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Present true polar wander in the frame of the Geotectonic Reference System

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ABSTRACT

The Mesozoic-Cenozoic evolution of the Earth's lithosphere reveals a fundamental hemispherical symmetry inherent in global tectonics. The symmetry is documented by the concurrent regular growth of the Pacific and African plates over the past 180 million years, and by the antipodal position of the two plates. The plates are centered on the equator, where center P of the Pacific plate is located at 170° W/0° N, and center A of the African plate at 10° E/0° N. P and A define a system of spherical coordinates, the Geotectonic Reference System GRS, which shows a distinct relation to Cenozoic global tectonics. P and A mark the poles of the geotectonic axis PA.

The degree-two pattern of the residual geoid displays two major highs, the Pacific high and the African high. Poles P and A are located in the centers of the respective geoid highs. The stable configuration of excess masses m_P and m_A which are responsible for the two geoid highs results in the long-standing stability of location of the geotectonic axis PA. The Earth's rotation axis is oriented perpendicularly to the PA axis. Owing to the extraordinary stability of the geotectonic axis, any change of orientation of the rotation axis, e.g. induced by post-glacial rebound, occurs in such a way that the axis remains in the equatorial plane of the geotectonic system, i.e. in the 80° W/100° E meridional plane. Observed present polar wander is directed towards 80° W (79.2 ± 0.2° W). This indicates that the present true polar wander is directed exactly along the GRS-equator, identical with the 80° W/100° E great circle of the Earth. It is concluded that the phenomenon of polar wander is basically related to the symmetry of the geotectonic system defined by the Pacific pole P, at 170° W/0° N, and the African pole A, at 10° E/0° N.

Introduction

It is generally agreed that the present drift of the Earth's rotation pole is primarily due to late-Pleistocene melting of continental ice-sheets, such as the ice-sheets of Laurentia, Fennoscandia, and related redistribution of mass within the Earth system (e.g. Vermeersen et al. 1997; Mitrovica & Milne 1998; Johnston & Lambeck 1999; Mitrovica et al. 2006). In addition to external loads, internal loads due to endogene processes, such as thermal convection, will undoubtedly also contribute to polar drift. Little is known about the spatial and temporal distribution of uncompensated loads in the Earth's interior. This may explain why traditional predictions of glaciation-induced polar wander neglect endogene contributions to the motion of the spin axis. In the present paper the contribution of endogene processes to the phenomenon of polar wander will be discussed and emphasized. To that end a brief historical review will be presented.

The systematic observation of polar motion in the frame of the International Latitude Service, ILS, beginning in 1900, brought about a growing interest into the phenomenon of polar wander. Wegener (1912, 1915), a geophysicist, was well aware of the fundamental insights into the structure and dynamics of the Earth provided by the geodetic observations of Earth rotation changes. In all of his papers on continental drift he emphasized the fundamental role that isostasy plays in geodynamics, and thus favoured a plastic deformable Earth. Wegener stated: "polar motion must be understood as a consequence of mass displacements within the Earth" (Wegener 1912, p. 194). From the pattern of observed motion of the North pole in the period 1900–1910, he found a weak indication for a systematic displacement of the solid Earth's axis of figure towards the Atlantic ocean (Wegener 1912, p. 309).

In a fundamental paper Gold (1955) discussed the absence of long-term rigidity of the solid Earth. Apart from isostasy and other observations, the absence of long-term rigidity is clearly documented by the "free" or "Eulerian" nutation of the Earth, the Chandler wobble. The wobble corresponds to a periodical movement of the Earth around its axis of rotation, with a period of 435 days, whereby the direction of the rotation axis remains nearly fixed in space. Origin, period and damping of the wobble are related to the physical conditions on and within

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the Earth. Gold (1955) pointed to the observed high damping of the wobble.

In a plastic deformable Earth, the existence of gravity anomalies over large regions must be understood as being related to geotectonic processes which control the origin and redistribution of lateral heterogeneities in the mantle. Since these geotectonic processes are long-lived, the related non-hydrostatic loads and gravity anomalies must be also long-lived. The distribution and extent of the excess masses shows up in the undulations of the geoid. Since there is plastic flow, the rotation axis of the Earth will follow closely any imposed changes of the axis of maximum non-hydrostatic moment of inertia. The stability of the spin axis is therefore dependent upon the stability of the geoidal shape (Gold 1955). An extensive summary of previous studies dealing with rotation of the Earth is presented in the book of Munk & MacDonald (1960).

