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Ocean. History of water and the Earth's crust

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Views on the origin and evolution of water (the amount and mode of incorporation into crustal and mantle rocks) on Earth are quite diverse. To substantiate them, arguments from various sections of geography, geology, geochemistry, cosmochemistry, and cosmogony are used. A comprehensive analysis allows us to fairly confidently assume that the appearance of water is associated with the final stage of the formation of the planet, which began after the accumulation of 60—90 % of its volume. This period coincided with the entry of water-bearing carbonatites,among other chondrites,into the accretion zone. Having estimated their contribution to the formation of water from different sources, we can compare it with the geological and geophysical data on the Earth's early history. For this purpose, the author's idea of the global asthenosphereas a relic of an ancient magmatic ocean, was used. The framework made it possible to estimate the volume of matter from which the emergence of a magma ocean made it possible to extract water. The synthesis of these independent results allows us to state quite confidently that water to fill the ocean was available (in one form or another) throughout the entire studied geological history of the planet.

The problem of the ocean itself (a deep-water reservoir with a crust different from the crust of the continents — less powerful and more basic) is considered mainly using the well-known results of B.A. Bluman and E.M. Rudich on the oceans and M.I. Budyko and co-authors on the continents. Their conclusions agree with the schemes of deep processes in the ocean tectonosphere considered by the author. These processes are controlled by a series of geological phenomena and anomalies in geophysical fields.The processes are reduced to heat and mass transfer in the eugeosyncline superimposed on the anomalously basic continental crust and subsequent activation.Thus, a fairly definite picture of the formation of the modern ocean due to the previous development of the Earth's tectonosphere in the Mesozoic-Cenozoic is emerging.

Key words: ocean, water on the Earth, oceanization of the continental crust.

Introduction. The origin and development of the oceans is one of the basic questions of geology. The answer can be approached, in particular, by studying the water that fills it. The ideas found in the literature about the origin of ocean water, its age, and changes in its amount and salinity in the course of geological history are quite diverse [Budyko et al., 1987; Shu et al., 1999; Hay et al., 2006; Mikhailov et al., 2007; Orlenok, 2010, etc.]. Equally different are the arguments used by the authors to substantiate the points of view offered to the reader. Often, they cannot be compared since they were obtained using information from different sections of geography, geology, geochemistry, cosmochemistry, cosmogony, etc. Nevertheless, in recent years, the general recognition of the antiquity of the bulk of the water on Earth, its appearance in the early stages of the planet's history, fol-

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lowing the division of matter into a core and shells, is growing clearer.

The long and complex path of material condensation, accretion of the inner planets of the Solar System, leading to such an event, on its own contains many elements that have not yet found an unambiguous explanation [White, 2020]. Some of them belong to branches of science unknown to the author, so we have to focus on the opinions of specialists, in this case, mainly presented in [Grimm, McSween,1989; Peslier et al., 2017; Lunine, 2022], of course, not always joining them. Nevertheless, since the separation of the core is well reasoned and geologically justified, it can be considered that at this point in the process, the agreement of the independently established result in different ways increases its reliability.

Of course, recognition of the reality of such an event is not enough to answer many specific questions regarding the evolution of the modern ocean and its predecessors that may have existed. It seems promising to consider these problems based mainly on geological and geophysical information since only its involvement makes it possible at different historical stages to use even if incomplete, often fragmentary data, but still within the same evolutionary process. The geological theory proposed by the author [Gordienko, 2022] allows to include, with sufficient certainty, the results of the previous development of the Solar System substance, and to conduct their independent quantitative comparison with the existing oceans. This step is possible due to the emergence of the «magma ocean» and the conservation of its near-bottom part throughout the Earth's history after the separation of the shells.

Magma ocean and global asthenosphere. This part was identified as the global asthenosphere [Gordienko, 2017, etc.], a zone of partial melting in the mantle (Fig. 1).

The thermal evolution model for the mantle is based on the concept of the initial temperature (T) distribution that prevailed about 4.2 billion years ago. If we disregard aspects of the process that are not essential for our purpose, it was due to the antecedent accretion (that led to the planet's heating by 1,500—2,500 °C, on the average, depending on the process scheme used), to the Earth's differentiation into the core and outer shells (which was responsible for the average rise in temperature by 1,200 °C) during 10—100 million years [Windley, 1980; Ringwood, 1981; Peslier et al., 2017, etc.], and to the formation of a «magma ocean» with a depth of about 1,000 km. «The magma ocean is becoming enriched with volatile and incoherent elements by contrast with solid magma, which is becoming very dry and devoid of volatile elements» [Windley, 1980, p. 28], with crustal material being removed from it. The process is accompanied by intensive heat and mass

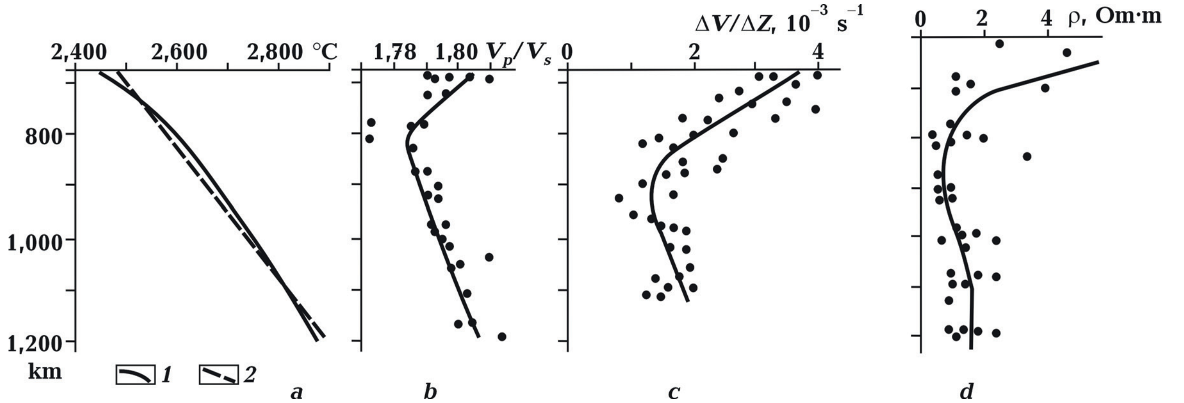

Fig. 1. Criteria for identifying the global asthenosphere: *a* — thermal model of the Precambrian platform mantle (*1* — temperature distribution, *2* — solidus temperature distribution in the mantle rocks); *b* — change in the ratio of longitudinal and transverse seismic wave velocities by depth; *c* — change in the vertical velocity gradient of longitudinal seismic waves by depth; *d* — change in the electrical resistivity of mantle rocks by depth.

transfer (in all likelihood, through continuous convection) and by a cooling of the tectonosphere to the level of rock solidus temperature. Once this temperature is reached, the viscosity of the mantle material increases significantly, and continuous convection at the rate required for enabling heat and mass transfer during actual active processes becomes unlikely. Subsequent temperature variations are linked to conductive cooling through the surface, emission of radiogenic heat (with an intensity varying with time and, in the absence of heat losses, capable of heating the upper mantle of a future platform by 2.000—2.500 °C), and to heat efflux through advection during active processes. Additional sources of heat (its generation or absorption) can emerge during displacement of the top of the polymorphic transformation zone in the upper mantle's lower portion.

It goes without saying that a structure in which not just solidus but also liquidus of mantle rocks within the depth range of hundreds of kilometers are excessively high cannot be stable. Heat and mass transfer diverting excess heat toward the surface is inevitable.

When calculating thermal variation models reflecting the effects of heat and mass transfer, we superposed results of displacement of the material in each active episode of the region's history on the initial model (distribution of solidus temperature down to 1.000—1.100 km depths 4.2 billion years ago) and results of its evolution under the effect of heat generation and heat release through the surface. Studies of the composition of magmatic rocks in the Ukrainian and other shields [Gordienko, 2017, etc.] have shown that in the course of active Precambrian processes, depths of the top of the asthenosphere varied in the same manner as they did in Phanerozoic geosynclines and rifts. For that reason, designations such as «geosyncline» and «rift» were attributed to ancient processes, although tectonic effects there might have differed from Phanerozoic ones.

