THE INNER STRUCTURE OF THE EARTH

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Introduction

It is extremely difficult to determine the material of the Earth and the physical state ad the chemical composition of this material at depths where is no direct observation. Rock samples originate from depths not exceeding 9 km since this is the greatest depth attainable by the present drilling techniques. Though some rock materials find their way to the surface by geological processes - primarily by volcanic eruptions - from depths exceeding those of drillings, even these samples provide only limited information concerning at most only some portion of the upper mantle of the Earth. At present, no means are available for the direct observation of deeper regions of the Earth. Nature offers possibilities to recognize the inner structure of the Earth by indirect ways. This explains why, up to now, a number of suggestions have been proposed concerning the inner structure of the Earth and why these suggestions differ from each other in several fundamental ways.

In these researches the study of earthquake waves have decisive importance because these waves passing through the inner parts of the Earth, act like X-rays and yield information on the state of the layers passed by them. Besides these seismological observations, the results of laboratory experiments, and of research on gravitation, geomagnetism, geoelectricity, geothermics, radioactivity, geochemistry and other disciplines, furthermore the mechanical properties of the Earth as a celestial body play an important role.

1. The zonal structure of the Earth based on earthquake waves

Because of tectonic processes occurring in various parts of the Earth, elastic energy is accumulated in the rocks. When this energy attains the breaking strain of the particular rock, an earthquake occurs and the energy propagates in the form of elastic waves. Based on observations the earthquakes do not occur at depths exceeding 700 km. Consequently, elastic energy is not accumulated or cannot be accumulated in materials deeper than that. Consequently, material at depths exceeding 700 km either has plastical behavior against durable and not too great deformations or it is eventually in a state of complete rest. (If the latter were true, it would lead to contradictions.)

According to the solution of the wave equation describing the propagation of elastic energy (p. 150 in [1]), two types of spatial waves are able to propagate in a solid elastic medium: longitudinal or dilatational waves (P) and transversal or shear waves (S). The velocities of these two waves are expressed by the formula

$$v_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\vartheta}}$$

and

$$v_S = \sqrt{\frac{\mu}{\vartheta}}$$

where is the density of the medium, *K* is the bulk modulus and is the shear modulus. It follows from relation (2) that since the rigidity of liquids is zero ($\mu = 0$), $v_S = 0$ as well, i.e. the shear waves do not propagate in liquids. In a homogeneous isotropic medium, the elastic waves starting from one point propagate in a homogeneous isotropic way. When, however, they reach the boundary of two different media they are reflected, and they creating each other according to the Descartes' law. This latter statement means that when in the way presented in *Fig. 1* only longitudinal waves arrive at the given boundary, in addition to these longitudinal waves, transversal waves will be reflected from the boundary and generate into the other medium.

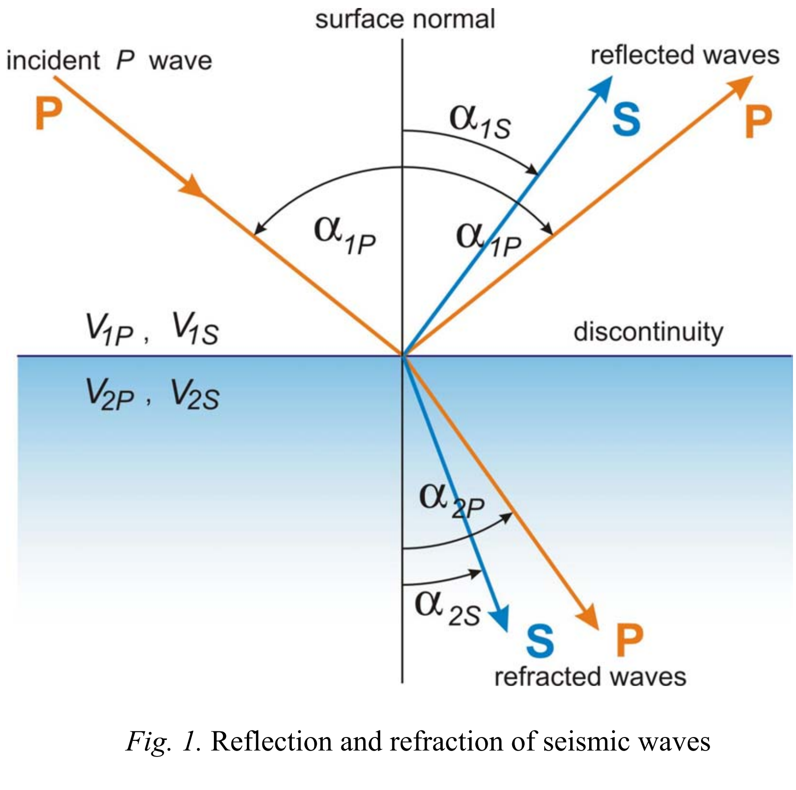

Fig. 1. Reflection and refraction of seismic waves

When in the hypocenter of an earthquake a quake of adequate energy occurs, the arrival of the seismic waves will be recorded after a certain time in the seismological stations located at various points of the Earth. It can be seen in *Fig. 2* that elastic waves arising from greater epicentral distances bring information from the deeper parts of the Earth.

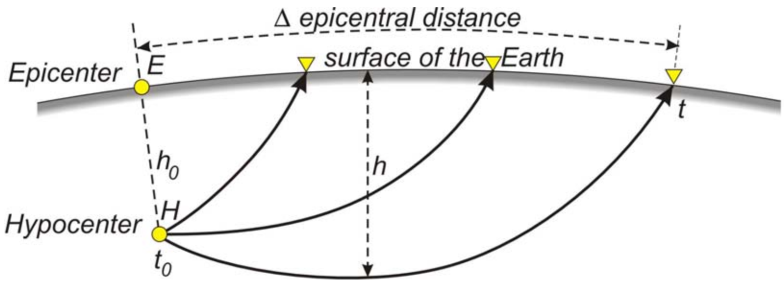

Fig. 2. Propagation of seismic waves from the hypocenter

Since the velocity of seismic waves according to relations (1) and (2) has a different value for the various materials, it is possible to draw conclusions on the velocities from the time of arrival of these waves and thus in an indirect way also on the physical properties (eventually the material composition) of the medium through which the waves passed. Analysis of seismic waves has shown that discontinuities exist inside the Earth and that the Earth is divided by these discontinuities into zones having different physical parameters.

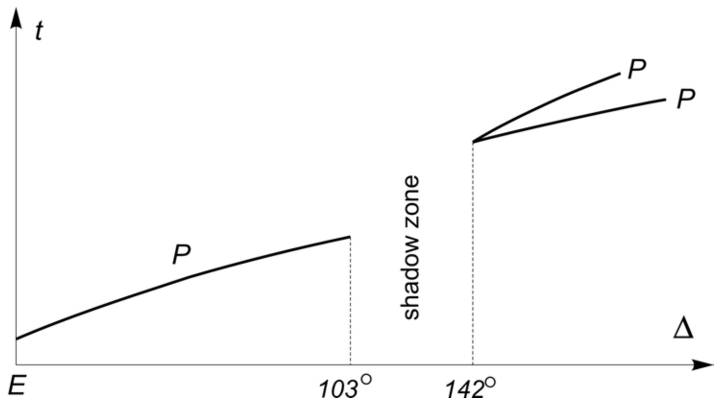

Fig. 3. Schematic travel-time curves for waves passing through a two-layered sphere if the velocity increases

The initial observations pointed out that the velocity of seismic waves increases with depth. However, R.D. OLDHAM called attention, as far back as 1906, to the fact that the P waves arrive much later than the expected time at the seismological stations located on the side of the Earth opposite the epicenter of the earthquake. Thus, since these waves pass through the central parts of the Earth, a lower velocity zone must exist there [2]. GUTENBERG investigated this phenomenon in some detail in 1914 [3]. He found that the travel-time curve of P waves increases steadily in the way shown in *Fig. 3* from 0° to an epicentral distance of 103°, then from 103° to 142° the longitudinal waves are completely absent whereas from 142° on, the curve is decomposed to two parts in that immediately after the first P wave another P wave arrives to the surface. This so-called shadow zone between 103° and 142° is due, according to GUTENBERG's calculations, to the existence, in the inside of the Earth at a depth of 2900 km, of a boundary which, when it is passed results in an abrupt decrease of the velocity of earthquake waves. By this so-called *Gutenberg-Wiechert boundary,* the inside of the Earth is divided into two parts: the mantle and the core. The shadow zone and the travel-time curve of P waves shown in *Fig. 3* can be explained by the conditions of wave propagation presented in *Fig. 4*. In *Fig. 4,* the quake sourced at the hypocenter denoted by H. The quake waves cover, with increasing epicentral distance, an ever-longer way, and they are immersed ever deeper into the mantle. The wave arriving at an epicentral distance of 103° may just pass beside the core but the next wave collides with the core. Thus, since the seismic velocity is lower in the core, the wave is refracted towards the incident perpendicular then, on attaining again the boundary of the core after passing through the core, it is refracted from the incident perpendicular, arriving at the surface at a distance of about 190° from the epicenter of the quake. The next waves whose incident angles at the boundary of the core become smaller and smaller cover a similar way and emerge at the surface at smaller and smaller epicentral distances. The smallest epicentral distance is 142°. If the incident angle of the quake waves decreases further, the waves attain the surface of the Earth at ever-increasing epicentral distances.

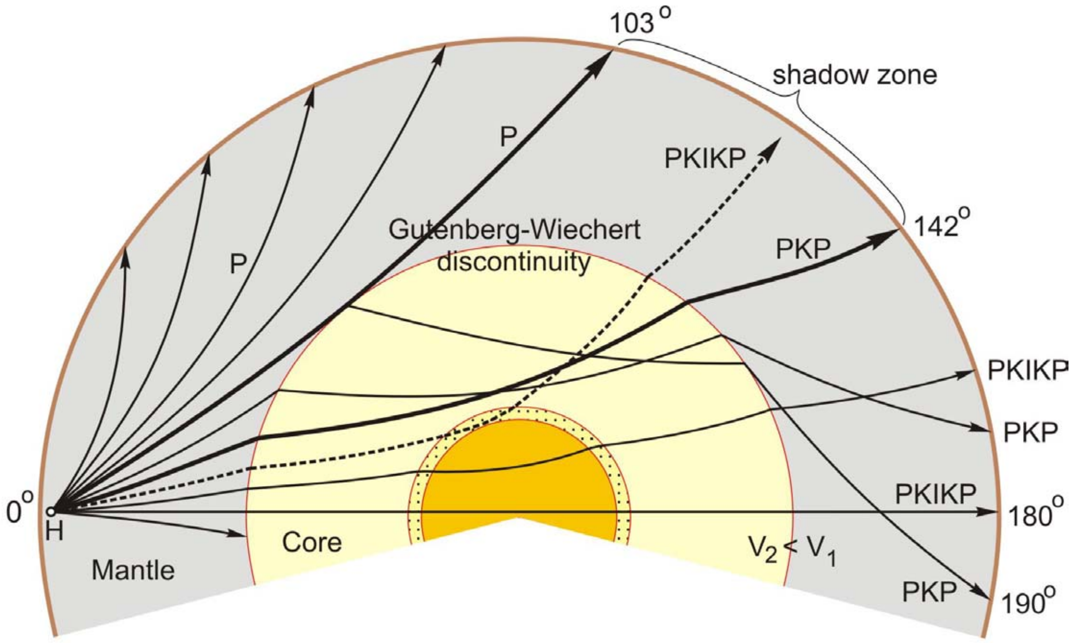

Fig. 4. Vertical section through half the Earth, showing the propagation of the longitudinal waves from a hypocenter (transition zone between outer and inner core is dotted)

According to further detailed investigations of LECHMAN [4], even the shadow zone is not completely free of the P waves, some weak longitudinal waves can be recorded even here. From this fact, he concluded that even the core itself is not homogeneous and it may be divided into an outer and an inner core. In the inner core, the velocity of P waves is much higher than that in the exterior part of the core and thus the waves arriving at an adequate angle are refracted in a way that they attain the surface of the Earth within the shadow zone. It is rather difficult to determine the boundary between the outer and the inner core since this boundary is not as sharp as the separating line between the core and the mantle. Here instead of the boundary a transition layer whose thickness is about 100 km, is presumed by seismologists [5]. This so-called *Lehman zone* separates the outer and the inner core at a depth of about 5000 to 5100 km. According to BARTA the uncertainty of the depth of the *Lehman zone* may also be due to the fact that the inner core is not located exactly in the geometrical centre of the Earth

[6, 7, 8], and thus calculations from the waves of earthquakes occurring at various points of the Earth give different depths.

The outermost and best-known zone of the Earth is its crust, which can by no means be considered as a homogeneous zone. In 1909 A. MOHOROVICIC, the Croatian geophysicist, was the first to indicate that under the Balkan peninsula, at a depth of about 50 km, a boundary can be found below which a rapid velocity increase can be observed [9]. Seismological investigations carried out later proved that this boundary could be found throughout the Earth at an average depth of 33 km. This boundary named after its discoverer as the Mohorovicic (abbreviated to Moho) discontinuity can be considered as the lower boundary of the Earth's crust representing the boundary between the crust and the mantle.

Thus it can be stated that in the inside of the Earth two boundaries exist on passing through which the seismic velocities are altered rapidly. These two boundaries are denoted as the Moho and Gutenberg-Wiechert discontinuities and they divide the Earth into three main zones: the crust, the mantle and the core. However, the seismic velocities are not constant in any of the mentioned three zones but varies.

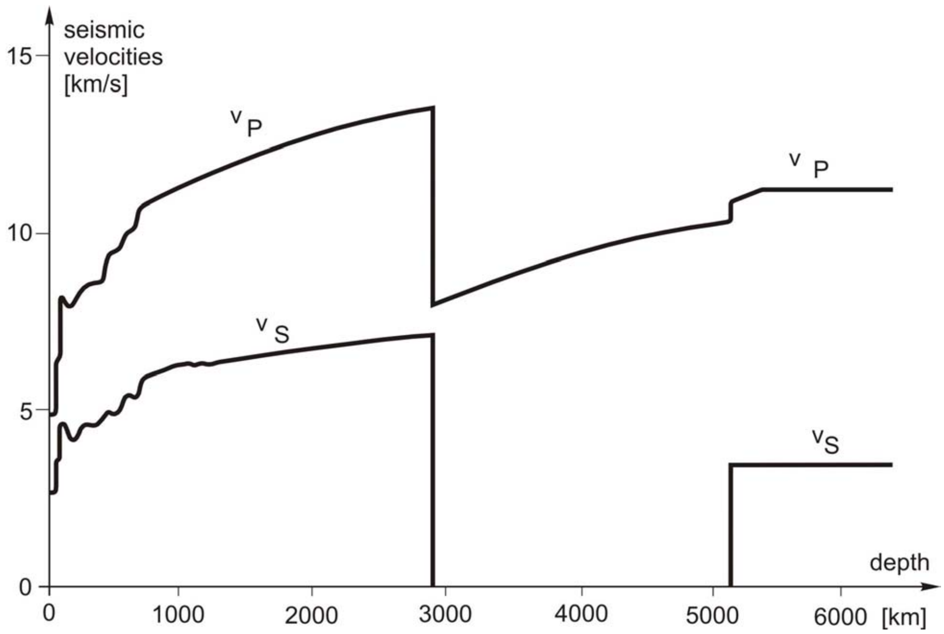

Fig. 5. Variation of seismic velocities in the Earth's interior

The velocity of seismic waves (*P* and *S* waves) advancing to the inside of the Earth can be determined at various depths in the knowledge of the apparent superficial velocity and of the depth of immersion of the waves. It can be seen in *Fig. 2* that the seismic waves emerging at ever-increasing epicentral distances immerse into ever-deeper parts of the Earth and supply information concerning the conditions of velocity existing there. We shall not deal here with the determination of the velocity of seismic waves in the depths; we are concerned here with presenting a survey of the results obtained. In *Fig. 5,* the variation of seismic velocities with depth given by A. H. COOK (p. 76 in [10]) is shown. Based on a variation the three main zones of the Earth mentioned earlier can be divided into further sub-units. Namely, though the velocities increase steadily within the same main zone, the measure of the increase (the first derivative of the function) changes abruptly at certain depths. Spots where the velocity of seismic waves, abruptly changes in the way shown in *Fig. 6* are denoted as surfaces of discontinuities of first order whereas those where their derivatives change as those of second order (p. 44 in [11]). In the plot of the variation of seismic velocities with depth shown in *Fig. 5* the great velocity decrease at a depth of 2900 km is striking. In the mantle of the Earth, the velocity of the longitudinal and transversal waves shows a gradual increase. At the bottom of the mantle, the velocity of the *P* waves attains 13.6 km/s whereas that of the *S* waves is 7.3 km/s. On passing through the mantle-core boundary, the velocity of the longitudinal waves decreases abruptly to 8.1 km/s then later gradually increases in the *Lehman zone* (interpreted in different ways by the various researchers) and attains in the centre of the Earth a value of 11.1 km/s. It is most striking that the velocity of propagation of the transversal waves decreases to zero at the boundary of the core. According to relation (2) this is possible only when $\mu = 0$, that is, the shear modulus zero. However, from this it follows that the outer core behaves as liquid.

