Genesis and evolution of magmas according to data on hot heterogeneous accretion of the Earth

Vladimir Shkodzinskiy
Yakutsk, Lenin street, 39, Diamond and Precious Metal Geology Institute, Siberian Branch, Russian Academy of Sciences, 677000, Russia
shkodzinskiy@diamond.ysn.ru

Abstract. The obtained numerous proofs of hot heterogeneous accretion of the Earth lead to a fundamentally new solution to the problems of genesis and evolution of magmas. According to these data, the Earth's core was formed earlier than the silicate mantle as a result of the agglutination of iron particles of the protoplanetary disk under the influence of magnetic forces, because with a small body size, these forces were billions of times more powerful thangravitational ones. The accretion of the silicate mantle created a global magmatic ocean under the influence of impact heat release. Its bottom part crystallized and fractionated as a result of the pressure increase of the formed upper parts. Cumulates formed the ultrabasic mantle, and residual melts formed the magmatic ocean. The increase in ocean temperature and depth caused the evolution of bottom residual melts from acidic to ultrabasic, the appearance of corresponding layers in the ocean, and the reverse geothermal gradient in the mantle. As a result of the cooling and crystallization of the ocean from top to bottom after 3.8 billion years ago early Precambrian crystal complexes, acidic crust, and the lithosphere of ancient platforms were formed. The separation of residual melts from various layers caused the evolution of magmatism on them from acidic to alkaline-ultramafic and kimberlite. Heating of the mantle by a high-temperature core led to the appearance of a direct geothermal gradient at the end of the Proterozoic, convection in the mantle, and modern geodynamic environments. In them, magmas are formed by the frictional and decompression melting of the differentiates of the magmatic ocean.

1. Introduction
According to the hypothesis of cold homogeneous accretion of the Earth [1], it is usually assumed that the core and mantle arose by gravitational separation of iron and silicate particles in the earth's interior. Early Precambrian crystal complexes are the result of metamorphism of sedimentary-volcanic strata, magmas are formed by separation of melts from partially molten rocks. However, numerous proofs of hot heterogeneous accretion of the Earth have been established that contradict these assumptions. This formation is indicated by the results of calculations on the impact heating of matter during accretion at 34,000 °C [2], the existence of trends in magmatic fractionation in mantle xenoliths from kimberlites and in Early Precambrian crystal complexes, a decrease in the isotopic age and crystallization temperature of their various rocks in full accordance with the sequence of origin during fractionation, and the projection of the earliest geothermal gradients into the region of very high temperature (up to 1000 °C) [3] on the Earth's surface. The sharp chemical disequilibrium of mantle rocks with metallic iron and the presence of water and carbon dioxide, rather than the products of their reduction by iron, indicate that silicate and metallic particles were never mixed in the earth's interior and, consequently, fell out separately.
These results lead to a fundamentally new solution to the problems of the genesis of geospheres, magmas, and the evolution of magma formation processes. According to these data, the Earth's core was formed earlier than the silicate mantle as a result of the agglutination of iron particles in the protoplanetary disk under the influence of magnetic forces, since with a small body size, these forces were billions of times more powerful than gravitational ones. The Sun at this time was at the evolutionary stage of Tau Taurus and therefore had a thousand times more powerful magnetic field than the modern one.

Figure 1. Scheme of formation of the various geodynamic setting and magmas: 1 – acidic, 2 – basic, 3 – anorthositic, 4 – alkaline-basic, 5 – alkaline-ultrabasic with carbonatites, 6 – kimberlitic, 7 – oceanic and trap sometimes with core xenoliths

2. Magma formation at the early stage of the Earth's evolution
The silicate particles deposited on the core melted under the influence of impact heat generation and formed a global magmatic ocean. An increase in the pressure of the upper parts that occurred during accretion led to the crystallization and fractionation of its bottom layer. Cumulates formed the mantle. The still small depth of the early magmatic ocean and the reduced force of gravitational attraction on a small Earth caused a low pressure during its bottom fractionation and the appearance of a large number of acidic residual melts. This explains the subsequent mass formation of acidic igneous rocks on Earth and the crystalline crust. The low-pressure tholeiitic residual melts that arose at a lower degree of fractionation caused mainly such a composition of primary basic magmas and a very wide spreading of rocks of this composition. As the intensity of mantle accretion increased, the temperature and depth of the magma ocean increased. This led to the evolution of residual melts to basic and ultrabasic, and the formation of corresponding layers in the magmatic ocean (figure 1) and the inverse geothermal gradient in the mantle.

