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SYMMETRY AND ASYMMETRY IN GEODYNAMICS

by

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Abstract

The paper defines the symmetry pattern of the global earthquake zone system, its relation to plate tectonics and to shearing processes overlapping it. The deviations from symmetry are discussed taking into account different factors: the possible deep mass asymmetry, the influence of convection system with its evolution, and the changes of rotational axis. These different factors might be joined in a sequence, forming a kind of a long term chain reaction and a basis for studying paleoseismicity in a global scale.

1. *Introduction*

Global seismicity is one of the most important effects of the global dynamics. The symmetry properties of the global pattern and deviations from the symmetry are considered in this paper. The symmetry pattern enables us to define the deviations, that is to define some of its asymmetry properties. Deep deviations from symmetry, even an inner core eccentricity, would have remarkable effects on the global surface patterns of different fields (gravity, magnetism, distribution of seismicity). In this paper we consider some important processes which overlap the plate motions. One of them is expressed by the role of fractures and shearing field. The influence of deep convection and its evolution is also considered.

2. *Global earthquake system and the symmetry of its pattern*

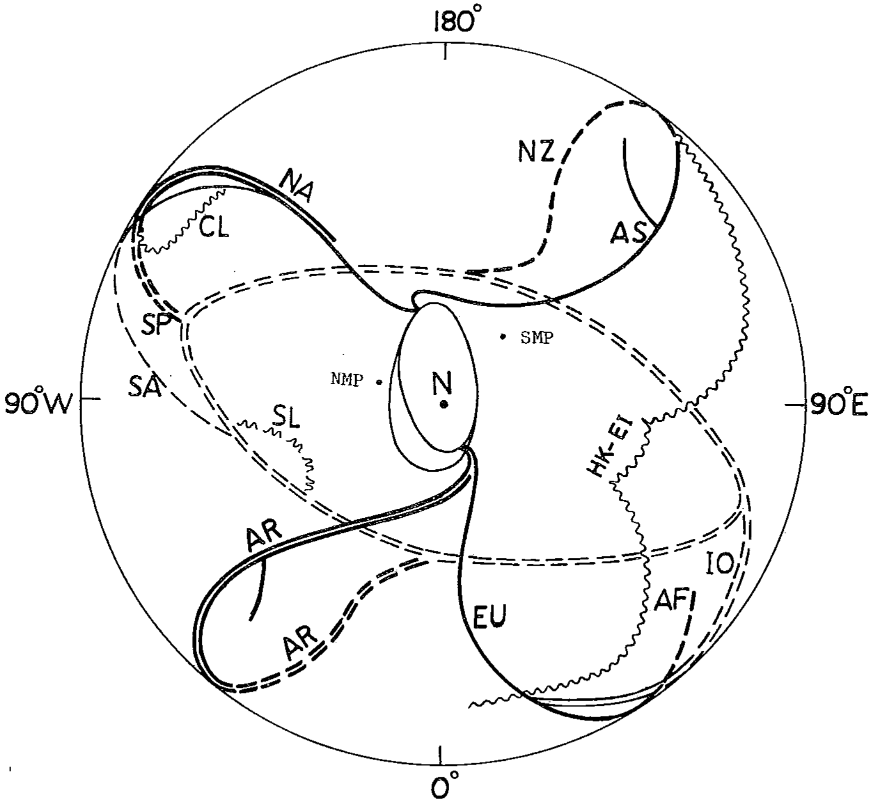

Fig. 1. Scheme of the global seismic system.

The seismicity of the Earth is limited in the north and in the south by borders almost elliptical in shape (VESANEN *et al.,* [17], [18]). These borders form zones of low seismicity. The northern ellipse is much smaller than the southern one. They seem to be oriented eccentrically, with their major axes almost perpendicular to each other. Between these two elliptic zones, there are seven main seismic zones. Thus the seismic system as a whole consists of nine zones. Four of them run between the elliptic zones and are located about 90° from each other, except in the north, where two zones begin from the same point at one end of the major axis of the ellipse, and the other two, similarly, begin at the opposite end of the major axis. The three remaining zones deviate from this symmetry scheme and run nearly horizontally. Two of them are small in size but quite active.

This global earthquake system is represented schematically in Fig. 1, in a polar

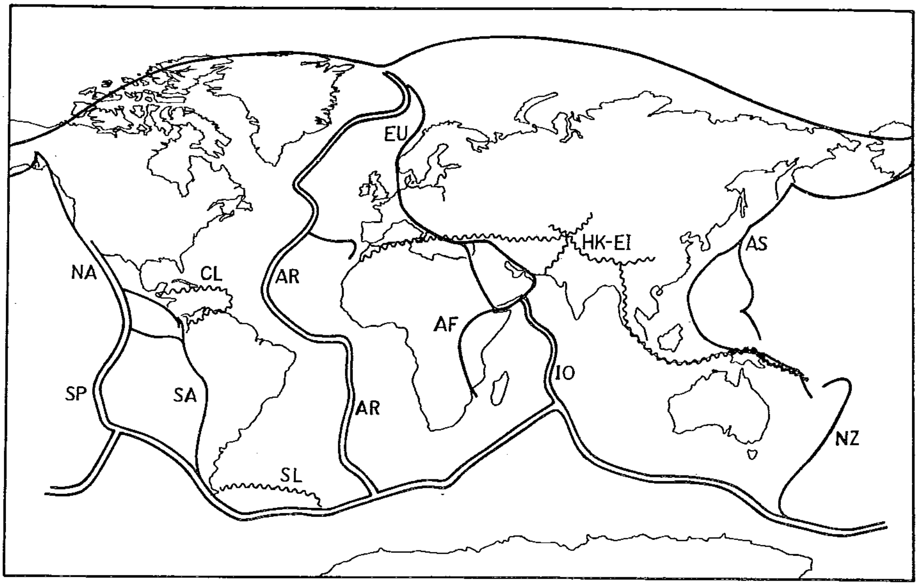

Fig. 2. Main seismic-zones.

projection, with the North Pole above. In this Figure ridges mainly with shallow earthquakes are indicated by double lines; borders of plate collisions and consumptions (mountain ranges, trenches, island arcs) with shallow or shallow and deep earthquakes are marked by a single line; and the remaining cases are indicated by single wavy lines. The differences in pattern and specific symmetry are here striking.

For the southern ellipse, the coordinates of the major axis are 25°S, 70°E and 35°S, 110°W, and of the minor axis 55°S, 2°W and 62°S, 160°E. The length of the axes are about 120° and 63°. In the northern ellipse the corresponding figures are 85°N, 0°, and 70°N, 180° for the major and 75°N, 135°W and 75°N, 135°E for the minor axis. The lengths of the axes are 25° and 10°, respectively. The north and the south magnetic poles, NMP and SMP, are also indicated in the figure, their locations being 76°N, 100°W and 67°S, 140°E.

