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Letters

Paleo movement of continents since 300 Ma, mantle dynamics and large wander of the rotational pole

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ABSTRACT

Apparent polar wander (APW) is known to be mainly linked to internal mass distribution changes and in particular to changes in subduction and large-scale upwellings in the mantle. We investigate plate motions during the last 410 million years in a reference frame where Africa is fixed. Indeed, Africa has remained a central plate from which most continents diverged since the break-up of Pangea. The exact amount of subduction is unknown prior to 120 Ma. We propose an approach, based on one hand on the study of the past subduction volcanism to locate ancient subduction activity, and on the other hand microplate motion history in the Tethyan area derived from geology and paleomagnetism. The peri-Pacific subductions seem to be a quasi-permanent feature of the Earth's history at least since the Paleozoic, with however localized interruptions. The "Tethyan" subductions have a complex history with successive collisions of continental blocs (Hercynian, Indo-Sinian, Alpine and Himalayan) and episodical rebirth of E–W subduction trending zones. Assuming that subducted slabs sink vertically into the mantle and taking into account large-scale upwellings derived from present-day tomography and intra-plate volcanism in the past, we compute the time variation of mantle density heterogeneities since 280 Ma. Due to conservation of the angular momentum of the Earth, the temporal evolution of the rotational axis is computed in a mantle reference frame where the Africa plate is fixed, and compared to the apparent polar wander (APW) observed by paleomagnetism since 280 Ma. We find that a major trend of both paleomagnetic and computed APW are successive oscillatory clockwise or counter-clockwise motions, with tracks separated by abrupt cusps (around 230 Ma, 190 Ma and 140–110 Ma). We find that cusps result from earlier major geodynamic events: the 230 Ma cusp is related to the end of active subduction due to the closure of the Rheic Ocean basin after the Hercynian continental collision (340–300 Ma) and to renewed subduction zone West of Laurentia, whereas the 190 Ma cusp results from the Indo-Sinian collision (270–230 Ma) and the subsequent end of the Neo-Tethys ocean subduction.

1. Introduction

True polar wander (TPW) refers to the large-scale motions of the Earth's rotation axis through geological time (for a review, see Besse et al., 2011). Paleomagnetists have provided quantitative evidence that the instantaneous geographic or rotation pole had moved with respect to continents since the 1950s: the paths followed by the paleomagnetic poles in the geological past have been termed apparent polar wander paths (APWPs), because it was not clear whether it was the pole or the continent that had moved. Plates are known to move with respect to each other and a significant part of APW was actually due to these relative motions. TPW is the remaining fraction in polar wander, which would be a characteristic of Earth as a whole, and which would not be accounted for by plate tectonics. To separate both effects, most studies performed in the last two decades followed an approach, based on the possibility that hotspots could provide a valid reference frame for the mantle. If hotspots are indeed fixed with respect to each other and are fixed within the mantle, then hotspot apparent polar wander describes the wander of the Earth's rotation axis with respect to the mantle. For the 0–200 Ma time period, TPW would be a go-stop-go phenomenon, with long standstills in the tens of millions of years, and periods of faster, rather uniform polar wander at velocities often not exceeding 3 cm/yr (Besse and Courtillot, 2002).

In view of the angular momentum theorem, TPW may be interpreted physically as the motion of the rotational axis with respect to a fixed terrestrial frame. On geological time scales, this motion is most likely controlled by the large-scale heterogeneity structure of the mantle (Goldreich and Toomre, 1969; Ricard

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et al., 1993b). Modeling the time variation of mantle density heterogeneities since the Mesozoic led authors to reproduce some features of the observed TPW (Richards et al., 1997; Steinberger and O'Connell, 1997; and more recently Rouby et al., 2010; Steinberger and Torsvik, 2010).

For pre-Jurassic time, ocean floor has been subducted (together with evidence of plate kinematics and most hotspot traces) and TPW cannot be estimated in the way indicated above. Evans (2003) proposed using APWP only to obtain a crude estimate of TPW in the case when TPW velocity would have been much faster than between-plate motions. This should be the case for the 200–360 Ma period, when continents were assembled in a simple continent, Pangea. All continents should display at first order a unique common APWP with exception of Tethyan blocks. Further justification of the method can be found in the fact that in the case of Africa, hot spot and paleomagnetic APWP displayed strong similarities in the stop-track-stop pattern during the 0–200 Ma time period (Besse and Courtillot, 1991, 2002).

Part of the path also displays remarkable features such as cusps (at 230, 180 and 140–110 Ma) and tracks. In this paper we investigate the causes for these abrupt changes in polar wander. We first built a geodynamic model of plate motions since 410 Ma in order to estimate mantle mass redistribution vs. time since 280 Myrs in the mantle due to subducted slabs and large-scale upwellings in a mantle reference frame in which Africa is fixed. We calculate the perturbations of the inertia tensor and the associated principal inertia axes (PIA) induced by these mantle mass anomalies, and based on the conservation of angular momentum we derive the polar motion in terrestrial reference frame fixed with respect to Africa. Computed path is finally compared with the observed one.