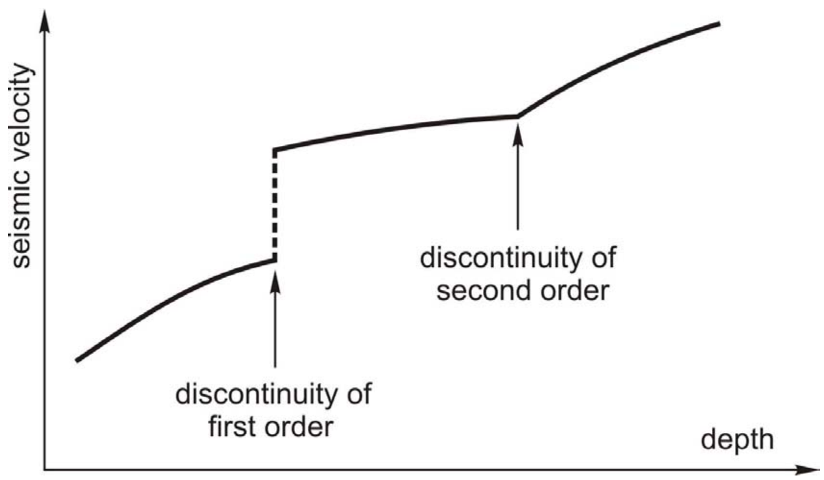

Fig. 6. Discontinuities of first and second order

In the knowledge of P and S velocity distributions the zonal structure of the Earth can be determined quite accurately [12]. The zonal structure showing the depths of the discontinuities of first and second order, the denotations of the individual discontinuities and zones, furthermore the relative volumes of the individual zones can be seen in *Fig. 7.* The model was established by K. E. BULLEN [12] who, in turn, made use of the velocity-depth function of H. JEFFREYS [13]. The most discussed part of the BULLEN model is the Byerly discontinuity of second order denoted at a depth of 410 km. In GUTENBERG's opinion the BYERLY discontinuity does not exist, instead of it a zone of low velocity beginning at a depth of 100-150 km, the low-velocity zone can be found in the upper mantle (p. 75 in [14]). This low-velocity zone plays an important role in the movements, which create the main features of the Earth, in the formation of mountains and in the development of the ridges of the oceans and of the rift valleys of deep seas, etc. From the decrease of velocity, one may presume here that the material has a lower rigidity and greater plasticity.

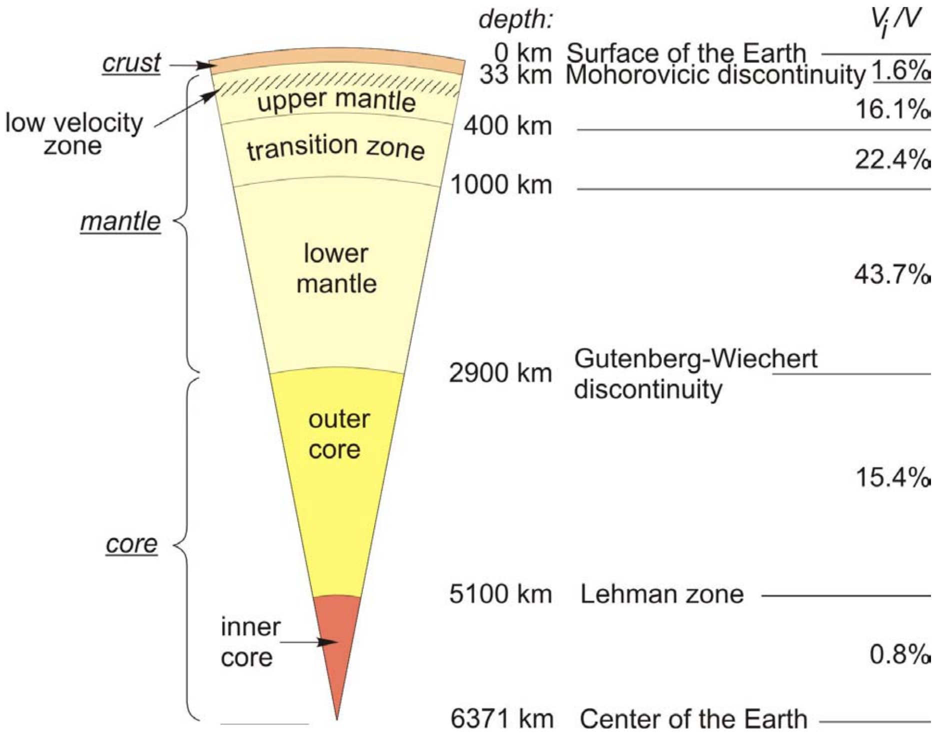

Fig. 7. The layering within the Earth

The newest researches are directed to the recognition of the finer structure of the zones of the Earth. At the determination of the "fine structure" of the Earth, the observations of the free oscillations of the Earth (p. 101 in [10]) and the underground nuclear explosions are utilized. These investigations also supported the assumption that a liquid-like zone is located around the centre of the Earth and a rigid but elastic mantle surrounds this zone. However, it was found at the same time that the theory of zonal structure is not completely correct because the material quality and the structure depend to a small extent also on the location of the point under the surface of the Earth. Essential differences exist, for example, between the deep structures below the oceans and below the continents. It has been proved by nuclear explosions that these differences are present even at depths of several hundred kilometers. Moreover, investigations of the free oscillations of the Earth have indicated that the core-mantle boundary is not flat but has a real "topography" in that the depths below the surface vary to a small extent from point to point.

2. Physical parameters in the Earth of zonal structure

The state and material of the inner part of the Earth can be determined in the best way by determining as many physical parameters as a function of depth as possible. Regrettably, besides the electric conductivity known up to not too great depths, at present the velocity of the elastic waves is the sole physical parameter whose variation with depth can be determined at the Earth's surface. However, based on the knowledge of the velocity vs. depth function also the dependence of some other physical parameters on the depth can be determined relatively accurately. These parameters are density, gravity, pressure and the coefficients of elasticity. These will be the first to be surveyed in the following.

2.1. Density and elasticity

The mean density (average density) of the Earth is the ratio of its mass and its volume. Measurements of artificial satellites have given a very accurate Earth's volume; value for its mass can be calculated by Newton's law of gravity (p. 98 in [15]). For this calculation, only the value of the gravitational constant and of the gravitational acceleration measurable at the Earth's surface must be known. In this way the value of $\vartheta = 5514\ kg \cdot m^{-3}$ is obtained for the average density of the Earth. At the same time, the average density of the rocks forming the continents is $2700\ kg \cdot m^{-3}$ and even the density of samples of rocks taken from the bottom of the oceans does not exceed $3000\ kg \cdot m^{-3}$. Comparison of these density values leads to the conclusion that densities of materials are much higher in the inside of the Earth. This is supported by astronomical observations according to which the moment of inertia of the Earth is $0.33\ Ma^2$ (where M is the mass of the Earth and a the radius of the Earth). At the same time the moment of inertia of a solid body of homogeneous density distribution whose mass and radius are equal to those of the Earth would be $0.4\ Ma^2$. These points also to the presence of material of higher density near to the axis of rotation of the Earth or, on taking into account its zonal structure, near to the centre of the Earth. More information is available from calculating the ratio of the coefficient of $J_2 = (C - A)/Ma^2$ in the harmonic expansion of the external gravity field and the so-called dynamical ellipticity of the Earth: $H - (C - A)/C$ (p. 111 in [10]):

$$\frac{J_2}{H} = \frac{C}{Ma^2}$$

where C denotes the polar moment of inertia. Of the orbital elements of the artificial satellites, we obtain from the precessional movement of the nodal line: $J_2 = 1.0827 \cdot 10^{-3}$ and from the lunisolar precession of the Earth: $H = 3.275 \cdot 10^{-3}$. On using these values, we obtain that $C/Ma^2 = 0.331$. This is a very important value indicating that the mass of the Earth is becoming more and more concentrated towards the Earth's centre. In *Table I,* some values relating to a special model are presented.

Table I. Ratio of densities for an Earth model

Ratio of density	C/Ma^2
1 : 2	0.367
1 : 3	0.340
for the Earth itself	0.331
1 : 4	0.318

This model divides the Earth by a spherical surface into two parts at the half radius of its outer surface, i.e. near the boundary of the mantle and the core. If we assume that the density of the outer shell is ϑ_1 and that of the inner sphere is ϑ_2, then the C/Ma^2 values in *Table I* pertain to the ratios of ϑ_2/ϑ_1. From these values, we can state that the density of the Earth's core must be nearly three times as great as the density of the outer parts.

The *Adams-Williamson equation* (p. 48 in [11]) offers a possibility to determine more accurate density-depth function. This equation gives the density gradient for a chemically homogeneous material in a hydrostatic state utilizing the velocity of seismic waves:

$$\frac{d\vartheta}{dr} = \frac{-kM_r\vartheta_r}{r^2\left(v_P^2 - \frac{4}{3}v_S^2\right)} \tag{3}$$

where k is the gravitational constant, ϑ_r the density at distance r from the Earth's centre, M_r the Earth's mass within a sphere determined by radius *r*, v_P and v_S are the velocities of the longitudinal and transversal waves at the given depth. The density-depth function $\vartheta(r)$ can be obtained from the differential equation (3) by numerical integration. For the solution the initial conditions must be given: in the present case at a starting level of $r = r_0$ the known density value is $\vartheta = \vartheta_0$. Then the numerical values relating to the given starting level $r = r_0$ are substituted for all the variables present at the right side of relation (3). In this way, the density gradient relating to the starting level is obtained. On multiplying the result by a distance value Δr chosen arbitrarily as a low number, the density change $\Delta\vartheta$ for the distance Δr is obtained. In this way, the new density will be $\vartheta_1 = \vartheta_0 + \Delta\vartheta$ at a distance of $r_1 = r_0 - \Delta r$ from the centre. At this new depth the values relating to the new depth can again be substituted for the variables present at the right side of relation (3), obtaining thus the new density gradient. This operation can be continued until the change of density becomes continuous. When however the density changes abruptly, relation (3) no longer gives the value of the density jump. We must choose the most likely value of the density jump on the basis of other, partly earlier discussed considerations, then on starting with the new value the density-depth function can be calculated further by means of relation (3): Two possibilities are available for checking, the density-depth function established in this way and of the value of the presumed density jump (eventually density jumps). On the one hand, the total mass of Earth having the obtained density distribution must be equal with the known mass of the Earth and, on the other hand, its moment of inertia must agree with the actually observed value. If any of the calculated models does not fulfill these conditions, it must be discarded. In practical calculations the Earth's crust is omitted because of its large inhomogeneities and when using relation (3) the starting level is the top of the upper mantle where $r_0 = 6340\ km$ and $\vartheta_0 = 3300\ kg \cdot m^{-3}$. If we assume that the Adams-Williamson equation can be applied up to the boundary between mantle and core, on then the density distribution obtained in this way enable us to determine the mass of the Earth's mantle. On subtracting this latter value from the total mass of the Earth, the mass of the core is obtained. Quite similarly, in the knowledge of the density distribution of the Earth's mantle also the moment of inertia of the core and from this the ratio I / Ma^2 related to the core can be determined. When first applying this procedure BULLEN obtained the value $I / Ma^2 = 0.57$ which is quite improbable since it is greater than the value related to an Earth's core of homogeneous density distribution, i.e. it would mean that density decreases with the depth or in other words: the core would have a hollow structure. The contradiction may be due to the omission of a sudden density jump in the mantle during the numerical integration of relation (3). According to BULLEN a density jump is conceivable also at a depth of about 400 km where the velocity of P and S waves changes quickly. Since however density is altered abruptly also at the boundary between mantle and core, and a density jump is likely at the boundary of the inner core as well, furthermore besides the velocity of propagation of seismic waves, the Earth's mass and its moment of inertia as known values; a great number of unknown values emerge during the determination of the density-depth function. Even so, according to an earlier consideration the moment of inertia of the core cannot be greater than 0.4 and this value limits the minimum density of the Earth's core and the maximum value of the density jump at a depth of 400 km.

In the knowledge of the velocity of seismic waves and of the function of density vs. depth, the values of the elastic parameters at various depths of the Earth can also be determined in a simple way by using relations (1), (2) and other relations (p. 272, p. 273 in [16]).

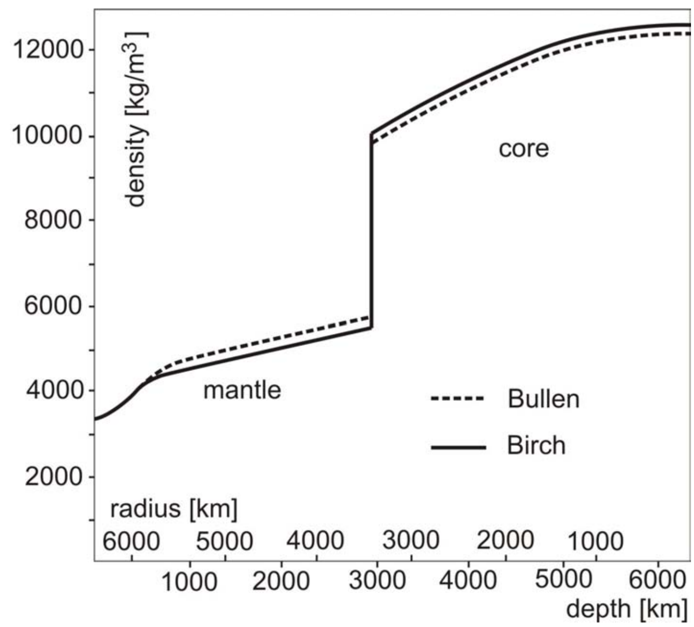

Fig. 8. The variation of density within the Earth (after Bullen and Birch)

Based on the above considerations a model was established by BULLEN for the dependence on depth of density and of elasticity [17]. *Fig. 8* shows BULLEN's model and the density depth function recalculated by F. BIRCH. This recalculation became necessary because recently, using artificial satellites for geodetic purposes, value that is more accurate has been obtained for the moment of inertia of the Earth [18]. Birch's model was prepared taking into account the new value. It can be seen in *Fig. 8* that the density value is $3300\ kg \cdot m^{-3}$ at the top of the upper mantle. Bullen's view is that this value increases more quickly at the beginning then attains, at a depth of 470 km, a value of $3880\ kg \cdot m^{-3}$; subsequently, near. The boundary of the upper and lower mantle at a depth of 1000 km, it becomes $4650\ kg \cdot m^{-3}$ and on increasing further steadily toward the boundary between the mantle and the core reaches the value of $5660\ kg \cdot m^{-3}$ at a depth of 2900 km. On passing through the Gutenberg-Wiechert interface the density jump reaches $4040\ kg \cdot m^{-3}$ and thus the density in the upper part of the outer core becomes $9700\ kg \cdot m^{-3}$ which latter value increases more quickly at the beginning, it becomes and slower later on until it attains a value of $12500\ kg \cdot m^{-3}$ in the centre of the Earth. The model recalculated by F. BIRCH (p. 215 in [13]) has values differing only slightly from the BULLEN's values shown in *Fig. 8*. Based on the density - depth function BULLEN also determined the dependence on depth of the elastic parameters shown in *Fig. 9*, where E is Young's modulus, K is the bulk modulus λ is the Lame parameter and μ is the shear modulus. It can be seen that in the core, μ and E are zero since, according to our earlier statement, the Earth's core (or at least its external part) is in a liquid-like state.