Goldreich & Toomre (1969) extended the ideas of Gold (1955) and also concluded that the gradual redistribution of density inhomogneities produced by convective processes within the Earth can cause large motions of the entire mantle relative to the space fixed axis of rotation (true polar wander, TPW). Since these works, satellite-derived data regarding the Earth's gravitational field and the geoid have become available (e.g. Kaula 1966). According to Goldreich & Toomre (1969) the inertial moment of the Earth may be separated into a hydrostatic part due to the equilibrium bulge under rotation and a non-hydrostatic part due the topical distribution of mass anomalies. The authors show that after subtraction of the hydrostatic part, the remaining non-hydrostatic part of the Earth's inertia figure is distinctly triaxial.

By the end of the 1960's, it had become clear that the Earth displays a high internal mobility due to plastic flow. TPW can occur on a varity of time scales, on the order of thousands to millions of years. On a shorter time scale, it is generally assumed that present TPW results from Pleistocene deglaciation. On longer time scales polar wander is caused by gradually changing density heterogeneities generated by long-lived geotectonic processes, such as thermal convection in the mantle.

In this context attention is drawn to the geotectonic bipolarity model, which is of relevance to the discussion below. The model is an attempt to describe the large-scale pattern of mantle convection as derived from the Mesozoic-Cenozoic evolution of the Earth's lithosphere. The bipolarity model was introduced in the 1960's, before the advent of plate tectonics. It was based exclusively on geotectonic and paleogeographic, i.e., on geological, evidence (Pavoni 1969). The model displays a fundamental, Pacific/anti-Pacific hemispherical symmetry in global tectonics and geodynamics. The symmetry is produced by mantle convection, consisting of two torus-like convection cells, the Pacific cell and the African cell, with cylindrical upwellings below the Pacific plate (center P, at 170° W/0° N) and below the African plate (center A, at 10° E/0° N), and sheet-like downwellings in the meridional plane located between the two centers of upwelling, mathematically described as quadrupolar spherical convection. This quadrupolar convection mode (Pavoni 1985b) with axis of symmetry located in the equatorial plane represents a very stable configuration (Busse 1975; Pers. Comm.). The geotectonic axis corresponds to the axis of symmetry, connecting centers P and A.

New space geodetic techniques, such as very long baseline interferometry (VLBI), satellite and lunar laser ranging (SLR and LLR), and utilization of the Global Positioning System (GPS) technology, which became available in the 1970s and 1980s allowed an accurate determination of the Earth's gravitational field. The observed long-wavelength geoid (Lerch et al. 1979), referred to the equilibrium hydrostatic figure of the Earth (Nakiboglu 1982), shows little resemblance to the distribution of continental and oceanic lithosphere. The same holds true for the residual geoid, which is obtained when the effect of subducted slabs in the upper mantle is removed from the observed geoid heigths (Chase 1979; Crough & Jurdy 1980; Hager 1984). As stated by these authors, the residual geoid heigths have the form of two broad, elliptical positive areas surrounded by lows. With regard to the geotectonic bipolartiy model mentioned above, the residual geoid displays the same Pacific/African hemispheric symmetry as expressed in the model, with the broad geoid highs corresponding to the cylindrical upwellings, the belt of geoid lows trending along 100° E/80° W corresponding to the downwelling flow of the proposed mantle convection (Pavoni 1983, Figs. 10, 11).

Concurrently with the survey of the Earth's gravitational field, the world-wide installation of modern seismograph networks in the 1960's, and new technologies of geophysical data aquisition and interpretation allowed a precise determination of the global pattern of seismicity, marking the advent of the theory of plate tectonics (e.g. McKenzie 1969). The global seismic data allowed the establishment of a preliminary reference Earth model PREM (Dziewonski & Anderson 1981), and a description of the lateral heterogeneities of seismic velocity and density in the Earth's mantle (Dziewonski 1984; Woodhouse & Dziewonski 1984). The large-scale pattern of lateral heterogeneities of seimic velocity in the lower mantle shows the same hemispherical symmertry as expressed in the residual geoid.

World-wide geophysical und space-geodetic research done in the 1970's and 1980's thus confirmed and completed the Pacific/African hemispheric symmetry observed in global tectonics. In particular, it confirmed the large-scale pattern of mantle-wide (or thermally coupled) convection in the Earth's mantle, with low-velocity material underlying the central Pacific and African plates, and high-velocity material beneath the circum-Pacific orogenic belt corresponding to sheet-like downwellings of subducted oceanic lithosphere.

The connection between excitation of polar motion and time-dependent mantle convection in the case of viscous and viscoelastic Earth models has been discussed by Moser et al. (1992, 1993) and Ricard et al. (1993). Matyska et al. (1994) converted S-wave velocity anomalies of model SH425.2 of Su & Dziewonski (1991) into thermal anomalies, employing recent measurements in mineral physics and also incorporating radiative heat transfer. It is notable that computations result in a convection pattern of order two with the distribution of hot material in the mantle beneath poles P and A of the GRS, comparable to the quadrupolar convection mode described in the geotectonic bipolarity model. The relatively stationary "megaplumes" act as strong attractors. The upward push exerted by the megaplumes may be responsible for the large aspect-ratio cells and the bipolar character of lower mantle structure. The megaplumes may, indeed, exert strong influence on the stability of the rotational axis, and thus partially control true polar wander. With the help of a specific test, Matyska (1995) demonstrated the dominant role of the geotectonic axis PA in mantle dynamics.

