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Komatiites: issues of geodynamics and metallogeny

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Abstract. In the current paper the authors make an attempt to provide a theoretical basis for regular features of enrichment of komatiites in the present-day subequatorial part of the Earth with gold, nickel and platinum group minerals. The authors suggest that Archaean komatiitic greenstone belts formed mostly in the subequatorial area under significant overheating of the mantle at that time. The paper suggests and describes in detail a possible mechanism of these processes. According to it, komatiitic magmas were enriched with siderophile and chalcophile elements during a gradual melt of the “cold” substance of the primary Earth. It melted along the equator due to the tidal effect of the Moon on it. In the Archaean the Moon was much closer to the Earth than nowadays, and its orbit was near the Roche limit. It considerably increased the tidal interaction of the two planets and provided overheating of the Earth’s equatorial belt. Therefore, more heated areas must have had melts with high clarkes of protocristallization elements and lower clarkes of concentration. It inevitably affected specific metallogenic features of produced komatiitic magmas and genetic diversity of deposit types in these areas. This paper corroborates the idea that the drift of the continents did not provide their chaotic movement along the mantle surface in the Earth’s history. Continental domains that formed in the subequatorial area in the Archaean are still near it and compose an ancient greenstone belt composed of komatiites.

1. Introduction

Greenstone belts are typical structures of ancient shields. These belts are composed of rocks with an age of 3.8 to 2.6 Ga. They are characterized by a greater thickness of the total section (10-22 km), sharp prevalence of volcanites over sediments, widespread komatiite-toleite and schist-jaspilite associations, homodromous volcanism and turbidite sedimentation. There are also a number of low-temperature facies of metamorphic changes in rocks, which are zonally arranged. One of specific features of greenstone belts is the komatiitic magmatism that clearly indicates the evolution of the mantle temperature regime in the period, when the Earth’s first supercontinent started to form. The spatial heterogeneity of its occurrence is the most important fact, indicating different degree of the mantle heating and predetermining a number of regular metallogenic features. As stated earlier [1], Archaean greenstone belts can be classified into two types, according to their composition and relative abundance of volcanogenic rocks. The first type is characterized by abundant lavas of komatiitic and high-magnesium basalts (up to 60-70 %). The second type is characterized by associations of toleitic basalts, andesites and rhyolites with a minor amount or absence of komatiites. We linked this difference to the formation of the first-type belts in conditions of the more overheated Archaean mantle. It was also noted that komatiitic magmas of Archaean greenstone belts that formed in conditions of the more overheated Earth’s mantle were rich in elements more typical of the mantle, i.e. Ni, Cr, Mg, Co, Au, PGE (standing in the



beginning of the “mantle row”, according to A.I. Perelman [2]). It provided formation of associated major deposits of gold, nickel and platinoids. In the current paper the authors attempt to provide a theoretical basis for these regular features.

2. Results and discussion

Temperatures of komatiites formation [3] correlate with their amounts in sections of greenstone belts of the time. In the Earth’s interior, there was a thermal convection of the Bénard cells type. Cores of future continents formed above its downward flows. It is known that at the Archaean stage of the Earth’s evolution, the primary substance of the mantle was overheated, melted down and differentiated. A number of papers are dedicated to corroborating this hypothesis [4-6]. Therefore, we will skip through its detailed description. We will mention only, that according to different sources, overheating of the mantle was about 300-400 °C at that time compared to the present-day settings, and in some epochs (at the Archaean-Proterozoic boundary) it was up to 550° C (Fig. 1). These values are average, as well as parameters of the present-day temperature regime of the Earth’s mantle. They provide just a general view on the nature of the Earth’s lithosphere evolution, not specifying it at the regional level.

If we refer to the present-day concepts of the Earth's structure in the Archaean (Fig. 2), we can see that the partly melted mantle layer encircled the Earth along the equator, while its central and polar areas were composed of a cooler solid substance of regolith. This idea is based on the concept of the “cold” Earth formation from a protoplanetary cloud and its gradual heating by generated inner energy and the energy of the Earth-Moon system interaction [6]. Meanwhile, tectonic activity of the Earth in the Archaean followed the zonal pattern of melting of the Earth’s substance [4]. In the Paleoarchaean, this activity was in a narrow equatorial belt only. In the Mesoarchaean, this belt extended to the temperate latitudes. By the late Neoarchaean, after the Earth’s core had separated, tectonic activity of the Earth engaged the whole mantle. Therefore, cores of future continental massifs might have formed only along the periphery of the active tectonic belt. Upward convective flows poor in ore elements were abundant in the centre of the active tectonic belt. At that time, convective processes in the mantle were associated with emission of Fe and Ni melts and their transition to the lower mantle lens (Fig. 2). Later, at the turn of the Archaean and Proterozoic, these melts formed the Earth's core of the present-day type [6].

