Table

$\delta^{13}C$ of carbonates and $\delta^{18}O$ of quartz of gold mineralization in the Amalia BIF

Sample	Host lithology	Carbonate	Remark	$\delta^{13}C_{PDB}$ (‰)	$\delta^{18}O_{smow}$ (‰)
C17-20	Vein in mineralized BIF	ankerite	Q-C vein	-3.2	17.2
C11-5A-3	-»-	Fe-dolomite	–»–	-3.7	16.3
C17-15B	-»-	ankerite	–»–	-4.8	13.5
C17-23B	-»-	ankerite	–»–	-3.1	16.3
C17-6	Vein in hanging wall schist (non mineralized)	Fe-dolomite	–»–	-3.8	16.3
V8-3	Mineralized BIF	Fe-dolomite	whole rock	-3.4	15.0
V8-10PIb	-»-	siderite	–»–	-5.0	13.5
V8-12PII	Cherty band from mineralized BIF	siderite	–»–	-4.8	13.8
AB22-15A	Mineralized BIF	siderite	–»–	-3.4	13.6
V8-26(b)	Mineralized BIF	Fe-dolomite	–»–	-4.2	14.4

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FORMATION OF THE EARTH'S CORE AND SILICATE LAYERS

Предложена принципиально новая модель гетерогенной аккумуляции Земли. Она позволяет объяснить механизм образования частично расплавленного железо-никелевого ядра на начальном этапе формирования Земли и обосновывает новый механизм дифференциации вещества в процессе аккумуляции Земли. Процесс аккумуляции завершается отложением на поверхности Земли материала углистых хондритов. Из этого материала будет сформирована внешняя твердая оболочка Земли.

The composition of the Earth's core and silicate layers depends on the way of the Earth's accumulation and later differentiation. The modern hypotheses assume that protoplanetary material had gone through two consecutive stages of (i) solid phase condensation from the gas and (ii) solid particle agglomeration in a gas-dust cloud [Dorofeeva, Makalkin, 2004] resulted in the planet formation [Vitiazev et al., 1990]. The currently available data of the cooling of the protoplanetary cloud (10^4–10^5 years) [Dorofeeva, Makalkin, 2004] shows that these processes cannot be separated by time and by distance from the Sun. It is beyond reason to exclude the possibility of the concurrent occurrence of these two stages. This allows us to use the sequence of the solid phase condensation, which was founded in laboratory experiment on mechanism of the planet formation [Ringwood, 1979].

The assumption that the solid particle agglomeration began after the primary gas condensation was completed and had gone in the cold cloud allows only homogenous Earth's accretion. This scenario leads to the primary homogenous cold planet. The portioning of the homogenous planet material on the iron core and silicate mantle is conceivable at the final stages of its formation, which could occur only after the secondary warming-up of the upper planet strata. The problem is an energy contributor to the start-up of the primary homogenous Earth differentiation. The radioactive decay was able to warm-up the Earth two billion years only after its formation. The suggestion that the warming-up of the Earth was caused by the impact of the Mars-sized space body is speculative and will not be the subject of our discussion. Moreover, the homogenous accretion models contradict the isotopic data, which indicate that the core and mantle reservoirs were separated at the initial stage of the Earth's formation [Harper, Jacobsen, 1996].

The heterogeneous accretion is an alternative hypothesis in contrast to the homogenous one. It proposes that the composition of material for the Earth's formation was inconstant and varied as the Earth's size increases. This idea was supported by many researchers [Anderson et al., 1972; Harper, Jacobsen, 1996]. The most radical point of view was stated by Anderson et al. [1972], who proposed that the inner core was built up from the early condensates, which were condensed before iron. The