Steinberger & O'Connell (1997) aimed at a calculation of the path of the Earth's rotation axis during the past 64 million years. They used a mantle viscosity structure obtained through geoid modelling, a mantle flow field consistent with tomographic anomalies, and time-dependent lithospheric plate motions to calculate the advection of mantle density heterogeneities and corresponding changes in the degree-two geoid. The resulting path of the rotation axis was compared with palaeomagnetic results. The authors conclude that a considerable fraction of the current polar motion may represent a secular trend, which has existed for millions of years, due to advection of mantle density heterogeneities through mantle convection.

In the present paper, an attempt is made to examine polar drift from a geotectonic point of view, in direct relationship to the Pacific/African bipolarity. The study was stimulated by the fact that the observed present true polar wander is directed towards 80° W (79.2° W), i.e., along the 80° W meridian. This is in close proximity to the 80° W/100° E meridional plane that is oriented exactly orthogonally to the geotectonic axis PA, which intersects the equator at 170° W and 10° E (Pavoni 1969, 1981). The question arises, as to what extent the polar drift direction might be determined by the position of the geotectonic axis.

A summary of astrometric and space-geodetic observations of rate and direction of true polar wander will be presented, based on the work of Gross & Vondrak (1999). A further summary of the Pacific/anti-Pacific hemispherical symmetry, which is inherent in the Mesozoic/Cenozoic evolution of the Earth's lithosphere (Pavoni 1991, 1997; Pavoni & Müller 2000), and a description of the geotectonic bipolarity model will be given. The present study will discuss how present polar motion can be explained by the geotectonic bipolarity model.

Present true polar wander

Since 1900 the motion of the instantaneous rotation axis of the Earth has been traced by the International Polar Motion Service (IPMS, formerly the International Latitude Service ILS) by means of repeated optical astrometric measurements of latitude variations at seven observing stations. The stations are well-distributed in longitude and all are located at nearly the same latitude of 39° 08`N. The measurements reveal systematic movements of the instantaneous rotation axis relative to the axis of figure, i.e., the rotation axis fixed to the Earth, defining the geographical poles.

Recent estimates of present polar drift from astrometric and space-geodetic measurements have been reviewed and compiled by Gross & Vondrak (1999). The polar motion exhibits a fluctuation of cyclically varying amplitude superposed on a linear trend. The linear trend represents a slow drift of the mean northern pole towards northern Canada. Of special interest to our concern are the results regarding the direction of polar drift. Most of the reported polar paths are directed towards 75–85° W, and according to Gross & Vondrak (1999), the preferred direction of present polar drift is directed towards 79.2 ± 0.2° W, relative to the mean lithosphere, i.e., the reference frame yielding no net rotation of plates. The preferred rate of present polar drift is estimated at 3.51 ± 0.01 milliarcseconds/year (mas/yr).

Geotectonic bipolarity

Pavoni (1969) introduced the idea of a Pacific/anti-Pacific hemispherical symmetry or bipolarity in geotectonics after compiling and synthesizing data about recent and late-Cenozoic crustal movements on a global scale. The study was based on a systematic kinematic analysis of late-Cenozoic structural features of young folded mountain belts. It established a pattern of major active strike-slip fault zones within the Eurasian and circum-Pacific orogenic belts that were later confirmed by geological and geophysical data. These belts were interpreted to represent a zone of intense crustal shearing and convergence located between two very large, expanding geotectonic units, the Pacific unit, centered in the central Pacific region (center P), and the Gondwana unit, centered in equatorial Africa (center A).

The results from combined geophysical and geological exploration of the oceanic regions in the late 1960's and 1970's provided additional arguments in favor of geotectonic bipolarity. The world-wide distribution of earthquakes associated with the active oceanic ridges led to a more precise location of the two centers A and P, and to the formulation of the geotectonic bipolarity model in 1969. According to this model, geotectonic bipolarity is defined by the Pacific pole P, located at 170° W/0° N, and the African pole A, located at 10° E/0° N. The error of location of the poles is estimated at ±3°.

