The Definition of Deviation of “Geoevolutionary” Plumb Line Based on Data from the Transformation of the Earth

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Abstract – This article is about dynamic transformation of the litosphere relative to the geoid. Calculated of deviation of “geoevolutionary” plump line, which is interpret as the angle between the normal to the surfaces of ellipsoids approximating the shape of the litosphere and the geoid. These values are converted into tangential force and determine the stress-strain state in the Earth’s crust.

Keywords – the geodynamic evolution of the Earth's, the deflection of the plumb line, transformation of Earth, tangencial forces.

I. Introduction

Earth – is a celestial body of Solar system and its shape is developed under the influence of external and internal factors, which have cosmogeneous, endogenous and exogenous origin [4]. Variations in rotational motion of Earth as cosmic body, along with endogenous and exogenous processes lead to the transformation of the Earth’s shape during geological history. Considering structural composition of the Earth with several layers with different rheological properties: lithosphere, asthenosphere, mantle, internal and external core, an assumption can be made that gravitational and rotational forces perform different influences on those internal layers. Consequences of such impacts may appear in: cyclic geodynamical instability of the Earth’s shape, Earth’s center mass movement, variations in geopotential coefficients, secular motion of terrestrial poles, ocean level changes and variations in Earth’s rotation. There is no doubt that internal and external factors such as climatic changes, seismic and volcanic activity and many other natural processes are interrelated to the Earth’s shape transformation.

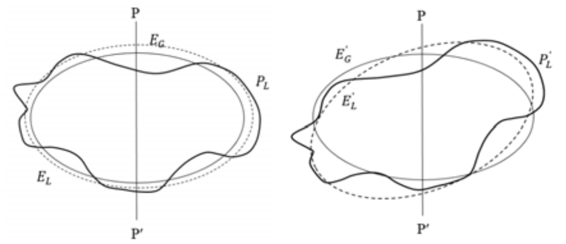
Let's consider the geodynamic evolution of the Earth's image as a consequence of the process of redistribution of its mass in a dynamically changing force field, with the acquisition of a form with minimal potential energy. These masses are under the influence of three groups of forces: the cosmogenic, endogenous and exogenous nature, the effect of which leads to processes of transition from one state of equilibrium to another in different time and space scales in the planetary field of geodeformation. This continuous process of reaction has its critical boundary depending on the physical and mechanical and geological properties of the rocks and the environment, the magnitudes and scales of geometric parameters, tectonic forms and duration of forces. After reaching the critical edge, the shape of the planet changes its shape. As a result, on its surface there is a destruction and huge geological faults are formed.

If we present the Earth without water, then we find that the relief of the earth's surface differs significantly from the geoid. Comparing the geoid map with tectonic maps, we arrive at a well-known conclusion that there is no link between geoid heights and tectonic structures. The heights of the geoid reveal an absolutely independent distribution, even in relation to the largest tectonic structures of the lithosphere: continental protrusions and oceanic trough. This absence of the relationship between the heights of the geoid and the structure of the lithosphere is due to the non-homogeneous placement of planetary structures of the physical surface of the Earth relative to the figure of a geoid, which may be caused by the displacement of lithospheric plates. The latter can lead to the rotation of the entire lithosphere of the Earth relative to a more stable figure of the geoid, which may have been reflected in the difference in the values of parameters and in the orientation of geometric shapes that approximate the physical surface and geoid.

II. Problem definition

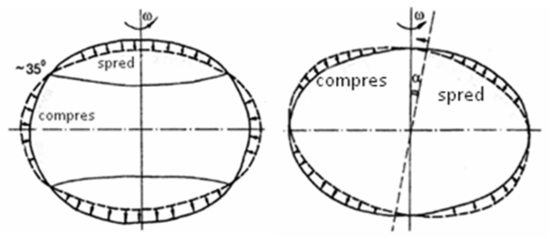
Scientific concepts of planets evolution show that in the past Earth was closer to the state of hydrostatic equilibrium than now. Consequently – external surface of lithosphere coincided with ellipsoidal shape, fitted geoid in best way. This means that in that past period plumb line direction coincided with normal to ellipsoid, which approximated external surface of lithosphere. Schematic illustration of Earth’s shape evolutionary forming process is shown on Fig.1, where the following notations were introduced: PP’ – Earth’s rotation axis, P_L – lithosphere surface, E_L – ellipsoid best suited to the lithosphere surface, E_G – ellipsoid that describes Earth’s shape in the ancient geological epoch. All notations in Fig. 1a are marked with a prime in Fig. 1b for the figure and surface of the Earth's lithosphere in the modern era.