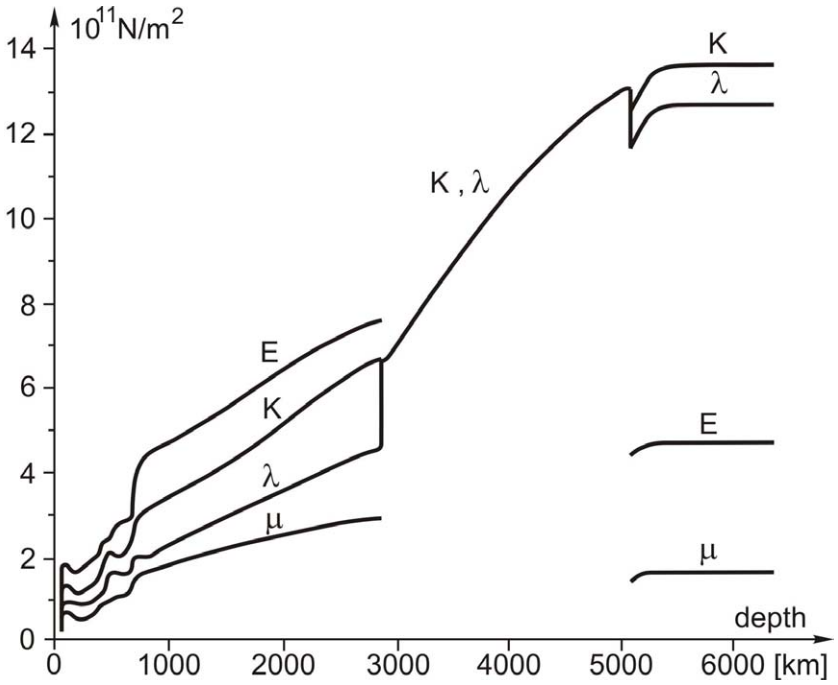

Fig. 9. Elastic moduli within the Earth

Earlier the use of the Adams-Williamson equation was the only possibility available to determine the density distribution in the inside of the Earth and the dependence on the depth of the elastic parameters. Now, however, other methods are utilized for this purpose; in particular, those methods taking into account the free oscillations of the Earth whose periods depend on the inner distribution of density and on the values of the elastic parameters. However based on the free oscillations of the Earth the determination of the dependence on depth of the relevant physical parameters is slightly more elaborate. This means that first, several different Earth models must be established wherein the density and the elastic parameters vary in a different way with depth; the free oscillation periods pertaining to these must then be calculated; finally, the particular series of calculated free oscillation periods must be found that agrees with the values actually observed. Obviously, the same method must be followed on fitting to each other the calculated and observed travel-time curves of the earthquake waves. With respect to the very great number of the possible cases, the problem can be solved only by means of electronic computers. F. PRES accomplished this task with the use of the Monte Carlo method. In his model investigated by means of a computer the actual values of the functions $v_P(r)$, $v_S(r)$ and $\vartheta(r)$ were produced by a random number generator. To check the values calculated in this way the velocity-depth function of P and S waves determined based on results of seismic measurements, the known mass of the Earth and the moment of inertia of the Earth and the periods of the free oscillations of the Earth were used. All models not satisfying the value of any known physical parameter were discarded. The remaining models, with the exception of the inner core, approximate well the BULLEN model already described.

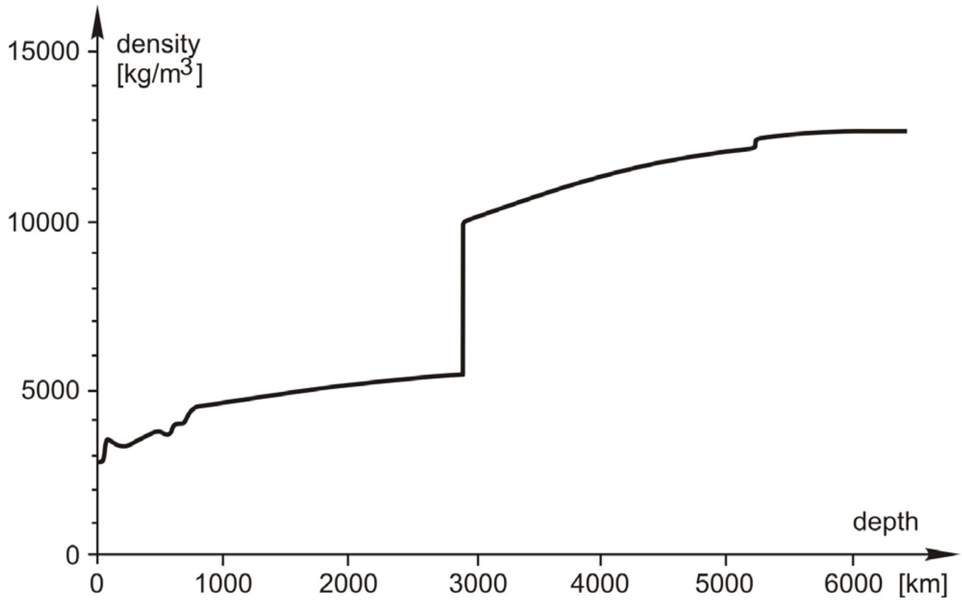

Fig. 10. The density distribution in the Earth's interior (after Anderson and Hart)

It is of interest to mention here the density-depth model established by D. L. ANDERSON and R. S. HART shown in *Fig. 10* [19]. A notable feature of the function presented in this figure is the density jump, which can be seen in the *Lehman zone*, furthermore the inner core of a nearly constant density of about $12500\ kg \cdot m^{-3}$ and the density decrease corresponding to the low-velocity zone that begins at a depth of about 150 km.

It is generally accepted that the established density-depth function can be considered as valid up to the boundary of the outer core within an accuracy limit of 1%, whereas in the outer core, the uncertainty is 3% and in the inner core, the given values are rather unreliable (p. 91 in [20]). In the inner core, the big uncertainty is because the volume of the inner core is, as shown in *Fig. 7*, only 0.79°/o of the total volume of the Earth. Thus, here a relatively great change of density can alter only by a very low value the mass and the moment of inertia of the Earth, i.e. the parameters that are taken into account in checking the density-depth function.

2.2. Gravitational acceleration

In the knowledge of the density-depth function, the gravity at various depths of the Earth can also be determined in a simple way. The gravity is, at any point of the inside of the Earth at a distance r from the centre,

$$g_r = \frac{kM_r}{r^2} \quad (4)$$

where k is the gravitational constant and M_r the mass of a sphere with radius r whose mass can be calculated in a simple way in the knowledge of the inner density distribution. The gravity of spherical shells caused by masses outside the surface of a sphere of radius *r* (which contains the investigated point) is zero at the investigated point because the gravity is zero in the inside of any homogeneous spherical shell. Figure 11 shows the gravity-depth function calculated by means of the density distribution established by BULLEN. An interesting feature of this curve is that gravity slightly increases at the beginning with respect to the value at the surface; and then attains a maximum value of $10.7ms^{-2}$ at the core-mantle boundary. From here on the value decreases almost linearly and becomes zero in the center of the Earth.

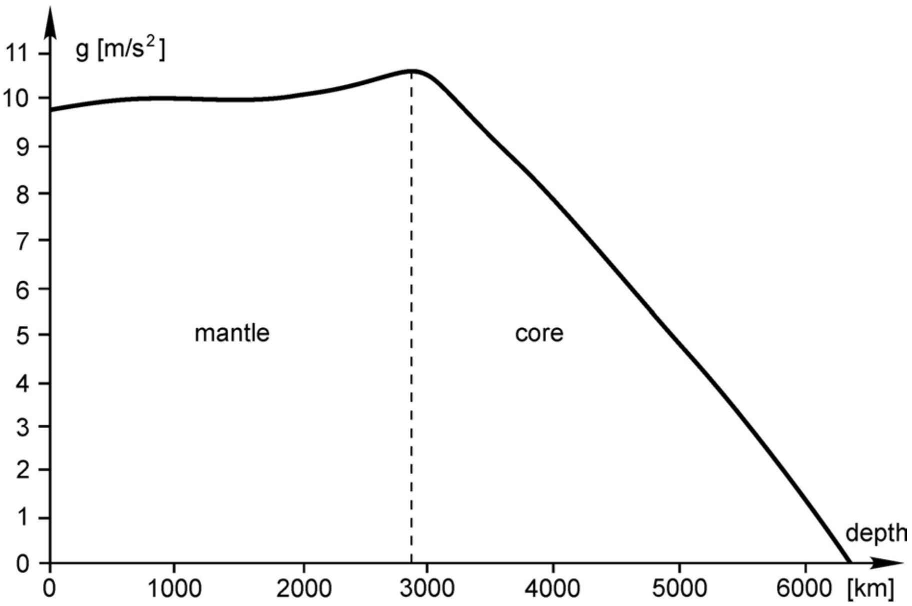

Fig. 11. The gravity at different depths in the Earth's interior

2.3. Pressure in, the inside of the Earth

The pressure in the inside of the Earth can be determined in the knowledge of the density distribution and of the gravity-depth function by applying the relation

$$P = \int_R^r g\vartheta dr$$

Since the pressure is additive, its value becomes steadily higher and higher with the increase in depth and attains a maximum value in the center of the Earth (see Fig. 12). In the Earth's core the order of magnitude of the pressure is already some millions of atmospheres, reaching in the center the maximum value of $3.64 \cdot 10^{11} Nm^{-2}$, i.e. nearly 4 million atmospheres.

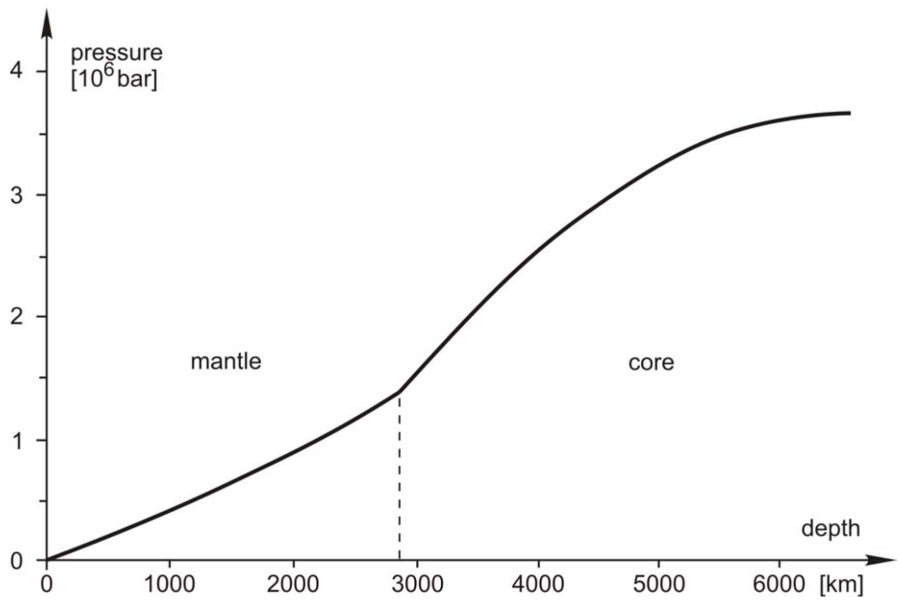

Fig. 12. The pressure at different depths in the Earth's interior

2.4. Temperature distribution in the inside of the Earth

The temperature of the surface of the Earth shows daily and annual fluctuations. The temperature of the superficial and of the near-to-surface layers is determined by the thermal energy of the Sun's radiation. However, at a depth of some ten meters these temperature fluctuations cannot be detected any more since at greater depths the effect of the internal heat of the Earth prevails. According to data of temperature measurements carried out at first in mines and then later in boreholes, temperature increases with depth. The measure of this increase is given by the so-called geothermal gradient whose value is different in various areas of the Earth. The mean value of the geothermal gradient is $0.03\ ^{o}C/m$, that is: the temperature increases on average by *1°C* per *33m* of depth. For some areas, the value of the geothermal gradient is only $0.01\ ^{o}C/m$ but places exist where it attains $0.05\ ^{o}C/m$. E.g. calculating with the average value of the gradient, the temperature is about *150°C* at the bottom of a borehole of *5000m* depth. It would, however, be erroneous to compute the temperature of deep layers of the Earth from the value of the geothermal gradient. A relevant point here is that data valid for some kilometers certainly cannot be extrapolated to a depth of *6000 km*. As an interesting assumption it can be mentioned here that on this basis a temperature of nearly *200 000 °C* would be obtained for the center of the Earth. The geothermal gradient can be applied at most to the Earth's crust.

The value of the geothermal gradient in any material is the higher the greater the thermal energy flowing through unit surface during unit time: i.e. the heat flow. However, according to Fourier's first equation the rate of the heat flow q depends also on the thermal conductivity of the given material:

$$q = \lambda\, gradT\ .$$

A great number of heat flow measurements at various (continental and oceanic) areas of the Earth have given quite unexpected results: that is: everywhere the same values about $0.06\,Wm^{-2}$ were obtained with only slight deviations. From this, it follows that for areas where the temperature increase with depth is smaller; the thermal conductivity of the rocks is higher whereas higher temperature gradients are due to a lower thermal conductivity of the rocks.

Thus, based on the former data each m^2 surface of the Earth releases heat energy of 0.06 Joule/second on average. This value of heat flow appears to be rather low. Considering however that in this way the whole surface of the Earth releases $9.66 \cdot 10^{20}$ Joule of heat energy, we find that this is a vast amount of heat (about 1000 times as much as the total energy released each year by earthquakes). According to radioactive age determinations, the age of the Earth is estimated to be about 4500 million years. It is questionable how long the internal energy reserves of the Earth can compensate the heat amount lost by the heat flow. If it is not assumed that heat is produced continuously within the Earth, then the temperature differences creating this heat flow ought to have been compensated long since, over this extremely long period. The great temperature differences existing even at present indicate that heat is being produced continuously in the inside of the Earth. This heat generation is due to the decay of radioactive elements. The proportion of radioactive materials in the Earth is extremely low (p. 173 in [10]) even so these materials produce an amount of heat sufficient to maintain the present temperature conditions even if the Earth was originated cold. On examining the half-lives of some radioactive elements of importance from the aspect of heat generation ($^{238}U \quad 4.5 \cdot 10^9\,year$, $^{232}Th \quad 13.9 \cdot 10^9\,year$, $^{40}K \quad 1.3 \cdot 10^9\,year$) it appears that radioactive materials can ensure heat generation for many millions of years.

Table II

Rock	Content of radioactive elements			Heat generation
	U	Th	K	$10^{-11}\,W\,kg^{-1}$
Granite	4.0	18	35000	94
Diorite	2.0	7	18000	42
Basalt	0.8	3	8000	17
Eclogite	0.04	0.2	1000	1.2
Peridotite	0.01	0.06	10	0.25
Dunite	0.001	0.004	10	0.02

It has been mentioned above that the heat flow values measured at oceanic and continental areas were the same. This is surprising on taking into account the following considerations. It is known from the investigation of the composition of rocks originating from the Earth's crust that the content of radioactive elements depends closely on the SiO_2 content of the rocks in that with the rise of the basicity the content of radioactive elements decreases according to the data of Table II. (The values of the radioactive elements presented in Table II indicate the number of atoms of the relevant element among 10^6 atoms.)

