon (1984) applied a time-dependent approach and computed the root mean square (RMS) velocities for continental blocks at 180, 144, 123, 83, 48 and 37 Ma to find that continents have moved faster in the past, and that oceanic plates have higher RMS velocities than continental plates. Although Schult and Gordon (1984) find that continental area and RMS plate velocities are inversely correlated, their results suggested that continental keels were unlikely to greatly resist plate motions because some continental plates (e.g., India) had moved more rapidly in the past. However, the small number of time-steps resulted in averaging over long time intervals where plate motions may have changed rapidly, such as rapid accelerations and decelerations of India (van Hinsbergen et al., 2011b), as well as major plate reorganisations over a few million years (Matthews et al., 2012).

1.2. Cratons and their effect on plate velocities

An early review of the continental tectosphere by Jordan (1975) established, from seismic wave experiments and heat flow modelling, that continental keels protrude several hundred kilometres into the convecting mantle. In the same year, Forsyth and Uyeda (1975) quantified forces acting on tectonic plates, concluding that continents impede plate motion likely because of the higher viscosities beneath them and their possible anchoring role. However, it has been difficult to consistently map and characterise lithospheric thicknesses globally to isolate the effect of cratonic keels