Thus, comparison of two positions of the outer shells of the Earth in Fig. 1a and Fig. 1b allows to assume the appearance of a stressed state due to changes in the rotation speed and the position of the rotation axis with respect to the Earth’s shape. Stress distribution within the Earth’s lithosphere, which may appear because of Earth’s shape transformation, is shown schematically in Fig.2. Such a stress distribution scheme was proposed by K. Tyapkin in a new rotational hypothesis of structure formation [3]. In the case of simultaneous changes of the parameters of the Earth’s rotational regime (angular velocity and the position of the rotation axis), it is assumed that the slowing down of the Earth's rotation causes the appearance of stresses in the lithosphere (distribution of which is shown in Fig. 2a) and change of position of the rotation axis leads to a reorientation of the figure and formation of compression and expansion zones (Fig. 2b). Actual geological evidences suggest that a significant role in this process is played by the tectonic factor caused by the displacement of lithospheric plates, which can affect the terrestrial poles position.



a b

Fig.1 Schematic illustration of the body forming the Earth: a – in the initial period when the Earth was closer to the state of hydrostatic equilibrium; b – the current state of Earth's shape and Earth's lithosphere surface



a b

Fig. 2 Schematic stress distribution within Earth lithosphere: a – due to changes in rotational movement around the axis; b – du to position changing of the rotational axis [6]

Geologists A. Malouf and G. Halverson [1] assumed that 800 million years ago the terrestrial poles shifted. This assumption may be considered as a confirmation of such interpretation for Earth’s figure transformation. By studying the magnetization of minerals in the old sedimentary rocks of the Norwegian archipelago, they discovered that the north magnetic pole shifted quickly by 50 degrees during 20-million-year period. Since the tectonic plates motion is very slow authors explained such displacement of lithosphere surface with respect to the core, where the magnetic field is formed, by the global mass redistribution, which may results in rapid change in the position of the rotation axis. Such process might have started after a large imbalance of masses in the mantle. For example, due to the appearance of a super volcano near the equator. The studies carried out by A. Tserklevich and A. Zayats [5] give grounds for a statement that tectonic structures of planetary scale appeared in the process of geological evolution of the Earth, which could significantly affect the rotational parameters and the figure. In particular, the hypothetical Darwin’s relic rise [2] on Earth could shift the pole by 15 km, and slow down the rotation speed by 0.09 sec. The volcanic Tarsis rise [3] on Mars respectively, could change the pole position by 6 km and the rotation speed by 0.06 sec respectively. Obviously, the obtained results are estimative and can be interpreted as a possible option of dynamic processes development, which can lead to changes in rotation axis position and result in appearance of stressed state and fault structures in the lithosphere of planets.

Such placement of the figure of the lithosphere and of the geoid figure can create a strain aimed at bringing the distribution of the masses in line with the figure of the geoid.

III. Method of solving the problem

We restrict ourselves to the definition of only the tangential forces that arise in connection with this redistribution of masses in the upper shells of the Earth (bark and upper mantle). We introduce the concept of deviation of “geoevolutionary” plumb line and assume that the tangential forces are proportional to the angle g , which is defined as the angle between the direction of the plumb lines in the past geological epoch and the direction of the plumb lines at a given point. Note that the ellipsoid E_L in the past approximately represented the level surface of our planet. Now he is responsible for the ellipsoid E'_L. It is clear that the dimensions of the ellipsoid E'_L in comparison with E_L the changed, since the external surface of the lithosphere has changed. Accordingly, the parameters of the ellipsoids are not identical. However, we can assume that the surface of the Earth in the past roughly coincided with the surface of ellipsoid E'_L, and in the case of such an assumption, the angle between the directions of the plumb lines (normal line to surface ellipsoids) is formed g .

When determining the angle g we will not take into account the discrepancy of the centers of ellipsoids E'_L and E_L, since it will not significantly affect the result.

In addition, the longitude will be measure not from the Greenwich meridian, but from the line of nodes, that is, from the line of intersection of the plane of the equatorial ellipsoids E'_G and E_L.

Consequently, at an arbitrary point of the ellipsoid surfase , we have the expression for calculating the radius of a vector:

$$r_0 = a_0\left(1 - a_0 \sin^2 j_0\right) \qquad (1)$$

where r_0 is the radius vector of the point, j_0 is the latitude, a_0 is the flattening of the Earth.

The radius vector r_0 crosses the surface E'_L at some point. Denote by ρ the radius vector of this point, and we will have an expression for its calculation:

$$r = a\left(1 - a \sin^2 j\right), \qquad (2)$$

where r – the radius vector of the point, j – the latitude, which is measur from the plane of the equator of the ellipsoid; a and a – respectively, the semi-major axis and the flattening of the same ellipsoid.