Within the past 180 million years, the entire oceanic lithosphere beneath the present oceans has been created from the mantle at oceanic ridges, and a corresponding amount has been subducted back into the mantle. This growth and recycling is a manifestation of large-scale circulation in the mantle. During this time, the Pacific plate, which remained approximately symmetrical with respect to the equator and today is centered over the Pacific mantle upwelling, has grown from a small plate to a very large one. The roughly concentric growth pattern of the plate displays diverging movement of neighboring plates away from the Pacific plate as it grew. This growth pattern appears to reflect a regular, diverging flow pattern produced by the mantle upwelling beneath the Pacific plate (Pavoni 1985a,b, 1991, 1997) (Fig. 1).

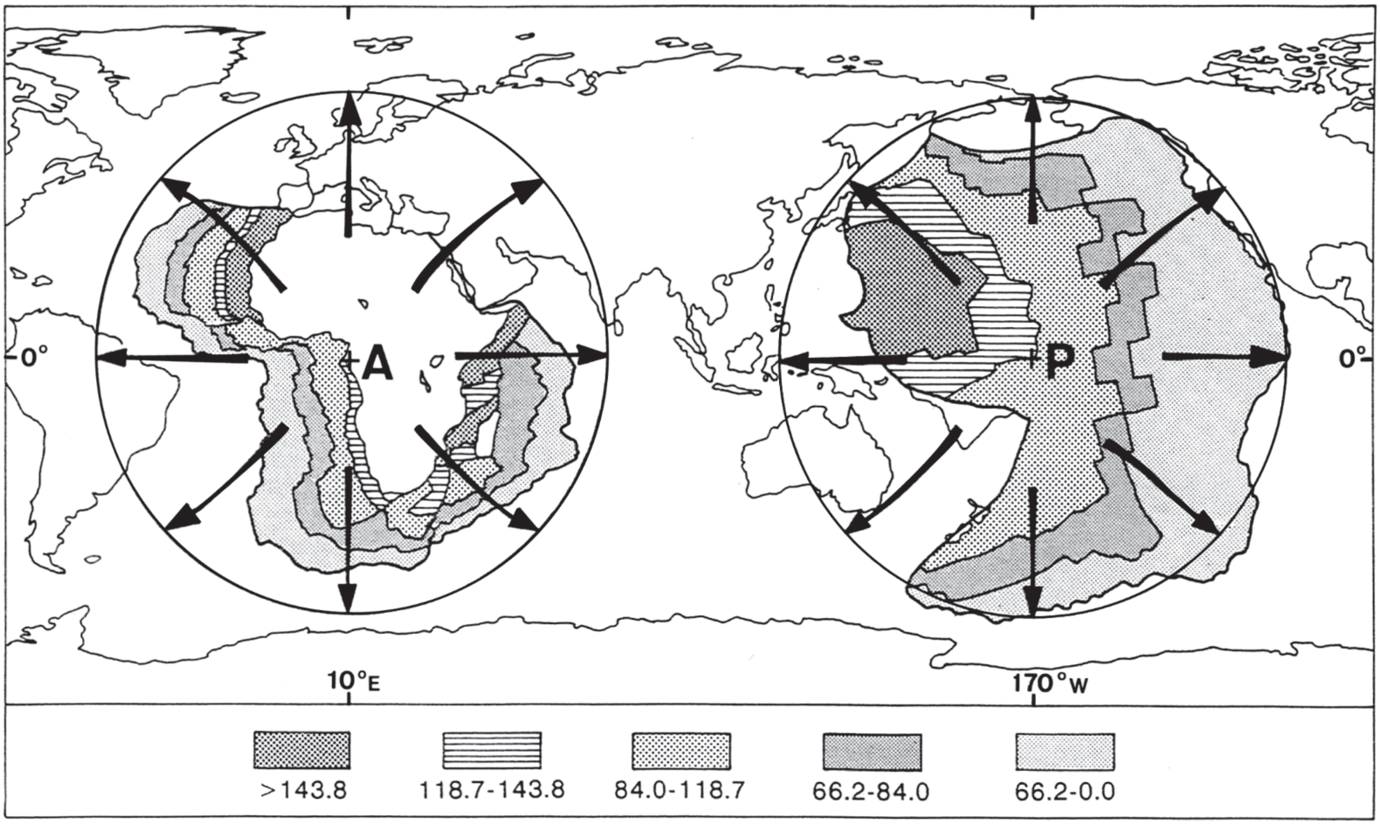

Fig. 1. Geotectonic bipolarity as revealed by the simultaneous concentric growth of the Pacific and African plates in the last 180 million years. Age of the ocean floor in million years is shown by pattern. Arrows show horizontal sub-lithospheric flow in the mantle beneath the two plates. After Pavoni 1991. P: Pacific pole at 170° W/0° N, A: African pole at 10° E/0° N.