We shall see later that the granitic zone of the crust is absent in the oceanic territories. Thus here the heat flow should be much smaller but, in fact, this is not the case. The only explanation seems to be that the upper mantle below the oceans is much richer in radioactive elements than the upper mantle below the continents, i.e. in the continental areas the sources of heat are mainly in the crust whereas in the oceanic areas they are located mostly in the upper portion of the mantle. Because of the different location of the sources of heat and to the different thermal conductivity of the crust, the temperature-depth function discloses a deviating shape below the continental areas.

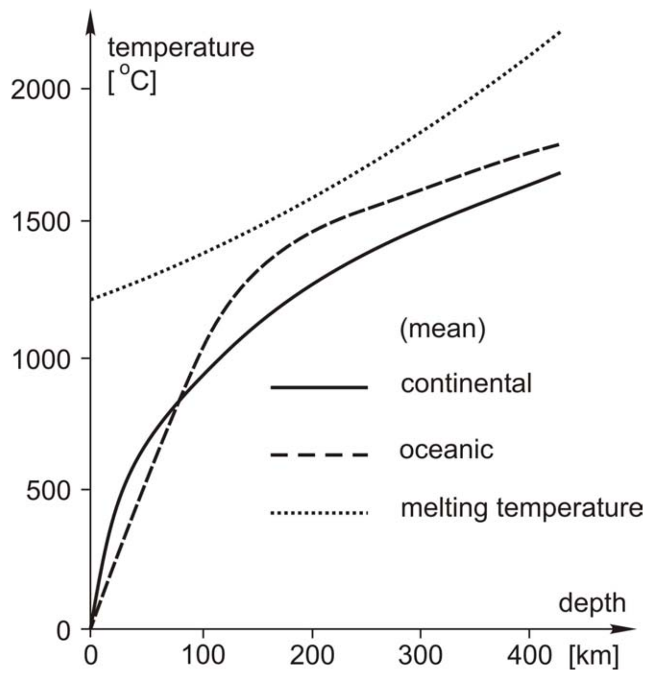

Fig. 13. The variation of temperature below the oceans and the continents

Figure 13 shows the temperature distribution of the oceanic and of the continental area with an average heat flow [2]. According to Fig. 13 up to a depth of 30-40 km, the temperature is higher below the continents than below the oceans whereas at greater depths the temperature of areas below the oceans is higher than that below the continents. The difference of temperatures below the oceanic and continental crusts at the same depth may attain even several hundreds of degrees centigrade, and it is likely that this difference disappears only at great depths (700-800 km). It can also be seen in Fig. 13 that the temperature of the upper mantle approaches 100-200°*C* of the temperature of the melting point of the material present there at a pressure prevailing at that site. It may thus occur easily that at spots where the concentration of radioactive elements is higher or surplus heat is being produced eventually by other processes, e.g. by exothermic chemical processes, the material of the upper mantle partially melts and in the course of volcanic activity comes to the surface. It is of interest to note that the zones of volcanic activity coincide with the territories of earthquakes at medium and great depths. The volcanic material effused in these areas consists mainly of andesite, dacite and rhyolite whereas the volcanoes of the oceanic basins produce mainly basalt. The first of these is denoted as andesite volcanism whereas the latter as basalt volcanism.

The lateral temperature differences present in the upper mantle decrease towards the greater depths and according to estimation, the temperature at the bottom of the upper mantle is already uniformly 2500-3000°*C*. At greater depths than these, determination of temperature based on available data is rather speculative. A number of models have been developed to study the inner temperature distribution (E. A. LUBIMOVA ~22~); the mostly accepted model is presented in Fig. 14. On accepting, that the temperature at the boundary between mantle and core has a value of about 4000°*C* the pattern of the inner temperature distribution must be very similar to the curve given in Fig. 14, according to which the temperature at the centre of the Earth is between 4000 and 5000°*C*. However, the presented curve summarizes the results obtained by several excellent physicists and geophysicists during their work for many years, because of the uncertainty of the basic assumptions and because of the lack of convincing experimental results, an error as much as 50% is conceivable.

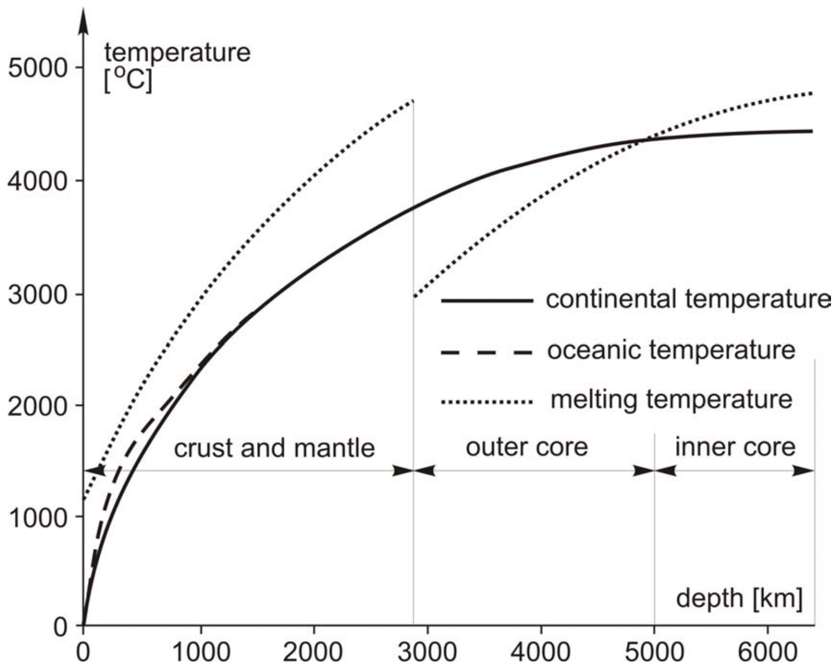

Fig. 14. The variation of temperature within the Earth

An interesting feature of Fig. 14 is that a possible explanation is given for the changes of states present in the inside of the Earth. If we assume that the material under the vast pressure prevailing in the inside of the Earth also behaves in a way similar to that experienced by us under conditions prevailing at the surface, we may conclude that the liquid-like state of the external core is due to a temperature above the melting point of the material located there. The melting point depends significantly on the quality of the material and on the pressure. If we accept the assumption that the material of the Earth's core consists mainly of iron and nickel, with some other lighter metals (e.g. silicon) in the external part, then on taking into account the pressure values shown in Fig. 12 the melting point vs. depth function presented in Fig. 14 would be obtained. This function shows that the curve of the melting point proceeds in the crust and in the mantle above the temperature curves; the material is solid here. Owing to the probable change in the material composition, an essential difference exists between the melting points prevailing at the boundary between the mantle and the core. In the outer part of the core, the temperature is higher than the melting point; therefore, here the material is in a liquid-like state. The two curves intersect each other at the boundary of the inner core, in the inner core, the temperature is again lower than that required to melt the material.

The experimental proof of the validity of the described model is extremely difficult. Until its correctness is proved, it cannot be accepted without strong reservations. Moreover, an argument against it is that at the mantle core boundary an unreasonably sharp difference is assumed in the material composition without taking into account the behaviour of the atoms building up the material above the critical pressure.

3. Inner structure of the Earth

In the previous chapters, some of the physical properties of the materials of which the Earth is built up were investigated. In the following, an attempt is made to discuss the building materials of the Earth, i.e. to describe the materials possessing these physical properties.

3.1. Structure of the Earth crust

The outermost zone of the Earth located between the surface and the Mohorovicic discontinuity is considered the Earth's crust. Man has investigated the part of the Earth's crust not covered by the oceans for many thousands of years and thus it is actually the most known zone of the Earth. Although the Earth's crust cannot be considered as a homogeneous zone, in its construction there is still some characteristic regularity.

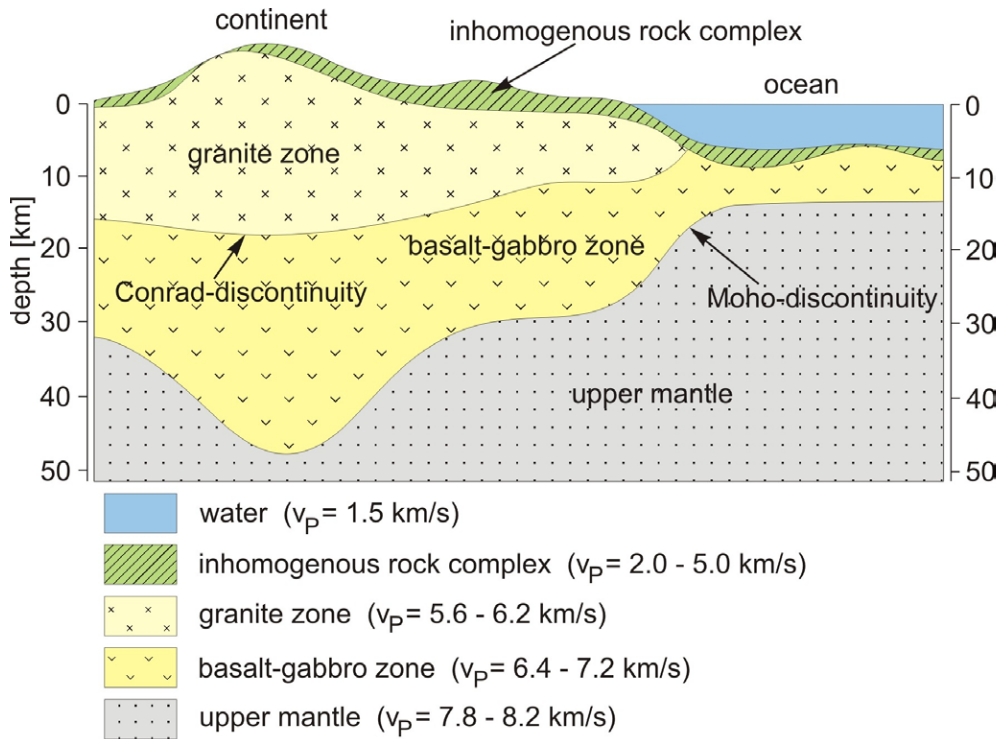

Fig. 15. The structure of the Earth's crust below the oceans and the continents

It was mentioned earlier that the average depth from the surface of the Mohorovicic discontinuity - which determines the lower boundary of the Earth's crust - is 33 km. This is however, a mean value relating to the Earth as a whole and it varies between about 5 and 65 km. The thickness of the crust is far from being random values but a close correlation can be found between the thickness of the crust and the superficial topography of the Earth. It can be seen in Fig. 15 that the thickness and the structure of the crust are quite different below the continents compared with those below the oceans. The law of isostasy [23] controls the thickness of the Earth's crust. Namely, according to Airy's isostatic principle the solid crust of the Earth is approximately in a floating equilibrium state with the material of the upper mantle of higher density, which is below the solid crust. This means that if the parts of various height of the crust are considered as independent prisms, they will become immersed into the material of the mantle until the buoyant force acting on them equals their weight. Accordingly, the thickness of the higher mountains may attain 40-70 km whereas the thickness of the crust below the oceans is scarcely 5-7 km. Obviously, the Earth's crust is not in a state of isostatical equilibrium everywhere, but most of the movements will still tend, even in this case, to attain the equilibrium state.

The appearance of modern geophysical methods and instruments made possible the study of the fine structure of the Earth's crust. An earlier very significant discovery was that the Earth's crust could be divided into two parts along quite a sharp boundary. CONRAD [24] was the first in carrying out seismic investigations with regard to this. Subsequently, JEFFREYS concluded, in the knowledge of more reliable data (p. 149 in [13]), that the so-called Conrad boundary dividing the crust into two parts can be found generally at a depth of 5-20 km from the surface. Furthermore it is of interest that the Conrad boundary can be detected only in the crust below the continents and also that the Conrad surface, similarly to the Moho surface, follows the superficial topography mostly in an opposite sense.

Based on the seismological investigations the velocity of seismic waves can be determined at various depths of the Earth's crust. Similarly, based on laboratory measurements the velocities of seismic waves in the main types of rocks found at the surface of the Earth can be determined for various parameters of temperature and pressure. The results of laboratory measurements are summarized in Table III.

Table III

Type of rock	Density $[kg\,m^{-3}]$	Velocities of seismic waves [*km/s*]					
		A		B		C	
		v_P	v_S	v_P	v_S	v_P	v_S
Granite	2650	5.6	3.4	5.9	3.6	6.2	3.7
Diorite	2760	6.4	3.6	6.5	3.7	6.8	3.8
Gabbro	3040	6.8	3.8	6.9	3.9	7.2	4.0
Peridotite	3350	7.4	4.2	7.5	4.2	7.7	4.3
Dunite	3290	7.9	4.5	8.1	4.5	8.2	4.6

Column "A" of Table III gives velocity values determined for the pressure value of about $1.3\cdot 10^8\ Nm^{-2}$ prevailing at a depth of 5 km below the Earth's surface; column "B" gives the velocities determined for the pressure value of $4.2\cdot 10^8\ Nm^{-2}$ prevailing at a depth of 15 km; in column "C" the velocities determined for the pressure value of about $10^9\ Nm^{-2}$ prevailing at a depth of 35 km are given.

Based on laboratory measurements the velocity of both the longitudinal and the transversal waves increases with the increase in basicity of the rocks. The same can be experienced with the rise in pressure as apposed to the velocities of seismic waves, which decreases, with an increase in temperature. The results of laboratory measurements are summarized in Fig. 16. A common feature of the investigated rocks is that the velocity increases quickly at the beginning but not so quickly later with increasing pressure. Figure 16 also indicates that at the real temperature and pressure parameters prevailing on Earth, the velocities of granite and gabbro are practically constant between depths of 5 and 35 km.