Due to a significant increase in density with depth (from 2.2 to 2.8 g/cm³) after the termination of accretion, extensive convection of melts did not occur in the layered magmatic ocean, so it cooled and solidified from top to bottom for a long time. This explains the absence of rocks on Earth older than 3.8 billion years and craters of the giant meteor bombardment that completed the accretion. The rapid cooling of the Moon, due to its small size, caused the spreading of rocks with an age of 4.3 – 4.4 billion years and giant impact pools. The absence of an acidic crust on the Moon contradicts the popular hypothesis of its impact formation from the Earth's matter. Up to 3.8 billion years ago, our planet had a panmagmatic geodynamic situation.
The crystallization of the upper acidic layer of the magmatic ocean led to the formation of Early Precambrian crystal complexes and acidic crust. The density of the solidified magmas became higher than the underlying ones. Therefore, the resulting rocks, together with the sediments that began to form on them, periodically sank and were overlaid by the magmas that surfaced. This explains the alternation of orthogneisses and paragneisses of different composition in Early Precambrian crystal complexes, the presence in them, as in typical igneous rocks, only regressive zoning of minerals, a very high (800 – 850 °C) magmatic crystallization temperature of their minerals, the absence of gradual transitions to low-temperature strata and traces of the existence of powerful (tens of kilometers) overlapping strata, the heat-insulating influence of which is usually explained by their hypothetical metamorphism. Due to the large volume of the magma ocean, the formation of Early Precambrian crystalline rocks lasted for more than a billion years.

Due to the existence of an inverse geothermal gradient, there was no extensive convection in the early mantle, and therefore there were no modern geodynamic settings on Earth. At this time, there was a situation of the formation of acidic crust as a result of the crystallization of the acidic layer of the magmatic ocean. After the appearance of the high-temperature crystalline basement, the formation of sedimentary-volcanogenic strata occurred on it, zonally metamorphosed under the influence of the hot base. The isotopic age of the base is often younger than that of the overlying strata, due to its very long cooling. The release of emanations from the magmatic ocean led to the formation of a large number of ore deposits. The large volume of the ocean has led to the often uniquely large reserves of these deposits (the Witwatersrand, Kryvoh Rho, etc.).

After the completion of the formation of the Early Precambrian crystal complexes about 2.2 billion years ago, the geodynamic situation of the formation of the lithosphere of ancient platforms by the crystallization of the deep layers of the magmatic ocean arose. The most important geological process at this time was the ascent of residual melts from various layers of the magma ocean. The negative slope of the solidus line on the quantitative P-T diagram of acid magmas (figure 2) illustrates that relatively low-temperature magmas evolving in the melt + solid phase field cannot pour out onto the Earth's surface (ascent lines 8 and 9) due to decompression solidification after boiling during ascent [3]. Therefore, the residual magmatic origin of melts that arose during the crystallization of the magmatic ocean determined the formation of intrusions by them mainly. This is especially pronounced for acidic magmas, which formed a large number of granite intrusions in Early Precambrian crystal complexes and practically did not form volcanic bodies.