The nine zones are depicted in Fig. 2. The basic map used in the USCGS World Seismicity Map 1961–1969. The zones are:

1) AS–NZ (East Asia – New Zealand). The zone begins at the end of the major axis of the northern ellipse, in northern Alaska, and joins the southern ellipse at the end of the minor axis, south of New Zealand. The very active side branch,

beginning in southeastern Japan, follows the Izu and Mariana trenches to the deepest point in the Pacific Ocean near Guam. From there it seems to continue, but with low seismicity, to the Solomon Islands along the ridge, with extinct or active volcanoes.

2) NA–SP/SA (North America – Southeast Pacific/South America). The zone starts from the northern ellipse at the same point as the previous zone, AS–NZ. The zone divides into two branches around the Cocos plate, and the branches continue separately. The western, SP, branch joins the southern ellipse at the end of the major axis, south of Easter Island and the SA branch east of it.

3) AR (Atlantic Ridge). The zone begins at the end of the major axis of the northern ellipse northwest of Spitsbergen and joins the southern ellipse at the end of the minor axis between South America and Africa. A side branch of low seismicity begins from the level of the Azores.

4) EU–IO/AF (Europe – Indian Ocean/East Africa). The zone begins from the northern ellipse at the same point as the previous zone, AR. The seismicity is low, beginning from Spitsbergen along the Norwegian coast and Rhine valley. The activity increases southward from the Alpine region. The zone divides into two branches around the Arabian plate, and the branches continue separately. The eastern branch, IO, joins the southern ellipse at the end of the major axis in the center of the Indian Ocean. The western branch, AF, is of low seismicity and seems to become extinct before reaching the southern elliptic zone.

5) HK–EI (Hindu Kush – East Indies). The zone extends to the Western Mediterranean area and in the east to Tonga, and it thus crosses and overlaps some parts of the EU–IO/AF and AS–NZ zones. There are also a few side branches, running radially from the Hindu Kush and the Eastern Himalayas.

6) CL (Caribbean Islands Loop). The zone runs along the Caribbean trench, around the Caribbean plate.

7) SL (Sandwich Islands Loop). The zone runs along the Scotia ridge and Sandwich Islands trench, reaching the southern ellipse between South America and the AR zone.

8) and 9) The polar ellipses.

A part from different physical processes which could have been related to each seismic zone, due to the material inhomogeneities, physical conditions, and other tectonic differences, it is remarkable that the contours of the first four zones seem to correspond to each other in pairs, AS–NZ ~ AR and NA–SP/SA ~ EU–IO/AF. This phenomenon must be more than a mere coincidence. We can follow the similarities between the corresponding pairs from point to point, from arc to arc. All four zones even have certain prominent features in common in their corresponding parts. This remarkable phenomenon strongly indicates a common origin of the whole system, with its primary driving mechanism on a global scale.

The common geometric features of the four symmetric main zones are as follows:

- They begin at the northern elliptical zone with a belt arching eastward; the angles between the zones and the ellipse are sharp toward the east.
- Before reaching the equatorial region, the zones split into two branches.
- Within the equatorial region, the zones bend prominently toward the east.
- On both sides of the eastward bend, the zones curve west; the northern curvature is larger and more prominent, the curvature of the southern belt is slighter.
- Upon reaching the southern ellipse, the zones are convex toward the west and join the ellipse by forming sharp westward angles.

Perhaps the most important of these common features is the prominent arching of the zones toward the east in the equatorial region. This phenomenon is common for a long, continuous chain of other curves, similar in shape, visually recordable, step by step, in the topography on the map. The following tabulation, with comments, begins from the AS–NZ zone and runs eastward:

1) and 2) There seem to be two such curves in the AS–NZ zone:

The first curve lies between the Solomon Islands and New Hebrides earthquake belts with the corresponding trench system and the island arcs.

The second curve is at the northern end of the Tonga earthquake belt with the corresponding trench and the island arc.

There is a discontinuity, about 15°–20° long, of the high seismicity belts between the southern end of New Hebrides and the northern end of Tonga. It is as if the zone had broken in the southern New Hebrides area and the southern part of the continuation had drifted northeast about 20° to the Tonga area. The natural continuation of the New Hebrides belt should be the ridge extending from the southern end of the New Hebrides to New Zealand. The ridge is, however, non-seismic. Similarly, the natural beginning of the Tonga belt in the north should be the ridges formed by the Gilbert Islands – Ellice Islands, which are volcanic. This part of the AS–NZ zone differs from the corresponding part of the AR zone. There is also a »lengthening» of about 30° in this part of the zone comparable to AR zone.

3) Between the Tonga Trench and the East Pacific Rise, there is a volcanic ridge, consisting of islands with extinct volcanoes and extinct or active submarine volcanoes.

4) The East Pacific Rise earthquake zone.

5) Halfway between the East Pacific Rise and the Peru-Chile curve of the South American earthquake zone, there is another, non-seismic rise, with extinct or active submarine volcanoes on the Pacific sea floor.

6) South American earthquake zone with the Peru-Chile Trench, South American west coast marginal line and the Andes, Cordilleria and Occidental.

7) In the middle of the South American continent, east of the Andes, the same curve appears on the lowland topography.

8) The western marginal line of the Brazilian Highland.

9) The eastern marginal curve of the South American continent and the shelf. There are also extinct and active submarine volcanoes on the sea-floor along the marginal line.

10) The Atlantic Ridge zone. Only shallow earthquakes.

11) The western marginal curve of the African continent and the shelf.

12) In the middle of the African continent, the mountain range, the watershed, joining with the East African (shallow) earthquake zone southward. The watershed is non-seismic.

13) The African Horn, Somali Penisula.

14) The Carlsberg Ridge earthquake zone.

The extension of the series of these eastward bends is not observed between the Carlsberg Ridge and the Solomon Islands. However, the geographical locations of the bends described above determine by their regular running a great circle, extending over as much as 3/4 around the globe. It coincides remarkable well with the present magnetic equator (Fig. 3). The magnetic equator ($I = 0$) deviates from a great circle mainly where the above mentioned bends are not prominent. Because of this coincidence a question arises whether some time ago the rotational equator of the Earth was close to this circle? The rotational speed could have slowed down rapidly and the global range of the crustal deformation followed, with the prominent bending toward the east and on both sides of the bends arching toward the west.