The choice of endogenous regimes was tied to the type of the preceding thermal variation model. If the temperatures exceeded solidus within a broad range of depths greater than 200 km, the situation was assumed to be suitable for the emergence of convection and a geosynclinal process within the asthenosphere. Also taken into account was the presence of a gradient exceeding adiabatic in the asthenosphere or a portion thereof. It was precisely such a segment of the asthenosphere that was considered suitable for a convective interfusion of the material and for shaping an asthenolith that floated upwards. If the asthenosphere was thinner, conditions were considered suitable for rifting or for a single activation episode (during which the material moved like at the initial stage of rifting). In that case, as a rule, the material was removed from the asthenosphere or its portion about 100 km thick, less frequently 50 km thick. In the absence of the asthenosphere or its insignificant thickness (less than 50 km), the evaluation (implying just the evolution of the background and smoothing of previous temperature anomalies) was continued until the required conditions were obtained. To simplify calculations, the diameter of a single quantum of tectonic action (QTA — a minimum volume of material capable of changing position) was in all cases considered to amount to 50 km. Every geosynclinal or rifting event was matched by the transfer of three QTAs. When necessary, the restriction of emerging heat sources in length and width was taken into account.

Of course, the modelling that was carried out does not reflect the only plausible version of the sequence of active processes in the shield's tectonosphere. When the heat model did not make it possible to conclusively opt for a type of endogenous regimes, we considered several varieties of the process with different thermal properties of the medium and different types of the process so that the active process could start or the time span of the «tectonic quiescence» could be extended to enable a more complete «maturation» of conditions for subsequent heat and mass transfer. In all cases, we observed largely the same pattern. There is nothing that could be added to or removed from the estimated heat and mass transfer episodes.

Computations performed for the depths

beneath the zone under study have revealed a peculiar situation. Within a depth range of about 700—1.000 km, a layer with insignificant partial melting left by the «magma ocean» has remained intact throughout geological history. This global asthenosphere is commensurable in volume with the outer core and is larger than the inner core. Presently available velocity models of the mantle do not detect it. There only exist indirect indications of changes in the elastic parameters, but geoelectric studies clearly identify the layer [Gordienko, 2022, etc.] (see Fig. 1).

From depths of 200—250 km, the density of the liquid is higher than that of the crystalline material with the same composition. For that reason, no supernatant asthenoliths take shape in the global asthenosphere. Low viscosity causes seismicity to cease in the upper part of the asthenosphere at an approximate depth of 700 km.

In the described way, we obtained an idea of the volume of the magma ocean from which water could be formed. It is 0.47 trillion km^3; the full volume of the modern Earth is 1.08 trillion km^3. This is consistent with the currently widespread opinion of the completion of the creation phase of the planet with a volume of about 70±20 % of the modern one.

In the subsequent time (from 10 to 100—150 million years from the beginning of accretion, when the planet gained 99 % of its current mass), meteorite material of uniform age and isotope composition (D/H) came to the surface, the role of comets is negligible. Its parameters are consistent with data on terrestrial rocks, i.e., if the composition of the Earth contains significant fragments from other parts of the Solar System (the substance of the last stage of accretion clearly does not contain the amount of iron necessary for the core), then they are located in the lower mantle and core. «The number of water-rich bodies in the Earth's «feeding zone» is increasing (with time — author). The Earth began relatively dry, i.e., poor in water, and received the first significant influx of volatiles after reaching 60—90 % of its current size. The subsequent accretion is dominated by bodies rich in volatiles … such as water-rich mantle fragments or undifferentiated material originating from the primordial asteroid belt (e.g., carbonaceous chondrites) … or between and beyond the giant planets» [Peslier et al., 2017, p. 776].

The reliability of the agreement of terrestrial matter exactly with chondrites according to isotopic D/H data is called into question by the results of comparisons for isotopes of other elements. But their involvement in such a procedure often turns out to be less justified than for deuterium and hydrogen. This, in particular, was shown by E.M. Galimov for carbon [Galimov, 1973]. According to E.M. Galimov, «… the heterogenous fractionation of carbon isotopes could be used for studying a vast range of geological processes. At the same time, however, it is precisely the presence of subtle and multiform isotopic effects in the process of graphite formation that must caution us against resorting to excessively straightforward conclusions regarding graphite genesis based on measurements of its isotropic composition» [Galimov, 1973, p. 352—353].

Amount of water on Earth. The total volume of the Earth's free water (on the surface and near it) is 1.46 billion km^3, 4 % more than the oceanic [Mikhailov et al., 2007].

Determination of water concentration in crystalline crustal and mantle rocks in the volume of the former magma ocean is considered according to the data given in numerous publications [Ryabchikov, 1985; Anderson, 1989; Drybus et al., 1997; Solovova, 2004; Bolfan-Casanova, 2005; Katayama et al., 2006; Kovalenko et al., 2006; Li et al., 2008; Ohtani, Zhao, 2009; Babushkina et al., 2009; Peslier et al., 2017; White, 2020, etc.] and, in general, is quite heterogeneous in research methods and actual material used. The results were conditionally divided into two groups, mainly according to the estimating ways of the water amount in real rock samples.

It should be noted that «…most of the Earth's 'water' is actually trace amounts of hydrogen included in the rock-forming silicate minerals that make up the planet's crust and mantle» [Peslier et al., 2017, p. 746]. For the problem being solved, this is a quite reasonable way of estimation: the concentration of water, which at each moment of geological history may be in one or another «package», is determined. In crystalline rocks, there is much more of it than pore moisture. Some background information is provided in Fig. 2 [Peslier et al., 2017, p. 746].

The size of the pie slices represents the approximate volume percentage of the phases. The main reservoir of water in the mantle is nominally anhydrous minerals where hydrogen (H) enters their lattice in the form of defects and bonds to structural oxygen (gray field) [Bell, Rossman 1992].

The average water content in the continental crust (amphibolite+granulites) is estimated at 1.3 wt. % (0.1—5 wt. %), while in the oceanic crust (basalt+gabbro) — 1.5 wt. % [Bodnar et al., 2013]. The total amount of water of this type is 0.26 billion km^3.

The depths from which such samples come to the surface are limited by the location of magma chambers capable of producing a sufficiently low-density melt. They are limited by the pressure level above which a liquid becomes denser than a solid rock of the same composition. As a rule, it is reached for real rocks at about 250 km. Xenoliths from the 0—250 km layer are widely represented in regions with magmatism of various compositions and ages [Peslier et al., 2017, etc.]. The data for both selected groups in this depth

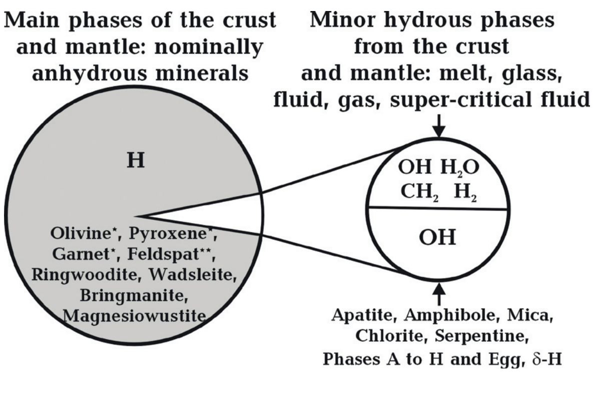

Fig. 2. «Sketch illustrating the «water» species present in the various phases of the Earth's mantle and crust. * — Olivine, pyroxene, and garnet can incorporate water as H_2 under reduced conditions [Yang et al., 2016], ** — K-feldspat can sometimes include water as H_2O and NH_4 [Johnson, Rossman, 2004].

interval do not differ significantly. One of them lacks information on the concentration of eclogites in the mantle, but this may be an accident.

A limited number of difficult-to-diagnose microscopic samples from the depth interval of 250—400 km («xenoliths within xenoliths») can be found. Their water content is not fundamentally different from less deep samples. The supply of material to the surface from the transition zone from the upper to the lower mantle and from the lower mantle is unrealistic from the author's point of view [Gordienko, 2017, etc.].

A detailed analysis of the problem was carried out by A.V. Ivanov and somewhat softens the restrictions.

It is impossible to corroborate by petrological evidence the assumption that material is supplied from the lower mantle and/or from the interface between the lower mantle and the core. It is a purely theoretical speculation. «... petrological studies of the substance that rose to the surface from the deepest levels have shown that the relevant depth is limited to upper levels of the lower mantle (~650—700 km), i.e., to the depth of the deepest earthquakes. Ferropericlase inclusions found in some diamonds do not rule out the involvement of deeper mantle levels, yet they do not provide explicit validation of such a theory either. Nor do geochemical data explicitly confirm the involvement of the lower mantle substance in the magma generation processes beneath volcanically active areas. At the same time, they testify to a complete material isolation of the core from processes in the upper mantle» [Ivanov, 2010, p. 87].

One of the two datasets presents results on the concentration of water deeper than the bottom of the magma ocean in the lower mantle and even in the core. Naturally, we are talking only about modeling results and the part of the planet formed «dry». The values do not differ from those attributed to the near-bottom part of the magma ocean. It is assumed that water entered this part of the Earth due to a very intensive mass transfer by the mechanism of tectonic plates (TP). Many geologists (including the author) point out the contradiction of this hypothesis to the facts [Rudich, 1984; Storetvedt, 1997; Bluman, 2008; Frolov, Frolova, 2011; Gordienko, 2017, etc.], its proponents have been repeating for decades speculative arguments in favor of the concept, without carrying out obvious experimental verification of at least its main elements. Therefore, one should not rely on the provisions of the TP as a real argument.

