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ON THE DISTRIBUTION OF TANGENTIAL MASS FORCES IN THE EARTH'S LITHOSPHERE

The study aims to determine and interpret the distribution of the global tangential mass force (TMF) vector field by azimuthal orientation and intensity. Using cluster and correlation analysis, we compared the direction of the TMF vector field with the direction of movement of permanent GNSS stations and the direction of movement of the GSRM model continental velocities from the Global Strain Rate Map Project. Methodology. The author continues their study of additional planetary stresses in the lithosphere caused by distributed mass forces. The forces in question may be linked to the repositioning of the Earth's lithosphere, which can create stresses aimed at aligning the distribution of lithospheric masses with the geoid's figure. This repositioning happens through the mechanism of gravitational forces and the principle of minimum potential energy. The presence of a deviation of the plum line from the normal to the surface of the solid Earth determines the appearance of TMF acting in the upper shell of the Earth. It is proposed to calculate the amplitudes and directions of the vectors of such TMF based on data regarding the difference in the parameters of two global ellipsoids that approximate the physical surface of the lithosphere and the geoid. Originality. For the modern era, the value of the angle of rotation between the smallest axis of the ellipsoid approximating the surface of the lithosphere and the axis of rotation of the Earth is 2.6°. The distribution of the TMF vector field is consistent with the contours of the continents, i.e., the arrows of the vectors indicate the directions of lateral movement of tectonic plates and the movement of continents during the Earth's evolution. As a result of the change in the orientation of the ellipsoid describing the lithosphere, an updated field of potential horizontal forces is formed, which, by the conservation of the momentum of motion, move lithospheric masses and generate stresses and deformations in the lithospheric shell. Since the TMF has different directions and intensities, a cluster analysis of the TMF distribution was performed. It revealed certain regularities in the distribution of these parameters. We also compared the directions of the TMF vector field with the directions of movement of permanent GNSS stations and the directions of movement of model velocities of the continents of the GSRM (digital model of the tensor field of the global velocity gradient). Scientific novelty. The study detailed the peculiarities of the connection between the directions of the TMF vector field, the directions of movement of permanent GNSS stations, and the ones of the model velocities of the GSRM continents. Studies of the TMF, which arise as a result of the reorientation of the thin solid shell of our planet, have shown that a deformation field of shear is formed on its surface. In our opinion, this is one of the likely factors of the process that triggers global movements of lithospheric blocks. As a result, the shape of the lithosphere is transformed, which is characterized by a change in the size of the axes of the ellipsoids describing the surface of the lithosphere and their orientation. Practical significance. The research results make it possible to more reliably interpret the peculiarities of the TMF distribution. These forces can trigger mechanisms for discharging accumulated stresses, which is important for studying seismicity.

Key words: the physical surface of the Earth; tangential mass forces; planetary stresses; movement of tectonic plates; geodynamics

.*Introduction*

Today, the most popular tectonic hypotheses are theories of plate tectonics. Within the framework of plate tectonics, the Earth's surface is represented by rigid plates that are separated along discrete boundary faults [Morgan, 1968; Turcotte and Schubert, 2014].

Conceptually, plate tectonics is most responsible for changes in the Earth's landforms. Over the past 50 years, many dynamic models have been developed to estimate the forces acting on tectonic plates. Despite the wide acceptance of the theory of plate tectonics, there is currently no clear and agreed-upon mechanism to explain the movement of plates. A recent article published by Coltice et al. (2019) raises a fundamental question: whether the mantle of the Earth controls plate movement or whether the plates themselves control the flow of the mantle. Other questions include if the dynamic balance between plates and mantle changes during long-term tectonic reorganizations and at what spatial wavelengths these processes occur.

Models of global mantle convection with plate-like behavior allowed the authors to investigate the sources of lateral movements on the Earth's surface within the concept in which the mantle and lithosphere constitute a single self-organized system.

The modeling results, perhaps for the first time, performed by [Forsyth and Uyeda, 1975] indicate that the plate thrust force prevails over the mantle resistance at the base of the plates. Based on these results, they suggested that tectonic plates control mantle flow. The mantle rocks, together with the oceanic and continental crust, belong to a single convective system in which the lithosphere is a thermal boundary layer. According to [Koptev and Ershov, 2010], the movement of tectonic plates may originate from within the plates themselves. Differences in the thickness of the Earth's crust, along with variations in density, create forces that work to even out these differences and bring the lithosphere into a more uniform state with a lower potential energy value.Forces that shape the Earth's crust include various factors such as ridge slip forces caused by thermal differences in mid-range ridges, gravitational forces that spread the thickened crust of mountain belts, spreading forces that act on masses in areas with thermal anomalies, and slab pulling into a trough, etc. Some methods for quantifying the magnitude of such forces were proposed in [Frank, 1972; Forsyth and Uyeda, 1975; Artyushkov, 1979]. However, there are a number of difficulties in modeling these processes.