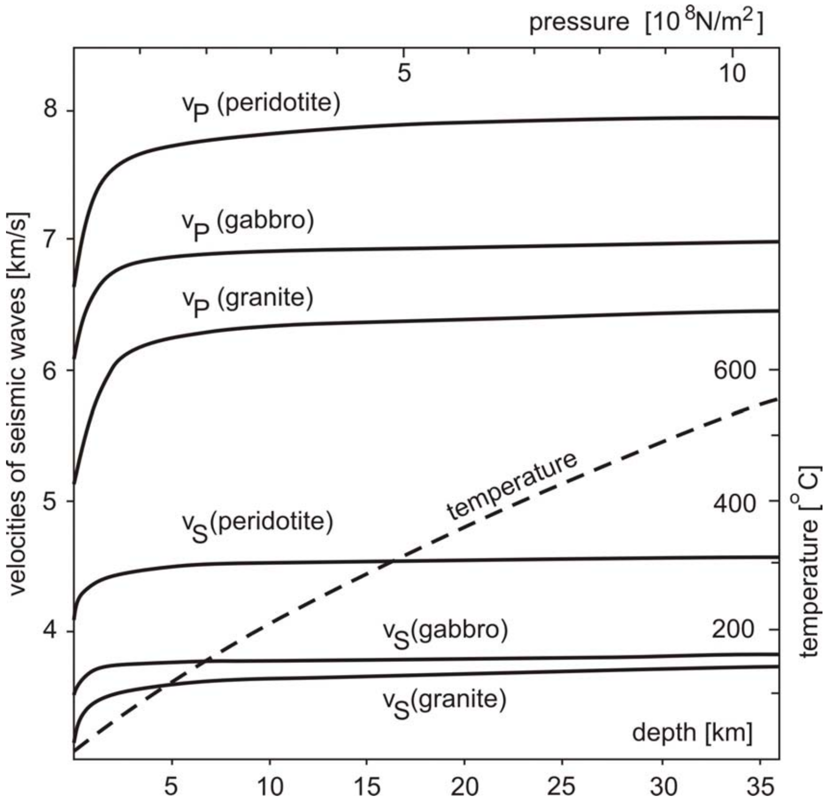

Fig. 16. The results of laboratory measurements of seismic velocities

In the knowledge of the results of laboratory measurements, it is relatively easy to determine the rocks composing the Earth's crust, and, in the knowledge of these rocks, the percentage distribution of the major chemical elements can be given as a function of depth. Consequently, our task is solely to compare the actual velocity values obtained based on the seismic waves with the laboratory results. In this way, the pattern presented in Fig. 15 is obtained for the structure of the Earth's crust. Figure 15 shows the average or rather the ideal crust structure below the continents and the oceans. We shall not deal here with the rocks of various composition and thickness located near the surface and containing varieties from the superficial loose sediments to the crystalline basement rocks because the structure and composition of these rocks are more or less well known mainly from the data of mines and deep drillings. Below these rocks on continental territories a layer of 5 to 20 km thickness is located wherein the velocity of P waves varies from area to area but only within the range between 5.6 and 6.2 *km/s*. The bottom of this layer is the Conrad discontinuity. In the layer of 10-30 km, thickness located between the Conrad and the Moho surface the velocity of P waves is 6.4 to 7.2 *km/s* and lastly at the top of the mantle velocity values between 7.8 and 8.2 *km/s* can be measured. At the bottom of the oceans directly under the inhomogeneous rock complex consisting mainly of sedimentary rocks the lower zone of the continental crust can be found, the upper layer is completely absent. On comparing, the above values of velocity it can be stated that most of all rocks of granite or granodiorite nature correspond to the upper part of the crust; rocks of gabbro and diorite nature to the lower part; and dunite or periodotite nature rocks correspond to the part below the crust. Geochemieal investigations agree well with this result since the rocks become more and more basic with the increase in depth and the composition of the crust is near to the composition of granite. Accordingly, the upper part of the crust is denoted as the granite zone. According to the average values of analyses of several thousands of samples (p. 326 in [1]) the elementary composition of the upper zone of the crust is the following:

O	46.59 %	H	0.130 %
Si	27.72 %	Mn	0.100 %
Al	8.13 %	As	0.052 %
Fe	5.01 %	V	0.050 %
Ca	3.63 %	Cl	0.048 %
Na	2.85 %	Cr	0.048 %
K	2.60 %	C	0.032 %
Mg	2.09 %	F	0.030 %
Ti	0.63 %	Zr	0.026 %
P	0.13 %	Ni	0.020 %
total of all other elements:			0.084 %

On considering the above data, two important points deserve attention. On the one hand, the number of elements present in amounts greater than 1% is only eight and these elements account for 99% of the crust whereas the above listed twenty elements make up nearly 100%. On the other hand, it is of interest that the elements are present to the greatest extent as oxides. This is indicated also by the fact that almost half the total material consists of oxygen. The ten oxides occurring the most frequently and present at a frequency above 1% total 99% of the rocks of the granite zone representing the upper part of the crust. The percentage distribution of the oxides is as follows (p. 326 in [1]):

SiO_2	59.12 %	MgO	3.49 %
Al_2O_3	15.34 %	K_2O	3.13 %
CaO	5.08 %	Fe_2O_3	3.08 %
Na_2O	3.84 %	H_2O	1.15 %
FeO	3.80 %	TiO_2	1.05 %
total of all other oxides:			0.92 %.

The composition of the lower part of the crust approaches - according to the seismic velocities - that of the "more basic" diorite and gabbro, respectively, which are poorer in Si but richer in Ca, Mg and Fe. Diorite occurs in masses smaller than gabbro therefore the lower part of the crust is also denoted as the gabbro zone. Since, however, the compositions of gabbro and basalt are similarly near each other, the zone also used to be called the basalt zone. It is likely that the composition of the so-called plateau-basalts approaches to the greatest extent that of the gabbro zone. The composition of the plateau basalts is as follows:

O	44.30 %	Mg	3.76 %
Si	22.90 %	Na	1.91 %
Fe	10.40 %	Ti	1.49 %
Al	6.99 %	K	0.68 %
Ca	6.89 %		
total of all other elements:			0.68 %.

The percentage composition, according to oxides of diorite, gabbro and plateau-basalt which rocks approach to the greatest extent the composition of rocks forming the lower part of the crust, is the following (p. 327 in [1]):

	Diorite	Gabbro	Plateau-basalt
SiO_2	56.77 %	48.24 %	50.60 %
Al_2O_3	16.67 %	17.88 %	17.40 %
CaO	6.74 %	10.99 %	8.09 %
MgO	4.17 %	7.51 %	4.89 %
FeO	4.40 %	5.95 %	6.29 %
Fe_2O_3	3.16 %	3.16 %	4.57 %
Na_2O	3.39 %	2.55 %	3.23 %
H_2O	1.36 %	1.45 %	1.83 %
TiO_2	0.84 %	0.97 %	0.68 %
K_2O	2.12 %	0.89 %	1.76 %
all other elements	0.38 %	0.41 %	0.66 %

The compositions of the above three rocks show quite a good agreement. On accepting any of these rocks as a representative of the basalt zone, their common characteristic feature is that, similarly to the material construction of the granite zone, the oxides of silicon and aluminium are the oxides occurring in them the most frequently. Therefore, the Earth's crust over the Mohorovicic discontinuity used to be denoted frequently as the *SIAL* crust.

The structure and material construction of the Earth's crust as sketched above can be considered reliable based on the analysis of the seismic waves and of the results of geochemical investigations. However, we must fully understand that the reliability of the data decreases with the depth rather slowly at first then quicker and quicker. Consequently, until drilling samples are available from the deepest parts of the crust, it cannot be stated unequivocally that the continental crust consists of a granite and a basalt zone.

3.2. Structure of the Earth's mantle

The Earth's mantle is bordered by two discontinuities of first order: at the border facing the crust the Mohorovicic discontinuity, at the border facing the core the Gutenberg-Wiechert discontinuity. It is known that the velocity of seismic waves changes abruptly along the borders between crust and mantle furthermore between mantle and core. Consequently, at these sites abrupt changes of density are also to be expected. However, density could change abruptly in two cases: either due to a sharp alteration of the material composition or due to a change of physical state. According to data presented earlier the change of physical state cannot be imagined at the temperature and pressure values prevailing at the border between the crust and the mantle. Thus, rather a sudden change of the material composition must be taken into account. A quite different situation exists at the border between the mantle and the core where pressures of the order of some million atmospheres and temperatures of several thousands of degrees centigrade prevail. It would be a great error to ignore the possibility of a change of the physical state.

Between the aforementioned two discontinuities a discontinuity of second order (the Repetti surface) exists which also divides the mantle into two parts: the upper and the lower mantle. On studying the velocity-depth function shown in Fig. 5 it is striking that whereas in the lower mantle the velocity curves rise continuously and smoothly, the velocity alters in the upper mantle fairly strongly and irregularly. This may indicate on the one hand that at greater depths our knowledge of the "fine structure" of velocity changes becomes less and less certain and, on the other hand, on accepting that the velocity-depth function is actually of this type, this may support the opinion accepted at present to an increasing extent that below a depth of about 800-1000 km no significant material differentiation exists and thus the chemical composition of the core does not differ essentially from that of the mantle. In this case however the sharp boundary appearing at the Gutenberg-Wiechert surface is caused by a change of the physical state rather than by a chemical alteration.

Fundamental investigations on the structure and physical conditions of the mantle were carried out by BIRCH [25, 26] who detected that the mantle is of a homogeneous composition from a depth of 900 km to a depth of 2900 km, i.e. to the border of the Earth's core. Furthermore, BIRCH found that the ratio of the so-called adiabatic incompressibility to the density discloses a rapid increase between the depths of 300 and 800 km. From this, he concluded that this zone represents a transition from the material of ultrabasic silicate under the crust to the material complex of high-pressure modification in the mantle.

Now we may attempt to reply to the question: What are the materials of which the upper and the lower mantle of the Earth are composed? It was mentioned earlier that the velocity of P waves in the top zone of the upper mantle is between 7.8 and 8.2 km/s. According to the data in Table III the material of the upper mantle directly below the crust must be identified as dunite or peridotite. This does not mean any significant difference from the aspect of the composition expressed in the form of oxides (p. 328 in [1]) as follows:

	Dunite	Peridotite
SiO_2	40.49 %	43.95 %
MgO	46.32 %	36.81 %
FeO	15.54 %	6.34 %
Al_2O_3	0.86 %	4.82 %
CaO	0.70 %	3.57 %
Fe_2O_3	2.84 %	2.20 %
H_2O	2.88 %	1.08 %
Na_2O	0.10 %	0.63 %
K_2O	0.04 %	0.21 %
MnO	0.16 %	0.19 %
TiO_2	0.02 %	0.10 %
P_2O_5	0.05 %	0.10 %

On comparing the above values of oxides with those of the *SIAL* zone, the most striking is that after silica magnesium occurs more frequently rat her than aluminium. Therefore, this zone was also known as the *SIMA* (silicon magnesium) zone. (At present, the name peridotite zone tends to be applied.)

Statements concerning the chemical composition of the top zone of the upper mantle can still be considered as reliable. However, the chemical composition under the lower border of the peridotite zone and the top zone of the upper mantle is rather uncertain. Based on the principle of continuity and of observations, concerning the volcanic activities we may still assume that the upper mantle consists mainly of silicates and its composition is mostly of a peridotitic nature. Only the "boldest" research workers have attempted the determination of the chemical composition of the lower mantle in the knowledge of very sparse data available. For the solution of this problem, some Earth models may give some aid.

3.3. Construction of the inner parts of the Earth by use some Earth models

Up to the top zone of the peridotite, our knowledge of the inner construction of the Earth is quite reliable. However, concerning the material construction and structure of the layers under these zones only assumptions are available which are based on the results of observations of various physical processes made from outside, from the surface of the Earth. The combined uniform explanation of conceptions concerning the inner distribution of material, its arrangement, and physical states is denoted as the Earth model. In the following, a survey is given of the main features of some essential Earth models.

3.3.1. The geochemical - meteorite Earth model

The material distribution of meteorites served as a database for the construction of one of the oldest Earth models. According to the fundamental principle of this model, the members of the solar system are all of identical construction. Hence, because the meteorites probably are remnants of exploded planets, the distribution of materials in the inner Earth must be the same as those occurring in the various stone and iron meteorites and, respectively, their transitionary varieties. According to the two main types of meteorites (silicate and iron) the model assumes that the zone below the silicate mantle is similar to that of iron meteorites and that the seismic borders are identical with the borders of material types. According to the conceptions, the upper mantle (the *SIMA* zone) is the zone corresponding to the stone meteorites. No essential changes are presumed in the composition of the upper mantle with the increase of depth; rather some polymorphous transformations and the formation of crystal forms of higher density are thought to be likely. According to GOLDSCHMIDT an eclogite zone is located in the lower part of the upper mantle whereas the lower mantle below this zone is a zone of oxides-sulphides poor in silicates wherein the oxides of heavy metals are enriched. Some authors divide this zone into two parts: an upper "*chrofesima*" layer richer in chromium compounds and a lower "*nifesima*" layer enriched in nickel compounds, assuming also that with the increase of depth metallic iron similarly appears in increasingly greater amounts.

If we make an analogy with the material composition of meteorites, then the percentage composition according to elements present in the lower mantle can be given. This is however actually the percentage composition of the meteorite groups by means of which the material of the lower mantle has been identified. According to POLANSKI [27] this percentage distribution is as follows:

O	36.2 %	Al	1.00 %
Fe	23.6 %	Na	0.66 %
Si	18.0 %	Cr	0.37 %
Mg	13.8 %	Mn	0.22 %
S	2.1 %	K	0.17 %
Ni	1.9 %	Ti	0.14 %
Ca	1.5 %	Co	0.10%
all other elements:		0.24%	

According to the geochemical-meteorite Earth model the material composition of the Earth's core can be considered identical with that of the iron meteorites whose percentage composition is also, according to POLANSKI [27] as follows:

Fe	90.50 %	C	0.04 %
Ni	8.50 %	S	0.04 %
Co	0.57 %	As	0.04 %
P	0.18 %	Cr	0.03 %
Ge	0.05 %		
all other elements:		0.05%.	

According to these data, the Earth's core consists of 99% iron plus nickel. Hence, at one time this zone was known as the *NIFE* zone.

At present, hardly any point of this geochemical-meteorite Earth model is acceptable because of the undermentioned considerations.

Even the basic assumption is disputable that suggests that the meteorites are remnants of an exploded planet whose construction before its explosion was precisely the same as the present material construction of the Earth. Even so, if we accept this assumption, we cannot give any satisfying explanation as to why the ratio of stone and iron meteorites found is not the same as for Earth with its ratio of materials present in the mantle and the core. In other words, the question emerges whether the identification of the Earth's core with the iron meteorites can be regarded at all as a proper one.

Similarly, another difficulty in connection with the discussed model is the explanation of the sharp border of the Earth's core. Based on our present knowledge no differentiation can be imagined at which the material differences would appear as sharply as assumed. The prerequisite of any such differentiation would be the appearance of significant changes in the physical parameters affecting it. Nevertheless, according to Figs 11, 12 and 14 no sudden changes occur at this depth in the values of gravity, pressure, or temperature.

Whatever the way of the assumed origin of the Earth, the initial state was very likely a nearly homogeneous, uniform state. If the Earth were originated at a high temperature, the convectional flows induced by the thermal effects would have counteracted any type of differentiation. If, in turn, it is assumed that the Earth was originated in a cold state, no material differentiation could have occurred because of the extremely high viscosity.

Differentiation from the homogeneous state cannot be imagined due to the decrease of gravitational force with depth.

The greatest defect of the model is that no explanation can be given for the liquid-like behaviour of the outer core. The fact that the velocity of the transversal waves falls to zero in the outer part of the Earth's core can by no means be explained by the above-mentioned material differences between the mantle and the core. Similarly, in the case of the geochemical-meteorite model an unsolvable problem is that the material composition does not change within the *NIFE* core and still shearing stresses occur again in the inner core since here the transversal earthquake waves propagate again.

Owing to the aforementioned causes, the geochemical-meteorite Earth model is unsuitable as a means of explaining the inner structure and the material composition of the Earth.

3.3.2. The Kuhn-Rittmann Earth model

In the development of their theory KUHN [28], KUHN and RITTMANN [29] started from the statement of certain theories of formation according to which the Earth originated from the Sun. Therefore, they investigated first how the "Sun-like" homogeneous material of high temperature whose external surface is exposed to a strong cooling will be transformed to material of zonal structure, how it will be differentiated according to material types. If the material of the Earth had been identical with that of the Sun, then owing to the low gravitational acceleration compared with that of the Sun the most part of the light elements "evaporated", i.e. they were scattered in Space at the beginning. Owing partly to this "evaporation" of the light elements and partly to the loss of heat energy by radiation the upper layers cooled down gradually. The density of these external layers gradually increased partly due to their cooling and partly by the loss of elements of lower weight, thus they sank to greater depths. Since they have been replaced by masses richer in lighter elements emerging from greater depths, a circulation developed in the top layers. Because of this circulation, the top layers of the Earth soon showed an essential deviation from the material of deeper parts, which are considered homogeneous. When the temperature at the outermost zones decreased to such a degree that materials of higher boiling point became liquid, further differentiation took place. The gaseous lighter elements approached the surface mainly as gas bubbles then entered the atmosphere mostly through the surface and they have been partly scattered. In this way the materials located near the crust were separated during the gas development from the melts in that magma - which is considered according to the vulcanologists to be even today full with gases - was segregated. According to KUHN and RITTMANN's opinion in the deeper parts no possibility existed for gas evolution to such an extent and thus in the inside of the Earth even at present the original Sun-like material can be found. According to this conception, the density of masses changes continuously from the surface to the Earth's centre. It was shown by KUHN and RITTMANN that it is possible to express the density of the Earth as a continuous function of the depth in a way that the value of both the total mass and of the moment of inertia derived from observations agrees with the calculated values.