Some publications [Bolfan-Casanova, 2005; Peslier et al., 2017, etc.] contain information on anomalously high water content in the transition zone between the upper and lower mantle. Up to 18 oceans are located in this depth interval [Peslier et al., 2017]. More precisely, an appropriate amount of water could fit in the rock structures arising under the *PT*-conditions of the transition zone. Above and below, such a phenomenon is not expected. That is, the rocks differ not only in conditions but also in composition. The transition zone is believed to include a «slab graveyard» of submerged fragments of the oceanic crust. For the author, this idea is unacceptable in principle. But it is also inconsistent with the basic provisions of plate tectonics. The «productivity» of spreading zones (which proponents of TP do not calculate by the intensity of magmatism at mid-ocean ridges (MOR) but simply declare it to be equal to the volume of crust from the MOR to the subduction zone) is orders of magnitude lower than necessary to support the postulated subsidence of plates. Focal zones of at least 400 km depth exist only at 10 % of continent-ocean contacts.There is quite a lot of water in the presumably submerging oceanic crust (see above). But in the case of the necessary immersion, the slab can't deliver it to the transition zone. It is by its melting that plate tectonics explains the magmatism of island arcs. Melting occurs at a relatively shallow depth (50—150 km), very intensively («Pacific Ring of Fire»). Under such conditions [Peslier et al., 2017], the rock loses almost all water. The reality of hydration of the transition zone has been controlled seismologically. The result is negative. «The velocity data show no evidence that wadsleyite or ringwoodite have been globally hydrated by subduction or initial terrestrial conditions» [Houser, 2016, p. 94]. Over the entire territory of Northern Eurasia between the Pacific and Atlantic oceans, a 0.6—0.7 km/s difference in the velocity of longitudinal seismic waves at the roof of the transition zone was detected by studying the velocity structure of the upper mantle with the help of nuclear explosions [Pavlenkova, Pavlenkova, 2014]. It is consistent with the conversion of olivine to wadsleyite without «water additive».

Calculation of water in the mantle rocks of the former magma ocean for the two mentioned groups of publications gives an average value of 0.8±0.2 billion km^3, together with crustal rocks — 1.06 billion km^3, together with liquid surface and near-surface water — 2.5 billion km^3.

The calculation of the amount of water introduced into the Earth's shell by meteorites before the formation of the magma ocean was carried out using data from publications [Anderson, 1989; Grimm, McSween, 1989; Bodnar et al., 2013; Peslier et al., 2017; Braukmüller et al., 2018; White, 2020; Lunine, 2022, etc.]. It was believed that only carbonaceous chondrites make a significant contribution, occupying about 4 % by volume of the total material received during this period.

These formations differ markedly (Fig. 3) in composition and properties; six groups are distinguished within this class, and out-of-group specimens were noted in a small number, information about which was not included in the consideration due to rarity and insignificant water content. Unfortunately, there is little specific information on the water content of carbonaceous chondrites.

Part of it is presented in Table 1. Not very accurately, partly by circumstantial evidence, it is possible to estimate the relative amounts of these meteorites in groups. The CI, CV, CR, and 1, 2, 3 groups were averaged with the full equal weights, the CO and 4 groups with a weight of 3/4, and the CV, CK, and 5.6 groups with the same 1/2 weights. Therefore, the calculations were performed twice for each of the classification options. Relatively close values were obtained, the average value being 15± ±1 vol. %. The total amount of water brought by meteorites is 2.8 billion km^3. The agree-

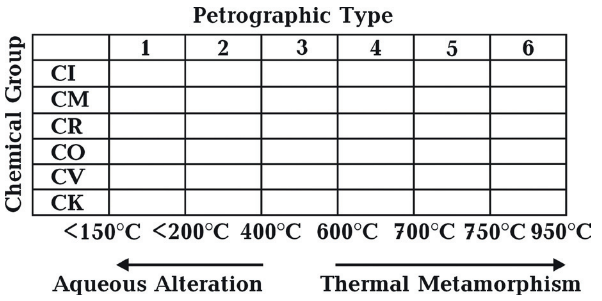

Fig. 3.Classification of Carbonaceous Chondrites. Carbonaceous chondrites are classified by their gross chemical composition, which categorizes them into groups (CI, CM, etc.), as well as by the degree of aqueous alteration (petrographic types 1 and 2) and heating without much water (3—6) [Sephton, 2002].

ment with the value established in a fundamentally different way is quite good. Naturally, one should not attach decisive importance to coincidence. The above description of the procedure for obtaining results contains, albeit very likely, but still value judgments. As more complete data become available, they may be supplemented or revised. But now, for further constructions, we will accept the possibility of an ocean of modern volume on Earth right from the moment of crystallization of the rocks of the magmatic ocean 4.2 billion years ago. Of course, a slightly larger figure can be used, but too few objects or events with sufficiently accurate datings are known in Hadea, with which the calculated ones can be compared.

Table 1. The water content in Carbonaceous Chondrites groups [Sobotovich et al., 1982; Grimm, McSween, 1989; Peslier et al., 2017; Braukmüller et al., 2018; White, 2020]

Group	Water, wt. %	Group	Water, wt. %
CI	14—19	1	18—22
CM	3—16	2	2—16
CR	3—4	3	0.3—3
CO	0—6	4	1.5
CV	0—2	5	1.5
CK	0—1	6	1.5

Ocean in geological history. The results allow us to consider that the volume of liquid water on the planet has not fundamentally changed during its geological history (or has changed in a pulsating manner). It is possible to judge the events taking place with the ocean by the preserved sediments, mostly located on the mainland. Continents with shelves and continental slopes account for 42 % of the Earth's area with 91 % of precipitation, on the ocean floor (58 % of the area) for 9 % of the precipitation volume [Budyko et al., 1987, etc.]. Oceanic sediments are also limited to an age range of about 200 Ma (excluding fragments of the continental crust buried under them).

Zircons aged 4.2 billion years in clastic rocks are known in Australia; one can assume their oceanic origin. But only the Isua Formation in southwest Greenland (3.7—3.8 billion years) reliably belongs to such formations. The belt contains variably metamorphosed basalt and sedimentary rocks in which carbon of organic origin has been found. The structure of the rock indicates its formation in water. Because of the specific distribution of zinc isotopes, it was concluded that these rocks were formed at the bottom of the primitive ocean, at great depths, near the analogue of the black smoker [Budyko et al., 1987]. In the rocks of the formation there is a skew in the ratio of light and heavy isotopes of carbon and zinc. The appearance of jaspilites in their composition may indicate that these rocks are photosynthetic.

The salt composition of the primary oceanic water after a period of condensation and circulation between the surface and the atmosphere becomes distinctly related to the composition of sediments, changing over time from predominantly geosynclinal to predominantly platform [Budyko et al., 1987]. Accordingly, the evolution of the prevalence of the main cations of the solution is outlined (Fig. 4). It has been established that the Early Precambrian ocean water contained more calcium, magnesium and potassium, and less sodium, compared to modern water.

The overall salinity of ocean water changes in a rather complex way.

Halite deposits periodically accumulate in the sedimentary strata, sink to a depth inaccessible for dissolution, are brought to the level of erosion by changes in the direction of epeirogenic movements, etc. It is difficult

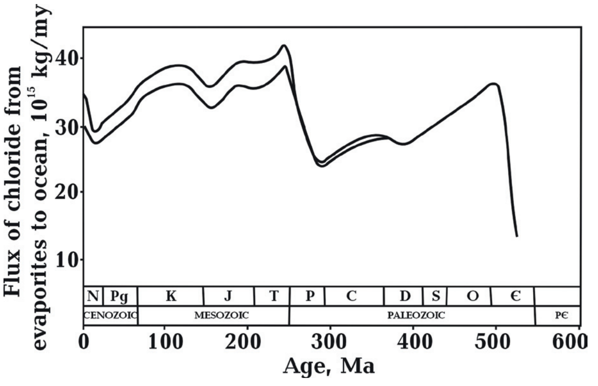

Fig. 4. Chlorine input (maximum and minimum estimates) into the ocean during the Phanerozoic due to erosion of evaporite deposits [Hay et al., 2006].

to talk about a directed change in salinity. The models presented [Hay et al., 2006, etc.] include hypothetical elements. Therefore, considering the corresponding data array is hardly interesting for solving the problem.