An alternative variant of the mechanism of lithospheric plate movements is the presence of thermal convection flows [Schubert et al., 2001; Bercovici, 2003; 2007; Tackley, et al., 1994; Tackley, 2000; Trubitsyn, 2019], but the mechanical probability of the existence of such flows remains uncertain. For example, according to seismic tomography data, stable isometric superplumes, the absence of an upward convection flow in spreading zones, etc. cannot be explained by such thermal convection models. Plate movements may go undetected or may cause destructive events such as earthquakes or volcanoes. Over time, the combination of these shifts changes the shape of the Earth's surface, altering existing landforms and creating entirely new ones. It is clear from all of the above that we cannot fully reject the validity of other orogenesis theories at this time. But this will happen only when more factual data about our planet is accumulated.

It is widely accepted in the field of Earth sciences that the Earth's rotation plays a crucial role in the formation of various phenomena such as tectonic activation, global transgressions and regressions, and the creation of a magnetic field. These changes in the Earth's rotational regime, including variations in its angular velocity and movement of the rotation axis, are a result of geoevolutionary processes. For example, Dovbnich [Dovbnich, 2008] concluded that the main contribution to the field of rotational stresses is not provided by variations in the rotation speed, but by changes in the position of the rotation axis in the Earth's body. Based on the results of numerical modeling of the stress-strain state of the Earth due to the planet's rotation, he estimated that the maximum stresses in the tectonosphere caused by changes in the position of the rotation axis reach values of the order of 10^7 Pa. The stresses caused by variations in angular velocity are characterized by values of the order of 10^5 Pa, i.e., two orders of magnitude less. Thus, our calculations suggest that the Earth's rotational mode makes a significant contribution to the stress state. Changes in the position of the rotation axis should lead to a significant restructuring of the Earth's stress state and, as a result, affect tectonic processes.

The articles [Rebetsky, 2016; Rebetsky and Myagkov, 2020; Tserklevych et al., 2017; Tserklevych and Shylo, 2018; Tserklevych et al., 2019] consider the role of (TMF) in the occurrence of lateral movements of lithospheric plates. The TMF values were calculated on the basis of data on the differences in the parameters of two global rotation ellipsoids.

The article [Rebetsky, 2016] shows that the coefficient of dynamic compression of the Earth equal to 1/305.5 corresponds well to the average polar compression of two ellipsoids of rotation that approximately describe the shape of the Earth's physical surface separately in its continental and oceanic parts. Thus, the physical surface of the Earth is best described by an ellipsoid that has less polar compression than the reference ellipsoid (1/298.25), which approximates the shape of the geoid. The angles of deviation of the gravity vector from the normal to the physical surface of the Earth, calculated from these ellipsoids, were quite small (maximum value 16.4" at latitude 45°), which determines the minimum values of TMF ($2.15 \cdot 10^{-4}$ g/cm^3 at latitude 45°). These small tangential forces are capable of generating tangential stresses of 0.3 MPa in the foot of the continental lithosphere (120–150 km deep). Stresses of this level can produce horizontal fluidity in the asthenosphere, which ensures the speed of movement of lithospheric plates in the first centimeters per year. Our estimates allow us to consider the TMF as a possible source of lithospheric plate motion.

TMFs are also generated as a result of the deviation of the minor axis of the ellipsoid (by about 3°), which describes the surface of the lithosphere, from the axis of rotation of the Earth, and they are 2–3 times larger compared to the above forces [Tserklevych et al. 2016; Tserklevych et.al. 2017; Tserklevych and Shylo 2018]. The position of the lithosphere and the shape of the geoid can cause tectonic stresses that aim to align the distribution of mass in the lithosphere with the geoid shape. This is due to gravitational forces and the principle of minimum potential energy. As the stresses are released, a mechanism is created that brings the polar axis of the lithosphere shape closer to the rotation axis, which is also the polar axis of inertia. [Tserklevych et al., 2019].

Objective

The aim of the study is to determine and interpret the distribution of the global TMF vector field by azimuthal orientation and intensity. Using cluster and correlation analysis, we compare the directions of the TMF vector field with the directions of movement of permanent GNSS stations and the directions of movement of model continental velocities from the Global Strain Rate Map Project [Kreemer et al., 2003].