The theory explains in a rather peculiar way the absence of the transversal waves and the decrease of the velocity of longitudinal waves at the depth of the Gutenberg-Wiechert surface. According to the theory this is not at all a real boundary but is originates only from certain changes in the elastic properties of materials. The investigations of Maxwell served as a theoretical basis of the conceptions of KUHN and RITTMANN. Namely, according to Maxwell the viscosity of the materials is proportional to the shear modulus μ and to the relaxation period τ characteristic of the given material (the relaxation period being the time required to reduce the stress pertaining to the deformation to the e-th part of the original value due to the rearrangement of the molecules, where e is the base number of the natural logarithm):

$$\eta = \mu\tau$$

It is known from relations (1) and (2) that the velocity of seismic waves is also a function of the shear modulus μ. Earthquake waves induce, during their propagation, changes of volume and shape in bodies of solid nature. The stress formed at the shape change - by terminating the shape change - ensures at the same time the propagation of the elastic energy. However, owing to the relaxation a part of the elastic energy is transformed into molecular energy. Until the period of the earthquake wave, i.e. the time of one vibration is shorter than the relaxation period, the major part of the elastic energy is propagated as an elastic wave. If, however, the vibration period is longer than the relaxation period, the stress due to the deforming effect of the earthquake wave is suspended or at least significantly reduced during one period of the arriving vibration with the rearrangement of the molecules, i.e. the energy is "absorbed", converted into molecular energy, and is not propagated. If we are in a medium wherein the relaxation period decreases with depth, then the value of μ must be considered equal to zero at the point where the vibration period of the earthquake waves exceeds the relaxation period. Below this depth, no transversal waves can be observed and a sudden velocity decrease must occur in the longitudinal waves. According to KUHN AND RITTMANN at a depth of 2200 and 2400 km, viscosity and shear modulus attain on the effect of pressure and temperature such a value that the relaxation period will be identical with the order of magnitude of the period of earthquake waves. Therefore, the velocity of the longitudinal waves decreases whereas the transversal waves are completely absorbed. If it is assumed that under conditions corresponding to a depth of 2900-5000 km the relaxation period has a minimum as shown in Fig. 17 and then again increases below 5000 km depth on the effect of the high pressure, the phenomenon can also be explained by saying that the transversal waves are again passing through the inner core of the Earth. Thus according to the theory, the discontinuity of first order present at a depth of 2900 km indicates only that the relaxation period of the material of which the Earth consists and which can be considered otherwise as homogeneous decreases below the period time of the earthquake waves.

Thus, on summarizing what has been said, the outermost part of the Earth is, according to the KUHN-RITTMANN conception, a crystalline, rigid mass, which from the aspect of its construction corresponds to the upper part of the *SIAL* and *SIMA* zones. This crystalline, rigid part is estimated to be a zone of 70-80 km thickness. Below this, a still differentiated molten alkali basalt zone of non-crystalline structure has been assumed which zone is becoming more and more enriched in olivine with increasing depth. The differentiated magma contains a dissolved gas, mainly hydrogen. The gas content comes into the foreground at about 2200 km depth and here the material may be considered as a homogeneous one. However, differentiation is quite out of question at a depth of about 2400-2500 km where the material of the Earth is represented by a "solar mass" consisting of atoms of generally low mass number and present in a primitive and mostly ionized state.

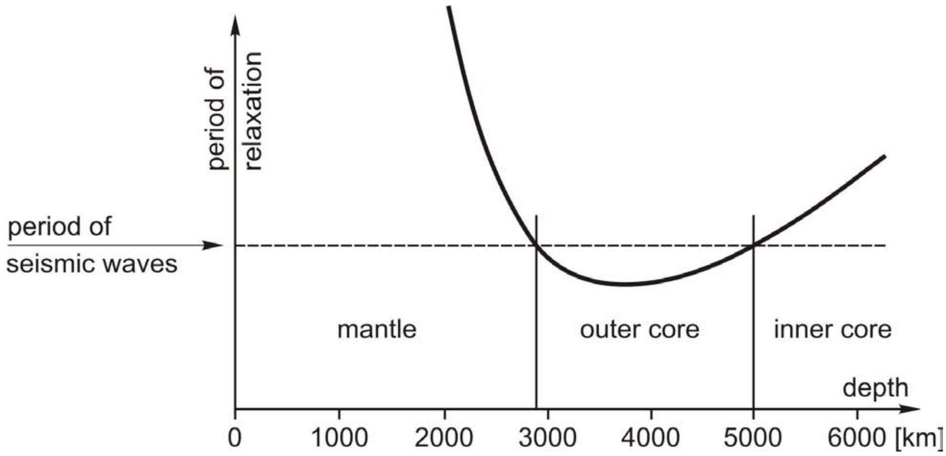

Fig. 17. The variation of the relaxation period

Even the Kuhn-Rittmann Earth model cannot be defended against some serious objections. One of the most essential defects of this theory is its unsuitability for the explanation of the reflection of seismic waves from the mantle - core boundary though these reflected waves can be detected unequivocally. Furthermore, according to the Kuhn-Rittmann Earth model no sudden density increase exists along the mantle - core boundary though the value of density can be determined even at the border of the Earth's core to an accuracy of at least 3% and according to the relevant calculations a nearly 50% increase of density is detectable.

3.3.3. The astrophysical Earth model

This conception tends to create a liarmony between all physical phenomena pertaining to the Gutenberg-Wiechert surface, i.e. it attempts to present an explanation as to why the propagation of the transversal waves is suspended at this interface, the velocity of the longitudinal waves decreases by about 40% and at the same time the density rises by nearly 50%. On adding the fact that the core temperature is several thousand degrees centigrade and that a pressure of an order of magnitude of a million atmospheres prevails, it appears that the above-mentioned physical phenomena cannot be explained by the alteration of the material composition or by a decrease in the relaxation period.

The starting point of the astrophysical Earth model is that on advancing towards the Earth's centre the differentiation becomes increasingly lower since no reasons exist for that (e.g. the gravity decreases rapidly with the depth) and the available time is also too short for the completion of the segregation of materials in the layers. The theory explains the existence of the Gutenberg-Wiechart surface and of the Lehman zone by a physical phase transition (p. 419 in [13]).

Studies of the inner structure of the stars provided physical fundamentals of the astrophysical Earth model. There exist stars (the white dwarf stars) whose density is so high ($10^9 - 10^{11}\ kg\, m^{-3}$) that the equation of state of the ideal gases is already invalid. In the inside of these stars all individual quantum states of the phase space are filled and the distribution of particles according to impulses already no longer follows the classic Boltzmann distribution. Instead, the Fermi-Dirac statistics are valid. In this case, the equation of state of the gas is independent of the temperature (degenerated state) (p. 129 in [32]). Thus, the material of these stars is not of molecular structure but of a so-called degenerated state. This degenerated state is a quantum-mechanical concept for denoting states of the physical system whose energies are equal (p. 41 in [33]). According to some theoretical investigations [34], the transition of the material into a degenerated state may take place even at a relatively low temperature when the pressure is adequately high. In order to attain the degenerated state the atoms of the material must be closely packed so that the external electrons of the various atoms interact following the Pauli principle of exclusion (p. 170 in [35]). The applicability of the above conceptions on planets has been discussed by SCHOLTE [36].

According to the astrophysical Earth model, in the Earth's mantle the atoms take up the pressure by means of their outer electrons. On the effect of high pressure, they are compelled to occupy a lattice structure and thus each atom has a definite position related to its neighbors. When the particle moves from this position on the effect of a force, e.g. of an earthquake wave, the force induced by the constrained lattice structure force them, as shearing forces, into their original position. Consequently, the transversal waves propagate throughout the whole mantle. The Gutenberg-Wiechert discontinuity is a surface of critical pressure where the material occupies a degenerated state and only Coulomb forces exist until the pressure exceeds a given value. The degenerated state is connected with a volume decrease (therefore the density increases) and this explains the absence of shearing stresses. However, on advancing towards the centre of the Earth, also, the density rises with increased pressure and the particles so closely pressed together that in order to take up the pressure they are forced into a lattice-like arrangement despite their degenerated state. The consequence of a lattice-like arrangement of this type is the appearance of shearing forces. According to the theory, the border of the inner core indicates just that this critical pressure has been attained.

Here also the Earth model of RAMSEY [30] must be mentioned which actually presumes a "milder" variety of the degenerated state (p. 420 in [13]). According to the RAMSEY conception, the dunite- or olivine-like composition of the inner Earth changes with the depth only in a way that the heavier components are enriched in the deeper layers. However, this enrichment becomes smaller with depth. The Gutenberg-Wiechert discontinuity is because the material of the inner Earth is changed on the effect of pressure from the non-metallic state (which is more stable at low pressures) into a metallic state which is in turn more stable at higher pressures. Since the change into the metallic state is connected with density increase, according to the theory an abrupt density increase should occur at the border of the Earth's core; this is quite in accordance with the observations. RAMSEY's conception is that if there is an inner core within the Earth's core present in a metallic state it indicates another phase transition in that the material of the inner core probably takes up a crystalline structure. In order to support his theory RAMSEY has considered it that for elements of lower atomic number under high pressure the transition into metallic state is attained even theoretically. In the course of laboratory experiments carried out under high pressure it vas found that whereas, for example, the yellow modification of phosphorus is a good insulator, its black modification formed from the yellow one on the effect of high pressure has an electric conductivity higher by 10^{11} orders of magnitude and a density higher by about 50%. It has been observed in general that some elements have metallic and non-metallic modifications and the metallic modification always shows an essentially higher density [31]. The Ramsey Earth model, though it is able to explain successfully several details of the data of physical observations from the aspect of atomic theory, but passes lightly over the explanation of some essential phenomena. Among others it cannot present an acceptable explanation as to why the transversal waves are absent at the border of mantle and core.

It can hardly be expected that the pressure attain the value required for the occurrence of phase transition just at the same depth as the temperature attains the melting point of the metallic modification of the olivine-like material.

As was mentioned earlier, the astrophysical Earth model is capable of answering this question as well as others concerning another degeneration of "higher degrees" of the material.

The astrophysical model appears to be the most up-to-date and the most acceptable model though the physical basis still requires further proof. With regard to investigations into the inner structure of the stars, it is known reliably that the material exists in a degenerated state. In order to attain this degenerated state a definite temperature and pressure are needed. Inside of the Earth, the prevailing temperature and pressure conditions are quite different from those in the interior of the stars. It is questionable whether, with the physical parameters prevailing in the interior of the Earth, a degenerated state similar to that in the stars could be formed. Further essential questions are, for example, whether the material in the degenerated state occurs as a liquid or is in a gaseous state (and thus shearing stresses cannot be developed); it is not cleared up whether the atoms of all elements enter the degenerated state at the same pressure (this is important because the boundary between mantle and core is a sharp boundary: and last but not least whether the material present in a degenerated state attains along the Lehman zone actually a lattice-like arrangement. A correct reply to the above and to similar other questions can be given only after carrying out some relevant laboratory experiments. However, pressures prevailing in the core at orders of magnitude of 1 million atmospheres or even more can be reproduced in laboratories now only by explosion waves. These pressures can be maintained and observed for extremely short periods whereas the conditions prevailing in the interior of the Earth have been developed over many million years. In laboratory experiments at present, even the role of temperature can hardly be established, but in the Earth's core, the temperature attains several thousands of degrees centigrade.

4. Interactions between the various zones of the Earth

The zones of the Earth discussed so far cannot be considered as completely independent units since the neighboring zones are continuous physical and material interactions with each other.

It has been mentioned that lateral temperature differences occur in the upper mantle and this is very likely due to the unequal distribution of radioactive materials. Temperature compensation may take place in two ways: partly by heat radiation and partly by means of convectional current. In the material of the not too rigid upper mantle somewhat complex systems are formed on the effect of temperature differences and these systems also carry along the Earth's crust "floating" on their surface [37]. The simplest convection model that can be imagined is shown in Fig. 18. That part of the upper mantle which acts as a solid material against the rapid seismic waves whereas against the slow continuous force effects as a very thick viscous "liquid" is denoted as the asthenosphere. The asthenosphere is a zone of a thickness of about 600-700 km located directly below the Earth's crust, and it is in the asthenosphere that these convection cells are formed.

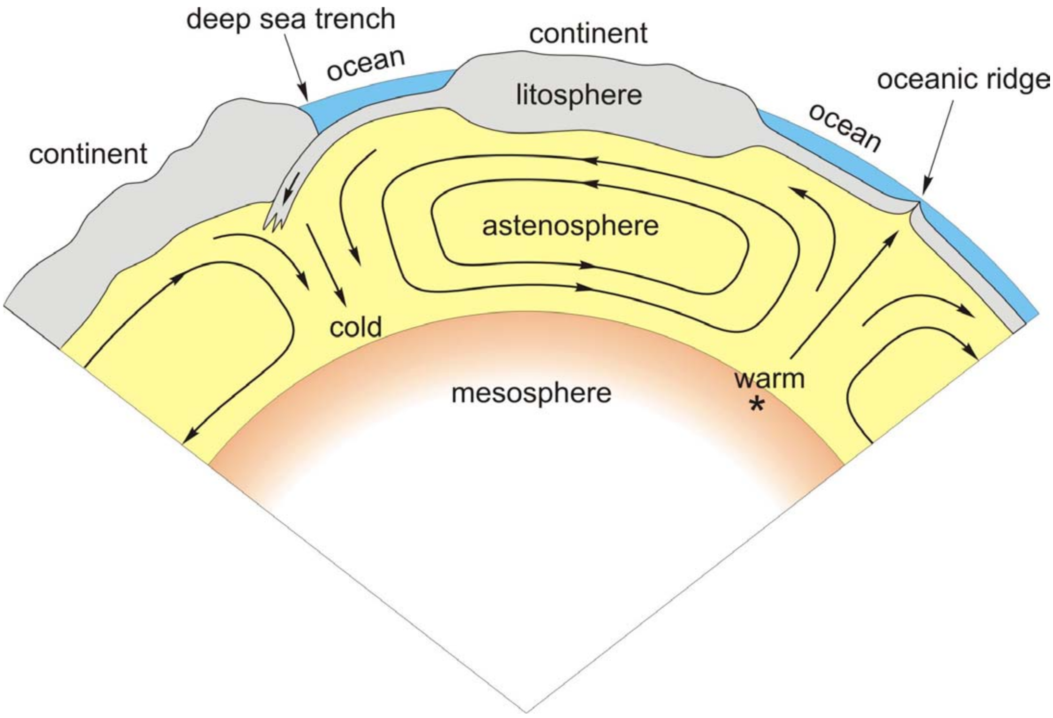

Fig. 18. Thermal convection in the upper mantle

The theory of the enormous horizontal displacements of the Earth's crust (lithosphere) being in close interaction with the asthenosphere is discussed by a theory developed in the seventies as the "most successful" theory of the geosciences this theory is plate tectonics [38]. According to the theory of plate tectonics, the surface of the Earth can be divided into six major and several smaller lithosphere plates of a thickness of about 60-200 km that may consist of both oceanic and continental areas as illustrated in Fig. 19. These plates are in continuous relative motion with respect to each other. Three types of motion are possible: the plates can slide past each other, they can move apart on opposite sides of an oceanic ridge or they can converge, in which case one of the plates must be consumed. The boundaries of the plates are particular spots of the Earth where significant tectonic activity can be experienced: here occur the earthquakes and these are the areas of mountain formation and volcanic activity. Furthermore, the plate boundaries may be considered the zones of the most intensive interactional activity between the mantle and the crust where exchange of materials takes place between the two zones. Where plates move away from each other, new rock material comes to the surface from the astenosphere (from the upper mantle) and new surface area is generated. These are the accreting plate boundaries such as the oceanic ridges, the network of trenches formed at present in East Africa, the Red Sea and perhaps the fracture system of Lake Baikal. These are special areas of the Earth where the Earth's crust is continuously created. At the boundaries of plates moving towards each other (colliding) one of the plates plunges below the other, sinking to a depth of several hundred kilometers and then it is scattered in the asthenosphere. These are the consuming plate boundaries or so-called subduction zones such as the trenches in deep seas where volcanic zones and orogenic belts are located parallel to these trenches. The third form of motion is the horizontal sliding of the two plates the so-called transform faultage. Plate tectonics can successfully explain some fundamental problems of geosciences such as the formation of mountains, the continental drift the distribution in time and space of seismic and volcanical activities, etc.