The information presented in [Budyko et al., 1987] on the distribution of geosynclines and platforms on modern continents over 0—3.5 Ga (Fig. 5) is fundamentally consistent with the results of the author, which received a quantitative explanation as a consequence of a reduction in radiogenic heat generation in mantle rocks along course of geological history [Gordienko, 2017]. With a change in the presentation, the matching can also become visual. This is important, as other similar comparisons will be discussed below.

Fig. 6 shows that the seas occupied a large part of modern continents in the Phanerozoic. Unfortunately, the depth of the continental seas is unclear, and it is impossible to estimate the part of the surface water in them [Budyko et al., 1987]. Changes in the prevalence of seas on the platforms in a smoothed and weakened form reflect variations in geosynclines, which were vast, long-existing reservoirs at the first stages of the cycles. Of course, the main interest is the last (Late Alpine) rapid reduction in the area of continental seas, close in age to the radical deepening of the ocean.

It is more convenient to consider the preceding decrease in the area of continental seas using other data. For comparison with the known geological information in Fig. 6, its «youngest» part can be used. We are talking about the data from [Rudich, 1984, etc.], the behavior scheme of the ocean floor in the last tens of millions of years (Fig. 7).

These data (as well as information in the publications of B.A. Bluman [Bluman, 2008]) indicate a long-term existence of shallow or land conditions in the modern ocean, starting from the Jurassic—Triassic boundary, with the accumulation of sedimentary-volcanogenic strata that were replaced by 30±15 Ma years ago by a very rapid sinking of the bottom. From the author's point of view, the deepening is associated with the final phase of oceanization, the eclogitization of the main part of the continental crust [Gordienko, 2017]. The average value of the «bottom failure» of the oceans is 3±0.8 km. It should be noted that this is an estimate based on a small sample of data obtained more than 40 years ago. Approximately half of the water needed to fill the basin is formed when the crust is replaced by a mantle (see above). The second may come from the continental seas. In the latter case, we are only talking about an assumption; there are no necessary data for the calculation.

The episode reviewed shows the possibility of judging ocean processes from data on the formation of sediments on the continents, which we would like to use. On the

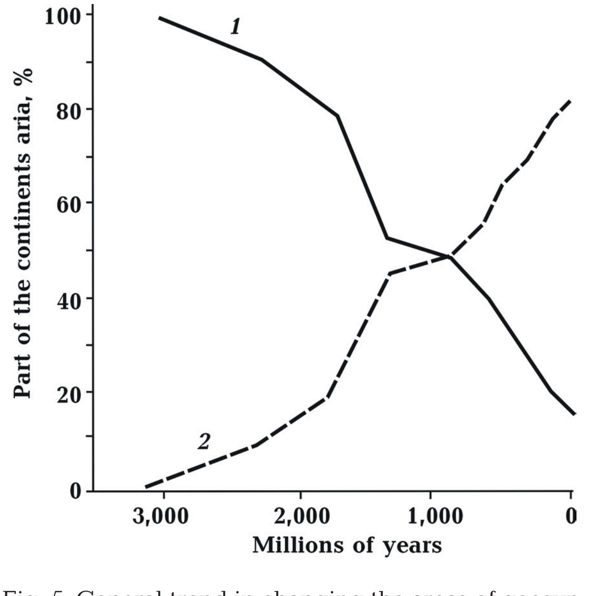

Fig. 5. General trend in changing the areas of geosynclines (*1*) and platforms (*2*) within modern continents.

continents, the present epoch of the completion of the Alpine geosynclinal cycle is also a period of rifting (in a weakened form — a one-act activation), accompanied by general uplift and widespread magmatism. This contributes to the «flowing» of water from the continents into the deepened ocean. It seems

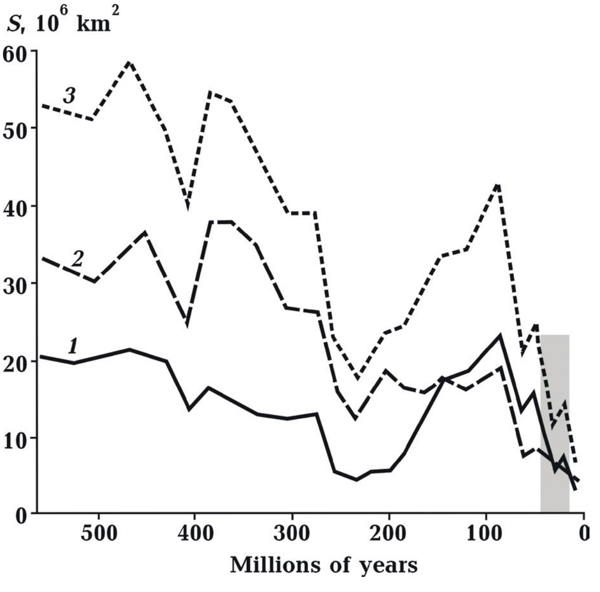

Fig. 6. Areas of the seas on modern continents in the Phanerozoic within platforms (*1*), geosynclines (*2*), and both (*3*). The gray band is the period of anomalously rapid plunging of the ocean floor (see Fig. 7).

that a similar thing happened during the end periods of the Hercynian and Caledonian cycles (see Fig. 6).

The conclusion E.M. Rudichdrew from the analysis of materials in Fig. 7: «...the wide development of Late Mesozoic and Cenozoic shallow-water sediments within the modern abyssal zones, their lithofacies uniformity with deposits of the same age present in the continental margins, certainly indicate that the boundaries of the latter were relatively recently located much more seaward than modern ones» [Rudich, 1983, p. 262], i.e. the subsidence also covered the continental margin, the ocean was advancing. The cover basalts of the Paraná province (~130 Ma) continue into the eastern South American continental shelf, and the traps of the Etendeka province (~120 Ma) of South Africa — into the Whale Ridge (Atlantic Ocean). Already in the most recent episodes of geological history, we see the same trend. The cover basalts of the continent (~50 Ma), together with the weathering crusts formed over them, were traced by deep-sea drilling wells to the adjacent waters of the eastern continental shelf of Greenland and the Outer Hebrides, the basalts of the Columbia Plateau (~15 Ma) — to the Rapozos Gulf, and the Afar traps (~35 Ma) to the Red Sea [Bluman, 2008]. Obviously, the removal to the surface of a large amount of basalt melted out of the mantle is insufficient for oceanization.

At the end of the Caledonian and Hercynian cycles (see Fig. 6), vast areas of the continents are covered by rifting; examples are given in Fig. 8.

On the territory of the EEP, one can see a dense filling of most of the platform with manifestations of the process (we take into account that a significant part of the magmatic rocks is hidden by the sedimentary layer, many are simply not found).

Within one of the Hercynian rifts, the Dnieper-Donets Basin (DDB), one can consider in detail the results of crustal transformation during rifting (Fig. 9).

The velocity section of DDB in Fig. 9 is shown without the upper part occupied by diagenetically and catagenetically altered sediments. The reduction in the thickness of the consolidated crust and its basification are evident (possibly, some of the effects are related to the Riphean-Vendian rifting), i.e., components of oceanization. An area with moderate changes in the crust during the rifting of the platform was selected in the DDB. The section of the Pannonian Massif is also shown without the upper layer. Here, too, in the central part of the Alpine geosyncline of the Carpathians, rifting also leads to a reduction in the thickness of the crust and its basification. V.V. Belousov called such regions «failed oceans» [Belousov, 1991]. Recent activation covers the same territory of the DDB (without magmatism, at least until now). Thus, at least a threefold impact does not lead to oceanization. To the north of the EEP and WSP, the picture is different. The known ages