Research methodology and results

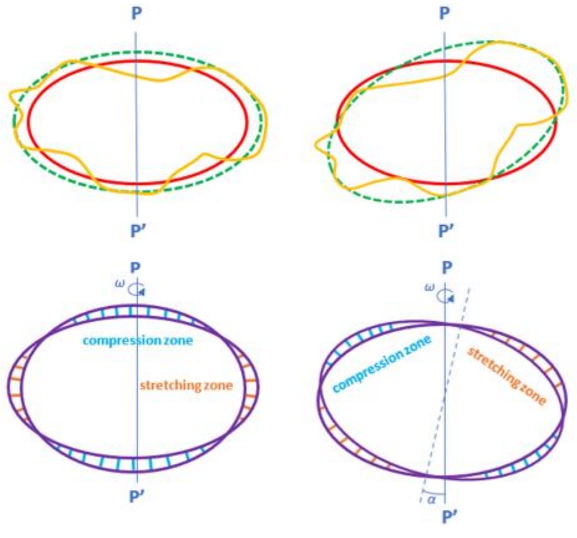
According to previous research results, we found that the shape of the lithospheric surface is geometrically rotated relative to the geoid shape and that the orientation of these shapes and the parameters of the ellipsoids that approximate them have changed in geologic time [Tserklevych et al., 2019]. For the modern era, the value of the angle of rotation between the smallest axis of the ellipsoid approximating the lithospheric surface and the Earth's rotation axis is 2.6° [Tserklevych et al., 2017].

A schematic illustration of the evolutionary formation of the Earth's shape is shown in Fig. 1. If we compare two positions of the Earth's outer shells, we can observe the occurrence of a stress state due to changes in the rotation speed and position of the lithosphere axis relative to the rotation axis. In the case of simultaneous changes in the Earth's parameters (angular velocity and position of the ellipsoid axis), it is assumed that the slowdown of the planet's rotation and its reorientation leads to stresses in the tectonosphere. The release of these stresses, when they reach critical values equal to the tensile strength of lithospheric rocks, leads to tectonic activation of the Earth.

Actual geological data indicate that a significant role in this is played by the tectonic factor caused by the movement of the poles of the Earth's shape.

Fig. 2 shows a map with elevation isolines that define the distances between the surfaces of ellipsoids that generally represent the surface of the Earth's lithosphere and the geoid.

This map illustrates the largest uplifts and downlifts of the Earth's lithosphere, which is an ellipsoid that approximates the planet's surface. The map shows these uplifts and downlifts in the form of wide arcuate stripes that we have conventionally named "tectonic watershed" and "tectonic thalweg." These stripes characterize the differences between the lithosphere's surface and the Earth's ellipsoid surface, which represents the geoid.



a b

Fig. 1. Schematic illustration of the formation of the Earth's shape and stress distribution in the lithosphere:
🟨 lithospheric surface; 🟩 ellipsoid that best fits the lithospheric surface; 🟥 ellipsoid that best fits the geoid surface; a – change in compression of the lithospheric shape; b – change in reorientation.

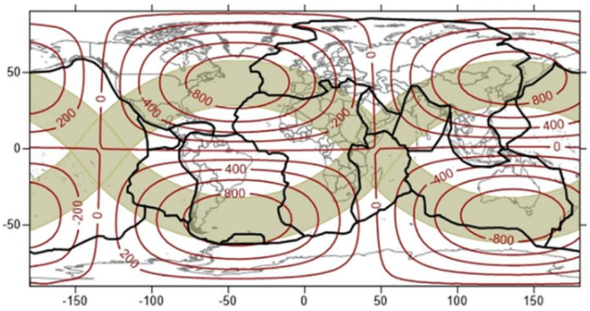


Fig. 2. Map of distances between ellipsoids. Heights are given in metres. The curved lines in the figure correspond to the "tectonic watershed" and the "thalweg".

It turns out that the boundaries of the tectonic plates are almost exactly covered by these bands of "tectonic watershed" and "tectonic thalweg", except for the South American and Pacific plates. Thus, these two bands, representing a kind of structural planetary "watershed" and "thalweg" on the globe, cover almost all the boundaries of the major lithospheric plates. The surface of the lithosphere can therefore be viewed as a deformation ellipsoid, where global spalling zones coinciding with diagonally placed planetary "watershed" and "thalweg" bands are clearly visible.

This figure also shows a clear pattern in the placement of the two elevations and depressions of one ellipsoid on top of the other. This arrangement of ellipsoids creates the distribution of directions of tangential force vectors under the influence of which lithospheric masses flow from uplift to downflow.

