Earth and Planetary Science Letters 458 (2017) 349–356

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Impact of uncertain reference-frame motions in plate kinematic reconstructions: A theoretical appraisal

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ARTICLE INFO

Article history:
Received 7 April 2016
Received in revised form 28 October 2016
Accepted 1 November 2016
Available online 17 November 2016
Editor: P. Shearer

Keywords:
finite rotations
reference frames
plate motions

ABSTRACT

Geoscientists infer past plate motions, which serve as fundamental constraints for a range of studies, from observations of magnetic isochrons as well as hotspots tracks on the ocean floor and, for stages older than the Cretaceous, from paleomagnetic data. These observations effectively represent time-integrals of past plate motions but, because they are made at present, yield plate kinematics naturally tied to a present-day reference-frame, which may be another plate or a hotspots system. These kinematics are therefore different than those occurred at the time when the rocks acquired their magnetisation or when hotspot-related marine volcanism took place, and are normally corrected for the reference-frame absolute motion (RFAM) that occurred since then. The impact of true-polar-wander events on paleomagnetic data and the challenge of inferring hotspot drifts result in RFAMs being less resolved – in a temporal sense – and prone to noise. This limitation is commonly perceived to hamper the correction of plate kinematic reconstructions for RFAMs, but the extent to which this may be the case has not been explored. Here we assess the impact of uncertain RFAMs on kinematic reconstructions using synthetic models of plate motions over 100 million years. We use randomly-drawn models for the kinematics of two plates separated by a spreading ridge to generate a synthetic magnetisation pattern of the ocean floor. The kinematics we infer from such a pattern are outputs that we correct for synthetic RFAMs using two equivalent methods (a classical one as well as another that we propose and test here) and then compare to the 'true' motions input. We assess the misfits between true and inferred kinematics by exploring a statistically-significant number of models where we systematically downgrade the temporal resolution of RFAM synthetic data and add noise to them. We show that even poorly-resolved, noisy RFAMs are sufficient to retrieve reliable plate kinematic reconstructions. For relative (i.e., one plate with respect to another) and absolute (i.e., relative to the deep mantle) plate motions, estimates upon RFAM correction differ from the true kinematics by less that 10% and 3%, respectively.

1. Introduction

Reconstructions of past plate motions, whether relative to one another or absolute (i.e., with respect to a fixed reference-frame – typically the deep mantle), are important constraints for tectonic studies (e.g., Torsvik et al., 2010), mantle circulation models (e.g., Schuberth et al., 2009; Davies et al., 2012; Colli et al., 2015), studies of dynamic topography and associated sea-level (e.g., Moucha et al., 2008), inferences on torques acting on lithospheric plates (e.g., Bird et al., 2008; Copley et al., 2010; Austermann and Iaffaldano, 2013; Iaffaldano and Bunge, 2015), among others. One infers past relative motions of plates from reconstructions of their relative positions through time, based on the present-day magnetisation pattern of the ocean floor (e.g., Gordon and Jurdy, 1986; Dyment, 1993; DeMets et al., 1994; Gaina et al., 2013; Seton et al., 2014) and a geomagnetic polarity time scale (e.g., Cande and Kent, 1995; Lourens et al., 1995). Because young, hot crust recorded the polarity of Earth's magnetic field when it was accreted to the lithosphere along mid-oceanic ridges, one can estimate from the present-day magnetisation pattern how two plates separated by a spreading ridge have moved relative to each another since a particular time in the past, and thus reconstruct their past relative positions. These inferences, referred to as finite rotations, express the relative rotation between two plates over a finite interval of time that is known from the geomagnetic polarity time scale (Cox and Hart, 1986). Finite rotations effectively represent time integrals of plate motions. Geoscientists reconstruct the past relative positions of any two plates – particularly those on opposite sides

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http://dx.doi.org/10.1016/j.epsl.2016.11.003