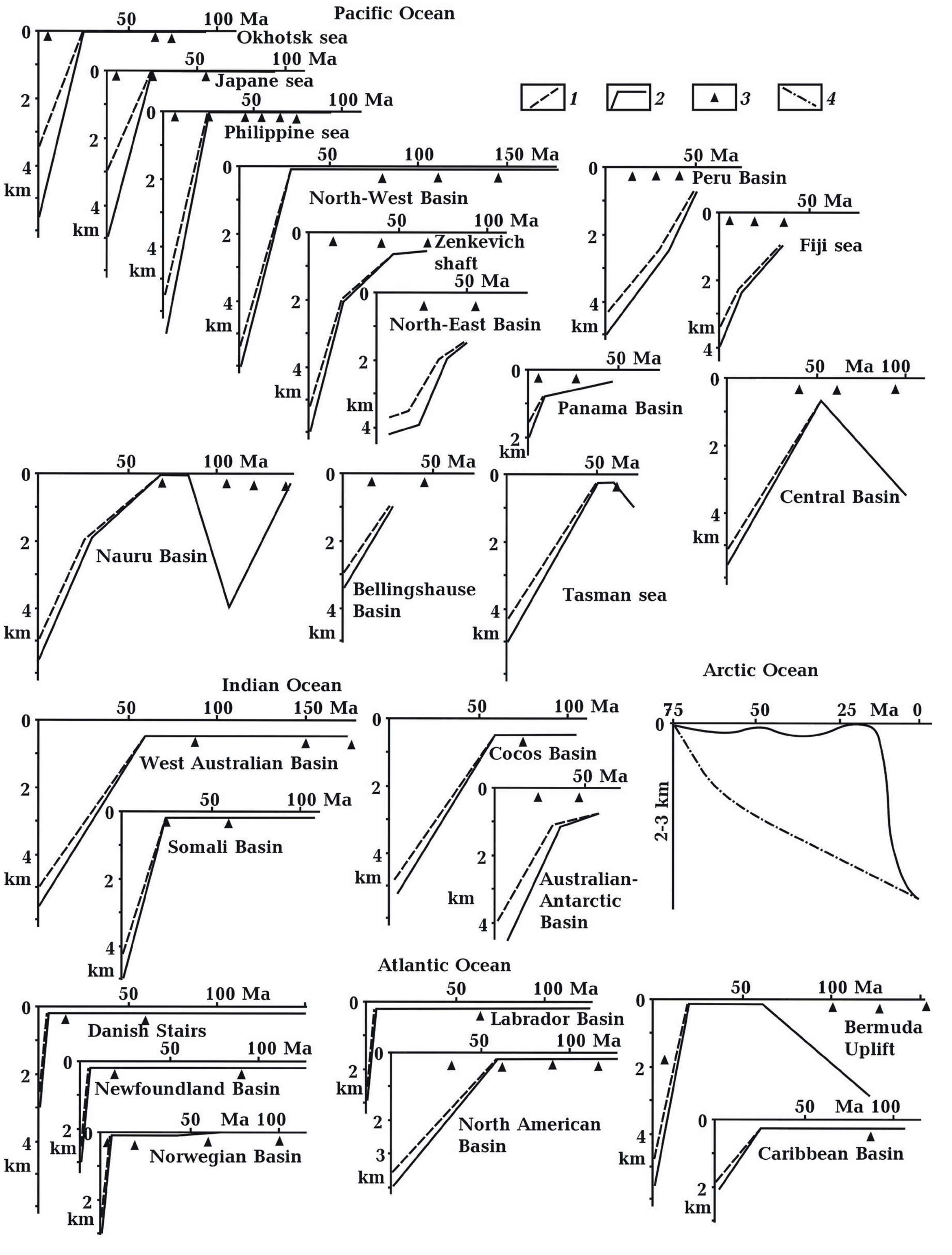

Fig. 7. Change in the depth of the ocean floor in the period up to 200 million years ago: *1* — bottom depth, *2* — basement surface depth, *3* — manifestations of magmatism, *4* — sclater curve for the Arctic.

of the Arctic Ocean crust transformations are limited to the Cretaceous, but in the central part, it has already reached a thickness of less than 10 km. I.e., the emerging correlation between continental and oceanic events is manifested only in the synchronism of ac-

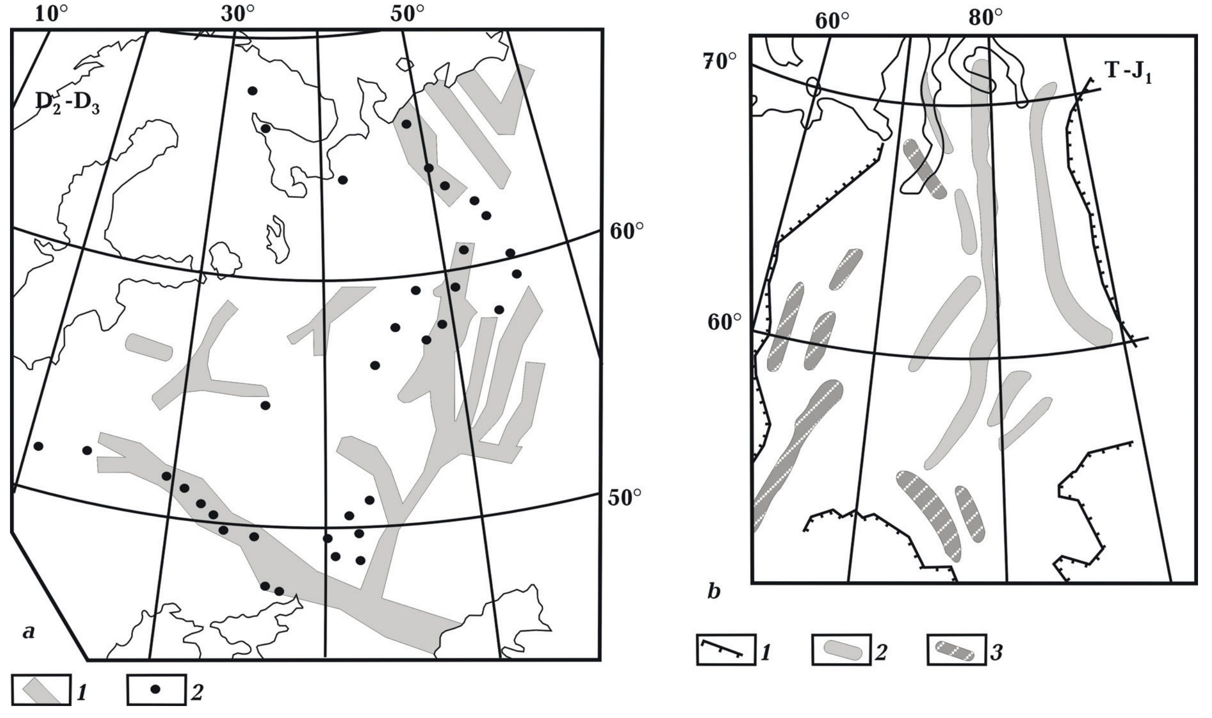

Fig. 8. Manifestations of rifting on the East European Platform (EEP) (*a*) and the West Siberian Plate (WSP) (*b*). EEP: *1* — rift contours, *2* — manifestations of magmatism [Milanovsky, 1983, etc.], WSP: *1* — plate boundaries, *2* — rift contours, *3* — pre-Jurassic basins of unclear origin [Milanovsky, 1987].

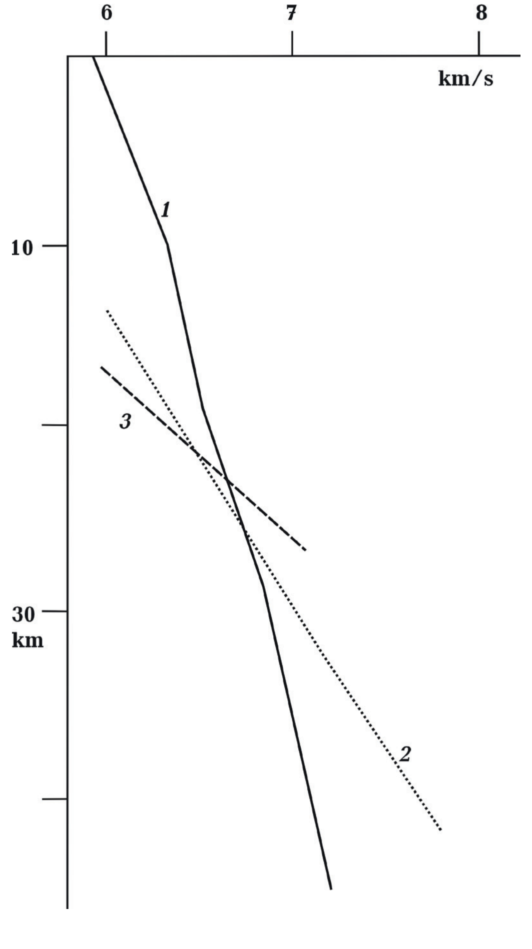

Fig. 9.Velocity sections of the Earth's crust of the slopes of the Ukrainian shield and the Voronezh massif (*1*), the central part of the Dnieper-Donetsk depression (*2*) and the Pannonian median massif (*3*).

tivity but not in a clear connection between endogenous regimes. The geological history of the ocean (the region with the oceanic type of the Earth's crust) is not visible at a reliable level earlier than the Mesozoic.

Corresponding to the arrival of crustal material, an increase in the heat generation of upper mantle rocks creates (over time) a new type of endogenous regime. Now, only the first manifestations of it can be observed.

Oceanization of the Earth's crust. The petrological evolution of the Earth's crust within its framework, briefly touched upon by the author earlier [Gordienko, 2017, etc.], makes sense to consider in more detail. Let us first dwell on the characterization of the coastal crust beforetheoceanization. It is represented mainly by data on the Pacific and Atlantic Oceans (Fig. 10).