To describe the tangential forces generated in the lithosphere due to the reorientation of the Earth's ellipsoid pole, we use the approach presented in [Tserklevych and Shylo, 2018]. The presence of a deviation of a straight line from the normal to the surface of the solid Earth determines the appearance of the TMF acting in the upper mantle of the Earth:

$$F_{\varphi} = \frac{Bg}{R} \sin 2\phi_0 - \frac{Cg}{R} \sin 2\phi_0 \sin^2 \lambda_0 + + \frac{2Dg}{R} \cos 2\phi_0 \sin \lambda_0 , \qquad (1)$$

$$F_{\lambda} = \frac{Cg}{R} \cos^2 \phi_0 \sin 2\lambda_0 + \frac{Dg}{R} \sin 2\phi_0 \cos \lambda_0 , \qquad (2)$$

where g is the acceleration of gravity.

$$F_S = \sqrt{F_{\varphi}^2 + F_{\lambda}^2}. \qquad (3)$$

Fig. 3 shows a map of the TMF.

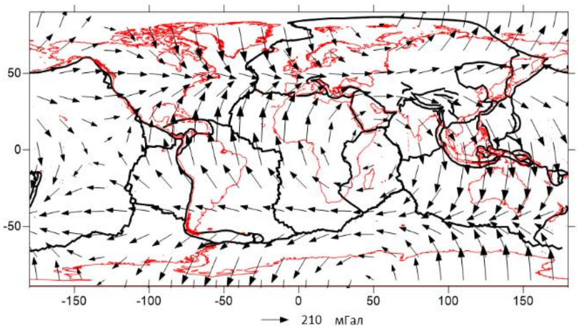


Fig. 3. Map of the TMF.

The figure shows that the distribution of the TMC vector field coincides with the contours of the continents, i.e. the arrows of the vectors clearly indicate the directions of movement of the tectonic plates, the movement of the continents, and the formation of the ocean surface during the Earth's evolution. The epicentre of the TMF vortex twist coincides with the point on the equator where the zero isolines separating the highs and lows in the distribution of heights (distances) between the surfaces of the two ellipsoids practically meet. When the ellipsoid describing the lithosphere changes orientation, it creates a new field of potential horizontal forces. According to the law of conservation of momentum, this field moves lithospheric masses, resulting in the generation of stresses and strains in the lithospheric mantle. When a given volume of matter rises (e.g. a plume rises), the orientation of the shape of the Earth's lithosphere changes over a large regional area, leading to the generation of horizontal forces aimed at aligning symmetry with respect to the axis of rotation. Therefore, the Earth's rotation and the dynamics of the reorientation of the outer surface of the lithosphere are obviously associated with characteristic tectonic structures on a planetary scale. Upon examining the forces, it can be concluded that the areas with the highest tectonic activity and deep earthquakes coincide with the maximum tangential vortex forces.An approximate estimate of the stresses and strain rates resulting from the obtained TMF can be determined from the solution of the mechanical equilibrium equation with volumetric forces corresponding to the weight force. Let us consider the mathematical formulation of the problem according to [Artyushkov, 1979]. If the anomalous density is given as a function of points in the bulk medium, then the deformations and stresses can be determined from eq.

$$\Delta p + \mu \Delta v + \delta g = 0, \qquad (4)$$

where p is the pressure, μ is the viscosity coefficient, v is the displacement velocity vector, and g is the average free-fall acceleration.

Equation (4) is called the Navier–Stokes equation and, when inertial forces are neglected, describes the slow steady motion of a viscous incompressible fluid.

The calculation of the stress-strain state in the lithosphere itself requires the solution of the Navier–Stokes equation for a spherical shell. Understanding the rheological properties of the internal structure of the lithosphere is a complex task, and finding a rigorous solution can be challenging. Hence, it is recommended that we limit ourselves to approximating the characteristics of the stress-strain state.The full solution of the problem is determined by the action of internal forces associated with density inhomogeneities in the lithosphere [Maslov, 1983]. In this formulation of the problem, strain rates and normal stresses can be approximated by the following formulae with an accuracy of up to one order of magnitude:

$$\varepsilon_{\varphi\lambda} \cong \frac{g}{4\pi f \mu} \cdot F_S, \qquad (5)$$

$$\sigma_z \cong \frac{g}{2\pi f} \cdot F_S, \qquad (6)$$

where f is the gravitational constant.

The above relations allow (at a viscosity of 10^{19} Pa·s and an asthenospheric layer thickness of 200 km) to recalculate the obtained TMF in terms of strain rate (1 mGal corresponds to 0.16 mm/year) and normal stress (1 mGal corresponds to $2.5 \cdot 10^5$ Pa). Taking into account the maximum value of the tangential massive forces, which according to Fig. 3 is 210 mGal, we obtain continental movement rates of ~ 4 cm/year and stresses of ~ $5 \cdot 10^7$ Pa. Thus, a simplified formulation of the problem of determining the quantitative characteristics of the Earth's surface deformation field to an order of magnitude confirms the significant influence of the TMF on tectonic processes, which will improve the current understanding of the mechanisms of lithospheric plate movement.