Concurrent with the growth of the Pacific plate, is a comparable growth pattern of the African plate centered over the African mantle upwelling. This is responsible for the breakup of Gondwana and Laurasia beginning some 180 million years ago. Relative to the African plate, the North American plate moved northwestward, the South American plate to the west, the Antarctic plate to the south, and the Australian plate to the east. The bipolar growth of the African and Pacific plates over the last 180 million years is consistent with mantle upwelling beneath each plate and descending flow at 70–90° distance from the central pole of each plate (Fig. 1).

With regard to their present configuration, the Pacific and African plates show several significant characteristics: 1) they represent the two largest plates; 2) they are of "circular" shape, whereby the Pacific plate has a mean diameter of about 130°, corresponding to a length of 14400 km and the African plate has a mean diameter of about 115°, corresponding to a length of 12800 km; 3) in spite of their large size, both plates extend symmetrically with respect to the equator; and 4) both plates are surrounded for the major part by active oceanic ridges.

The optimum center (P_r) of the Pacific plate was determined from the semi-circular trend of the belt of active oceanic ridges bordering the plate in the south, east and northeast, and, similarly, the optimum center (A_r) of the African plate was defined from the circum-African belt of active oceanic ridges extending from the Azores to the Gulf of Aden. P_r is located at 169.8° W/2.6° S, and A_r at 11.6° E/2.4° N. The location error is less than 2.8° (Pavoni & Müller 2000). Notably, the two largest plates of the Earth are centered in nearly antipodal position on the equator. In a strict manner, the two centers define an axis dipping at 2.5° towards 169.1° W. Within the limits of error, the center P_r coincides with the Pacific pole P at 170° W/0° N, and the center A_r with the African pole A at 10° E/0° N. Therefore, P_r and A_r may be considered to represent directly the geotectonic poles P and A which define the GRS. The present antipodal position of the Pacific and African plates, as well as their concurrent, regular growth over the last 180 million years, document a fundamental hemispherical symmetry or bipolarity inherent in geotectonic processes.

Pacific-African bipolarity related to lateral heterogeneities in the Earth's mantle

It should be noted that the same Pacific-African bipolarity, as derived from geological observations, is also found in the global distribution of lateral heterogeneities of seismic velocity and density in the Earth's mantle (Chase 1979; Crough & Jurdy 1980; Pavoni 1983, 1985 a,b, 1991; Dziewonski 1984;

Hager 1984; Richards & Hager 1988; Su & Dziewonski 1991; Matyska 1995; Matyska et al. 1994; Romanowicz & Gung 2002; Tanimoto 1990). A concise historical review is presented by Bostrom (2000). The excellent correlation between geotectonic and geophysical data on a global scale is demonstrated by the representation of the degree-two patterns of seismic velocity and density heterogeneities (e.g. Richards et al. 1988) in the frame of the GRS.

The geoid is of particular interest to the present discussion. The degree-two pattern of the satellite-derived residual geoid (Richards et al. 1988, Fig. 4a) displays two major geoid highs, the Pacific geoid high and the African geoid high, centered on the equator. It is noted that the Pacific pole P and African pole A are located in the centers of the respective geoid highs (Pavoni 1983, 1991, Fig. 10) that are surrounded by a north-south trending belt of geoid lows. Pacific and African geoid highs document the existence of two large, non-hydrostatic excess masses m_P and m_A centered antipodally in the equatorial plane, and these represent by far the largest excess masses of the Earth. They are considered to be associated with thermal convection in the mantle.

GRS and triaxiality

Poles P and A define the spherical coordinate system of the GRS. The location of a point in the GRS is given in Pacific coordinates. Pacific colatitude θ_p and longitude ϕ_p correspond to the distance, in degrees, from Pole P and the prime meridian, respectively. The GRS prime meridian corresponds to the great circle passing through Pole P and the North Pole (Fig. 2). The system displays a close relation to Cenozoic global tectonics. In the areas extending to about 60° distance from poles P and A, i.e., in the GRS polar regions, the lithosphere exhibits extension and growth. In the GRS equatorial zone, i.e., 70–90° distance from the two poles, the lithosphere undergoes convergence and transpression, the oceanic lithosphere is subducted into the mantle, and the continental lithosphere accumulates at the Earth's surface.

The pattern of large-scale geoid undulations is of special interest to the question of triaxiality of the Earth. A representation of the residual geoid after Crough & Jurdy (1980) in the GRS shows that the mean angular distance of the +20 m-, 0 m-, –20 m-, and –40 m-isolines of geoid heights from GRS pole P in the Pacific hemisphere and from GRS pole A in the anti-Pacific hemisphere, respectively, is nearly identical (Pavoni 1985b, Figs. 6, 7), and distributed symmetrically with respect to the GRS equator. This means that the GRS poles P and A are located on the principal axis of the least non-hydrostatic moment of inertia, connecting the Pacific geoid high and the African geoid high. Similarly, the fundamental geotectonic bipolarity becomes evident if the degree-two pattern of the residual geoid (Richards et al. 1988) is reproduced in the frame of the GRS (Pavoni 1991, Fig. 10b). The GRS poles P and A are located near the centers of the two geoid highs. Moreover, the very same Pacific/anti-Pacific hemispherical symmetry shows up in the degree-two pattern of lower mantle P-wave velocity heterogeneity (Pavoni 1991, Fig. 10a). The GRS poles P and A are located in the center of the two minima.