At the late stages of crystallization of the acidic layer of the magmatic ocean, leucocratic residual acid melts formed in it, forming widespread granite intrusions of sometimes subalkaline composition (figure 2). The subsequent crystallization of the deeper diorite and basic layers caused the formation and surfacing of various subalkaline and alkaline residual melts. The rise of magmas rich in plagioclase cumulates led to the formation of autonomous anorthositic, widespread on ancient shields. After complete solidification of the upper parts of the magma ocean, their introduction stopped. This explains the limited age range (2.8 – 1.1 billion years [4]) of the formation of autonomous anorthosites and their usually significant antiquity. The participation in their formation of the diorite layer of the magmatic ocean is the reason for the often andesine composition of their plagioclase.
According to experimental data, the crystallization of mafic magmas containing more than 0.6 mole fraction of carbon dioxide in the fluid component leads to the formation of carbonatite residual melts at a pressure of less than 2.5 GPa and kimberlite – at a higher pressure. This explains the formation of carbonatites and kimberlites on ancient platforms. The top-down crystallization of the magma ocean is responsible for the older age of carbonatites compared to kimberlites – on average, 688 and 236 million years, respectively (figure 1). The expansion of the continental lithosphere during the formation of oceanic regions is usually the reason for the absence of kimberlites in them (Clifford's rule).

Carbonatites contain up to two thousand chondrite norms of the most meltophilic light rare earths, which indicates a decrease in the volume of the initial magma by thousands of times during the formation of residual carbonatite melts. The intense accumulation of meltophilic chemical components in these melts and the very high degree of fractionation explain the often uniquely high contents (up to the first percent) of rare earths and some other components in carbonatites. A large volume of fractionated picrite layer with a thickness of about 80 km (figure 1) is the reason for the usually large reserves of ore components in alkaline-ultramafic intrusions, their multiphase nature and usually a huge duration of formation (up to many hundreds of millions of years).

3. Origin of magmas in Phanerozoic oceanic and subduction environments

The gradual warming of the mantle by the initially very hot core should have led to the appearance of a direct geothermal gradient and a powerful all-mantle convection. A sharp increase in the intensity of tectonic processes after 1.2 billion years ago, the thickness of the formed sediments and the age of the bottom of the modern oceans is less than 0.15 billion years ago [5, 6] indicate that intense convection began at the end of the Proterozoic. From the standpoint of the prevailing hypothesis of the origin of the core and the mantle as a result of the sinking of iron particles in it, these geospheres should have had almost the same temperature, so the cause of convection is unclear. The most exotic assumptions were made about its nature – about the high content of radioactive elements in the core, about the presence of antimatter in it. However, these assumptions are not confirmed by the results of the study of iron meteorites, which are fragments of the cores of small planets [7]. Small cores on other Earth-group
planets failed to warm up their mantles. This explains the absence of convincing signs of plate tectonics and modern magmatism on them.

In the hot heterogeneous accretion of the Earth, the core should be significantly hotter than the mantle, since it quickly formed with the participation of powerful magnetic forces. This is consistent with the geophysical data on the 1 – 2 thousand degrees higher core temperature [8]. With such accretion, there should be two types of mantle plumes – very large, mostly ultrabasic, and smaller basic plumes. Heating of the mantle by the core led to the emergence of its hot lower parts after the establishment of a direct geothermal gradient. Due to the large size of these parts and the small difference in the densities of heated and non-heated rocks (hundredths of g/cm²), only huge superplumes could float. The predominantly ultrabasic composition of their substance caused a reduced degree of decompression melting during ascent and its enormous viscosity. Judging by the viscosity of the asthenosphere, it is about 10¹⁹ poise. Due to its very large size, the matter of superplumes spreading under the lithosphere has a huge dynamic effect on it. It leads to its expansion, the emergence of oceanic, subduction and collision areas, to the drift of continents and to other manifestations of lithospheric plate tectonics. These superplumes are predominantly tectonogenerating.

