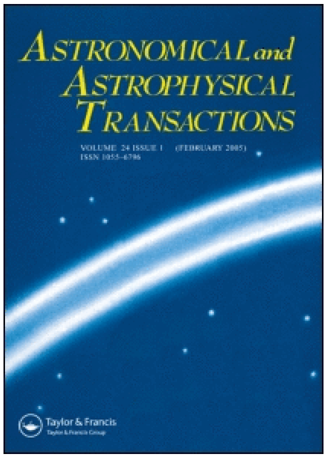

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TOWARDS ON EXPLANATION OF THE SECULAR MOTION OF THE EARTH'S ROTATION AXIS POLE

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The data on the motion of the Earth's rotation axis pole, obtained recently by astrometric and paleomagnetic methods (with respect to the mantle frame of reference), indicate that at the present epoch the paleomigration of the pole constitutes only a part of its observed drift. We show that the pole paleomigration is caused by tectonic mass redistribution and formation of heterogeneities in the upper mantle, which is accompanied by the global relative displacements of the lower mantle, upper mantle and other envelopes. As a principal mechanism we consider the geodynamical processes of subduction and accumulation of masses of the oceanic plates. We found that the pole of the Earth's rotation axis is moving at velocity $\nu_\omega = 0^\circ.40$ Myear^{-1} along the meridian $\lambda_\omega = 56^\circ.2$ W. The parameters found are in a good agreement with their 'observed' values for the Earth's pole, obtained by paleomagnetic methods.

KEY WORDS Earth rotation, pole drift, pole paleomigration, plate tectonics, formation of heterogeneities

1 INTRODUCTION

The problem of investigating the secular motion (drift) of the Earth's rotation axis pole with respect to the Earth's surface (or body) is one of the central problems of geodynamics and astrometry, which has been extensively studied over many years (Podobed and Nesterov, 1982).

In the last 100 years, the drift velocity has been determined by astrometric and geodesic methods, and in the last 20 years by methods of space geodesy, using laser ranging measurements with the dedicated geodesy satellites LAGEOS, ETALON, and others (Eubanks, 1984). This present-day motion of the pole is lightly connected with the problem of paleomigration of the Earth's pole at geological time intervals (scores of millions of years). This method of investigation of the pole migration is based on paleomagnetic data and uses the essential assumption that the Earth's paleomagnetic axis and relational axis in the mean (at geological time intervals) coincide (Parkinson, 1986).

The interpretation of the data of astrometric and paleomagnetic measurements is considerably complicated by the motion of the lithospheric plates, on the surfaces of which the geodesic measurements are carried out. The plate motion refers either to the mean lithospheric frame of reference or to the frame of reference connected with the hot spots (it is sometimes called also the mantle frame of reference) (Argus and Gordon, 1991). Modern investigations (in particular, the study and modelling of plumes and hot spots) demonstrate that the above-mentioned frames of reference and the Earth's rotation axis commit certain motions with respect to each other (Gordon and Livermore, 1987).

The data on the motion of the Earth's rotation axis pole, obtained recently by astrometric and paleomagnetic methods (with respect to the mantle frame of reference), indicate that at the present epoch the paleomigration of the pole constitutes only a part of its observed drift.

These data may be interpreted as follows. The slowest pole motion, taking place over millions of years, is its paleomigration. This motion of the pole P_ω over the Earth's surface takes place at typical angular velocities of the order of $0^\circ.1$–$0^\circ.5$ per million years. On this slow geological motion of the pole, faster long-period variations with characteristic periods of $\approx 10^5$ years are superimposed (with the velocity of about 1° per million years). The former of these motions is caused by the global tectonic process, whereas the latter is caused by geodynamic processes in the hydroglacial shell of the Earth, etc.

Dynamic investigations (Barkin, 1995; 1996a) show that the secular motion p_ω is due to redistribution of masses in the deformable Earth, which lead to variations of the Earth's products of inertia or of the corresponding geopotentiai coefficients C_{21}, S_{21}. In these papers an analytical description of secular effects in the rotational motion of a celestial body with a deformable outer shell is presented. According to these works, the main components of the pole drift velocity P_ω in coordinate axes Cx_0, Cy_0 are given by the following simple formulae:

$$\dot{p} = \omega\left(\frac{\omega}{\Omega}+1\right)\frac{\dot{C}_{21}}{I}, \quad \dot{q} = \omega\left(\frac{\omega}{\Omega}+1\right)\frac{\dot{S}_{21}}{I}. \tag{1}$$

Here ω and Ω are the frequencies of the unperturbed Chandler motion of the body, $\omega+\Omega$ is the rate of the Earth's diurnal rotation, $I = C/(mR^2)$ is the dimensionless moment of inertia (C, m and R are the polar moment of inertia, mass, and mean radius of the deformable body, respectively), and $\dot{C}_{21}$, $\dot{S}_{21}$ are secular variations of geopotentiai coefficients C_{21}, S_{21}. The motion of the pole with velocities (1) is referred to the main central axes of inertia of the body for the given epoch $Cx_0y_0z_0$. The vector of angular velocity describes the rotation of precisely this system of coordinates. The variations $\dot{C}_{21}$, $\dot{S}_{21}$ are determined with respect to the system of coordinates $Cx_0y_0z_0$, too.