Our earlier study of the South American seismicity and the distribution of seismic belts (TEISSEYRE *et.al.,* [13]) suggests that the Andes have been bent in a way described above.

It should be made clear that the symmetry in the earthquake system is related to the rotational axis and not to the centre of the globe. This fact demonstrates that the rotation must play a decisive part in the geodynamical processes of the Earth.

From the foregoing it may be assumed that the lack of equatorial bends between the Carlsberg Ridge and the Solomon Islands could mean that certain fundamental processes occurred there and that these processes have influenced the position of

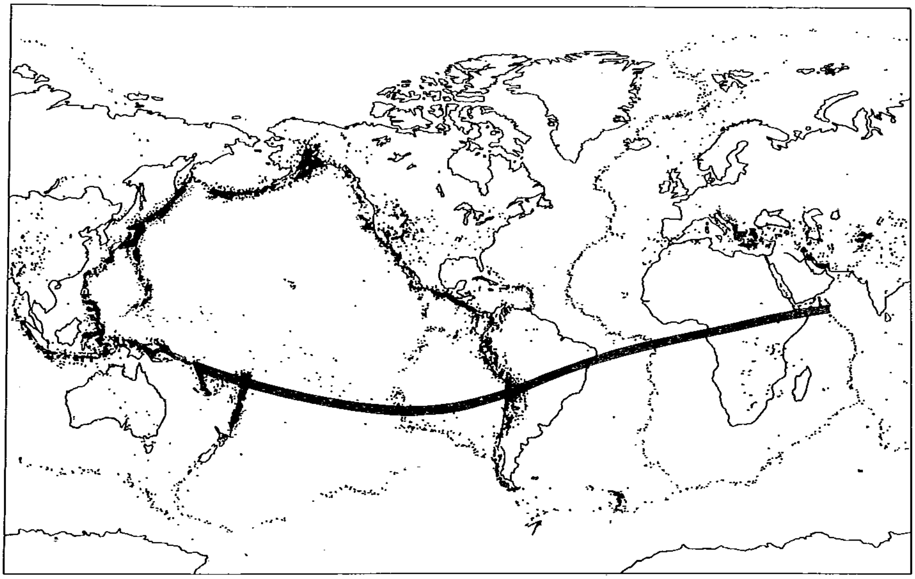

Fig. 3. Path of the equatorial bends.

the rotational axis. The main part of the non-symmetric HK–EI zone is also between these meridians, which cannot be a pure coincidence either. The zone is inclined in a nearly northwest-southeast direction. The earthquake zone and the massive Himalayan mountain range, together with the great Sunda arc, produce two major bends in the Hindu Kush and the eastern Himalayan regions. The bends run north and northeast and on both sides the arched belts are convex in opposite directions. The crustal movement should have taken place here toward the north-northeast and the tilting of the rotational axis should have been toward opposite direction.

The curves of the African Horn and the Carlsberg ridge, although falling on the above-mentioned great circle, are located farther north than they might be expected in relation to the corresponding SP/SA zone; the corresponding bend in the Carlsberg ridge should, as a matter of fact, be about 3–4 degrees north of the present equator.

As to the other two »non-symmetric» zones, CL and SL, they are similar in shape, having shallow and intermediate earthquakes and being connected by trenches. The zones run symmetrically in relation to the South American continent, but even more clearly they are symmetric with respect to the equatorial circle indicated in Fig. 3. Their locations are also symmetric in relation to the Himalayan region *i.e.* to the main part of the HK–EI zone. The Himalayas are in the median region in relation to these two zones almost on the opposite side of the globe.

All earthquake zones seem to consist of arched parts, often broken. An experimental model (Fig. 6) gives an idea of how the arched belts and the larger combined arched belts could have developed *e.g.* from a simple original model zone. The shapes of the zones and their similarities compose a complicated global pattern of twisting, distorted movements in the Earth's crust.

The rotating globe might be viewed as a gyroscope, firmly balanced and spinning evenly. If the rotational axis of a gyroscope is tilted briefly, the gyroscope will start to oscillate conically and will resume after a while its original balanced spinning. Depending on the rotational speed and the nature of the tilting (*e.g.* rhytmical), this oscillation can become uneven. And if the center of gravity of the rotating mass has shifted during the tilting movement, the rotation will stabilize around a new axis.

To summarize: The global earthquake system demonstrates that the Earth has undergone the following processes:

1) tilting of the rotational axis,
2) slowing down of the rotational speed,
3) complicated crustal distortion involving also the deeper structure, and
4) restoration of the rotational balance around a new axis.

3. *Facture pattern along ridge system*

The motion of a plate seems to be very useful to explain the observed surface displacements. It is believed that plates take part in rather rigid movements, which result from the dynamic processes involving a major part of the Earth's mantle. The evolution of global dynamics requires that a plate can not only break but also that it can be deformed to some extent. McKENZIE and MORGAN [7] have considered the global evolutionary processes in terms of triple junction mechanics. Such mechanics was introduced in a rather formal manner – however, the physical reality requires quite extensive plate deformations. These deformations could be revealed not only at plate boundaries and not only by the actual formal dynamics of plate system. Plate tectonics mainly deals with plate processes which are related to changes of the plate areas: new litosphere creation and plate consumption. The latter process together with shearing process will be called here the collision process, taking place along collision boundaries.

Our hypothesis is that a plate can also be deformed in shape by fracturings and shearings inside the plates. The plate can be considered as a body which is cut by a fault system still reacting and remaining as a unit. We cannot surely indicate how

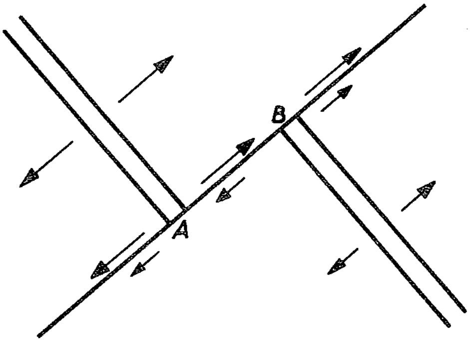

Fig. 4. Ridge segments and shearings.

deep the fracturings extend into the plates. Nevertheless, plate mechanics can be treated to some extent as mechanics of a sliced plate body. Analyzing the fault pattern of a ridge system allow us to draw several conclusions (Fig. 4):

1) Between ridge segments, A and B, we have transform faults explained by the sea-floor spreading;
2) Outside A and B a direction of relative motion depends on the differences in the rate of sea-floor spreading at adjacent segments;
3) Regional (global) shearing stresses contribute to faulting and influence the character of shear motion and relative displacements.