The impact craters formed during accretion at the bottom of the magmatic ocean were filled mainly with tholeiitic bottom melts, which quickly solidified by compression and formed large bodies of the basic rocks. They have an average about 0.1 – 0.3 g/cm³ lower density than the host ultramafic rocks. Therefore, they should have float after the establishment of a direct geothermal gradient in the mantle. That is, in addition to the convection associated with the heating of the mantle material by the core, there is a convection due to the primary heterogeneity of the mantle composition. Due to the fusibility, the substance of the basic plumes is almost completely melted under the influence of huge decompression during ascent and therefore has billions of times lower viscosity (first poises) than the ultrabasic substance of superplumes. For this reason, the basic plumes have little mechanical influence on the lithosphere. But the predominantly molten state of their substance leads to the rapid formation of large volumes of igneous rocks. This explains the formation mainly in the Phanerozoic for 1 – 2 million years and less of giant trap fields with a volume of millions of cubic kilometers. Such plumes are predominantly magma-generating. The presence of large (up to tens of tons) bodies of native nickel iron (up to 7 %) in the traps with the lowest lithophilic components sometimes indicates the formation of these rocks from the basic rocks of the earliest impact craters that reached the core and captured its xenoliths. Their presence confirms the considered model of magma formation.

Due to the low initial temperature of the earth's interior, according to the cold accretion hypothesis, the heating of the substance as a result of the decay of radioactive elements is assumed to be the cause of melting during magma formation. However, in the modern heat flow, the share of this heat is less than 10 % due to the low content of these elements in the mantle [9]. The huge impact heating during accretion is the main source of deep heat. The degree of partial melting of primary ultramafic rocks is assumed to be very small (0.1 % for kimberlite magmas and about 15% for basic magmas) [10], since at a higher degree the composition of the melts does not correspond to the composition of natural magmas. But with a small degree of sub-melting, the viscosity of the rocks is 10²⁰– 10²² poise. As calculations have shown [11], with such a huge viscosity, melts in the entire history of the Earth can float up to a fraction of a centimeter, which can not lead to the formation of magmas. This is confirmed by the absence of processes of separation of the melt and solid phases in peridotites, which were melted in experiments by less than 30 % [12].

The autochthonous nature of the melts is fully confirmed by the results of the study of migmatites – the only observable example of natural mass partial melting. The straightness of the lines of the ratio of the successive sums of the capacities of the bodies of the anatectic vein material and the substratum in figure 3 indicates the absence of processes of separation of the anatectic melt in migmatites, even at a content of about 40 % (line 1). This is due to the huge viscosity of poorly fused rocks. The relatively large
granite bodies found among migmatites have a different composition and isotopic age than the anatectic vein material of migmatites. Therefore, they were not formed from anatectic melts of migmatites.

As illustrated by the uplift lines in the P-T diagram (figure 2), the content of solid phases in natural granite magmas under the influence of high pressure in deep conditions is 60-80%. Therefore, in the Phanerozoic, not the melt, but mainly solid-phase magmas of granitoid composition began to rise from the foci of magma origin. During the ascent, the solid phases in them were melted under the influence of decompression and frictional heat release, which is confirmed by the homogenization of the substance of granite-gneiss diapirs during the ascent [3, 11]. Therefore, in addition to the impact heat release during mantle accretion, decompression and frictional heat release are powerful magma-forming factors. As is known, even cold near-surface rocks sometimes melt in tectonic fault zones to form pseudotachylites. Calculations have shown [13] that stresses of 0.2 – 0.4 GPa characteristic of subduction zones can lead to the formation of magmatic rock volumes observed in these zones by means of frictional melting of the lithosphere.

![Diagram](image)

**Figure 3.** Correlation of successive sums of thickness of anatectic veins and of bodies of substratum in biotite-garnet migmatite of r. Ameditchi on Aldan shield

The high efficiency of frictional melting is confirmed by massive modern volcanism on Jupiter's small moon Io. On it, intense deformations under the influence of the variable gravitational attraction of Europa, Ganymede, and Jupiter, which are approaching and receding during the rotation, lead to the eruption of more than four hundred volcanoes and the formation of lava lakes with a diameter of up to 200 km. The frictional melting of rocks of different composition of the lithosphere under the influence of the powerful pressure of the moving oceanic plates is the reason for the formation of a large number of different magmas in subduction environments and their close connection with tectonic movements. At the same time, depending on the composition of the intensively deformed rocks, acidic and more basic magmas could occur in different sequences, and only the initial and final products of magmatic fractionation (basalt-dacite formation) can be present in contrasting formations. This explains the diversity of the composition and evolution of subduction magmatism.