TMF vary in focus and intensity. Therefore, it is advisable to perform a cluster analysis and identify certain patterns in the distribution of these parameters. Figs. 4 and 5 show the results of the cluster modelling.

Coloured circles indicate the cluster to which the TMF belong.

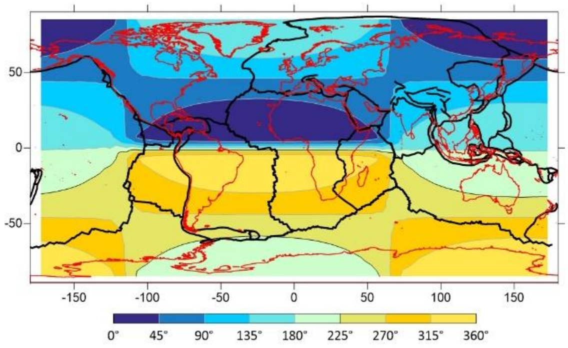


Fig. 4. Map of TMF cluster analysis by azimuthal direction.

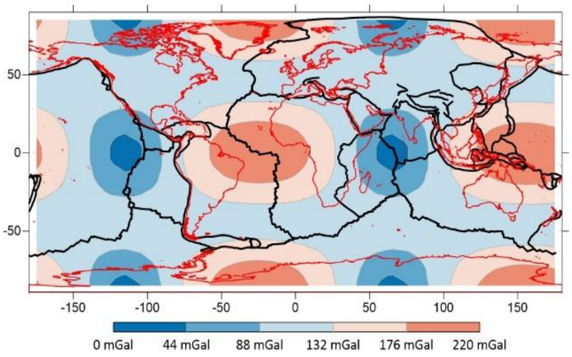


Fig 5. Map of the cluster analysis of TMF by intensity.

Fig. 5 shows the distribution of the five clusters that the program generates randomly. Their boundaries can be found in Table 2. In this figure, you can see that there are four minima and four maxima. Two near the poles and two near the equator. With this division into clusters, in planar terms (visually) the maxima are at least twice as large as the minima.

The studies below analyze how the directions of the TMF vector field compare to the directions of motion of permanent GNSS stations and the ones of the GSRM model continental velocities from the Global Strain Rate Map Project [Kreemer et al., 2003]. The GSRM is a digital model of the global velocity gradient tensor field associated with the representation of modern crustal motion. It was developed from geodetic, seismic, and geological data. A total of 5170 horizontal velocities were used. These velocity vectors were obtained from GNSS observations (86 published sources were used). Seismic data were also used to build the GSRM model, i.e. shallow earthquakes (up to 40 km) that occurred between 1 January 1976 and 31 December 2003 (inclusive). The relevant information was obtained from the Harvard Catalog of Centroid Moment Tensors. The geological data are Quaternary fault slip rates for Central Asia, converted to strain rates. All references to the input data can be found on the official project website [Kreemer, et al., 2023]. A total of 3024 GNSS stations were used from the database [(Scripps Orbit and Permanent Array Center, 2023]. Motion velocities were determined using the method described in [Bock et al., 2021]. Daily solutions for a period of at least 2.5 years were used. Station displacement rates included amplitude and vector data and their uncertainties (in mm/year). Since the time series analysis was performed separately for each component (N, E, U), the velocities were assumed to be uncorrelated. Velocity uncertainties were calculated using the algorithm proposed by [Williams, 2003] to account for noise in GNSS measurements. New velocities were generated weekly using a combined weighted average time series. Links to the input data can be found on the official project website (http://sopac-csrc.ucsd.edu/index.php/velocities/).

To visualise the results of comparing different vector fields, we used the arguments of the cosine function for the corresponding points from the difference of the azimuthal directions of the displacement vectors (A_{GNSS}), (A_{GSRM}) and the modelled TMF (A_{TMF}), i.e.

$$r_{(A_{GNSS},A_{TMF})} = \cos(A_{GNSS} - A_{TMF}), \quad (4)$$

$$r_{(A_{\mathrm{GSRM}},A_{TMF})} = \cos(A_{\mathrm{GSRM}} - A_{TMF}), \quad (5)$$

where A_{GNSS} , A_{GSRM}, A_{TMF} are the azimuths of the GNSS station displacement vectors, GSRM displacement vectors and TMF displacement vectors respectively. r is the comparison index in percent.

For the possible values of the function (from –1 to +1) as a percentage, we have constructed the graph shown in Fig. 6.