Let us consider the Atlantic ridge system. We can trace here many sequences as shown in Fig. 5. Distinct bending of the ridge sometimes reaches almost an angle of $\pi/2$. Such pattern is explained by simple shear field.

To visualize the dynamics of a sliced plate we have conducted experiments with rubber plane models (Fig. 6). Similar spherical modelling has also been undertaken. Simple plane models are sufficient however to demonstrate the mechanics of the plates cut by fracture systems. In the case of the Atlantic ridge we can see (Fig. 6) that the shearing field twists its pattern and the ridge is also crossed by the fault system. The relative displacement of the ridge segments results mainly from the action of this shear field, and the fact that these segments are not exactly parallel but show small deviations also reflects the shearing influence. These facts do not depend on possible differences in the rate of sea-floor spreading. The role of the global fault system has been considered in our previous paper (VESANEN *et al.*, [18]). Here we underline that the system takes an important part in the dynamics of a sliced plate. The specific pattern of ridge segments and its deviation from

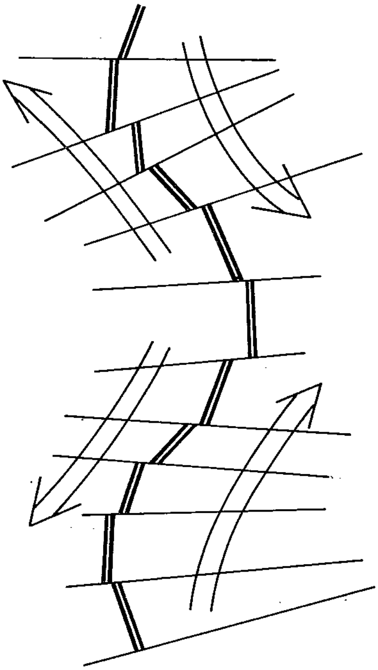

Fig. 5. Scheme of ridge with shear field overlapping.

parallellity has been explained by MENARD and ATWATER [9] by changes in direction of sea-floor spreading. They considered a new tectonic generation which is characterized by some small change in the floor spreading direction. It seems that, the influence of shearing field, considered here, is more natural and simple. Small changes in the direction of sea-floor spreading can also be regarded as the surface effect influenced by the shear.

4. *Earth's symmetry, its deviations and secular motion*

In our previous paper (VESANEN *et al.*, [18]) we demonstrated that the Earth's seismicity space distribution is limited in the north and south by almost elliptical seismic zones. These zones are of low activity and the northern ellipse is smaller than the southern one.

RICHARDS [11] has considered the possibility of the existence of the global system of shear planes manifesting on the surface as a system of lines. The shear planes in the RICHARDS' model are determined by the influence of rotation on a sphere with a rigid thin crust and plastic interior. The model explains flattening

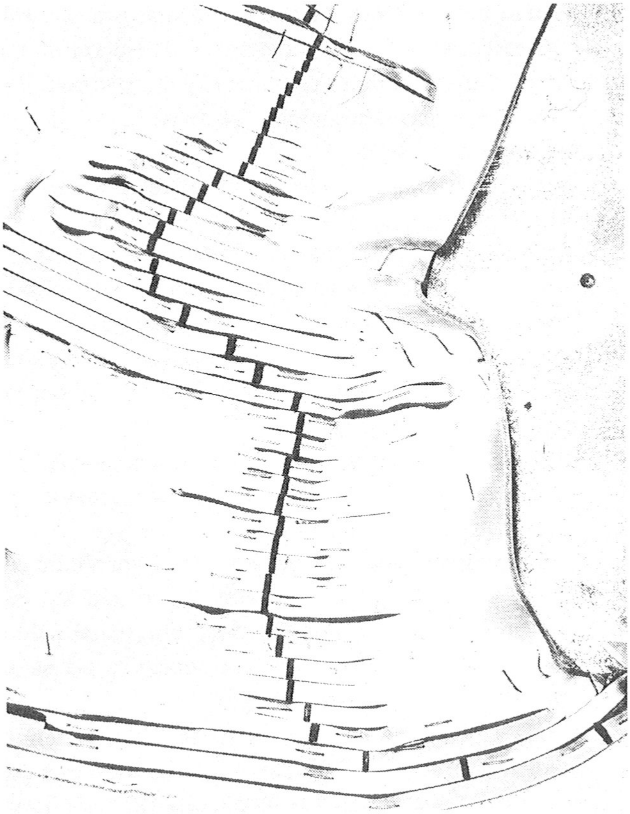

Fig. 6. Example of the experimental models of a sliced plate, the model of a »ridge».

$-e$ along the NS axis and the corresponding deformations $e/2$ along the two axes in the meridian plane. In the direction from the center of the sphere towards the points on the sphere with latitude 35°16', there is no radial deformation, but maximum shear deformations are present. Any axis determined by two perpendicular shear planes passing through the two points with the above latitude on the northern and southern hemispheres, can be regarded as the axis of shearings. The shear planes define the orthogonal system of lines on the Earth's surface. The system of lines determined by RICHARDS reaches in the north and south the latitude 55° only. The envelopes of the lines form the corresponding circles 55°N and 55°S. Thus this simple model can explain the aseismicity of the northern and southern areas and limiting circle envelopes, and at the same time it introduces the global shear fracture system. In reality the limiting lines form ellipses, the global seismicity pattern besides some symmetric features has many deviations and its asymmetry is connected with planetary dynamics. There are of course many geophysical phenomena deviating from the symmetry distribution. Some of these distributions, and their deviations determining the evolution of global dynamics, were revealed in the seismicity pattern.

Among these, the most striking is the land and sea distribution. A spherical harmonic analysis suggests that deep convection has influence on the development of continents (VENING MEINESZ, [16]). It should be noted that it is also possible to define the Earth's main inertia axes using the »mass centers» of lands and seas, respectively, but possible deeper deviations from the symmetric mass distribution makes such approach unrealistic. For better understanding of this situation we should take into account the differences in the continental and oceanic crusts and even in the upper mantle.

Moreover, there are some indications that the asymmetry or deviation from the symmetry is of very deep origin and can be caused by the eccentricity with respect to the Earth's rotation axis or the Earth's center.

The geoid anomalies, defined as deviations from the hydrostatic equilibrium shape, are of the global scale. The satellite geodesy shows that not only the pear-like geoid shape but also smaller distortions of the gravitational field can be represented as a sum of two systems of rotational symmetry whose axes point, respectively, to Australia and India (BARTA, [3]).