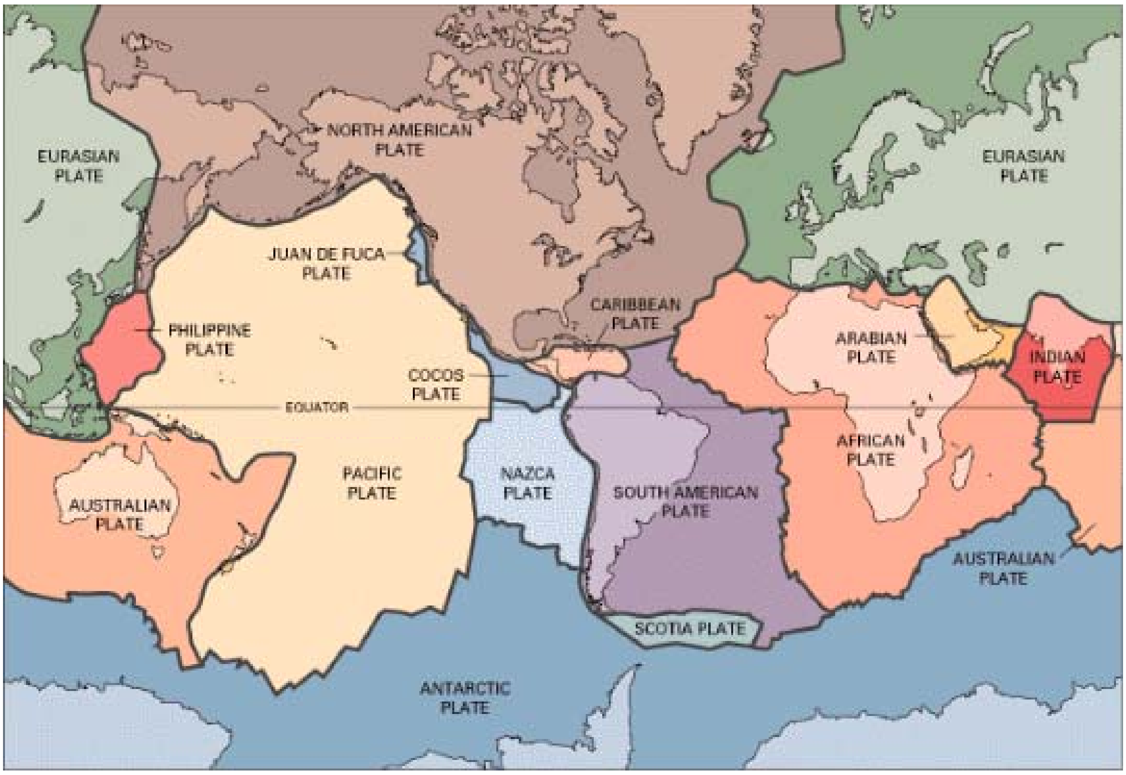

Fig. 19. Mosaic of plates forms the Earth's lithosphere. According to the theory of plate tectonics, the plates are not only rigid but also in constant relative motion. The boundaries of plates are of three types: ridge axes, where plates are diverging and new oceanic floor is generated; transform faults, where, plates slide past each other, and subduction zones, where plates converge and one plate dives under the leading edge of its neighbor.

From the aspect of the inner structure of the Earth it is of importance to mention here that according to plate tectonics the Earth's crust and a part of its upper mantle form a contiguous and together-moving layer, the lithosphere, which is called frequently as the lithospheric plate, with respect to its rigidity and to its horizontal extent which is larger by 1-3 orders of magnitude than its thickness. The zone of several hundred km thickness located below the lithosphere plates and having a low rigidity - the asthenosphere - can be more or less identified as the seismological low velocity zone: the Gutenberg channel. The residual part of the mantle which has again high rigidity and which does not participate in the tectonic processes, used to be denoted as the mesosphere.

To summarize what has been said, we can state that the accreting plate boundaries and the subductional zones are the zones of the most intensive interaction located between the Earth's crust and the mantle. Along the accreting plate boundaries, continuously new material comes to the surface from deeper parts of the mantle and at the same time, an opposite process takes place along the subduction zones where the material of the crust intrudes to very great depths and is there assimilated with the material of the Earth's mantle. According to the investigations of the so-called Benioff zones [39] the litosphere can intrude into the mantle to a depth of 700 km, as proved by the earthquakes that occur just here.

Because of the continuous exchange of materials between the Earth's crust and the mantle, the material build-up of each of these two layers cannot deviate significantly.

At present, no process between the mantle and the core is known which would be similar to the exchange of materials taking place between the crust and the mantle. However, earlier a material interaction of another character was already assumed between the lower mantle and the Earth's core. The best representative of this conception is the Hungarian scientist L. EGYED. According to EGYED's [40, 41] conception the present states in a degenerated phase of the outer and inner parts of the Earth's core were formed at the time of the origination of the Earth under pressures much higher than the present ones. The state of the material of the inner core corresponds to the first phase of ultra-high pressure whereas the material of the outer core to the second phase of ultra-high pressure. The material of the mantle is in the third (stable) phase. When the modifications of the phase of ultra-high pressure are exposed later to a lower pressure, its state turns unstable even in the case when the ultrahigh pressure resulted in some change in the atoms (eventually also in the atomic nuclei). The transition into the new, stable state does not occur suddenly and quickly, it is rather a process of statistical character resembling radioactive decay. A continuous and irreversible transition takes place from the material in the first phase of the inner core into the material in the second phase of the outer core and, respectively, from the material in the second phase of the outer core into the stable material in the third phase of the mantle. This means an interaction (exchange of materials) unidirectional in a certain sense between the inner zones of the Earth: the continuous unidirectional phase transformation continuously increases the mass of the mantle at the cost of the mass of the Earth's core. Since the density of the inner core is higher than that of the outer core and the density of the outer core significantly exceeds the density of the mantle, the phase transformations result in a steady decrease of the average density of the Earth. However, the total mass of the Earth can be considered as constant and thus the assumption of the phase transformations leads to the surprising conclusion that the volume of the Earth is continuously increasing, i.e. that the Earth is "expanding". The model of an expanding Earth is quite in accordance with several geological and geophysical observations. Furthermore, it is suitable for solving a number of geological problems. Even so, it should be said that it is a less accepted theory since on one hand, its physical fundamentals are not proved and on the other hand, it contradicts a number of novel observations [42].

5. The origin of the Earth

The problem of the origin of the Earth is in essence identical with that of the origin of the solar system. The great number of relevant theories indicates that on one hand scientists have long been dealing with this problem and on the other hand, that the problem is still unsolved. With our present incomplete knowledge, a number of ways are imaginable which could have resulted in the origin of the present solar system. However, a theory of origin can be correct only if it does not contradict the most important properties of the solar system:

- even though the mass of the central celestial body, the Sun, is 750 times larger than the total mass of all the other celestial bodies of the solar system, the total moment of momentum of the planets is still nearly 200 times larger than that of the Sun,

- the solar system consists of 8 large planets which revolve around the Sun on nearly the same orbital plane and in the same direction (some scientists suggest that the 9th planet, Pluto, can be considered as an escaped planet (p. 178 in [32]),

- the Jupiter-type planets have a 100 times larger mass than the Earth-type planets,

- the chemical composition of the Jupiter-type planets is similar to the chemical composition of the interstellar material whereas in the material of the Earth-type planets the amount of hydrogen and of helium is smaller.

The several dozens of theories concerning the cosmogony of the planets can be divided into two classes (p. 179 in [32]):

Class 1: The origin of planets is independent of the formation of the Sun. The planets were originated when the Sun was already a normal star. This Class can be divided into two subclasses:

Subclass 1/a. Catastrophe theories: the material from which the planets were originated was torn off the Sun or another star, due to an external effect.

Subclass l/b. Captation theories: the material of the planets was captured by the Sun from interstellar space.

Class 2: (nebular theories): the same process created the planet system and the Sun at the same time or immediately after each other.

5.1. Theories of the catastrophe type

According to the catastrophe theories, another star passing by the Sun induced the segregation of the planets from the Sun.

BRUFFON in 1880 assumed that the Sun collided with a star and the planets developed from the material scattered at the time of this collision. Later T. CHAMBERLIN and F. R. MOULTON pointed out that it is not completely necessary to assume a collision, viz. if a star passed then sufficiently near the Sun then owing to the tidal force material could have been drawn from the Sun or the star into the space around the Sun. The planets were subsequently formed from this material, which could originally have been a gaseous substance on the effect of various thickening processes. The planets revolve around the Sun on a common orbital plane and in the same direction determined by the direction of movement of the star, which caused the catastrophe.

This conception was further developed by JEANS who proved that the gas emitted from the Sun remained gaseous until the origin of the planets and had a "cigar-like" shape. The big planets developed from the material of the widest part of this "cigar". Thus, J. JEANS could explain the distribution of planets according to their size in the solar system.

Besides the above-mentioned theories several other variants of the theories of catastrophe type were developed.

Theories of the catastrophe type can be refuted from several aspects. One of the aspects is because the present very great moments of momentum of the planets cannot be explained by these theories. Another aspects is that the stars are, on average, extremely far from each other and thus two stars are likely to approach each other only extremely rarely to an extent required for the origin of the planets. Consequently, the planet system would be the result of a random and rare process and thus it may be a unique or at least extremely rare phenomenon in the galaxy. However, this contradicts the observations, and thus all variants of the catastrophe theories must be discarded.

5.2. Captation theories

The group of captation theories consists of conceptions according to which the material of the planets was captured by the Sun from interstellar space. These theories consider the solar system not as an isolated phenomenon but they take into account in explaining its origin the construction of the galaxy - a part of which is actually also the solar system. On taking into account interstellar material it is possible to explain the very great moments of momentum of the planets since the stars, which are moving to each other and the gas and dust clouds, disclose immense moments of momentum in relation to each other.

The best-known representative of the captation theories is that of O. J. SMIDT [43]. The fundamental aspect of the theory of SMIDT et al. is that on passing through a galactic gas and dust-fog the Sun captured a part of this fog. At the beginning, these captured parts revolved around the Sun in separate orbits then the planets were originated by the combination of a great number of such particles. Based on this assumption the approximately circular orbit of the planets is understandable, because the particles circulated prior to their fusion along elliptical orbits of various shape and size but after their adherence average orbits of approximately circular form developed. From considerations based on symmetry it follows that the orbits of the planets are approximately on the same plane, the so-called Laplace-type invariable plane perpendicular to the vector to the moment of momentum, and that the direction of their circulation is the same. The structural difference between the planets of Earth-type and those of Jupiter-type is explained by this conception by assuming that a part of the particles were scattered in Space by the significant radiation pressure acting in the vicinity of the Sun whereas the light gas molecules frozen originally onto the solid dust particles evaporated on the effect of the Sun's radiation. These processes did not take place at distances farther from the Sun on the contrary rather more and more gas was frozen onto the solid particles. Thus, the nearer vicinity of the Sun became relatively poor in light elements whereas a significant portion of the material of planets farther from the Sun consist s of light elements.

One of the important conclusions drawn from the Smidt theory is that the temperature of the planets was very low at the beginning and that they were heated only later due to the decay of the radioactive elements present in them. Under the effect of the formed heat the inner material of the Earth did not melt, it only became plastic. Thus, the materials of higher density sank gradually towards the Earth's centre whereas the lighter materials approached the surface. According to Smidt this gravitational differentiation is not complete even today, and it is just this that causes mountain formations and earthquakes. (Although the theory of an originally cold Earth is inconsistent with the geosciences, but it may serve as a good example to show how the conceptions concerning the processes and states in the interior of the Earth are affected by the changes of the cosmogonic considerations.)

Notwithstanding the proof by Smidt et al, that in some exceptional cases captation (i.e. the capture of dust- and gas-clouds) is theoretically possible but its occurrence is to be expected only with an extremely low probability. Since it cannot be assumed that the great number of planet systems in the galaxy were created by a rather unlikely process, Smidt's cosmogonic theory cannot be considered as a final solution of the problem of origin of the solar system despite the fact that it can explain many of the solar system's properties.

5.3. Nebular theories

The nebular theories have it that the Sun and the planets were all formed from the same material by the same process. In addition, the historically first cosmogonic conceptions belong, among others, to this type.

I. KANT in his work entitled “The general natural history and theory of the sky” published the first really scientific theory concerning the cosmogony of planets in 1755. Kant assumed that the Sun and the planets were formed from some primary matter in a chaotic state, the so-called "primary fog" consisting of different sized meteoritic bodies and dust particles. These particles moved at random, those of lower density collected around the particles of higher density by the attractive force of the latter. This thickening process meant that most of the particles concentrated in the centre from which the Sun was formed. The other particles began to circulate around the Sun and were condensed into planets on the effect of collisions.

The above theory contradicts the laws of physics. Namely, the planets ought to have their moments of momentum at the beginning of the origin of the solar system whereas according to Kant the particles of the "primary fog" moved completely randomly, which means that the moment of momentum of the fog should have been zero at the beginning, or at least nearly zero. Accordingly, the theory was incorrect in assuming that the interaction of irregularly moving particles may lead to a circulating and rotating movement.

P. S. LAPLACE published the first theory of planet cosmogony attempting to eliminate the difficulties in connection with the theorem of the conservation of the moment of momentum in 1796. Laplace’s theory was that at one time a gaseous fog of very high temperature and of very great volume, rotating around an axis (i.e. having from the beginning a moment of momentum) was present at the site of the solar system. This rotating gaseous fog can also be considered as the "primary Sun". The at first extremely hot gaseous fog began to cool and thus to shrink. Since during the shrinkage the moment of momentum ought to have remained unchanged, the velocity of rotation should have been increased. This, however, would have resulted in an increase of the centrifugal force under which effect the gas ball obtained a more and more oblate shape. During the increase in speed of rotation, a point was reached when the centrifugal force acting on the particles along the equator just exceeded the gravitational attractive force. Consequently, an "outflow of matter" started along the equator, i.e. certain parts were split off the rotating gaseous fog in the form of a ring on a plane perpendicular to the axis. The separated ring formed in this way was then split to pieces, its matter condensed spherical into a body of approximately spherical form and continued its circulation around the central part at a distance equal to the radius of the ring at the time of its very formation. The orbit of the planet formed in this way indicates the borders of the original volume of the rotating gaseous fog (the "primary Sun"). This phenomenon was repeated several times until all the planets were originated. The satellites were originated from the planets in the same way as the planets from the "primary Sun".

According to Laplace's theory the material of the Earth separated from the Sun as a gas in a glowing state. The solid crust was formed only later during the cooling. In the course of its further cooling, the crust became folded, forming in this way the mountains. Volcanism points to the fact that the gradual cooling of the Earth began in its external part and even so did not attain its interior.