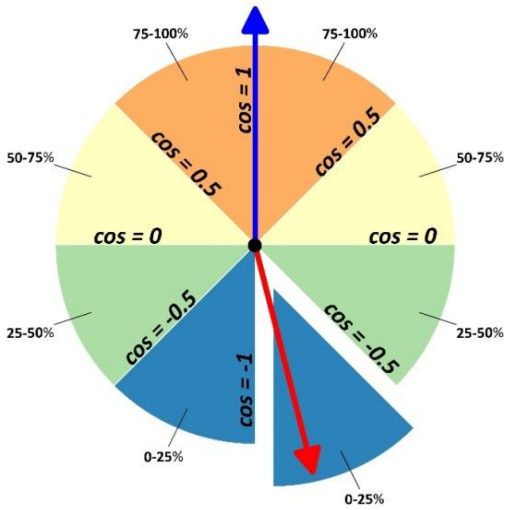


Fig. 6. Scheme of clusters for analysing the directions of movement of tectonic plates.

The two arrows conventionally show the displacement vectors – the blue is GNSS or GSRM and the red is TMF. The percentage coincidence values are shown outside the diagram. The corresponding values of the cosine function are written in the radial directions. In this case the coincidence is very low and lies in the 0–25 % cluster. This cluster is highlighted in the figure. We also note that the discrete data for GNSS stations were selected on an irregular grid and for GSRM on a regular grid with a step of $1^0 \times 1^0$.

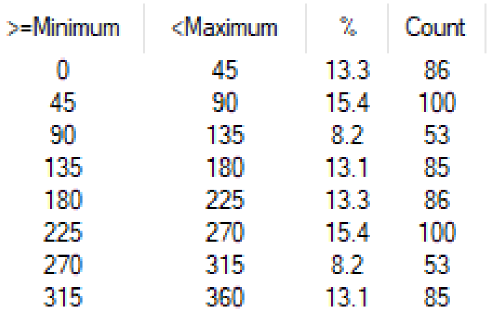
For the azimuthal division, 8 clusters were created with an angular range of 45°. It can be seen that this division of the clusters in Fig. 4 covers almost the entire surface in a uniform manner.

Visually, we can see that the surface of the planet is filled with approximately the same area. It is logical to assume that these clusters cannot have the same area in an equilateral projection, since the tangential forces are different in intensity. Relevant statistics on the number of nodes in the azimuthal direction of the TMF that fall into the cluster are given in Table 1.

The percentage of nodes ranges from 8.2 % to 15.4 %. From Fig. 4 it can also be seen that the boundaries of the cluster zones fall on the “watershed and thalweg” strips, which may be one of the factors in the emergence of global fault structures of plate tectonics.

Table 1

Cluster analysis statistics by azimuthal direction of TMF

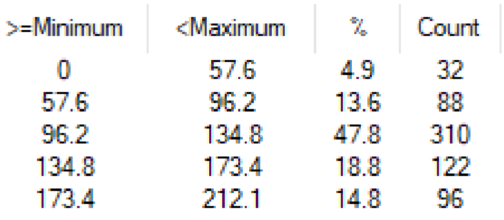


>=Minimum	<Maximum	%	Count
0	45	13.3	86
45	90	15.4	100
90	135	8.2	53
135	180	13.1	85
180	225	13.3	86
225	270	15.4	100
270	315	8.2	53
315	360	13.1	85

In terms of number of nodes, this ratio ranges from 4.9 % to 14.8 % of the total. The largest number of nodes in terms of intensity is in the “medium” cluster – 47.8 %. This particular cluster falls on the “tectonic watershed and thalweg”, which illustrates the persistent stress in these areas due to the reorientation of the figure.

Table 2

Statistics of cluster analysis by the intensity of tangential mass forces



>=Minimum	<Maximum	%	Count
0	57.6	4.9	32
57.6	96.2	13.6	88
96.2	134.8	47.8	310
134.8	173.4	18.8	122
173.4	212.1	14.8	96

As shown in Fig. 7, the most similar GNSS and TMF vectors are tracked in Eurasia, South America, and Africa. From a global tectonic point of view, the directions of the GNSS and TMF vectors on the Caribbean and Arabian plates are quite similar. There are also local anomalies due to the presence of some GNSS stations in Asia Minor and in the area of the Guiana Shield in South America.