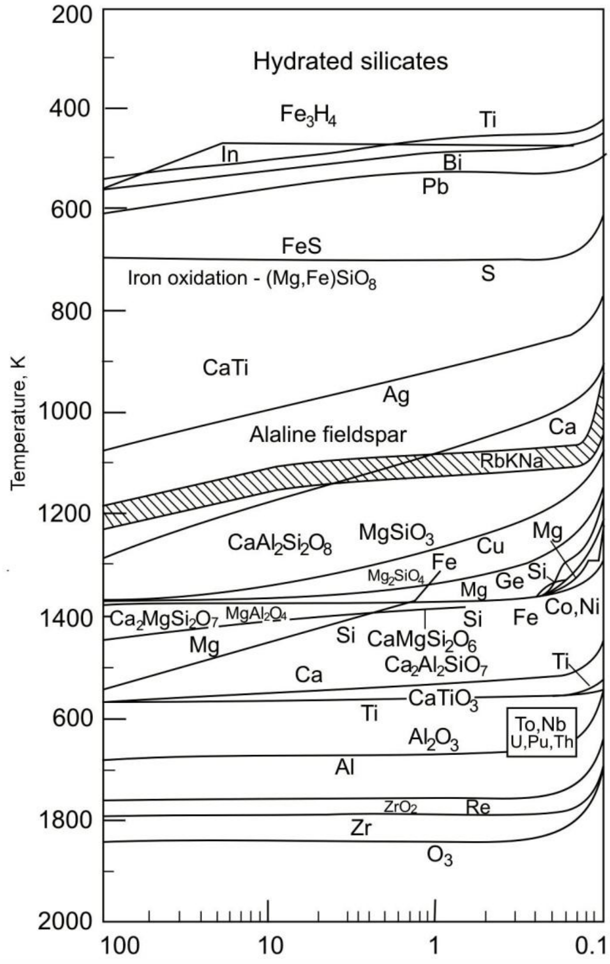

Fig.1. The condensed element fraction.

possible composition of the Earth's layers and their evolution are discussed on the basis of the two stage model of the Earth's formation in the given work.

Simultaneous condensation and solid particle agglomeration allows proposition that the composition of the central part of the planets at the first stage of the planet formation was close to CAI – white inclusions in the Allende meteorite [Anfilogov, Khachay, 2005]. They are most high temperature and ancient condensates in the Solar system [Brearley, Jones, 1998]. As the embryos grow and the protoplanetry cloud cools, the composition of the condensate changes (Fig. 1) and the iron and iron-silicate fractions will precipitate on the embryo surface owing to the high temperature. The planet embryos, which size is the first hundred kilometers, will be formed as a result of the impacts and partially integration of the planetesimales. The structure of these embryos is shown in the Fig. 2.

The warming-up of the embryos as a result of the short-live radioactive decay occurs during the growth. ^{26}Al is the major short-live isotope with half decay period of 7.38?10^{5} years. The ^{26}Al/^{27}Al ratio in the protoplanetary material is 5?10^{-5} [Merk et al., 2002]. The temperature in the embryo center may be as much as 1850–2200 K at this ^{26}Al content if the embryo size is 200 km [Anfilogov, Khachay, 2005]. It is large enough for the partial melting of Al-Si mixture in the central part of the embryo and for complete melting of the Fe-Ni mixture in its intermediate layer. The outer layer complicated by olivine-pyroxene chondrite material remains solid at this time (Fig. 2).

The further evolution of the planet goes in the following manner. In accordance with the Safronov's model of the planet accumulation [Robie et al., 1978], the amount of embryos, which are formed at initial stage of agglomeration, is high and they often impact each other. The impact of two embryos with similar size partially smelts the core and medium iron layer and makes hard the outer silicate layer, terminating the failure. The intermediate smelt iron layers will coalesce after the impact and form a new embryo complicated from Fe-Ni molten alloy. The material of Al-Si cores will be pressed out from the inner part of the primary embryos and thrown out partially beyond the new embryo. The outer solid layers will be destroyed and a part of their fragments goes out the growing planet. The impact of two primary embryos is schematically shown in Fig. 3.

According to the dynamic estimations [Khachay, Anfilogov, 2007], the duration of the first stage is >10^{6} years that is in agreement with period of formation of chemical reservoirs of the Earth's core and mantle separation [Harper, Jacobsen, 1996].

The integration of the iron layers after the impact of the primary embryos gives rise to the second embryo generation, the most part of which represents the Fe-Ni molten core. Two problems may be solved this way: the core formation at initial stage of the Earth's formation and possibility of MHD dynamic start-up and geomagnetic field formation, which are inducted in the smelt iron core by the outer magnetic field [Khachay, Anfilogov, 2007]. The dynamics of further process of the Earth's formation is described by the Safonov's model. When the Fe-Ni core reaches the most part of its modern mass, it becomes able to hold and form a silicate layer around itself.

The two stage model of the Earth's formation discussed above represents the heterogeneous accretion scenario. Contrary to the scenarios suggested before [Ringwood, 1978], it proposes the real mechanism of the smelt iron core formation at initial stage of the Earth's formation, removal of the primary light Al-Si material from the center of the embryo and explains the origin of high temperature in the growing Earth.

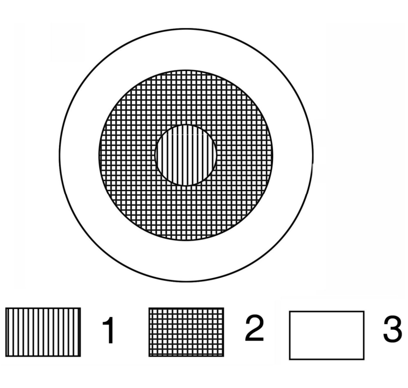

Fig. 2. The schematic structure of the primary Earth embryo. 1– the high aluminum core; 2 – the smelt iron envelope; 3 – the outer hard envelope.