The above data show what the Earth's crust should be like, which is ready for oceanization, at least in some of the regions presented. Obviously, the regions whose velocity sections are shown in Fig. 9 cannot yet become «successful oceans». The available data on the advance of the oceanization front [Krasny, 1983; Dickins, 1994; Storetvedt, 1997; Bluman, 2008, etc.] allow us to estimate the order of the process speed — 1 cm/year. It is consistent with the speed of the «Aubouin wave» moving across the geosynclinal region. The same rate is typical for the subsidence of eclogitic crustal blocks into the mantle of the active region [Gordienko, 2022]. Of course, the velocity estimates are approximate; the centrifugal and centripetal directions of motion of the oceanization fronts established by Bluman for the oceans with active and passive margins [Bluman, 2008] are preliminary. But it can be assumed that only 200—250 million years (Mesozoic—Cenozoic) may be enough to create a modern ocean.

As noted earlier [Gordienko, 2017], the considered process includes essential elements of mantle heat and mass transfer in the geosyncline, supplemented by postgeosynclinal activation. Obviously, we are talking about a Cimmerian geosyncline. When building a thermal model, the initial distribution of T before the process is important. There is no such information for the oceans themselves. The Carpathian geosyncline, suitable for age, in its central (eugeosynclinal) part can be used. For this region, the previous geological history is known from about 1200 Ma ago, the ages of activity stages accompanied by volcanic manifestations have been determined, young activation and a sharp decrease in the thickness of the crust are known [Gordienko et al., 2011, etc.]. In the model of heat-mass transfer, it was considered that the movement moments of quanta of tectonic action (QTD) [Gordienko, 2017, 2022] occurred 200, 150, 100, and 50 Ma ago. The calculation of the effects of these advective events is supplemented by a change in the initial distribution of T due to the cooling of the Earth through the surface and the influence of radiogenic heat generation in the mantle rocks at the geosynclinal level (0.06 $\mu W/m^3$).

It should be noted that the thickness of the upper (sedimentary) layer in the Cimmerian geosyncline is noticeably less than that shown in Fig. 10. According to data in the Carpathians, Balkanides, and some areas of the Pacific fold belt, it averages about 4 km, i.e., 1.5 times less than in the miogeosyncline.

In the consolidated crust of the platforms, the complex of physical properties can be explained by the presence of up to 30 % ultrabasites in the lower third [Gordienko et al., 2005]. In the Phanerozoic geosynclines, a decrease in heat generation of the rocks of the crust consolidated part is recorded, which can be explained by the appearance of ultrabasites throughout its thickness in concentration at the level of 20 % [Gordienko, 2017].

The first QTA comes from the depth interval of 230—470 km to the interval of 230—170 km with an anomalous temperature of about 320 °C; the lower reservoir cools down by 60 °C. The initial magmatism is relatively small in volume, and the surface displacement due to thermal anomalies of different signs is close to zero. The polymorphic trans-

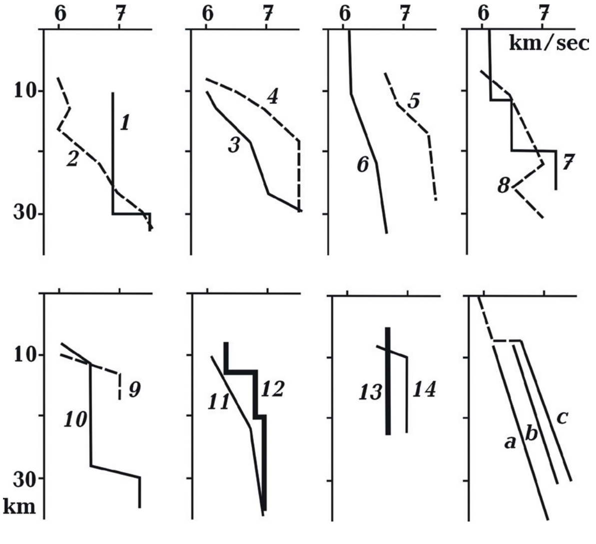

Fig. 10. Velocity sections of the consolidated Earth's crust at the continents and oceans margins: *1* — Hokkaido, *2* — Sakhalin, *3* — Tatar trough, *4* — Kamchatka, *5* — Kuriles, *6* — Honshu, *7* — Cordillera Coastal Range, *8* — Cascadia, *9* — Rokol Plateau, *10* — British Hercynides, *11* — Andes, *12* — Appalachians, *13* — Kerguelen Plateau, *14* — northeastern shelf of the Pacific Ocean; *a*—*c* — average velocity sections (*a* — Precambrian crystalline shield, *b* — sections in regions *1*—*14*, *c* — section *b* corrected for the deep temperature difference between the shield and regions *1*—*14* (dashed line — sedimentary part of the section)).

formation of rocks at the bottom of the upper mantle is almost imperceptible: temperature changes at this depth do not exceed the calculation errors (Fig. 11). Changes in the crust are reduced to the appearance of basic dikes penetrating the rocks of the consolidated crust and sedimentary layer. The rocks of the latter during heating (mainly at the next stages) to the level of catagenesis, the velocity of longitudinal seismic waves in them increases to 6 km/s. Saturation of the layer with dikes leads to a V_P of about 6—6.5 km/s.

The second QTA from the depth interval of 170—460 km arrives at 110—170 km with an anomalous temperature of 300 °C, the source cools by 60 °C. In this case, the rise and fall of the surface due to temperature anomalies of different signs are practically equalized. For the first hundreds of meters, the thickness of the effusive-sedimentary layer on the surface increases, and the swarm of dikes in the crust increases.

The third QTA (the final geosynclinal process) rises from depths of 130—250 km to a level of 70—130 km with an anomalous temperature of 400 °C, cooling the source by 200 °C. Some of the partially melted material in the volume of the layer 7—8 km thick is carried out from the formed subcrustal asthenosphere into the crust to depths of 20—30 km (occupying ½ of the volume) and 10—20 km (occupying ¼ of the volume). The material that descended into the subcrustal asthenosphere cools it by 150 °C. The final magmatism continues the build-up of the upper volcanogenic layer.

Fig. 11 shows the temperature distributions before each another active event. By this time, thecrustal heating under the influence of the second and third QTAs is already less noticeable than soon after the start of each of these stages, especially the intrusion of large masses of partially molten rocks from the mantle into the crust. Conditions of granulitefacies metamorphism are achieved everywhere in the consolidated crust; it continues to be replenished with ultrabasites, and the level of seismic wave velocity noticeably exceeds 7 km/s.

The postgeosynclinal stage of heat-mass transfer is prepared by heating rocks directly above the bottom of the upper mantle (see Fig. 11). About 50 million years ago, a partial melting layer of about 70 km thick was formed here, enough to create the next QTA. It rises under the crust (to a depth of 40—100 km) with an anomalous temperature of about 950 °C, cooling the focus by 800 °C. By now, the anomalous cooling at the depth of the upper mantle bottom has already been significantly decreased, and the boundary of the polymorphic transformation of peridotite is located at a depth of about 395 km. The compaction of olivine and the transition of some pyroxenes into garnet lead to an overall rock compaction by 0.22 g/cm^3 in a depth interval of about 70 km. Information on the process rate is unknown, but it seems highly likely that it has been completed. According to [Korolyuk et al., 2004], at shallower depths, the corresponding changes in PT conditions are sufficient for the geologically rapid transformation of rocks (Table 2).

The described compaction leads to the subsidence of the entire crust-mantle block by 4.5 km. The solidus temperature is exceeded under the crust during the rise of the QTA, and a zone of intense partial melting of peridotite is formed (up to 30 % [Kadik et al., 1990]). Powerful volcanism increases the thickness of the surface effusive layer to about 1.5 km. Together with the weight of the water that filled the basin, this displaces about 3 km of rocks from the lower part of the crust beyond the eclogitization boundary

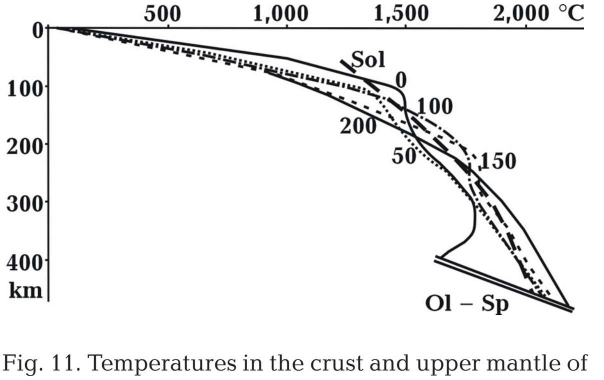

Fig. 11. Temperatures in the crust and upper mantle of the oceanization period. The numbers next to the curves indicate the age in Ma. Sol is the solidus of peridotite. Ol-Sp is the transition zone of olivine to wadsleyite.

and stimulates an additional 0.5 km of surface submergence.