The concept of Laplace was a generally accepted theory until the end of the 19th century. However, at this time insurmountable difficulties arose in connection of the maintenance of the theory. Namely, satellites rotating in a retrograde way, opposite to the direction of rotation of the axis of the planet were discovered in the planetary system. A similarly unsolvable problem was the explanation why the planets belong to two entirely different types (the first type consists of Earth-type (inner) planets of relatively small mass, high density and low velocity of rotation whereas the second type includes Jupiter-type (external) planets of vast mass, low density and high velocity of rotation). At the same time J. C. MAXWELL, the British physicist, proved by calculations that the material of the rings separated from the rotating gaseous fog cannot be condensed to planets according to the laws of physics because the ring-shaped mass is kinetically more stable than the matter condensed to a spherical body. Besides that, the Laplace theory is unable to solve a problem connected with the distribution of the moments of momentum. Namely, according to his theory 99.8% of the total mass of the present solar system falls to the Sun whereas 98% of the total moment of momentum of the system falls to the planets. On imagining the origin of the solar system on the basis of the Laplace theory we must assume that the gaseous fog from which the Sun and the planets were originated extended at least to the orbit of the outermost planet and the system rotated at a velocity such that the velocity of its outermost parts along its equator was the same as the velocity of the outermost planet according to Kepler's third law. If any density distribution within the gaseous sphere is assumed, under the mentioned conditions a very great value is obtained for the moment of momentum of the gaseous fog, and from that only a minimal value may fall to the planets. Since not more than 2% of the total moment of momentum of the solar system falls to the Sun, the Laplace conception cannot be maintained. V. G. FESENKOV attempted to eliminate the difficulties concerning the distribution of the moment of momentum by taking into account the corpuscular radiation of the stars. A characteristic feature of the development of stars is that in the initial period of their development, the emanation of particles (electrons, protons, etc.) is very intensive and thus the stars undergo an essential loss of mass during a relatively short time. According to the calculations of Fesenkov the mass of the Sun immediately after the formation of the solar system was about ten times as great as its present mass. At the beginning the Sun lost considerable amounts of its mass but later this happened to a much smaller extent. On taking into account the loss of mass of the Sun the difficulties concerning the moments of momentum are eliminated because the mass lost during the many millions of years took away a significant part of the moments of momentum.

However, according to the conceptions concerning the development of stars, the stars of relatively small mass (to which the Sun belongs) did not possess at the beginning of their development such an intensive corpuscular radiation as that presumed by Fesenkov. The relevant calculations of Fesenkov already appear obsolete ones though even the theories concerning the development of stars accepted at present can be considered open to dispute.

In the cosmogony of planets the scientists returned recently again to the nebular theories. In the Laplace theory, the conceptions were based on the theorems of mechanics and thermology whereas in the second third of our century it became quite apparent that on explaining the origin of the solar system we must not neglect the electric and magnetic properties of matter. H. ALFVEN was the first in pointing out that the contradictions of the Laplace theory, which appeared originally to be insurmountable, can be solved by applying the methods of plasma physics.

According to Alfven's conception, on the basis of the laws of magneto-hydrodynamics, if the conductivity of a high-temperature ionized gas is infinite (which is not unrealistic in the case of the flattened hot gaseous sphere suggested by Laplace, the lines of force of the magnetic field all follow the movement of the ionized gas (the lines of force of the magnetic field are "frozen" in the material). Since the external ranges of the cloud from which ranges the planets were originated are lagging behind in relation to the inner ranges rotating much quicker according to Kepler's third law the magnetic lines of force are "rolled up" around the inner material. Then, according to the laws of magneto hydrodynamics, magnetic forces are developed on the effect of which the rotation of the interior parts will be slower and that of the outer parts quicker. Consequently, the Alfven mechanism is capable of transferring the moment of momentum of the interior parts to the outer parts and of explaining in this way the irregular distribution of the moments of momentum of the solar system.

Quite recently the Alfven conception was further developed by F. HOYLE the astronomer taking into account the newest result of physics and astronomy. Hoyle's theory is that the solar system was originated by the condensation of interstellar dust and gas cloud which cloud was a priori rotating due to the conditions of motion (the so-called differential rotation) of the galaxy. The contracting gas cloud rotated quicker and quicker in order to maintain its moment of momentum. According to the detailed calculations of Hoyle, when the cloud had already shrunk to a diameter of about 60 million km, i.e. to about the length of the radius of the orbit of Mercury, its rotation became so rapid that along its equator (similarly to the conception of Laplace) the continuous emission of material began. At the beginning of this throwing out of material due to the extensive shrinkage the gas cloud became heated up to about 1300 °C (in essence the gravitational energy of the particles related to the centre of the gas cloud was converted into heat energy). Gas at about 1300 °C is already in a plasma state because the gas atoms are ionized by the violent collisions of the particles of the gas cloud. The above-described conceptions developed by Alfven are valid to this plasma. Besides these, Hoyle synthesized in his theory all the positive results present in earlier conceptions. At present, Hoyle's cosmogony of the planets appears to be the most-up-to date and the most acceptable one.

6. Conclusions

Our task was the investigation of the inner structure and material buildup of the Earth. Initially a short survey was given of the geophysical methods suitable for obtaining information on the inner structure of the Earth. We then attempted to draw some conclusions concerning the inner structure of the Earth partly by utilizing geophysical information and partly by means of the best-known theoretical considerations. In the following a short summary is given of the most essential results and then in the sense of what has been said above, we will attempt to present some conclusions and remarks concerning the most important problems.

Based on seismological investigations the geometrical structure of the Earth's interior and the depths of the zones separated from each other by discontinuities of first and second order axe known fairly accurately. In first approximation, the material can be considered homogeneous within the individual zones. However, according to investigations that are more precise this homogeneity is not complete, mainly in the outer zones. The structure of the crust is, for example, quite different the continental areas from that below the oceanic areas. Moreover, similar differences can be observed also in the upper mantle. Similarly, based on seismological investigations the velocity of seismic waves is known quite accurately as a function of the depth below the surface, and from these data the density vs. depth function can be determined with sufficient reliability just as the dependence on depth of some other parameters of the material. The statements that the value of density abruptly increases along the border between the mantle and the core, and that the outer core is in a liquid-like state whereas the inner core is again in a solid-state are of decisive importance. These are facts with which any conceptions explaining the inner structure and build-up of the Earth must be strictly in accordance.

Though the material build-up of the outermost parts of the Earth are relatively well known mainly by virtue of direct observations, the build-up of the interior parts can be determined only in a speculative way. However, according to our conceptions the material composition of the inner parts cannot differ significantly from that of the outer zones. In order to support this statement we ought to consider it that the most frequent elements, in particular H, He, O, Si, Mg, Al, C, N and Fe are the same not only in the solar system but also in the galaxy. The most up-to-date theories of planet cosmogony explain rightly the phenomenon of the planets of Earth-type losing a significant part of light elements (in the first place hydrogen and helium). If we leave out both of these light elements in our count, then the distribution of the residual elements - according to the data of investigations of the Earth's surface - is roughly identical with the material composition of the space around us. On taking into account the conception which is mostly accepted in the cosmogony of planets, namely that both the Sun and the planets were formed from the same interstellar material by the same process, it is not likely that the material composition in the deeper parts of the Earth could be completely other than that at the surface of the Earth. There is further essential evidence proving that no essential changes can occur in the material composition to a depth of at least 700-800 km below the surface since according to the theory of plate tectonics a significant part of the upper mantle (the asthenosphere) is in material interaction with the Earth's crust. For that part, it can only be proved petrographically that the rocks become more and more basic with increasing depth. As regards the conditions at still greater depths, no information is available. However, it must be taken into account that at greater depths the effect of the prevailing conditions of pressure and temperature on the behaviour of matter is not known accurately up to the present. There is reasonable ground for assuming that at greater depths physical phase change may occur. Because of this, it is more reasonable to assume a physical phase change between the mantle and the core, further between the outer and inner core than starting from material differentiation, which is conflicting and unexplainable. A reliable and final solution of the problems can be expected only from the results of further theoretical researches and laboratory experiments.

The behaviour of elements significantly heavier than hydrogen at higher pressures and temperatures can be calculated based on the Thomas-Fermi atomic model, which gives at low pressures results, which do not agree with experiment. For this reason, interpolation is usually carried out between the experimentally available range and the range of very high pressures in which latter the Thomas-Fermi model is certainly valid [44]. The pressure in the interior of the Earth still does not attain this latter range. Practically insuperable difficulties are faced on attempting to carry out the theoretical calculations of rocks consisting occasionally of very complex molecules. It is regrettable that for the time being this problem cannot be approached even by the laboratory investigation of rocks since the highest static pressure attainable at present is of an order of magnitude of 100000 atmospheres. (Static pressure means that in the course of compression there is sufficient time to attain a stationary state.) However, it is possible to produce pressures of 4-5 million atmospheres by an explosive technique this pressure could be maintained only for periods shorter than a millionth of a second. Thus, these measurements tend to be of interest only from a technical aspect and are not suitable for investigating materials under extremely high pressures. Despite this fact the great number of various phase transformations observed frequently even at small pressures in laboratory experiments must not be neglected when investigating the inner structure of the Earth. The existence of high-pressure phases must be taken into account necessarily on the one hand owing to the ionization due to pressure and on the other hand because with the increase of the pressure the terms of the various atoms or molecules and, respectively, the bands of the solid bodies may be shifted in the function of compression and they may cross each other which all mean obviously phase transformations. The order of magnitude of the greatest density changes measured at phase transformations observed thus far in laboratories is of the order of $100\, kg/m^3$ [44]. It is quite reasonable to assume that with pressures of a million atmospheres changes that are even more drastic may occur in the electron structure and these changes may eventually explain the mentioned density jump at about $4000\, kg/m^3$ which occurs at the boundary of the mantle and the core.

In our opinion, besides the conceptions developed thus far, also the study of the geomagnetic field may play an important role in the researches concerning the inner structure of the Earth. Nearly 94% of the dipole field of the Earth originates from causes inside the Earth. Geophysicists have investigated the origin of the dipole field for very many decades. The relevant theories are all closely connected with the inner structure of the Earth. Of the various theories, it is worth here to mention the so-called ferromagnetic theory (p. 36 in [45]) which based on the geochemical - meteorite Earth model starts from the assumption that the Earth's core contains 90% iron. According to this conception, the magnetic nature of this iron mass is the cause of the existence of the geomagnetic field. However, it is known that the ferromagnetic materials lose their ferromagnetic property and become paramagnetic at a specific temperature (the so-called Curie point). (The Curie point of iron is 780 °C.) Since the temperature of the Earth's core is certainly some thousands of degrees centigrade, the origin of the geomagnetic field cannot be explained by ferromagnetic theory. It might be suggested however that the high pressure compensates the effect of increasing temperature, i.e. the Curie point is higher in the deeper parts of the Earth. This has been experimentally refuted because it was found that no changes of the Curie point are detectable even on the effect of pressures of some hundreds of thousands atmospheres. Otherwise the ferromagnetic theory cannot explain the origin of the magnetism of the iron mass of the Earth and cannot state the cause why the geomagnetic poles are exchanged at periods of about 500000 years. Similarly, the origin of the geomagnetic field cannot be explained by the electric charge of the Earth or by the so-called telluric currents under the surface. However, it appeared recently that the existence of the geomagnetic field could be explained by the so-called dynamo theory (p. 108 in [46]). The dynamo theory itself will not be presented here, only some conclusions drawn from it concerning the inner structure of the Earth will be discussed. As a first step, the dynamo theory assumes that the solid inner core is coupled mechanically to the similarly solid mantle only loosely, with the mediation of the outer core in a liquid state. Thus it may be assumed that the angular velocity of the inner core slightly differs (e.g. it is lower) from the angular velocity of the mantle (p. 105 in [47]). (This appears otherwise to be likely, due to the various changes of the geomagnetic field.) The angular velocity of the liquid outer core of extremely high conductivity and present in a "plasma-like" state varies accordingly on advancing from outside to the centre. However, in this case the magnetic lines of force of the dipole field of the Earth are rolled up according to the laws of magneto hydrodynamics in the outer care to two toroidal systems of lines of force much stronger than the dipole field (Fig. 20); the directions of rolling of these two systems are opposite each other. This toroidal space is limited only to the Earth's core and it is indispensable for the "reproduction" of the external dipole field. In order to clear up the processes of this self-supporting dynamo operating in the interior of the Earth, if it is assumed that there are rotations at various angular velocities in the outer core, then further flows of material are sought which would be capable of maintaining the dipole field. According to the view of the dynamo theory, it is conceivable that the flows in the liquid outer core are maintained by the temperature difference between the inner core and the mantle, by means of the density change of the material due to thermal expansion. The energy required to maintain this temperature difference might originate from radioactive decay. The dynamo theory is still quite new and is not yet quite developed. However, it appears to be the sole conception capable of describing the origin of the magnetic field of the Earth in accordance with experience; if it can do this then it will enable science to advance considerably towards an understanding of the inner structure of the Earth.

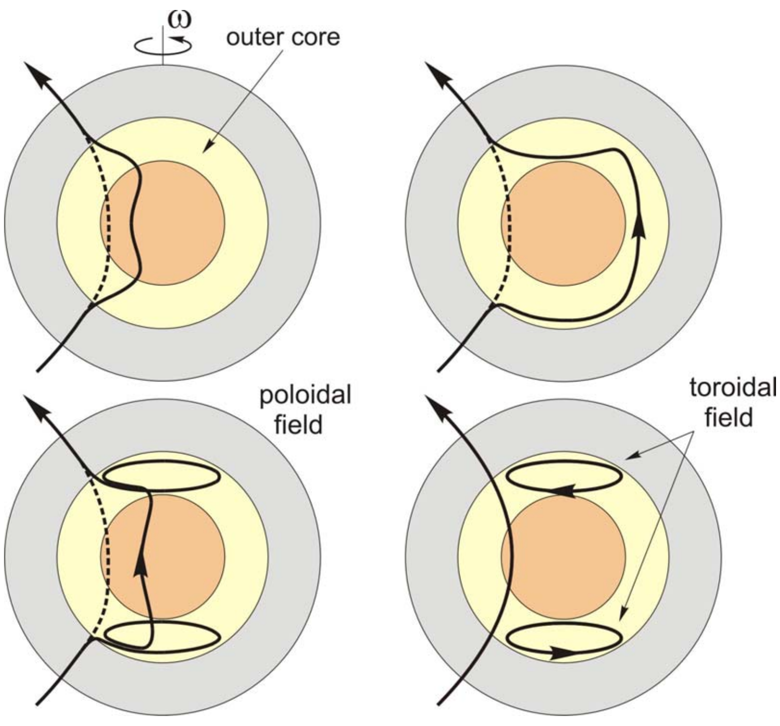

Fig. 20. Twisting of the magnetic field lines

A short discussion is still necessary of the reasons of material currents detectable in the interior of the Earth. According to the various conceptions, these are due to inhomogeneities of temperature in the interior of the Earth. Most of the conceptions assume that temperature differences are due to the inhomogeneous distribution of the radioactive elements. It is known that of the radioactive substances those which are β^- active emit a radiation of antineutrinos ($\tilde{\nu}$) [48]. The free path length of the antineutrinos is at least $10^{15}\,km$. Thus, an antineutrino formed anywhere in the Earth can attain the surface without any hindrance. From the aspect of geophysics, it would be very significant if it were possible to determine by the direct measurement of the antineutrino radiation the amount of radioactive substances in the interior of the Earth (and their actual distribution by volume). It is regrettable that on investigating the detectability of the antineutrino radiation we obtain a rather unfavorable result.

In the present study, some already solved and still unsolved problems concerning the research of the inner structure and material build-up of the Earth were discussed. It is apparent that the number of unsolved problems essentially exceeds that of already solved problems. Still we have confidence in the future with particular regard to the rapid development of physics and space research on the one hand, and to that of geophysics on the other. Much can be expected in the near future from the more detailed recognition of other planets of the solar system and of the newest achievements of up-to-date physics.

Summary

The authors based on systematic processing and evaluation of the traditional and newer theories and conceptions describe the inner structure of the Earth.

The main chapters of the work are as follows: Introduction, 1. The zonal structure of the Earth based on earthquake waves; 2. Physical parameters in the Earth of zonal structure; 2.1. Density and elasticity; 2.2. Gravitational acceleration; 2.3. Pressure in the inside of the Earth; 2.4. Temperature distribution in the inside of the Earth; 3. Inner structure of the Earth; 3.1. Structure of the Earth crust; 3.2. Structure of the Earth's mantle; 3.3. Construction of the inner parts of the Earth by use some Earth models; 3.3.1. The geocliemical-meteorite Earth modell; 3.3.2. The Kuhn-Rittmann Earth model; 3.3.3. The astrophysical Earth model; 4. Interactions between the various zones of the Earth; 5. The origin of the Earth; 5.1. Theories of the catastrophe type; 5.2. Captation theories; 5.3. Nebular theories; 6. Conclusions.

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