The geotectonic axis PA, representing the "major" axis in the equatorial plane, intersects the equator at 10° E and 170° W. The "minor" axis, oriented orthogonally to the geotectonic axis, intersects the equator at 100° E and 80° W. The error of location is estimated at ±3°. The non-hydrostatic excess masses m_P and m_A, responsible for the large residual geoid highs of the GRS polar regions, are associated with the cylindrical upwellings along the geotectonic axis. The sheet-like downwellings along the GRS-equator are responsible for the north-south trending belt of residual geoid lows, intersecting the equator of the Earth near 100° E and 80° W (Pavoni 1983, Figs. 10, 11).

The geotectonic and geophysical investigations mentioned above independently confirm a distinct triaxiality of the non-hydrostatic figure of the Earth. The three principal axes of non-hydrostatic moments of inertia are (1) the axis of maximum moment, the c-axis, oriented North-South, coinciding with the Earth's rotation axis, (2) the axis of intermediate moment, the b-axis, located in the equatorial plane, intersecting the equator at 100° E and 80° W, and (3) the axis of least moment, the

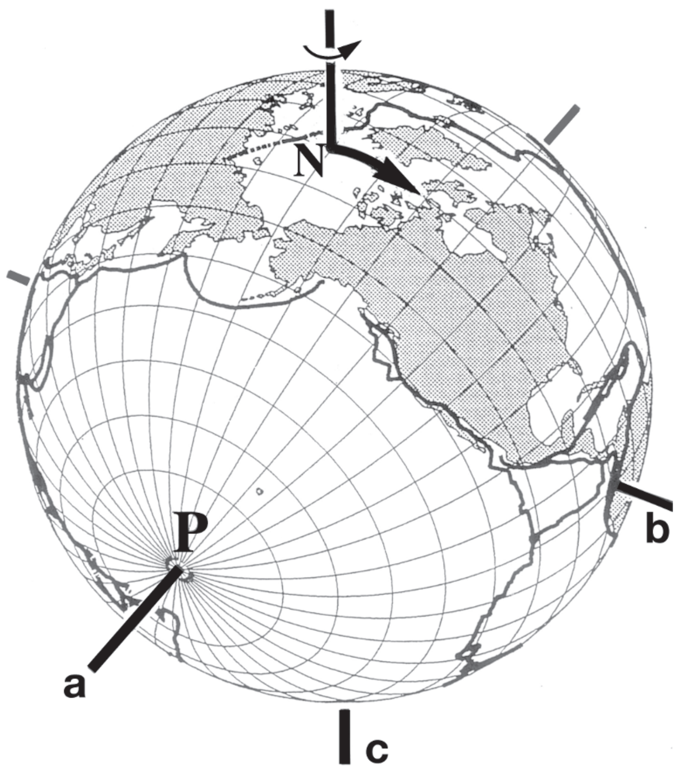

Fig. 2. Geotectonic Reference System GRS, defined by the Pacific Pole P, located at 170° W/0° N. The African Pole A, located at 10° E/0° N, is not visible. N: Geographic North Pole. Orthographic Projection. Thin lines: GRS small circles and GRS great circles. Continents shaded. Thick lines: plate boundaries. a: Geotectonic axis PA. Thick arrow at Pole N: Direction of present true polar wander towards 80° W, i.e., along the GRS-equator. a, b, c: Principal axes of least, intermediate and maximum non-hydrostatic moment of inertia.

a-axis, located in the equatorial plane, intersecting the equator at 10° E and 170° W.

The principal axes and principal moments of inertia have been estimated by Marchenko & Schwintzer (2003) from satellite derived gravitational harmonic coefficients of second degree in four recent Earth gravity field models. The orientation of the principal axes $\overline{A}$, $\overline{B}$, $\overline{C}$, is given in in spherical coordinates (rounded value, in degrees, geogr. lat./geogr. long., epoch 1997): $\overline{A}$: 0.0° N/345.1° W (14.9° E); $\overline{B}$: 0.0° N/75.0° W; $\overline{C}$: 90.0° N/(277° W). It corresponds within a few degrees with the orientation of the axes a, b, c.