The subcrustal asthenosphere generates the intrusion of partially molten peridotite into the crust in the usual volume for the activation process (7—8 km layer) with anomalous T about 350 °C in the upper half of the consolidated crust and 700 °C in the lower. When such a crust cools down, in the transformed part, it will turn out to be somewhat denser than the previous one and will subside for the first hundreds of meters. The material that descended into the subcrustal asthenosphere will lower its temperature by 60 °C and, upon cooling, will transform into eclogite, bringing the total surface subsidence to 5.5 km. The V_P values in the consolidated crust will be approximately 7.7 km/s.

The considered version of the structure and composition transformation of crustal rocks during oceanization did not include the phenomena that take place during the formation of UHP blocks [Gordienko, 2017, 2022, etc.]. The reality of eclogitization of basic rocks in this and other processes of crust-mantle exchange is beyond doubt. The intrusion of peridotite melt into the crust with an increase in the melting degree from 5 to 30 % to replace almost 40 % of its basic granulite should be accompanied by their sharp compaction. However, the author has not encountered a detailed description of the zone formation mechanism of sufficiently intense pressure around magma intrusions into the crust in the literature (except for prograde changes in gabbro outside the peak of the process [Oh, Liou, 1990; Zhang et al., 1995]). Therefore, in this case, only the conditions of eclogitization at sufficient lithostatic pressure (more than 1 GPa) are mentioned. It can be assumed that the intrusions during the final magmatism of the process geosynclinal part and the activation stage are accompanied by the appearance of eclogites and, accordingly, by an additional local increase in V_P deeper than 12 km. After all, in a short period after the invasion, thermoelasticstresses reach hundreds of MPa [Turcotte, Schubert, 1985; Grinfeld, Langman, 1988, etc.]. According to seismological data, this part of the lithosphere, as a rule, is not perceived as the Earth's crust.

Eclogites with pyropes can sink up to 250 or even 300 km, with almandines up to the bottom of the upper mantle. In this way, increased radiogenic heat generation of the oceanic mantle can be ensured. It provides a new type of endogenous regimen. The youngest events in the geological history of the oceans may not yet include all the phenomena representing such a regime.

The upper part of the crust is represented by the first oceanic layer of young loose sediments a few hundred meters thick, which arose after the accumulation of the second layer effusives. According to reference data, seismic wave velocities in the first case are limited to values of 2.0—3.5 km/s; in the second case, they depend on porosity and vary in a wide range of 3.5—5.0 km/s [Clark, 1969; Dortman, 1992; Ahrens, 1995; Dobrynin et al., 2004; Density…, 2016, etc.]. The rocks of the third layer should have V_P values (see above) of about 6.5 km/s.

Let us compare the results with experimental data. For comparison, about 200 V_P values were selected from velocity sections of the Atlantic and Pacific Oceans crust, and the same values in the subcrustal layer down to a depth of 40 km. Approximately at this level, the base of the crust, which has undergone oceanization and has sunk 5—6 km, may be located. The results are shown in Fig. 12.

The correspondence of the observed data to the calculated ones is satisfactory. In the subcrustal layer, the distribution of many eclogites

Table 2. Time (years) needed to equalize the chemical heterogeneity of garnets [Korolyuk et al., 2004]

T, °C	P, GPa	Grain size, mm		
		0.05	0.5	5
Immersion				
500—600	0.56—0.67	$3 \cdot 10^7$	$3 \cdot 10^9$	$3 \cdot 10^{11}$
500—700	0.56—0.78	$1.3 \cdot 10^6$	$1.5 \cdot 10^8$	$1.3 \cdot 10^{10}$
500—800	0.56—0.89	$1 \cdot 10^5$	$1 \cdot 10^7$	$1 \cdot 10^9$
500—900	0.56—1.00	$1 \cdot 10^4$	$1 \cdot 10^6$	$1 \cdot 10^8$
500—1000	0.56—1.11	$1.3 \cdot 10^3$	$1.4 \cdot 10^5$	$1.3 \cdot 10^7$

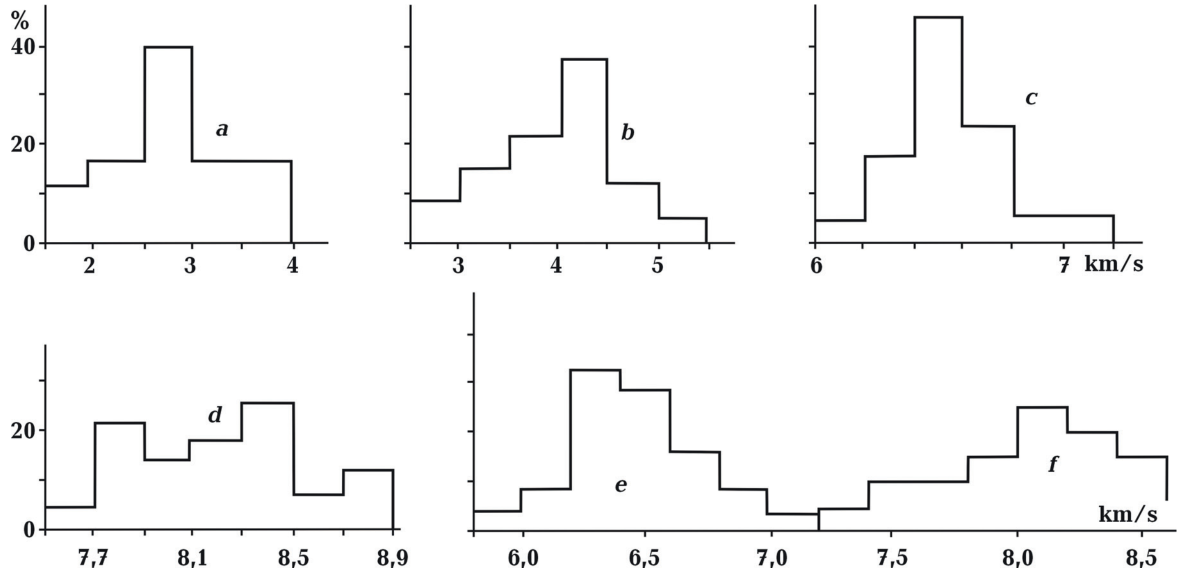

Fig. 12. Histograms of seismic wave velocity distributions in the crustal layers of the ocean basins (*a* — the first layer, *b* — the second layer, *c* — the third layer), in the subcrustal mantle (*d*) and in the transition zone (*e* — the middle one in the oceanic crust, *f* — in the mantle under the continental crust).

is discovered, most likely with a significantly variable ferruginicity.

To compare with the calculated thermal model of the period of maximum crustal heating, one can use the *PT* parameters of the xenolith rock brought to the bottom surface in the Pacific Northwest Basin [Vasiliev, 1989] (Fig. 13).

It should be noted that the analysis of the oceanic crust formation does not include, as an initial stage, the cutting off of the upper layer of the original continental crust by erosion, which seemed necessary to the author earlier [Gordienko, 2023, etc.].

It is interesting to compare the calculated values of seismic wave velocities in the layers of the oceanic crust and subcrustal mantle with data from one of the most studied profiles across the Atlantic Ocean [Pogrebitsky et al., 1990; Pavlenkova et al., 1993, etc.] — the Angolan-Brazilian geotraverse (Fig. 14).

When constructing the figure, data on the Mid-Atlantic Ridge region were not used. The experimental results are quite close to the average calculated throughout the profile, extending almost to the transition zones from the ocean to South America and Africa. This circumstance can be used to consider one of the provisions of the plate tectonics hypothesis. Its proponents argue that as one moves away from the spreading zone, the temperature of the crustal rocks decreases so much that they become denser than the upper mantle rocks under the continental margin and can sink into it. Fig. 15 shows velocities in the crustal rocks along the Angolan-Brazilian traverse. All V_P values are transferred to one side of the MAR. The distances are measured from the axis of the ridge.

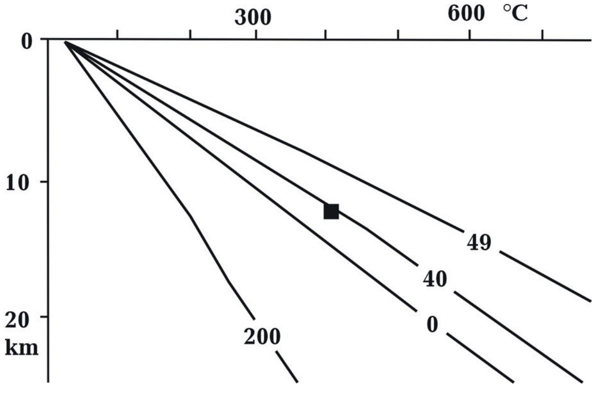

Fig. 13. Temperature distribution in the Earth's crust of the Pacific Northwest Basin. Depths are measured from the bottom surface. The numbers in the curves indicate age in Ma.