The distances between the ellipsoids and determine :

$$S = r - r_0 = a - a_0 + a_0 a_0 \sin^2 j_0 - a a \sin^2 j \qquad (3)$$

From the spherical triangle we express j through j_0 and l_0. Note that l_0 - the longitude of the point, which is measure from the line of nodes. Refer to Figure 3, where the following notation is taken: P'_G and P'_L the points reflecting the position of the poles of the ellipsoids (E'_L and E'_G) in the single sphere; $P'_G L$ – the initial meridian whose plane passes through a line of nodes; z - average distance between the poles and; T - point in which we determine the angle g .

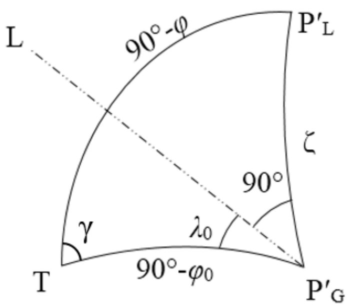


Fig. 3 Illustration to the definition of angle g

From the figure we have:

$$\sin j = \cos z \sin j_0 - \sin z \cos j_0 \sin l_0. \quad (4)$$

Now formula (3) can be written as:

$$S = a - a_0 + \left(a_0 a_0 - aa \cos^2 z\right)\sin^2 j_0 - - aa \sin^2 z \cos^2 j_0 \sin^2 l_0 + + \frac{1}{2} aa \sin 2z \sin 2j_0 \sin l_0. \quad (5)$$

We introduce the following symbols to simplify the writing of formula (5):

$$A = a - a_0; \quad (6)$$

$$B = a_0 a_0 - aa \cos^2 z; \quad (7)$$

$$C = -aa \sin^2 z; \quad (8)$$

$$D = \frac{1}{2} aa \sin 2z. \quad (9)$$

As a result we will receive

$$S = A + B\sin^2 j_0 + C\cos^2 j_0 \sin^2 l_0 + + D\sin 2j_0 \sin l_0 .(10)$$

The components of the "geoevolution" deflection of the plumb line in the plane of the meridian and in the plane of the first vertical, respectively, will have the form:

$$x = \frac{1}{R}\frac{\partial S}{\partial j_0}, \ h = \frac{1}{R\cos j_0}\frac{\partial S}{\partial l_0}, \quad (11)$$

where R - the mean radius of the Earth.

Taking the corresponding derivatives of expression (7), we obtain:

$$\frac{\partial S}{\partial j_0} = 2B\sin j_0 \cos j_0 - 2C\sin j_0 \cos j_0 \sin^2 + 2D\cos 2j_0 \sin l_0 ; \quad (12)$$

$$\frac{\partial S}{\partial l_0} = 2C\cos^2 j_0 \sin l_0 \cos l_0 + + D\sin 2j_0 \cos l_0 . \quad (13)$$

Accordingly, for the components of the deflection of the plumb line, we will have:

$$x = \frac{2B}{R}\sin j_0 \cos j_0 - \frac{2C}{R}\sin j_0 \cos j_0 \sin^2 l_0 + \frac{2D}{R}\cos 2j_0 \sin l_0 ; \quad (14)$$

$$h = \frac{2C}{R}\cos^2 j_0 \sin l_0 \cos l_0 + + \frac{D}{R}\sin 2j_0 \cos l_0 . \quad (15)$$

From the components of the "geoevolutionary" deviation of the plumb line, we turn to the tangential components of forces acting on a unit of mass in the upper layer of the Earth. To do this, we multiply the expressions (11) on g – acceleration of gravity.

Consequently, we obtain:

$$m = \frac{Bg}{R}\sin 2j_0 - \frac{Cg}{R}\sin 2j_0 \sin^2 l_0 + + \frac{2Dg}{R}\cos 2j_0 \sin l_0; \quad (16)$$

$$n = \frac{Cg}{R}\cos^2 j_0 \sin 2l_0 + \frac{Dg}{R}\sin 2j_0 \cos l_0. \quad (17)$$

Thus, according to the formula (10), we can calculate the distance between the ellipsoids E'_G and E'_L, that is, the reduction or increase distance of the lithosphere relative to the sea level due to the rotation of the tough part of the Earth caused by the displacement of the lithosphere as a single shell.

By formulas (13) and (14), we determine the potential forces that act as a gradual return of the mass distribution to the equilibrium state as a mechanical system with a rotation around the smallest moment of inertia.

Note that in the formula (10), in addition B, C, D to the coefficients A, there is a coefficient that needs to be corrected, taking into account the invariance of the volume of the ellipsoids.