Thus, owing to a slow rebuilding of the body's dynamic structure, the pole of the rotation axis P_ω is moving at angular velocity ν_ω along meridian λ_ω, where

$$\nu_\omega = \left(\frac{\omega}{\Omega}+1\right)\frac{\sqrt{\dot{C}_{21}^2+\dot{S}_{21}^2}}{I}, \quad \lambda_\omega = \arctan\left(\frac{\dot{C}_{21}}{\dot{S}_{21}}\right). \tag{2}$$

The Earth's dynamic structure is close to that of an axisymmetric body; therefore, formulae (I), (2) conserve their form if we use the Greenwich system of coordinates as the main one. In this case, λ_ω is the Greenwich longitude, and variations $\dot{C}_{21}$, $\dot{S}_{21}$ are also defined in the Greenwich system of coordinates.

In this work, we investigate the effect of global tectonic motions on the pole motion, namely the influence of the motion of plates, their subduction and accumulation of masses of the submerging oceanic plates along the subduction zones. The role and contributions of other geodynamic processes can be studied separately. The aim of this work is to explain the paleomigration of the Earth's pole at the modern geological epoch.

2 EXPLANATION OF POLE PALEOMIGRATION

In Khain and Zverev (1991) it is noted that one of the main regularities, found by the method of seismic tomography is the presence of excess masses along the subduction zones at depths of 350–550 km. The excess of masses in the subduction zones is caused by the relatively cool matter of the oceanic lithosphere, pushed under the volcanic arcs; this cool matter forces the hot mantle matter of the arcs upward. Dziewonski and Ekstrom (1996) connect the global structures, revealed in the mantle by the method of seismic tomography, with the accumulation of the oceanic-plate blocs, submerging along the subduction zones. The ring of the regions with increased seismic velocities, surrounding the Pacific Ocean, is due to subduction and accumulation of masses at depths of about 1000 km. It is noted that this process has been taking place for the last 200 million years.

An analysis of the global structure of the Earth's shells indicates their imbalance (Barkin, 1999). The displacements of the shells' centres of masses reach quite large magnitudes; their central axes of inertia are rotated by considerabie angles; this is caused by large values of the corresponding products of inertia of the shells. Of course, this asymmetry of the dynamic shells has been forming during geological time intervals.

In other words, the masses, accumulated along the subduction zones during geological time intervals, did not get complete isostatic compensation, but instead continued to accumulate at a certain rate over millions of years. An important task is to determine the intensity of the mass accumulation along the subduction zones. The accumulation of masses along certain zones of the Earth's outer shell is accompanied by the global relative displacements of the lower mantle, upper mantle and other envelopes (Barkin, 1999) and leads to a change in the position of the Earth's centre of masses (for instance, with respect to the centre of masses of the liquid core). These processes, of course, have many consequences: variations of volcanic and seismic activity, sea level changes, variations of tectonic processes and other with observed inversion property. In particular they lead to definite slow variations of components of the Earth's tensor of inertia and geopotential coefficients.

In earlier papers (Barkin 1996a, b; 1995) we for the first time estimated the secular variations of the position of the Earth's centre of mass and of the components of the Earth's centre of inertia, caused by the accumulation of masses of the oceanic plates, submerging in the subduction zones. We based this work on the theories of absolute and relative motion of lithospheric plates. In fact, in these works we got upper estimates for the variation of the components of the Earth's tensor of inertia and of the coordinates of the Earth's centre of masses.

The main result of these works is that for the first time we have shown the role of tectonic processes (plate motion, subduction and accumulation of the plate masses along the subduction zones) in the paleomigration of the Earth's pole.

We have proposed two methods of determination of the components of the Earth's tensor of inertia, caused by the mechanism of subduction and accumulation of masses (Barkin, 1995; 1996a). One of the mechanisms is based, on the analytical description of 'the effect of overlap of plates' along the subduction zones, it is based on the kinematic theory of the absolute motion of plates. The other method – a more direct one – uses the procedure of analysis of mass inflow rate over all the subduction zones and determination of the corresponding variations of the components of the tensor of inertia. This procedure is reduced to the calculation of volume integrals over the subduction zones. In this case. we use the well-known data on the thickness of the submerging lithosphere ($H = 80$ km), its mean density ($\rho = 3.3$ g cm^{-3}) as well as the parameters of the kinematic theory of the relative motion of plates (Ushakov and Galushkin, 1978).