The magnetic dipole which approximates the Earth's field is definitevely shifted from the Earth's center towards Australia. This could be used as a contradiction to the assumption that the deep part of our globe, and the core position particularly, are of spherical or rotational symmetry. BARTA [3] relates the dipole eccentricity to the hypothesis of the inner core eccentricity. Secular magnetic variations indicate that the dipole position is slowly displacing toward the WNW direction. The positive geoid anomaly centered towards Australia is in agreement with the eccentricity shift, while the negative geoid anomaly centered towards India probably not accidentally coincides with the symmetry center of the secular magnetic variation. The westward drift of the magnetic dipole could explain this coincidence if it is joined with the inner core drift. The main geoid anomalies are referred to low spherical harmonics and they are related therefore to the deep structure of the globe. This can justify the stated hypothesis relating them to the inner core. BARTA [3] gives also simple calculations of the density deviations in the outer core as determined by the condition of constant pressure value on the surface of the inner core. The appropriate angular deviations of the symmetric density distribution allow the position of the inner core to be eccentric with respect to the Earth's center and the axis of rotation at the same time. This position results from the equilibrium between the centrifugal force and the attraction force caused by the differences in density distribution in the outer core.

The hypothesis relating the westward drift of the magnetic dipole to the eccentricity of the inner core and its changes could be also proved by secular variations of the Earth's gravitational field. Such possibility is confirmed by the measurements carried out by SAKUMA [12] with a microgal accuracy.

We should mention here another hypothesis presented by ZIDAROV [19]. He assume that the whole core of the Earth is eccentric. In this case the condition of constant pressure on the core surface would lead to the angular deviations in the density distribution in the Earth's mantle. These deviations will reach extrema along the directions corresponding to the line of the core shift. ZIDAROV explains the formation of Pangaea by the fact that its position would have been opposite to that of the shifted hot core, that is to the Pacific.

ZIDAROV relates the westward drift of the core to a small decrease in the Earth's rotational velocity; the balance between the centrifugal force and that of mass attraction in the eccentric case would be disturbed, forcing a slow displacement of the core towards the Earth's center. Similar arguments can be applied to BARTA's hypothesis, however, here the westward drift would affect the mass displacement in the mantle resulting in the fracturing of Pangaea. ZIDAROV relates these facts to contemporary existence of two tectonic centers as postulated by PAVONI [10]. These centers roughly approximate the seismic belt distribution. Around the African center the big seismic zone is characterized by dilatational stresses, while around the Pacific center the seismic zone manifest the compressive stress field. PAVONI considers these two centers and the surrounding zones as zones of ascending and descending convection currents.

ZIDAROV has considered decrease in the Earth's rotation where the balance of moment of momentum $I\omega$ = const. leads to the relation

$$\frac{\Delta\omega^*}{\omega} = -\frac{\Delta I}{I},$$

where $\Delta\omega^*$ is defined as the part of angular frequency changes related to the Earth's inertia changes. In reality the changes of rotation are smaller than those predicted by the tide theory due to inner friction. Hence the remaining part is positive and for one hundred years can be estimated as

$$\frac{\Delta\omega^*}{\omega} = 1.4 \cdot 10^{-8}.$$

On the other hand, we can assume that the core has been displaced by as much as 0.1864 km in Trias (estimation based on the magnetic dipole position in that epoch). This gives the rate of inertia change for 100 years as

$$\frac{\Delta I}{I} = -0.8 \cdot 10^{-8} .$$

This value closely satisfies the balance of moment of momentum.

ZIDAROV also considers some oscillatory movements accompanying the core shifts. These oscillations can perhaps be are related to some other global periodical phenomena (AUER, [1]) which observed in the paleo-history of our planet. The mechanism of such movements may be related to the reaction of the surrounding medium subjected to deformation when the core is shifting from its eccentric position towards the Earth's center which in turn follows from the presented hypotheses of the westward drift of the core. The oscillations will be, of course, strongly damped.

A rather extensive study of the Earth's deep asymmetry has been presented by JANKOWSKI [5, 6], in his papers which are now almost forgotten. Considering the gravity potential, JANKOWSKI assumed that nondiagonal components of the inertia tensor (the so called inertia products) do not vanish in the second order term in the assumed coordinate system related to the geometry of the rotating Earth. Moreover, he has analyzed the influence of deep mass asymmetry on a force field resulting from potential higher order terms. The obtained results permit to define the specific horizontal field of forces, its poles, and its zones of »breaks» where the orientation of forces changes its sign. Thus JANKOWSKI formulated a quantitative geodynamical theory, which could well have been the first one, where tried to explain the global dynamics and evolution by field forces produced by an asymmetry of the inner mass distribution.

Considering the evolution of the Earth's interior we must also accept the evolution of the gravity field distribution as it is observed on the surface. Thus the form of the geoid undergoes changes. JANKOWSKI [5, 6] has assumed that the primary field V is consecutively distorted by perturbation fields U, T... related to some mass asymmetry, and that the geodynamical processes have been driven by this field of asymmetry.

Let us consider this hypothesis in some detail. A revolving body, possibly a gaseous or fluid one – as it was in an early stage of the planet's history – was not in hydrostatic equilibrium. That is, it was probably quite far from the stage of rotational symmetry. Later on it will approach the hydrostatic equilibrium and symmetry. This primary asymmetry, related to the Earth's origin process, can be overlapped by the influence of deep convection currents. Thus the perturbation fields of JANKOWSKI can be considered as those forces, with horizontal components of course, which force the body to the hydrostatic equilibrium and

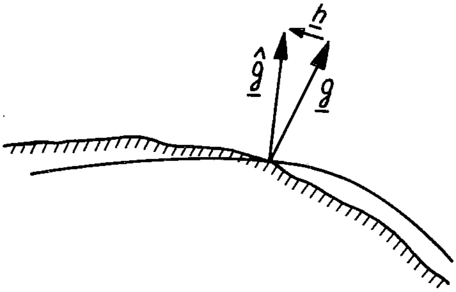

Fig. 7. Asymmetry force field causes by deviation from the equilibrium geoid.

rotational symmetry. If a geoid deviates from the shape of a body in equilibrium and the planet still undergoes evolution, then we can find this force. Fig. 7 shows the actual gravity $\underset{\sim}{g}$ and the theoretical gravity g related to the body in its final equilibrium. The field $\underset{\sim}{h} = \underset{\sim}{g} - \underset{\sim}{\hat{g}}$ is responsible for the field of evolution forces, independently from the causes which maintain the asymmetry. As we have already mentioned, the deep eccentric distribution of the mass may be considered under different assumptions. We will use the condition of BARTA [3] which demands the pressure to be constant on some discontinuity boundary independently whether it suffers a small eccentric shift or not. The BARTA's condition is a static one and can approximately be expressed for a spherical layer with density ρ as

$$\int_{R_0+\Delta_0 f(\lambda,\varphi)}^{R_1+\Delta_1 f(\lambda,\varphi)} \hat{\rho}\, dr = \text{const.} \tag{1}$$

This is valid for any λ and φ. Here we assume that the central inner sphere is shifted or deformed by $\Delta_0 f(\lambda,\varphi)$ and the outer sphere by $\Delta_1 f(\lambda,\varphi)$. The function $f(\lambda,\varphi)$ represents an angular change of density distribution: $\hat{\rho}$ differs from ρ due to its dependence on λ and φ.