Discussion

According to Gross & Vondrak (1999), the present polar drift is directed towards 79.2 ± 0.2° W, i.e., approximately towards 80° W, as documented by over 100 years of systematic observation of latitude variations. In general, it has been postulated that the observed polar drift direction is associated with the late-Pleistocene melting of the ice-sheets and post-glacial isostatic adjustment of the crust. However, the observed polar drift direction may also be related to the larger picture of the GRS. (Fig. 2, Fig. 3). The observed strict orthogonality between present polar drift, directed along the GRS-equator, and the geotectonic axis PA oriented perpendicularly to the GRS equatorial plane, reveals the close connection, which exists between the rotation axis of the Earth and the geotectonic axis PA. Due to the rheological behaviour of the Earth, the rotation axis will follow closely any imposed changes of position of the c-axis, whereby the orientation of the rotation axis is controlled by the rotational bulge of the Earth and by the geotectonic axis PA. From a geological point of view the readjustment of the bulge to a change in the position of the rotation axis may be regarded as a rather short-term phenomenon, whereas a change of the position of the geotectonic axis represents a phenomenon of very long duration. The geotectonic axis PA is a prime axis of symmetry in the frame of the proposed quadrupolar pattern of convection in the mantle. Its position is determined by the GRS poles P and A. The geotectonic axis coincides with the a-axis, the axis of least non-hydrostatic moment of inertia of the Earth. The position and stability of the a-axis are given by the position and stability of the non-hydrostatic masses m_P and m_A, which are responsible for the large geoid highs of the GRS polar regions. The long-standing location of the geotectonic axis within the equatorial plane allows one to conclude that the masses m_P and m_A, or their precursors, were in place already in early Jurassic time, about 180 million years ago. Presumably, they were in place already in late-Paleozoic time, as indicated by the existence of the significant, active triple-junction in the center of which the Pacific microplate originated. Besides their stable position, m_P and m_A represent by far the largest excess masses of the Earth. Altogether they exert an extremely stabi-