On average, the diorite composition of the continental crystalline crust caused the most widespread distribution of andesites among subduction igneous rocks. The increased magnitude of the unilateral pressure of oceanic plates in the near-oceanic magma belts leads to a high temperature of magmas arising here, to the formation of mainly volcanics by them, and to a widespread spreading of volcanoes. The complete
absorption of transverse seismic waves indicates a strong frictional melting of rocks in the roots of some volcanoes. The decrease in the intensity of tectonic deformations with the distance from the oceans explains the increase in the proportion of lower-temperature acidic igneous rocks in this direction and the formation of mainly intrusions by them.

As lines 3-6 in the P – T diagram illustrate (figure 2), the rise of the most common medium-temperature acid magmas should lead to their decompression solidification under near-surface conditions. It preserves the high pressure of the fluid phase. With a further rise, the difference between the external decreasing and the high internal pressure of this phase increases. Under the influence of such a difference, explosive disintegration of the solidified parts of magma columns can occur with the formation of various tuffs and breccias. This is confirmed by a higher value of the explosivity coefficient for acidic subduction rocks (70 – 80%) than for basic and andesitic rocks (10-12 %). Due to the very uniform distribution of the dissolved volatile components in the melt, the crushing of highly solidified rocks can be very fine with the formation of elastic particles of a fraction of a millimeter in size. The content of the main volatile component of water in magmas is on average about 1 %. It accumulated in the residual melt during the bottom fractionation of the magmatic ocean. Calculations [3] indicate that the removal of about 0.5% of the water from the ocean mass by residual melts could lead to the formation of the entire hydrosphere of the Earth. Due to the high solubility in melts at high pressure and the absence of pores and channels, water could not come from the mantle in the form of hypothetical fluid flows. The huge expansion of the water vapor released during the explosion led to a tenfold larger volume of the resulting scorching clouds compared to the volume of magmas.

In the lower parts of decompression-hardened magma columns, the degree of melt crystallization should be lower. This leads to less crushing and to the formation of plastic breccias. Ignimbrites that occur during the explosive disintegration of decompression-hardened acid magmas are of this origin [11]. The continued release of gases from the viscous debris after the explosion leads to the appearance of a gas “cushion” at the base of the scorching clouds and to their spread over a huge distance. Due to the very high content of acidic rocks in the lithosphere, the volume of acidic magmas formed during their frictional melting can reach thousands of cubic kilometers. It is obvious that decompression solidification during the rise of such a large volume of magmas can lead to catastrophic volcanic explosions, causing environmental disasters of a planetary scale, as in the explosion of the Tebo volcano in Indonesia. Such catastrophic eruptions can occur in the case of intense tectonic deformations of a large volume of acidic crust.

Usually, the increased values of the strontium isotope ratios in subduction igneous rocks (up to 0.7226 in acid volcanites of Peru) are due to the large accumulation of radiogenic strontium over a long time (more than a billion years) of the existence of Early Precambrian acid rocks in the continental crystalline crust before the period of their frictional remelting. This and the proximity of the composition of subduction acid magmatic rocks to the Early Precambrian confirm the frictional origin of subduction magmas. This proximity is not due to the formation of Early Precambrian rocks in these environments, as is usually assumed, but to the occurrence of subduction magmas by melting the crystalline crust. The presence of sometimes high-potassium varieties of subduction basic rocks is probably associated with the processes of high-pressure fractionation of the resulting magmas.