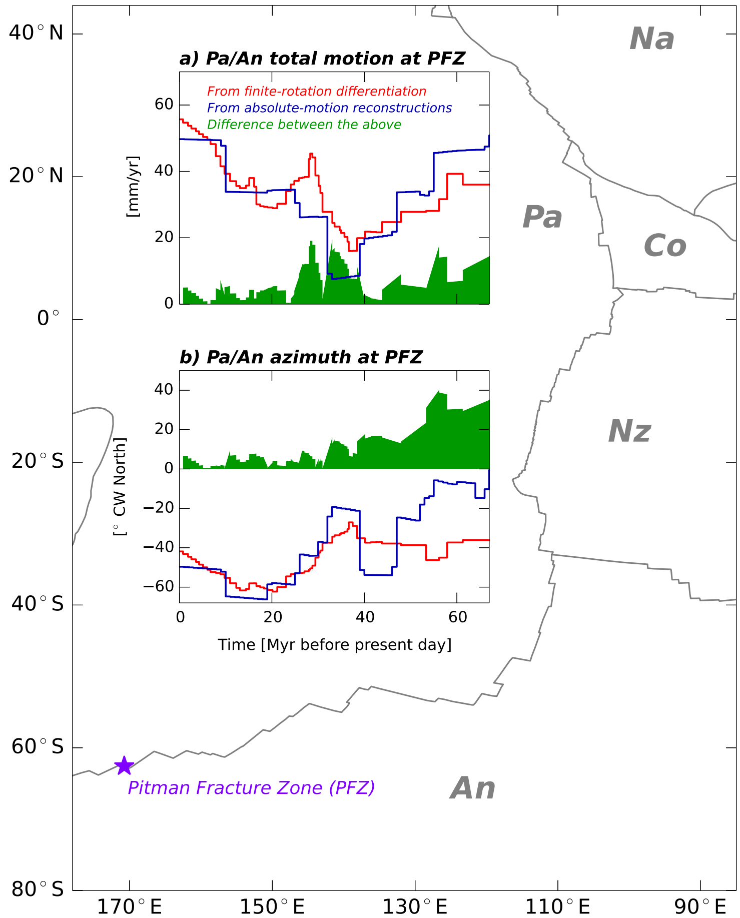

Fig. 1. Comparison of Pacific/Antarctica (Pa/An) relative motions along the Pitman Fracture Zone (PFZ) inferred from reconstructions of Pa and An absolute motions (blue) and from differentiation of Pa/An finite rotations (red). The upper inset shows the total motion, while the lower inset shows the azimuth of motion, in ° clockwise (CW) from North. The green areas show the absolute value of the difference between each kinematic parameter. Plate margins are in grey. Co, Na and Nz are Cocos, North America and Nazca plates, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of a convergent margin – by combining finite rotations of plate pairs along circuits that link one plate to the other. For instance, one may reconstruct the past position of India with respect to Eurasia from finite rotations along the India–Somalia–Antarctica–Nubia–North America–Eurasia circuit (e.g., Copley et al., 2010; van Hinsbergen et al., 2011). In addition, if the past position of one plate with respect to the deep mantle is inferred from hotspots tracks (e.g., Doubrovine and Tarduno, 2008; Tarduno et al., 2009) or paleomagnetic data (e.g., Torsvik and Cocks, 2004), these circuits allow inferring finite rotations for past absolute (i.e., relative to the deep mantle) positions, and thus past absolute motions (e.g., Torsvik et al., 2010).

From a single finite rotation, one may estimate an average of the instantaneous – that is, occurring over the shortest time interval one can possibly imagine – rotation axis, or pole, and angular velocity of motion. Such an estimate averages the actual instantaneous motion over an interval from the time associated with the finite rotation to the present. The rotation axis is assumed to be oriented along the axis about which the finite rotation occurred, while the angular velocity equals the rotated angle divided by the elapsed time. Similarly, from a series of temporally-consecutive finite rotations, one may derive intermediate finite rotations during consecutive stages – covering from the oldest reconstructed time to the present – and then infer the average instantaneous kinematics, also known as Euler vectors, during these consecutive stages (Cox and Hart, 1986), as described above. In the following, we will refer to such a method as finite-rotation differentiation. Geodynamicists are interested in stage Euler vectors of absolute (i.e., relative to the deep mantle) plate motions, because they enter the torque–balance equation of tectonic plates (Iaffaldano and Bunge, 2015), along with the torques controlling plate motions. Euler-vector variations through geological time are thus the prime constraint to study temporal changes in plate driving/resisting forces (e.g., Norabuena et al., 1999; Iaffaldano and Bunge, 2009; Copley et al., 2010). Similarly, stage Euler vectors of relative plate motions are important in order to study the past tectonic style of faults (e.g., Brune et al., 2016) or the structural evolution of Earth's crust (e.g., Wu et al., 2016), among others. However, the present-day magnetisation of the ocean floor and hotspots tracks allow direct inference of finite rotations, not stage Euler vectors. Geomagnetic reversals appear in the magnetisation pattern of the ocean floor as more-or-less defined lines, known as isochrons (literally, 'same age'). These formed as hot crust spreading out of ridges cooled below its Curie point and then travelled along with the associated plate, while the magnetic field reversed at times. Because geoscientists infer finite rotations from the present-day geography of isochrons (specifically, from observations of points along them called magnetic picks) and hotspots tracks, stage Euler vectors derived through finite-rotation differentiation are tied to a present-day reference frame. Therefore, they do not describe exactly the actual kinematics occurred when isochrons formed (Cox and Hart, 1986).

Fig. 1 illustrates such a discrepancy, or misfit, for the spreading motion between the Pacific and Antarctica plates. We chose this example because recent reconstructions (e.g., Croon et al., 2008; Wright et al., 2015), combined together, yield one of the longest