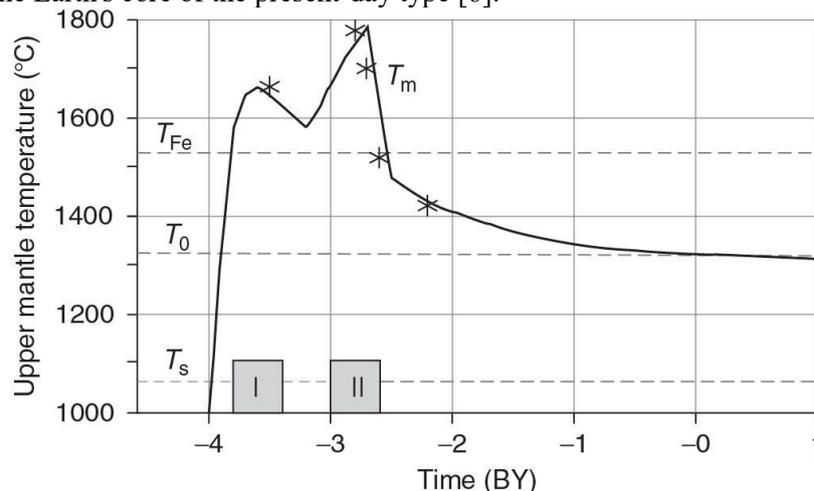


Figure 1. *Temperature of the Archaean upper mantle estimated for the surface (in degrees Celsius) [6]: $T_s = 1060$ – temperature of the mantle substance solidus; $T_0 = 1320$ – temperature of the present-day mantle estimated for the surface; $T_{Fe} = 1530$ – temperature of Fe melting under common conditions; asterisks indicate temperatures of basalts and komatiites, according to petrological data [6]; I–II epochs of overheated komatiite lavas flows, according to V.I. Kovalenko et al. [7]*

In the Proterozoic and Phanerozoic, most of the ore siderophile elements from the mantle were gradually transported to the Earth's core. As a result, the ore potential of endogenic magmatic formations decreased. Most of the siderophile elements of this age are associated with the secondary activation (recycling) of Neoarchaean and early Proterozoic ore-bearing formations [6].

At the same time, the significant overheating of the mantle (Fig. 1) caused thermal convection of the Benard cells type in the Earth's interior. In the Earth-type, but still idealized environment, convection cells occur as oval in plane, cylindrical formations with an upward flow in the centre and a downward flow along the periphery (Fig. 1).

According to the concept that our planet formed from a cloud of cold gas and dust, the primary substance of the Earth had a markedly ultrabasic composition with the silica content of about 31 %, but the Fe content was up to 13.2 %, and FeO was almost 24 % [4]. Besides, the primary substance of the Earth had increased contents of many siderophile and chalcophile elements, such as nickel, chromium, platinum, copper, lead and other polymetals, that later went down into the Earth's core. The substance rich in these elements was transported to the mantle by the mechanism of the tectonic-magmatic erosion. However, we should take into account the fact that under the maximal overheating of the mantle this matter was melted and transferred to areas of mid-oceanic ridges of Archaean oceans. Here, it enriched the produced basic-ultrabasic crust with the above mentioned elements. In a “colder” environment, some substance remained in restite and was absorbed by the core substance in the lower mantle.

Therefore, the enrichment of the mantle seems to be heterogeneous, because the peripheral proto-oceanic crust could contain a lower amount of the ore component, while the part turned to the equatorial area could have more of it. When the proto-oceanic crust appeared in areas of torsion or hummocking, it was partly melted and differentiated. Thus, germs of future continents originated (Fig. 2). It is known that parameters of convective cells of the mantle have strict physical constrains. Its dimensions cannot increase critical values. This pattern is described by a simple equation $L=H\sqrt{2}$, where L- length of a cell, H- thickness of a cell. Therefore, there should be at least two meridionally conjugated cells in the Meso- and Neoarchaeon, when the mantle lens became wide enough and approached high-altitude areas. The total amount of cells in the whole mantle lens of the Earth could be 6 to 10.