The effect of crustal rocks' increased velocity (and thus, density) with approach to the continent is not observed. The author has constructed velocity models under many island arcs, deep-sea trenches, and back-arc basins. It is shown that the seismic wave velocities in these regions at a small depth under the crust correspond to densities of 3.2—3.3 g/cm^3. In the oceanic crust next to them, the densities are 2.3—3.0 g/cm^3 [Gordienko, 2017, etc.]. The data of other authors who determined these parameters are about the same [Zverev et al., 1986; Levin et al., 2002; Pavlenkova, 2019, etc.].

In general, the modeling allowed us to consider the process much wider than it was done in [Gordienko, 2017]. The experience of testing the possibility of oceanic crust formation on the basis of the crust of coastal continental regions can be considered successful.

Conclusion. The information that has appeared in recent decades does not noticeably change the previously existing ideas about the presence of water onthe Earth, except for estimates of its concentration in «formally waterless» deep rocks. The opinion about the large distribution of water on the surface since the establishment of a sufficiently low temperature can be considered reliable.

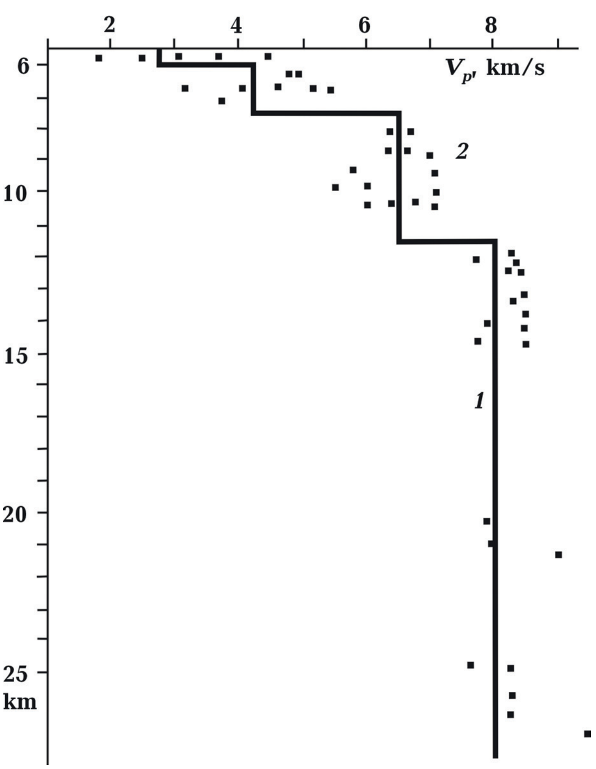

Fig. 14. Distribution of calculated (*1*) and experimental (*2*) V_P values under the Angolan-Brazilian geotraverse.

Such a statement is supported by the quantitative agreement of the result with the depth of the magma ocean independently established by the author, which arose at the end of accretion. In this case, the accretion order, which is currently supported by most specialists, is accepted, and the plate-tectonic model of water replenishment of the transition zone between the upper and lower mantle is rejected. The latter contradicts many geological facts [Gordienko, 2017, etc.].

The amount of liquid water on the planet's surface has long remained much smaller than today. It is distributed fairly evenly and is not

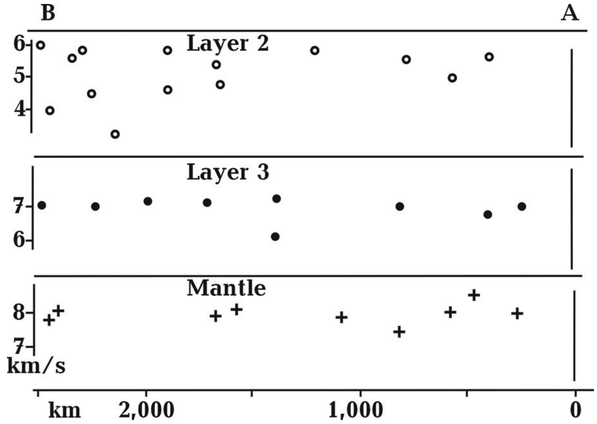

Fig. 15. Seismic wave velocities in the rocks of the second and third layers and upper mantle along the Angolan-Brazilian geotraverse. A is the MAR axis, and B is the area where the oceanic crust changes to the continental one.

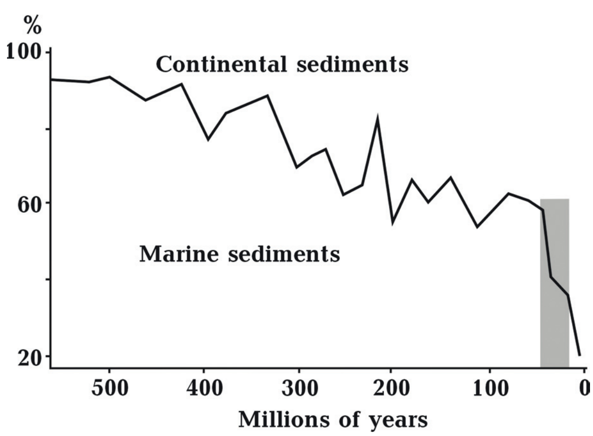

Fig. 16. Changes in marine and continental sedimentation areas on modern continents [Budyko et al., 1987]. The gray band is the period of abnormally fast ocean floor subsidence.

concentrated in deep water bodies similar to the present oceans (see Fig. 6, 14). There is a gradual replacement of geosynclines, common on the entire surface of the Earth, by platforms. The first (pre-Riphean) platforms often include granitic batholiths in their thick crust; they are distinguished as minimally active shields. The process of replacement of geosynclines by platforms is accompanied by rifting, including recurrent rifting, which also covers fragments of geosynclinal regions. Gradually, a fragment of the Earth with a significantly more basified crust than is typical for other regions of the continents is distinguished. It can be seen that such crusts are concentrated near the modern ocean shores.

In these regions, the deep process corresponding to the eugeosyncline and subsequent activation over 200 Ma leads to a number of geological events recorded in modern oceans: long-term preservation of the flat land or shelf, periodic resumption of magmatism, and crustal restructuring (basification with the transformation of its lower part into a depth interval with physical properties close to those of the mantle). This is followed by a period of rapid (over several tens of million years) surface submergence associated with a shift in the boundary between the upper and lower mantle. The calculated results of such a process agree with the experimental data on the oceanic crust. The processes of recent activation (MOR, flank plateaus, abyssal hills, deep-sea trenches) are superimposed on the oceanic crust; the crustal material submerged into the mantle increases its radiogenic heat generation and forms a new type of endogenous regime.

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Океан. Історія води і земної кори

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Погляди на походження та еволюцію води на Землі (кількість і спосіб її входження до складу порід кори та мантії) доволі різноманітні. Для їх обґрунтування використовують аргументи з різних розділів географії, геології, геохімії, космохімії, космогонії. Об'єднання багатьох даних дає змогу досить упевнено вважати, що поява води пов'язана із завершальним етапом формування планети, який разпочався після накопичення 60—90 % її об'єму. На цьому етапі надходили до зони акреції серед інших хондрити водомісткі карбонатитові. Оцінивши з різних джерел їх внесок у процес утворення води, можна зіставити відомі з геолого-геофізичні дані щодо процесів ранньої історії Землі. Використано розроблене автором уявлення про глобальну астеносферу — релікт древнього магматичного океану. Саме завдяки цій інформації оцінено обсяг речовини, з якої внаслідок виникнення магматичного океану могла з'явитися вода. Узгодження цих незалежних результатів дає можливість досить впевнено стверджувати, що вода для заповнення океану була (у тому чи іншому вигляді) протягом усієї вивченої геологічної історії планети.

Проблему власне океану (глибоководної водойми із земною корою, відмінною від кори континентів, — менш потужною і більш основною) розглянуто з використанням відомих результатів Б.А. Блюмана і Е.М. Рудича стосовно океанів і М.І. Будико зі співавторами щодо континентів. Отримані висновки добре узгоджуються з розглянутими автором схемами глибинних процесів у тектоносфері океанів. Останні проконтрольовані серією геологічних явищ та аномалій геофізичних полів. Процеси зводяться до тепломасоперенесення в евгеосинкліналі, накладеної на аномально основну континентальну кору, та подальшої їх активізації. Таким чином, складається досить повна картина утворення сучасного океану як результату розвитку тектоносфери Землі в мезозої—кайнозої.

Ключові слова: океан, вода Землі, океанізація континентальної кори.