Let us consider now only the inner core shift described by the function $\Delta\cos\lambda\cos\varphi$, assuming first that this shift lies in a perpendicular plane to the rotational axis. Taking into account the effect of centrifugal force we obtain, instead of (1), the dynamic condition:

$$\int_{R_0}^{R_1-\Delta\cos\lambda\cos\varphi} \left(K\hat{\rho}_1 \frac{M_0}{r^2} - \hat{\rho}_1\omega^2\bar{r}\right) r^2 dr - \int_0^{R_0} \rho_0\omega^2\bar{r}\, r^2 dr = \text{const.} \tag{2}$$

where $\bar{r}^2 = r^2 + 2r\Delta\cos\lambda\cos\varphi + \Delta^2$, and K is the gravity constant. For a moment

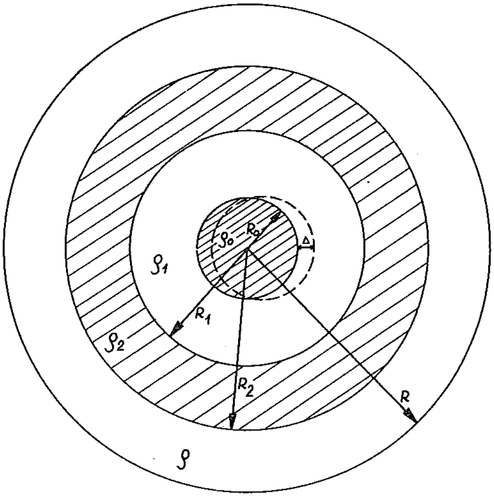

Fig. 8. Inner core shift.

we will, however, consider the case determined by condition (1). From this we obtain the expression for $\hat{\rho}_1$

$$\hat{\rho}_1 = \rho_1 \frac{R_1 - R_0}{R_1 - R_0 - \Delta\cos\lambda\cos\varphi}$$

while for $\Delta \ll R_1 - R_0$ we get

$$\hat{\rho}_1 = \rho_1 \left(1 + \frac{\Delta\cos\lambda\cos\varphi}{R_1 - R_0}\right) . \tag{3}$$

Similar expression for the casewhere the whole core is in an eccentric position can be obtained.

$$I_{ik} = \int_{-\pi/2}^{\pi/2} \cos\varphi' d\varphi' \int_0^{2\pi} d\lambda' \int_0^R r'^2 dr' \,\hat{\rho}(\delta_{ik} r'^2 - x_i' x_k')$$

where x_i', r', λ', φ' refer to the geometric center, through which the axis of rotation passes. The density in the outer core is given by (3). Limiting the calculations to the order Δ^2 we have

$$I_{ik} = \frac{8}{15} \pi \delta_{ik} (\rho^{\circ} R_0^5 + \rho' R_1^5 + \rho R^5) + $$
$$\frac{8}{15} \Delta^2 \pi \left(2\rho^{\circ} R_0^3 - \rho_1 \frac{R_0^4}{R_1 - R_0} - \frac{1}{5} \rho_1 \frac{(R_1^5 - R_0^5)}{(R_1 - R_0)^2}\right) (2\delta_{ik} - \delta_{i=1,\,k=1}) \tag{4}$$

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where: $\rho^{\circ} = \rho_0 - \rho_1$, $\rho' = \rho_1 - \rho$.

The problem of eccentricity can be also approximated in another way; we may consider that the core shift is related to a nonequilibrium position and is subject to a secular motion. In this case we omit condition (1) and distribution (3) and will consider the difference in forces related to the core shift (in the x_1 direction) for the model of the Earth (Fig. 8) with ρ_0, ρ_1, ρheld constant. The centrifugal force is

$$F_x = \omega^2 \Delta \frac{4}{3} \pi R_0^3 \rho^\circ , \qquad F_y = 0.$$

The effect of pressure on an element of surface displaced by Δ amounts to

$$d\underset{\sim}{f} = \rho^\circ \underset{\sim}{g_0} \Delta d\sigma$$

where g_0 is the corresponding value of gravity acceleration. After integration we have

$$f_x = \frac{4}{3} \pi R_0^2 \rho^\circ g_0 \Delta , \qquad f_y = 0.$$

Hence the difference becomes

$$F_x - f_x = \frac{4}{3} \pi R_0^2 \rho^\circ (\omega^2 R_0 - g_0) \Delta .$$

Thus, for the inner core we obtain the secular motion as

$$M_0 \ddot{u} = \alpha u, \qquad u \infty \exp\left(- \sqrt{\frac{\alpha}{M_0}}\, t\right) \tag{6}$$

where α is the coefficient in eq. (5) at the quantity Δ.

Let us now consider the case of the core shift along the mean rotational axis (Fig. 9). Static condition (1) can be used in a similar way, the rotation effect is nonexistent, is also no change of inertia related to the axis of rotation. However, the problem complicates when the effect of precession is taken into account. The value $\Delta \sin \varphi$ (Fig. 9) appears as an equivalent core shift in the plane perpendicular to the actual axis of rotation and leads to an additional force which disturbs precession (in eq. (5) ω should be replaced by the value of the precession frequency).

We mentioned two approaches to the eccentricity of the core (inner or outer): first approach searches for a density distribution which assures condition of the equality of pressure over the surface of the core (inner or outer), the second considers secular motion derived from the corresponding differences in resulting forces which act on the shifted core. The reality lies somewhere in between and needs a more exact solution for a realistic model of the Earth.