It is obvious that in the oceanic regions, the bodies of the basic rocks of predominantly tholeiitic composition in the rising matter of the superplumes should melt under the influence of decompression and frictional heat release and form the basic magmas. This explains the massive spreading of basalts in these areas. The rise of magmas from each melting body of the basic rocks in the mantle must have led to the formation of seamounts or islands on the ocean floor. Their abundance in the abyssal oceanic regions indicates the existence of a large number of bodies of the basic rocks in the mantle. The change in time in the islands of tholeiitic magmatism to alkaline magma indicates the processes of fractionation of magmas at the deep stages of ascent.
The lithophilic components accumulated in the residual melts during the fractionation of the magmatic ocean, so their contents in the igneous rocks mainly reflect the composition of its differentiates, the melting of which led to the formation of magmas. The lowest concentration of them in the basalts of the mid-Ocean ridges is due to the formation of their magmas by melting the earliest differentiates of the magmatic ocean. Their increased content in Early Precambrian and subduction rocks is associated with the emergence of their magmas from the differentiates of the late ocean, in which meltophilic components accumulated during fractionation processes. The presence of early phenocrysts indicates the non-superheatedness of almost all magmas and contradicts the widespread assumptions about the relationship of variations in the contents of secondary components in them with the processes of assimilation of the host rocks. The high viscosity of magmas does not agree with the assumptions about the wide spread of their mixing processes.

4. Conclusions

Thus, taking into account the data on hot heterogeneous accretion of the Earth allowed us to develop a fundamentally new model of magma formation. There are four main mechanisms of their origin: 1) by lifting melts from the magmatic ocean (primary and primary-residual magmas of ancient platforms); 2) as a result of decompression melting of solidified differentiates of this ocean in surfaced plumes (decompression-plume magmas of traps, rifts, oceanic regions); 3) by mainly frictional remelting of these differentiates in zones of intense tectonic deformations (frictional magmas of subduction, collision, and partially oceanic regions) and 4) as a result of fractionation in magma chambers under conditions of different depths (secondary-residual magmas of late phases of magmatic complexes of different environments).

The main reason for the diversity of terrestrial rocks and the evolution of magmatism is magmatic fractionation, and not the separation of smelts from poorly submerged rocks. This is due to the billions of times lower viscosity of magmas compared to these rocks. The Earth evolves directionally and irreversibly due to cooling.

References

[1] O. Y. Schmidt, “Origin of the Earth and the planets”, M.: AS USSR publishing house, 1962.
[2] A. E. Ringwood, “Origin of the Earth and Moon”, New York, Heidelberg, Berlin: Springer Verlag, 1979.
[3] V. S. Shkodzinskiy, “Global petrology according to modern data on hot heterogeneous accretion of the Earth”, Yakutsk: Publisher SVFU, 2018.
[4] O. A. Bogatikov, C. V. Bogdanova, and A. M. Borsuk, “Magmatic rocks. Evolution of magmatism in history of the Earth”, M.: Nauka, 1987.
[5] N. L. Dobrezov, “Fundamentals of tectonics and geodynamics”, Novosibirsk: NSU Publishing house, 2011.
[6] L. N. Salop, “Geological development of the Earth in the Precambrian”, Leningrad: Nedra, 1982.
[7] R. T. Dodd, “Meteorites: Petrology and Geochemistry”, M.: Mir, 1968.
[8] M. S. Bukowinskii, “Taking the core temperature”, Nature, N 6752. P. 432–433, 1999.
[9] O. G. Sorohtin O.G., “Evolution of the Earth in Precambrian”, M.: MGU, 2002.
[10] D. H. Green, “The composition of basalt magmas as a criterion for their origin during volcanism”, Petrology of igneous and metamorphic rocks of the ocean floor, M.: Mir. P. 242–258. 1973.
[11] V. S. Shkodzinskiy, “Phase evolution of magmas and petrogenesis”, M.: Nauka, 1985.
[12] N. T. Arndt, “The separation of magmas from partially molten peridotite”, Carnegie Inst. Wash. Yearb., vol. 76. P. 424–428, 1977.
[13] V.S. Shkodzinskii, “Magma genesis as result of hot accretion of the Earth”, Vestnik Geonauk IG Komi NZ, N 2. P. 6–14. 2019.