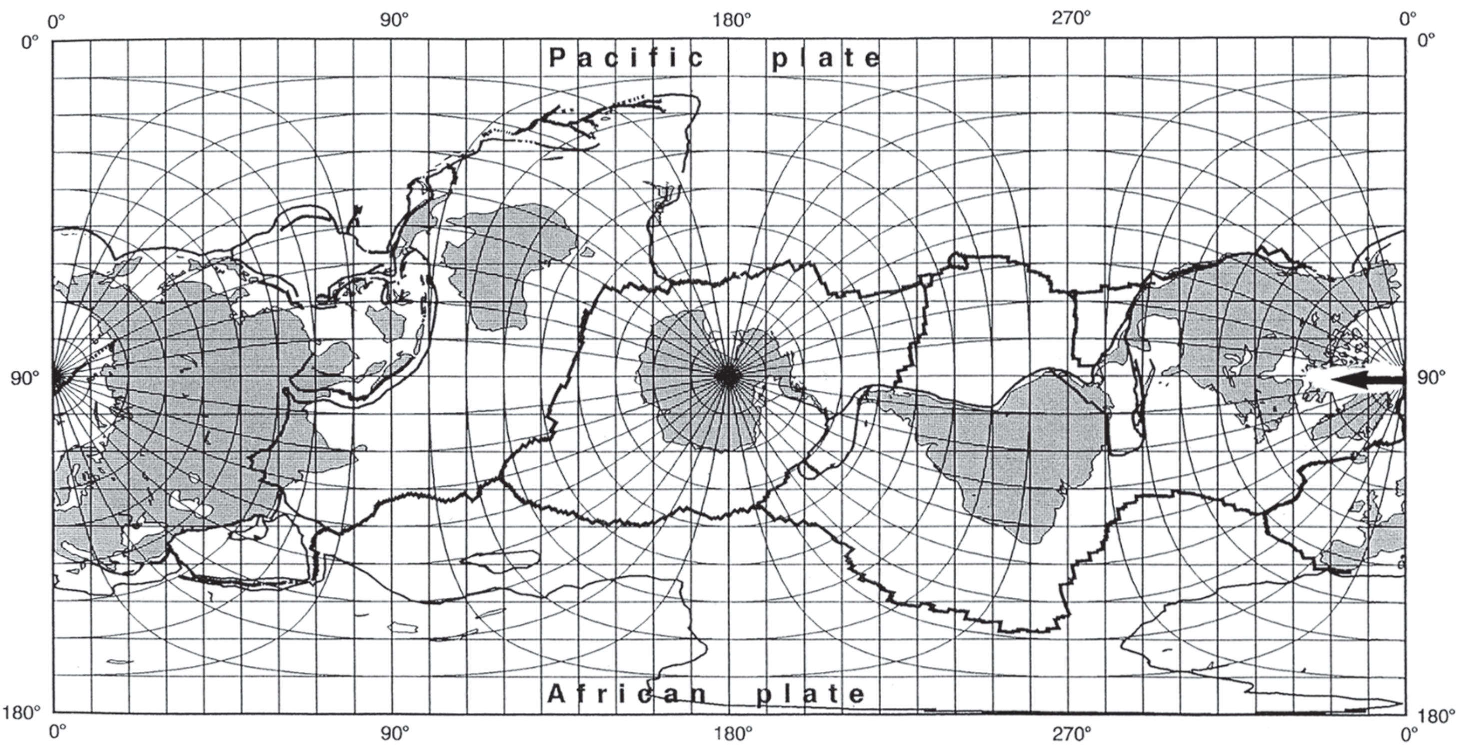

Fig. 3. Continents and major plates in the frame of the Geotectonic Reference System GRS. World map in cylindrical equidistant projection. GRS small circles and GRS great circles are straight lines forming a rectangular grid. Pacific colatitude θ_p: 0–180°. Pacific longitude ϕ_p: 0–360°. The GRS-equator runs along 90° Pacific colatitude. Also shown is the grid of Geographical coordinates. Arrow: Direction of present polar drift towards 80° W, i.e., along the GRS-equator.

lizing effect on the position of the geotectonic axis and, thus, on the position of the Earth's rotation axis. The long-standing existence of m_P and m_A points to a dynamic origin associated with large-scale thermal convection in the mantle.

As noted above, the Earth's rotation axis is oriented perpendicularly to the PA axis. With the contribution of the hydrostatic bulge removed, the spin axis could theoretically take up any orientation within the GRS equatorial plane, and there is no reason to assume a fixed position of the rotation axis within the GRS equatorial plane. Even a small additional uncompensated load, e.g., due to post-glacial rebound, may, over some period of time, cause a change in the orientation of the rotation axis. Owing to the tendency of the excess masses m_P and m_A to keep their position on the equator of the Earth, any change of orientation should occur in such a way that the rotation axis would remain within the GRS equatorial plane, i.e., within the 80° W/100° E meridional plane. Any true polar wander, driven by a load smaller than m_P or m_A, should follow a path that leaves the excess masses m_P and m_A in their position near the equator. Such a path would be a great circle at 90° distance from P and A. Consequently, true polar wander would be directed along the GRS-equator.

In this scenario, the contribution of the hydrostatic bulge would be to stabilize the rotation axis in its given position within the GRS equatorial plane. Rate and amount of long-term true polar wander would be expected to be rather small and possibly oscillatory due to variable loads, e.g., glaciation induced. Furthermore, continued precise observation of present true polar wander might allow us to better define the location of the geotectonic axis PA.

A mass load applied to a rotating viscoelastic planet will induce polar motion. In a reference frame fixed to the axis of rotation, a positive uncompensated mass load tends to increase its angular distance from the axis of rotation, i.e., to move away from the axis, a negative uncompensated mass load tends to reduce its angular distance, i.e., to move towards the spin axis. In the usual scenarios of true polar wander modeling, spheroidal Earth models are adopted where the equator is represented by a circle, with no preferred orientation of the minor axis of moment ($b = a$). In this case, the direction of drift is solely determined by the longitudinal position of the load. The final drift direction of the pole results from the combined contributions of the torques of the widely distributed individual load masses. In case of a spheroidal Earth model the true polar wander path is expected to display a higher variability as opposed to the case for a triaxial Earth model where the long-term polar drift, as shown above, is expected to be directed along the equator of the geotectonic system.

Conclusions

Geotectonic bipolarity is fixed by the Pacific pole P at 170° W/0° N and the African pole A at 10° E/0° N. P and A define a system of spherical coordinates related closely to Cenozoic global tectonics, known as the Geotectonic Reference System GRS. Geotectonic bipolarity reveals a triaxiality of the Earth. The geotectonic axis PA, intersecting the equator at 10° E and 170° W, represents a fundamental, stable axis of symmetry in the global tectonic evolution for the past 180 million years. It is the location of the principal axis of least non-hydrostatic moment of inertia. The Earth's rotation axis is oriented perpendicularly to the PA axis, i.e., it is forced to be located in the equatorial plane of the geotectonic system, i.e., in the 80° W/100° E meridional plane. The observed present true polar wander is directed towards 80° W (79.2 ± 0.2° W). This means that the present true polar wander is directed exactly along the equator of the Geotectonic Reference System, identical with the 80° W/100° E great circle of the Earth. In conclusion the phenomenon of true polar wander is basically related to the symmetry of the geotectonic system defined by the Pacific pole P, at 170° W/0° N, and the African pole A, at 10° E/0° N.

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