We will call the fraction of the accumulated masses in the total masses, submerging in the subduction zones, the coefficient of the mass accumulation intensity i_a. We estimated this parameter by two indirect methods. The first one involves an analysis of the parameters of the model of heterogeneous Earth's shells and of shells of its heterogeneities; this model was presented by Barkin (1999). Following this approach, we determined the products of inertia of the shell of heterogeneities, formed by the accumulated masses. As a result, we established that only a fraction $i_a = 1/3$ of the total mass of oceanic plates, inflowing to the subduction zones, is subject to accumulation, whereas the majority of these masses takes an active part in global dislocations and deformations, is involved in convective mantle motions, carried along by the global rotation of the lithosphere, etc. We found the coefficient i_a under the assumption that the considered process of formation of a shell of accumulated masses has been taking place at a constant rate over 43 million years (Barkin, 1999). In particular, this assumption is based on the well-known data on the variations of the Earth's polar moment of inertia and of the Earth's dynamic oblateness during the above-mentioned time interval (Chebanenko and Fedorin, 1984).

The second method uses an analysis of the related geodynamic phenomenon – the drift of the geocentre at geological time intervals (Barkin, 1996b). We may consider this phenomenon also as a shift of the centre of masses of the liquid core with respect to the Earth's centre of masses. Due to the shift, the relative velocity of rotation of the mantle and core changes. From the law of conservation of the kinetic moment of the mantle–core system it follows that the core rotation, observed by the westward drift of the magnetic field (Barkin, 1999), forms if the center of masses of the core is shifted by about 3.6 km from the Earth's centre of masses. The corresponding shift of the Earth's centre of masses just takes place for a rate of mass accumulation of the subducted plates during the last 43 million years $i_a = 1/3.0$; thus, both estimates, using the well-known observational data, approximately coincide.

Here we omit the detailed presentation of the results obtained; we will give only the final values of the variations $\dot{C}_{21}$, $\dot{S}_{21}$, calculated in the above-mentioned way by the method of Barkin (1996a) for the coefficient $i_a = 0.33$:

$$\dot{C}_{21} = -0.297 \times 10^{-9} \text{ century}^{-1}, \quad \dot{S}_{21} = 0.444 \times 10^{-9} \text{ century}^{-1}. \tag{3}$$

For values (3), we find with (1), (2) that the pole of the Earth's rotation axis is moving at velocity $\nu_\omega = 0^\circ.40$ Myear^{-1} along the meridian $\lambda_\omega = 56^\circ.2$ W. The parameters found are in good agreement with their 'observed' values for the Earth's pole, obtained by paleomagnetic methods (Stienberger and O'Connell, 1997):

$$\nu_\omega = 0^\circ.56 \text{ Myear}^{-1}, \quad \lambda_\omega = 40^\circ \text{ W}.$$

Note also that, because of the process of mass redistribution, the Earth's centre of masses shifts at geological time intervals at a velocity of 8.5 mm/century toward the geographic point 15° N, 168° E; this correlates well with the direction toward the Earth's magnetic centre (Barkin, 1996b; 1999).

Thus, the main cause of the Earth's pole paleomigration is the global tectonic process and the accompanying geodynamic processes of subduction and accumulation of masses of the oceanic plates. For the value we have found for the coefficient of the mass accumulation rate, the pole paleomigration at the present epoch gets a full explanation, in both magnitude and direction.

To conclude, let us note that Stienberger and O'Connell (1997), Sabadini and Yuen (1989) and Richards *et al.* (1997) have developed another approach to the explanation of the drift of the Earth's axis pole; in these works, the clue role belongs to the mechanism of mantle convection, taking into account the presence of heterogeneities in the mantle, peculiarities of plate geometry and motions, their subduction, etc. The model, proposed in this work, is simpler and, seemingly, more feasible from the mechanical point of view. It has allowed us to estimate secular variations of the geopotential coefficients (the first and second harmonics) and, in particular, to reveal a new fundamental phenomenon in geodynamics – secular drift of the Earth's centre of masses (Barkin, 1995; 1999). By means of modelling plate subduction in past geological epochs, the method proposed will permit us to investigate the motions of the pole and geocentre over the last 180 million years.

The results of this work also include arguments in favour of a global phenomenon – displacement of the centre of masses of the liquid core (with lower mantle) and upper mantle with respect to the Earth's centre of masses. This may constitute a basis for a new geodynamic conception of the interacting and moving Earth's envelopes (including plates). Fulfilled studies show that principal phenomena in seismology, volcanology, tectonics, climatology, in Earth rotation are mutually-coupled in the time (in the different scales from days to million years) and their connections are caused by one mechanism – regular and irregular relative translational and rotational displacements of the lower mantle and upper mantle and other Earth's envelopes.

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