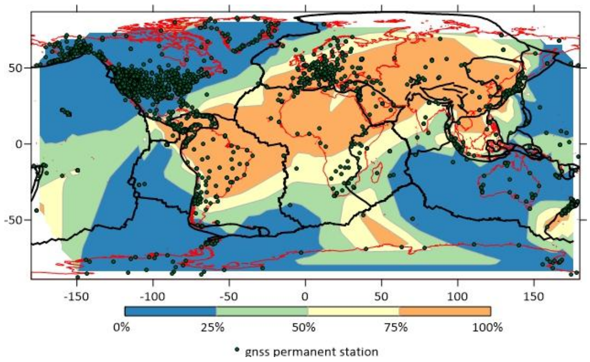


Fig. 7. Map comparing GNSS stations and TMF movement directions.

The comparison of the directions of continental drift according to the GSRM and TMF models is shown in Fig. 8. The model values of the GSRM vectors show complete agreement with the TMF vectors on the Arabian, Caribbean, and Cocos plates. In general, there is a higher correlation between the vectors without the presence of anomalous zones. The correlation between the GSRM and TMF vectors for the southern part of the Pacific plate is also clear. However, it is limited along its boundary; a similar correlation is observed at the boundaries of the Sunda Plate. In general, the correlation is observed over about a third of the planet’s surface.

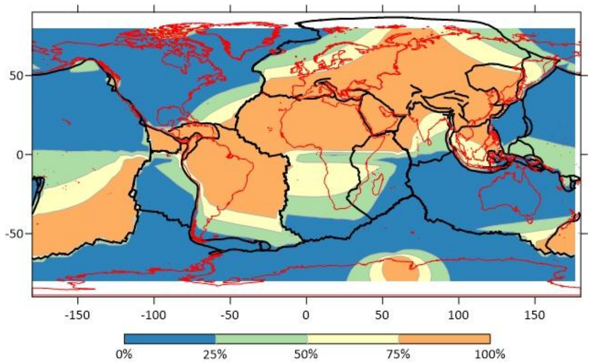


Fig. 8. Map comparing directions of continental drift according to the GSRM and TMF models.

Discussion

In summary, we can say that today we have fairly accurate data on the topography of the Earth’s surface, both for the continents and for the ocean and seabed. This has made it possible to calculate a generalised figure of the physical surface in the form of a biaxial ellipsoid with its own axis orientation parameters.

At present, there are no convincing data that would allow us to unambiguously identify the cause of lithospheric plate motion. Geodynamics considers three main sources of energy for stresses in the lithosphere [Turcotte and Shubert, 2014]. These are the energy of elastic deformation due to massive gravitational forces, thermal energy released from the mantle, and the kinetic energy of the rotating planet. Studies of the TMF generated by changes in the reorientation of our planet’s lithospheric mantle due to the action of gravitational and rotational forces have shown that a deformation field of lateral displacements is formed on its surface. Its vectors are arranged in the form of two vortices, the two foci of which are close to the equator. These research results illustrate the probable geometric explanation of tectonic plate movements, as well as the physical field of tangential deformation of the lithosphere. This level of tangential stress is $\sim 5 \cdot 10^7$ Pa and corresponds to the flow velocities in the asthenosphere, which makes it possible to obtain lithospheric plate motion rates in the first tens of centimetres per year. As a result of deviations in the two main figures of the Earth, which approximate the physical surface and the geoid, certain blocks of the Earth’s crust are in a permanent state of motion. This state certainly affects the deformation of the topology of the figure, which changes over geological time according to the change in the angle of rotation around the axis of rotation.

In our opinion, this is one of the likely factors in the process that triggers global movements of lithospheric blocks. As a result, the shape of the lithosphere is transformed, which is characterised by a change in the size of the axes of the ellipsoids describing the lithospheric surface and their orientation. These assumptions can be confirmed by analysing the comparison of the TMF vector field with the field of tectonic plate displacements based on the data of directions of GNSS stations and continental movements according to the GSRM model.

Scientific novelty

The approach to calculating TMF described above is unique. The idea has been developed over many years. It has been found that for large areas of lithospheric plates, there are systematic unidirectional deviations of the line from the normal to the surface. In the presence of a stable surface gradient over areas of the first thousand kilometres (oceanic parts of lithospheric plates), TMF can generate additional compressive or tensile horizontal stresses of the order of $\sim 5 \cdot 10^7$ Pa. These forces, when summed over the depth of the lithosphere, are able to overcome the level of tangential stresses and can therefore be considered as a source of plate motion. Thus, the concept of a source of lithospheric plate motion proposed and tested in this study can be considered as an alternative to mantle-wide convection.

Practical significance

The results of the study of TMF distribution will allow a more reliable assessment of the level and characteristics of seismic hazard for the Carpathian region of Ukraine and specific seismically active zones and structures on a global scale, as these forces can trigger release mechanisms for accumulated stresses.