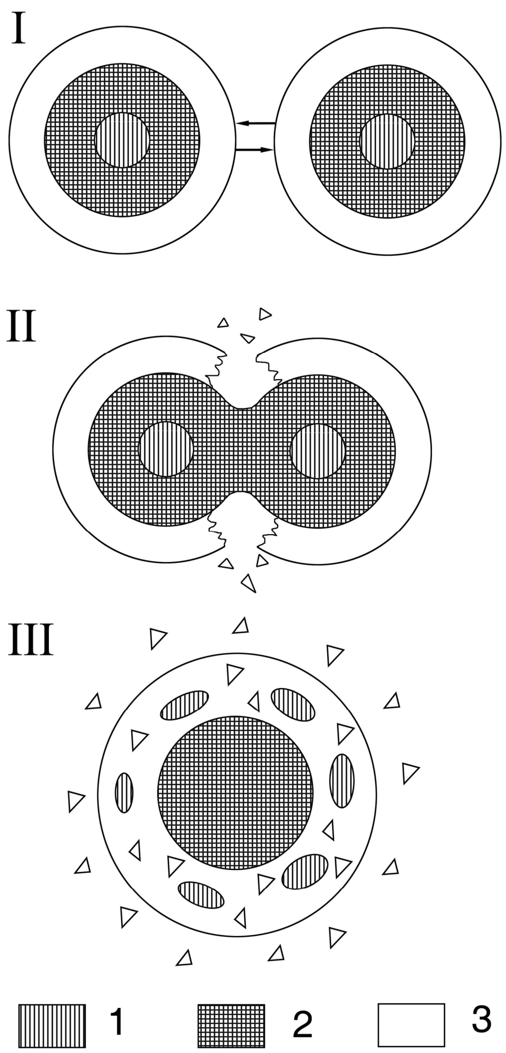

Fig. 3. Scheme of the new Earth embryo formation as a result of the two primary embryos collision. 1 – high aluminum material; 2 – smelt iron material; 3– ordinary chondritic material.

The two stage mechanism allows proposition of the Moon formation along with the Earth and explanation of the absence of metallic iron in the Moon and high primary temperature in the Moon interior. The Moon was mostly formed from the fragments resulted from the primary Earth's embryo destruction and went out from the feeding area of the growing Earth. Because the main part of iron is concentrated in the Earth's core, the Moon lacks material for the formation. In addition to iron, the Moon material accessible for investigation was depleted of potassium. In line with condensation sequence (Fig. 1), it allows us to exclude the alkali fieldspars and other solid phases, which are condensed at temperature lower than 1100 K. This suggests that the Moon was separated from the Earth before the accretion of the Earth was completed. In this case, the most part of potassium should accumulate by the Earth at the last stage of its formation and is concentrated in the upper mantle.

Let us consider the possible composition of the Earth's silicate layers. The meteoritic material is a primary information source about mantle composition. The iron meteorites give the data on the core composition and the stone meteorites considered to be a possible material for the Earth's silicate layers have rather different composition, thus the problem of the meteorite type necessary for the mantle composition is ambiguous. The problem is complicated, because some part of meteorites are the fragments knocked from the Moon and nearest planets [Shukolyukov, 2003] and cannot serve the material for the Earth's formation. A similar statement is true for meteorites, which age is younger than that of the Earth [Marakushev, 1991].

A.E. Ringwood has analyzed the complex of physical and mineralogical criterions (the distribution of seismic waves velocities, springiness, density, mineralogical composition, and phase transformation of minerals at high pressure) and drawn a conclusion that two alternative models can be considered [Dorofeeva, Makalkin, 2004]: (i) the lower mantle is pyrolitic and its density excess is conditioned by phase transitions and (ii) the lower mantle is enriched in FeO and, possibly, SiO_2.

We believe that these scenarios are not alternative. First, it is not evident that the composition of the material for the Earth's formation was constant during the whole period of its accumulation and it corresponded to carbonaceous chondrites. Second, the phase transformations of the mantle minerals are studied experimentally and it is impossible to build up the correct model of the lower mantle without account of these transformations.

Based on the sequence of solid phase condensation (Fig 1), it is most likely that the lower mantle correspond to olivine-pyroxene chondrites in composition. These chondrites are distinct from carbonaceous chondrites by the absence of water and presence of large amount of iron and troilite (Table).