2. Geodynamical model

We first present our simple model for the large-scale pattern of mantle dynamics. We combine contributions due to subducted lithosphere and to long wavelength upwellings. In this geodynamic model, the mantle is assumed to be homogeneous in density; the lithosphere, the upper and the lower mantles are viscoelastic with respective viscosity (1.1×10^{22} Pa s, 10^{21} Pa s and 40×10^{21} Pa s); the core is a homogeneous inviscid fluid.

2.1. Downwellings

Subducted lithosphere is one of the major components of mantle density heterogeneity. We start with the model of mantle density heterogeneity derived by Ricard et al. (1993b) and Lithgow-Bertelloni and Richards (1998). They used plate-motion reconstructions under the assumption that subducted slabs sink vertically into the mantle (see Fig. 5 of Lithgow-Bertelloni and Richards, 1998). When the slab is in the upper-mantle, its diving velocity is its surface velocity. When the slab crosses the 670 km discontinuity, its velocity is assumed to decrease by a factor 4 whereas its size (thickness) increases by the same factor 4, for a viscosity ratio between upper and lower mantle of about 40. For example, with a surface velocity about 8 cm/yr, the characteristic time needed for a plate to sink through the whole mantle is 120 Myrs. The temporal evolution of mantle density heterogeneities associated with large-scale pattern of plate tectonic motions since 280 Myrs is then modeled assuming that plates have been sinking down to the core–mantle boundary for the past 410 Myr.

We first investigate plate motions during the last 410 million years (Fig. 1) in a reference frame where Africa is fixed, the latter plate being a central plate from which most continents have diverged since Pangea break-up. For the past 120 Myr, we use a compilation of plates motions in the hotspot reference frame by Lithgow-Bertelloni et al. (1993), which we convert into our fixed Africa frame. For earlier periods, the starting point is based on the paleomagnetic set of reconstructions of McElhinny et al. (2003). These authors constructed the Paleozoic apparent polar wander path for Gondwana based on a review of paleomagnetic data. The drift history of Gondwana with respect to Laurentia, Baltica and Siberia during the Paleozoic was shown in a series of 530–320 Ma paleogeographic maps. We used the same reconstructions, with some minor differences. Indeed, due to the axisymmetric nature of the Earth's magnetic field, paleomagnetism is unable to determine ancient paleolongitudes. We thus feel free to move some blocks around their virtual geomagnetic pole (VGP) in order to account for geological constraints. For the 320–200 Ma period, we assumed a Pangea A type, with no relative motions between the Northern continents and Gondwana until 200 Ma, i.e. the age of initiation of Gondwana break-up through the opening of the Central Atlantic.

According to McElhinny et al. (2003), the main continental plate motions can be summarized as follows: by the end of the Early Devonian (around 400 Ma), Baltica had already collided with Laurentia, which was still separated from northwestern Gondwana by a 2000-km wide Rheic Ocean. The Rheic Ocean continued to widen until around 360 Ma and began its contraction in the early Carboniferous. Its closure marked the beginning of a large continental collision between NW Gondwana and SE Laurentia between 340 and 320 Ma. This continental collision is called the Hercynian/Variscan orogeny in Laurentia and Appalachian orogeny in North America. It marks the beginning of the Pangean supercontinent, and we assume that there was no motion of main continental blocks before the break-up at around 180 Ma. Furthermore, a collision through the Urals is linked to the closure of the Khanty-Mansi Ocean (see for example Sengor et al., 1993) between Siberia and Europe by the end of the Paleozoic. As shown by the inferred motions in Fig. 1, there is only a limited amount of convergence, and resulting subduction will not be accounted for in our further experiments.

The next crucial problem is to estimate the location of paleo-subduction zones and their amount. Indeed, all ancient oceans have been subducted and we cannot rely upon magnetic anomalies or fracture zones to constrain the evolution of oceanic plates, as it is classically done for more recent times. Multidisciplinary data suggest that convergent margin activity occurred for several hundred million years in the Tethyan area and on either side of the present Pacific Ocean. Docking of major continents caused ocean closure, such as the Rheic Ocean in the Devono-Carboniferous (Fig. 1: 410–270 Ma). Oceanic plates diverging from the ancient Pacific Rises were subducted on either side of the Pacific Ocean to produce the circum-Pacific orogenic belts. Laurentia and Gondwana have always been separated by an Oceanic domain, the Tethyan area. Terrane fragments were successively rifted and separated from Gondwanaland as continental slivers (Metcalfe, 1996). Indeed, geological evidence shows that a set of continental blocks were separated from Gondwana in the late Devonian (360 Ma), while a collision with the Kipchak volcanic arc (Sengor et al., 1993) occurred between the Late Carboniferous and Early Permian (slightly before 300 Ma). Then a second set of blocks comprising parts of Afghanistan, North Tibet and Indochina (the "Kimmerian continent", Sengor and Hsu, 1984) detached from Gondwana at around 270 Ma (Fig. 1: 300–270 Ma) and collided with Eurasia during the Triassic at around 230 Ma ("the Indo-Sinian collision", Fig. 1: 270–230 Ma). Quantitative estimates of the transit velocity have been obtained using paleomagnetic poles in Iran (Besse et al., 1998). The separation of these continental slivers was accompanied by the opening (and subsequent closing) of ocean basins, the Palaeo-Tethys and Neo-Tethys. In the Northern part of Tethys, oceanic slabs continued