Conclusions

1. Based on modelling the general shape of the lithosphere, it has been discovered that there is a deviation of ~ 3° between the minor axis of the physical surface of the planet and the axis of rotation. This deviation can potentially impact the stress-strain state of the lithosphere, which in turn could activate tectonic processes on the Earth.The largest rise and fall of one ellipsoid above the other, which generally represents the Earth’s lithosphere and geoid, is 950 m, and this rise leads to the formation of TMF.
2. The planetary distribution pattern of TMF vectors is mostly well correlated with the direction of the horizontal displacement vectors of permanent stations according to GNSS measurements.
3. The change in the orientation of the ellipsoid describing the lithosphere creates an updated field of potential horizontal forces that, according to the conservation of momentum, move lithospheric masses and generate stresses and deformations in the lithospheric mantle. The surface tension of the lithosphere due to the action of the TMF leads to continental drift (current movement of the lithospheric surface layer).
4. The maximum tangential vortex forces coincide with the zones of the planet where deep-focus strong earthquakes occur and, in general, where tectonic activity is highest.
5. The comparison between the TMF vector field and the field of tectonic plate displacements, based on GNSS station directions and continental drift using the GSRM model, was analyzed through cluster and correlation analysis. This analysis provided quantitative confirmation of the assumptions about the possible influence of these forces on the mechanism of tectonic plate movement..

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ПРО РОЗПОДІЛ ТАНГЕНЦІАЛЬНИХ МАСОВИХ СИЛ В ЛІТОСФЕРІ ЗЕМЛІ

Метою досліджень є визначення та інтерпретація розподілу глобального векторного поля тангенціальних масових сил (ТМС) за азимутальною спрямованістю та інтенсивністю. Здійснено порівняння напрямків векторного поля ТМС з напрямками переміщення перманентних GNSS станцій і напрямками переміщення модельних швидкостей материків GSRM з Global Strain Rate Map Project за допомогою кластерного та кореляційного аналізу. Методика. Продовжено попередні авторські дослідження проблеми формування в літосфері додаткових планетарних напружень від дії тангенціальних розподілених масових сил. Природа таких сил може бути пов'язана із переорієнтацією узагальненої фігури літосфери Землі відносно фігури референц-еліпсоїда, що може створювати напруження, спрямоване на узгодження розподілу мас літосфери з фігурою геоїда за механізмом дії гравітаційних сил і принципом мінімуму потенціальної енергії. Наявність відхилення прямовисної лінії від нормалі до поверхні твердої Землі визначає появу ТМС, що діють у верхній оболонці Землі. Запропоновано амплітуди та напрям векторів таких ТМС розраховувати на основі даних про різницю параметрів двох глобальних еліпсоїдів, що апроксимують фізичну поверхню літосфери та геоїда. Результати. Для сучасної епохи значення кута повороту між найменшою віссю еліпсоїда, що апроксимує поверхню літосфери, і віссю обертання Землі становить 2,6°. Розподіл поля векторів ТМС, узгоджується з контурами материків, тобто стрілки векторів чітко вказують на напрямки латерального руху тектонічних плит і переміщення материків в процесі еволюції Землі. Внаслідок зміни орієнтації еліпсоїда, що описує літосферу, відбувається формування оновленого поля потенційних горизонтальних сил, які відповідно до збереження моменту кількості руху переміщують літосферні маси і генерують напруження та деформації в літосферній оболонці. Оскільки ТМС мають різну спрямованість та інтенсивність, виконано кластерний аналіз розподілу ТМС , який виявив певні закономірності розподілу цих параметрів. Також виконано зіставлення напрямків векторного поля ТМС з напрямками переміщення перманентних GNSS станцій і напрямками переміщення модельних швидкостей материків GSRM (цифрова модель тензорного поля глобального градієнта швидкості). Наукова новизна. Деталізовано особливості зв'язку напрямків векторного поля ТМС з напрямками переміщення перманентних GNSS станцій і напрямками переміщення модельних швидкостей материків GSRM. Дослідження ТМС, які виникають внаслідок переорієнтації тонкої твердої оболонки нашої планети, показали, що на її поверхні утворюється деформаційне поле латеральних переміщень. На нашу думку, це один з вірогідних чинників процесу, що запускає глобальні рухи літосферних блоків. В результаті відбувається трансформація фігури літосфери, яка характеризується як зміною розмірів осей еліпсоїдів, що описує поверхню літосфери, так і їх орієнтації. Практична значущість. Результати досліджень дають можливість надійніше інтерпретувати особливості розподілу ТМС. Ці сили можуть запускати тригерні механізми розряджання накопичених напружень, що важливо для вивчення сейсмічності.

Ключові слова: фізична поверхня Землі; тангенціальні масові сили; планетарні напруження; переміщення тектонічних плит; геодинаміка.

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