Similarly, the base of the mantle is expected to correspond to the composition of H-chondrites with high content of iron. As the Earth's mass increases, the composition of the H-chondrite varied to L- and LL-chondrite. The proposed chondritic lower mantle has no strong difference from the pyrolitic one. As seen from Table, the intermediate composition of chondrites devoid of Fe and FeS is close to pyrolite. It differs from pyrolite by high FeO lower MgO contents. It well to bear in mind, that its initial composition was formed during the Earth's growing process. As the temperature and pressure increased, the lower mantle differentiated and Fe and FeS moved to the core. The part of iron oxide disproportionated and transformed into magnetite and metallic iron: $4FeO = Fe_3O_4 + \alpha Fe$. Then, it moved to the core too [Ringwood, 1978]. The final composition of the lower mantle became pyrolitic.

The pyrolitic model of the upper mantle put forward by A.E. Ringwood [1978] was generally accepted. The model is based on the correlation of composition of carbonaceous chondrites, alpine ultramafic rocks, and deep-seated xenoliths in kimberlites and alkali basalts. In spite of general acceptance, the pyrolitic model has some contradictions. It is agreed that the Earth's material corresponds to the intermediate meteorite. However, no meteorites, except for the Allende and rare ureilites, have high MgO and low FeO contents as pyrolite. Thus, the question arises, where is the excess of FeO and what is the source of the MgO excess in the mantle? By this is meant that models of pyrolitic and other mantle composition are approximate.

Let us consider the origin of the Archean crust, which is made up of mafic volcanic and acid igneous and metamorphic rocks [Salop, 1982]. V.E. Khain and N.A Boshko [1988] advocated that grey gneisses quantitatively dominate among the Archean rocks and could be formed by partial melting of the primary mantle with the specific toward Archean active constraint of water only.

The sequence of solid phase condensation, which is used by two stage model of the Earth's formation, suggests that water and carbon appear at the final stage of this process. Absence of carbon in the early condensates is caused by CO_2 generation, which remains in the gaseous phase of the protoplanetary cloud: $C + O_2 = CO_2$ ($\Delta G_{1400K} = -396.17$ kJ/mol [Robie et al., 1978]).

An iron is oxidized simultaneously with CO_2 production, the free energy of this process changed at 1400 K is –180.44 kJ/mol [Robie et al., 1978], and the oxidation of Fe is noncompetitive with CO_2 production.

Carbon, H_2O and organic compounds appear in the protoplanetary material and meteorites as temperature decreases, hydrogen concentration increase, and carbon is reduced: $CO_2 + H_2 + C + 2H_2O$ ($\Delta G_{600\,K} = -95.70$ kJ/mol [Robie et al., 1978]).

Table

Composition of chondrites and the Ringwood's pyrolite

Component	Type H [Mason, 1962] (53)	Type L [Mason, 1962] (79)	Type LL [Marakushev,1991] (17)	Pyrolite [Ringwood, 1979]
SiO_2	47. 0	45.2	42.8	45.1
Al_2O_3	3.0	2.9	2.7	3.3
FeO	12.9	17.7	21.5	8.0
MgO	30.1	28.6	27.8	38.1
CaO	2.5	2.2	2.0	3.1
Na_2O	1.1	1.0	0.9	0.4
FeS	5.6	5.8	5.3	
Fe	17.3	6.7	1.3	

It follows that the Earth's formation is finished by the formation of the outer layer enriched in water and carbon with chondritic composition of its silicate component. Two processes may occur in this layer at high temperature: (i) degassing of the outer layer, which gave rise to the atmosphere and ocean formation and (ii) production of the large volume of dioritic and granitic melt, which are able to be formed at the presence of water.

All stated above allows us to propose the hypothesis of the entire and upper mantle composition. The average mantle composition is most likely consistent with composition of olivine-pyroxene chondrites without metallic Fe and FeS. Compared to the Ringwood's pyrolite, it is enriched in FeO and depleted in MgO. The material of carbonaceous chondrites exists in the upper mantle. Three types of geochemical reservoirs may occur in the outer part of the upper mantle: primitive mantle consistent with average mantle composition, partially depleted mantle consistent with the Ringwood's pyrolite, and depleted mantle. The latter composition is formed after basaltic magma smelted from the pyrolite.

Thus, the smelt iron core is formed at initial stage of the Earth's formation by integration of the smelt iron layers and collision of the primary embryos. The overwhelming bulk of the mantle made up of chondrites, which composition is changed from H- to LL-chondrite. The carbonaceous chondrite was involved only during formation of the outer part of the upper mantle. The activity of the water during the differentiation produces the large volume of acid igneous rocks, which are known as Archean grey gneisses.

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