We can also add that the eccentricity can be responsible for some periodic phenomena in the earthquake activity. In the case of a shift along the axis of rotation

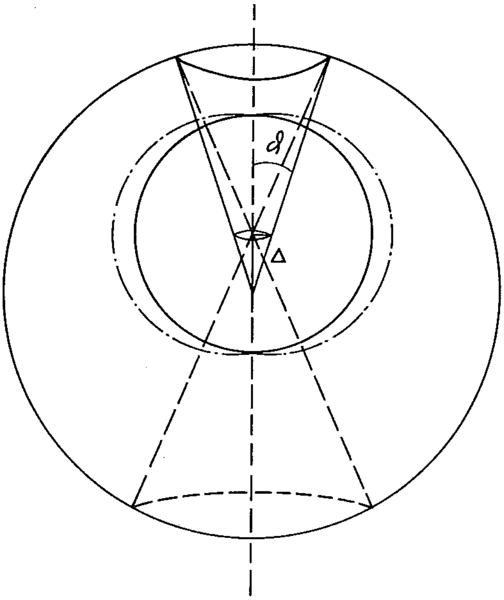

Fig. 9. Bell effect (conical oscillations) of the inner core.

this periodicity is related to the precession period and the phenomenon reminds a »bell» effect. As we mentioned before, the westward drift and some gravitational singularities can be explained by a core shift towards Australia. However, the distribution of the seismic activity, especially the difference in size of the northern and southern ellipses limiting the active zones, could be explained by assuming a northward core shift. Such a shift would cause greater activity in the northern hemisphere while the WSW shift will explain the elongation of the southern ellipse in the WE direction.

We pointed out that the pattern of symmetry extends over the four main belts, but it breaks in the area between the Himalayas and Australia. The asymmetry of the Earth's interior and the eccentricity towards WSW could also be responsible for this effect.

5. *Deep asymmetry and the evolution of the convection pattern*

Asymmetry of masses in the Earth's interior results from processes which have occurred during the evolution of the planet. Thus, similarly as the Earth's topography (VENING MEINESZ, [16]) the asymmetry may be related to different systems of the convection currents which governed internal dynamics in the past. The main term of asymmetry would reflect the primary system of convection, while other terms would correlate with more complicated convection stages. The same applies to the gravity field, but the integral character of this field does not permit to make such correlation in a simple way.

Let us consider the earlier stages of the Earth's evolution. Even if now the deep mass asymmetry could be almost neglected, we have reasons such as the theory of the planet's origin, to assume that the Earth's asymmetry has played an important role in the past. The asymmetry reflects also the convection pattern. In particular, neighboring convections could be of different size and also of different »strength» since they are governed by the temperature difference and depth involved. In evolutionary development a specific system of dynamics and paleoseismicity is attached to each plate pattern. Thus the evolution of the plates is probably controlled by differences in the convection activity. We believe that a collision border can change its position relatively quickly, which means that evolution, while a ridge system (upstream flow) seems to be more stable. These assumptions allow us to consider evolution of the convection pattern in terms of the geometry of convection cells, their intensities, and their velocity ratios, undergoing slow changes. Material flow caused by plastic yielding allows us in turn to consider shearing borders inside the mantle (TEISSEYRE, [14]). The shearing borders can be related to a system of noncompatible convection cells; a system of two cells with the same circulation is called here a noncompatible system – it cannot be maintained in a fluid, but it can exist in a viscous-plastic material. Let us consider two convection cells with different intensities, we will denote them by A and B, where $A > 0$, $B > 0$, and $A < B$. Such system is equivalent to a normal convection pattern $-\frac{A+B}{2}, \frac{A+B}{2}$ and to a noncompatible system $\frac{B-A}{2}, \frac{B-A}{2}$. The evolution and relative changes of the convection currents concur with the shearing borders in forming of different system of mountains, ridges, and rifts. As an example we can consider the two evolutionary stages of the convection pattern and their influence upon the surface response (Fig. 10):

Stage 1: the two cells are not equal in size, and a mountain range is formed at the collision border.

Stage 2: the pattern of the cells is changed, and the consumption process of a plate is started.

Different mountain system can be explained in a similar way. For a given stationary convection system in the spherically symmetric model of the Earth we obtain the fields of velocities and temperatures in terms of a spherical harmonic (WALZER,

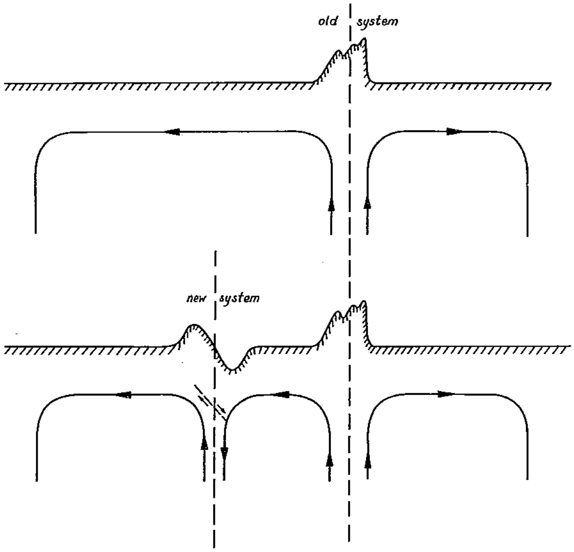

Fig. 10. Example of the convection evolution.

[15]; CHANDRASEKHAR, [4]). On the other hand, convection causes some changes in the gravity field due to both density variation and mass elevation (McKENZIE, [8]).

We will consider a qualitative influence of some chosen harmonics which can be related to a simple convection pattern. It should be noted that the present mass distribution and the observed gravity field reflect influences of the past dynamics of the Earth *i.e.* the consecutive evolutionary stages of convection pattern.

We will consider now the possible deep asymmetry which includes the inner core shift and deformation. We should also remind that all calculations of the gravity field and geoid shape are made under two assumptions: the mass ceter coincides with the geometric center ($P = 0$), and the inertia axes coincide with the geometry of a revolution body ($C_{21} = S_{21} = 0$).

The temperature disturbance of the density is given by

$$\rho = \rho_0(1 - \alpha\theta). \qquad (7)$$

Let us take the temperature distribution $\theta \propto f(\lambda, \varphi)$ given by the simple functions

$$\cos\lambda\cos\varphi, \quad \cos 2\lambda\cos^2\varphi, \quad \cos 3\lambda\cos^3\varphi.$$

The corresponding convection patterns are given in Fig. 11. We now assume that the appropriate solutions describe some small shift and deformation of the inner