Consequently, in determining A we will proceed from the fact that the volume of Earth in the last geological epoch has not significantly changed. This condition leads to equality

$$a_0^2 b_0 = a^2 b. \quad (18)$$

If we accept

$$\left.\begin{array}{l} a = a_0 + \Delta a = a_0\left(1 + \frac{\Delta a}{a_0}\right) \\ b = a_0\left(1 - a_0\right) = a\left(1 - a\right) \end{array}\right\}, \quad (19)$$

then we will get

$$1 - a_0 = \left(1 - a\right)\left(1 + \frac{\Delta a}{a_0}\right). \quad (20)$$

Taking into account small values and expanding in a series, we have

$$a_0 = a - 3\left(\frac{\Delta a}{a_0}\right) \qquad (21)$$

and

$$aa = a_0 a = c, \qquad (22)$$

where c – constant, which is calculated when replacing aa the corresponding value.

$$a = \frac{c}{a_0}, \Delta a = \frac{a_0}{3}(a - a_0). \qquad (23)$$

Taking into account the previous simplifications, the expression (10) can be represented as

$$S = \frac{aa}{2}\sin l_0 \sin 2j_0 \sin 2z - \\ - aa\cos^2 z \sin^2 j_0 - \\ - aa \sin^2 z \sin^2 l_0 \cos^2 j_0 + a - a_0 \qquad (24)$$

Conclusion

The calculated values of the components m, n illustrating the stress-strain state of the lithosphere in the modern era are shown in the form of a vector field in Figure 4. As can be seen from the figure, the largest values of the constituent forces are concentrated in the so-called "critical latitudes" from 35 ° to 45 °.

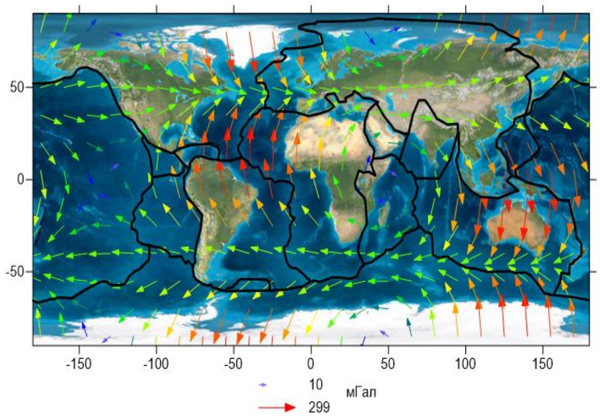


Fig. 4 Map of tangential forces against the background of continents and oceans and tectonic plates. Arrows show tangential forces in mGal.

Investigation of tangential forces arising as a result of reorientation of a thin solid shell of our planet has shown that a field of stress is formed on its surface. Its forces are located in the form of four vortices, two polar , located near the poles, as well as two equatorial ones. Having analyzed the acting forces, it is observed that the values of the forces acting near the vortex axis are minimal, and on the edges they are maximal. The axes of this vortex system are mobile, respectively, their force lines should be spiral, as illustrated by the map(Fig. 4).

It is very difficult to interpret these forces, it is certain that they have a role in the tectonic dynamics of our planet. The question is for how much they affect it, and these thin relation still need to deeply research.

References

[1] Maloof, A.C., Halverson, G.P., Kirschvink J.L. at al. Combined paleomagnetic, isotopic, and stratigraphic evidence for true polar wander from the Neoproterozoic Akademikerbreen Group, Svalbard, Norway // Geological Society of America Bulletin. – 2006. – v. 118, no. 9/10. – P. 1099-1124.

[2] Menard G.U. Geologiya dna Tihogo okeana [Geology of the bottom of the Pacific Ocean]. – M.: Mir, 1966. – 275 p.

[3] Mescheryakov G.A., Tserklevich A.L. Gravitatsionnoe pole, figura i vnutrennee stroenie Marsa [Gravitational field, figure and internal structure of Mars].–Kiev: Naukova dumka, 1987. – 240 s.

[4] Tserklevych A.L., Zayats O.S. and Shylo Y.O. Dynamics of the Earth Shape Transformation Kinematics and Physics of Celestial Bodies, 2017, Vol. 33, No. 3, pp. 130–141.

[5] Tserklevych A.L., Zayats' O.S. Heodynamichna evolyutsiya fihury Zemli ta Marsa [Geodynamic evolution shapes Earth and Mars]// Heodynamika. – 2012. – v. 2(13). – P. 38–42.

[6] Tyapkin K.F., Kivelyuk K.F. Izuchenie razlomnyih struktur geologo-geofizicheskimi metodami [Study of fault structures by geological and geophysical methods]. – M.: Nedra, 1982. – 239 p.