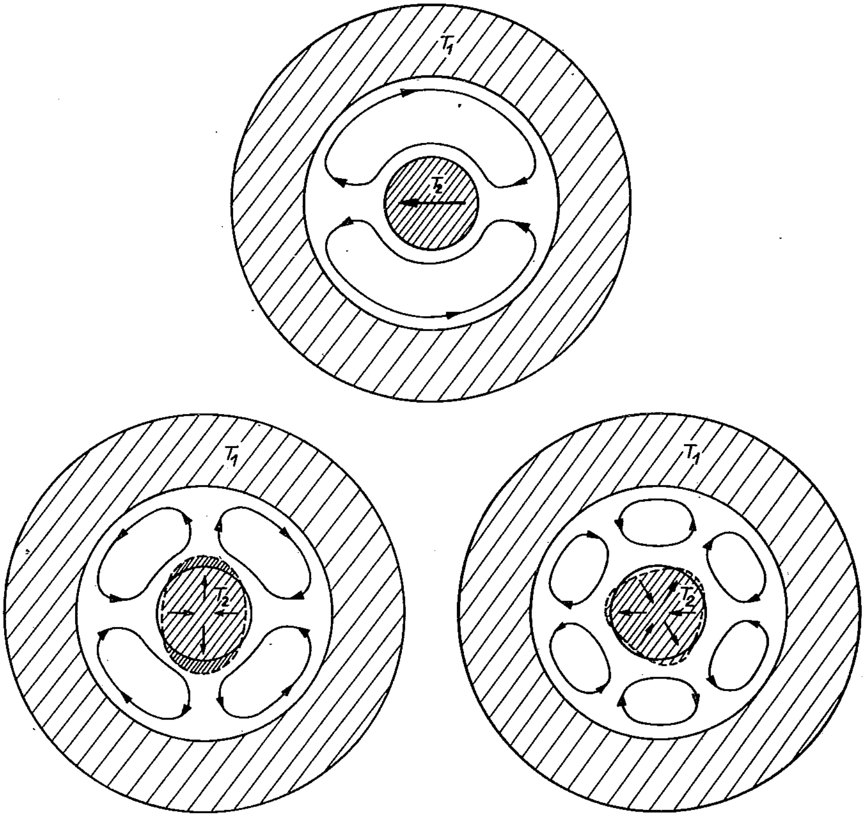

Fig. 11. Three examples of convection influence on the core shift and deformation.

core. The modified BARTA condition (1) can be written as

$$\int_{R_0+\Delta f(\lambda,\varphi)}^{R_1} \hat{\rho}_1 \, dr = \text{const.}$$

where $\Delta f(\lambda, \varphi)$ is the measure and angular distribution of the core shift and deformation, ρ_0 is the inner core density, and $\hat{\rho}_1$ is the outer core density disturbed in regard to ρ_1. The density $\hat{\rho}_1$ remains unchanged, it is equal to ρ_1 for the following selected arguments

$$\varphi_0 = 0, \ \lambda = \pi/2; \quad \varphi_0 = 0, \ \lambda_0 = \pi/4; \quad \varphi_0 = 0, \ \lambda_0 = \pi/6.$$

for each above convection pattern, respectively. Thus as an approximation to Δ^2, similarly as in equation (3), we obtain

$$\hat{\rho}_1 = \rho_1\left(1 + \frac{\Delta f(\lambda,\varphi)}{R_1 - R_0}\right). \tag{8}$$

This coincides with (7) where the temperature influence $\alpha\theta$ is opposite to $-\frac{\Delta f(\lambda,\varphi)}{R_1 - R_0}$. Thus the effect of convection counteracts the BARTA condition. The corresponding changes of the Earth's inertia tensor can now be easily computed. The same procedure can be applied to other systems of convections, given by the appropriate expressions of the spherical harmonics. The calculations can be repeated for different spherical layers and different shells undergoing deformations.

6. *Conclusions*

1. A simplified model of the earthquake zones (Fig. 1) shows important symmetry properties already pointed out in our previous paper (VESANEN *et al.*, [18]). One of these is the pairwise symmetry of the ridges and collision borders of the four main belts.
2. The revealed symmetry around the rotational axis indicates the role of rotation in the primary geodynamical processes, while the remarkable deviations (mainly the HK-EI zone) suggest that either a change (tilt) of the rotational axis or some deep deviation from symmetry influenced the whole system of the Earth's dynamics.
3. The plate mechanics with its ridges, collision and consumption boundaries is certainly accompanied by other processes, *e.g.* at the Atlantic ridge shearings counterparting with sea-floor spreading. The same, but even more complicated pattern, is observed in the northern part of the North American earthquake zone. It is similarly true for the other plate boundaries, especially along islands arcs. The important role of fractures is noted. The shearing field acting in the Atlantic ridge region was analyzed; it follows that the global dynamics should be regarded as dynamics of *sliced* plates.
4. The nature of the southern and northern seismic ellipses is considerably different. The northern ellipse is not clearly defined and remains inactive. The southern ellipse is more distinct, it is formed by a ridge system and intersected by fracturings and transform faults.
5. Several symmetry properties and asymmetric deviations are pointed out. Very remarkable one is the alpine earthquake belt crossing and extending almost latitudinally (HK-EI). In our previous paper (VESANEN *et al.*, [18]) the role of the Hindu Kush chimney zone was underlined. From this interpretation it

follows that the alpine belt is formed by different branches converging at this chimney. The eastern branch extends almost up to the Tonga region, overlapping the island arc system.

6. An analysis of the shape similarities suggests that some forces have distorted the seismic belts, plate margins, continental borders, and even mountain areas. Some lines seem to converge at certain centers. One of them is the Hindu Kush chimney, another lies in the Southern Pacific, north of New Guinea.
7. It seems obvious that the pattern of convection cells is not symmetric in relation to the north and south. A possible core shift towards Australia would affect the distribution of the continents and also the convection pattern as it was already pointed out by ZIDAROV [19]. The fracture pattern around Antarctica is striking. Fractures appear to elongate the large southern ellipse limiting the seismic activity towards a direction pointing somewhere between Australia and India. On the other hand, this is the same region towards which possible eccentric shift of the core has been considered by BARTA [3].
8. The influence of deep asymmetry in mass distribution, especially the eccentric shift of the core, could be responsible for the deviations from the main symmetry pattern. Periods of the increased activity, related to the effect of the core shift, seem to exist. Possible chain relations, which may correlate some part of the earthquake activity with the core oscillations and Earth's inertia changes, need more careful and further studies. The triggering effects should be also taken into consideration.
9. Even small asymmetry in the deep structure of the Earth can originate a specific field of forces which influences the global dynamics. This has been pointed out by JANKOWSKI [6] in his study of the potential gravity field.
10. This study is mainly based on the distribution of the contemporary active seismic zones. The global dynamics is a long term process and to understand it paleoseismological studies and reconstruction would be of extreme importance. Several approaches to this problem were made but it requires further discoveries.
11. The influence of convection currents on deep asymmetry was considered. The evolution of convection patterns and their response to an inner core shift was considered as a preliminary hypothesis.

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