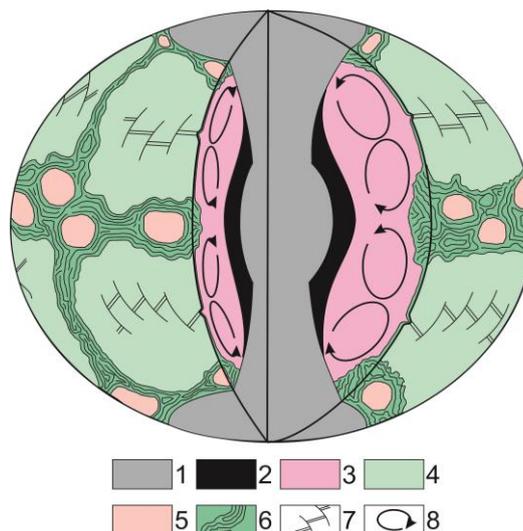


Figure 2. *Structural model of the Earth in the late Archaean. 1- primary substance of the Earth; 2- melts of iron and its oxides (core substance); 3- depleted mantle poor in iron, its oxides and siderophile elements; 4- proto-oceanic crust; 5- continental crust; 6- areas of proto-oceanic crust torsion and continental crust origination that later produced granite-greenstone areas; 7- mid-oceanic ridges; 8- direction of convective flows in the mantle*

According to this scheme, future continents should have originated above upward flows of the mantle, producing three sublatitudinal groups. The central group is an equatorial group of continents, two peripheral groups are the northern and southern ones.

Since in the Archaean the Moon rotated around the Earth in the equatorial belt in a much closer orbit (close to the Roche limit), the whole tidal energy was accumulated along the line of its rotation, turning into the thermal energy. Its main part went to heating and expanding of the mantle lens. This process could provide temperature heterogeneity in the interior of the young Earth. Strong tidal effects of the Moon were just some kind of a trigger that launched the tectonic activity of the Earth and provided melting and differentiation of its interior. The mechanism of zonal differentiation of the Earth's substance with separation of melted Fe from silicates was actually the main source of the gravitational energy that fed the tectonic activity of the Earth and heated its mantle in the Archaean. Noteworthy, the whole substance of the mantle was cooled by the primary substance at the flanks of the Archaean active tectonic latitudinal belt and considerably heated in the equatorial belt (Fig. 2).

There was no cooling of this kind at the bottom of the mantle belt (closer to the centre of the planet), since its matter was separated from the primary substance of the Earth by a layer of melted Fe and its oxides (future substance of the Earth's core). According to our estimates, the temperature range of the mantle in the equatorial and periphery areas might be up to 350-400°C. It is quite a significant factor that governs magmatic processes associated with the formation of the continental and proto-oceanic crust of the time. It could be the reason for a non-uniform genesis of Archaean metallogenic provinces, areas and belts in time and space.

According to S.A. Svetov [3], late Archaean komatiites crystallized in the world's greenstone belts within a temperature range of 1465-1880° C, which proves our conclusions. However, it is necessary not only to estimate the temperature of the komatiites crystallization, but also to consider parameters of melted magmas in their relation to basic volcanites. Hence, areas where komatiites are rare and compose a minor part of the section of greenstone belts should be conditionally considered “cold”, despite high temperature of their crystallization. Thus, it is reasonable to correlate this statement to our knowledge of the continental drift in the post-Archaean period and to define what location domains of the continental crust, containing different types of komatiites, occupied in the structure of ancient supercontinents. We used the most reliable paleodynamic reconstructions [8-13 and some other authors]. Notably, the younger the supercontinents, the more reliable their paleo-reconstructions of in the Earth history are. Four supercontinents that formed in the time span of 2.6 to 0.2 Ga are known. Three of them, i.e. Pangea (0.23 Ga), Mesogea (Rodinia) (1.05 Ga) and Megagea (1.84 Ga) have been reconstructed using paleomagnetic and geological data. The ancient supercontinent of Monogea (Pangea 0, according to V.E. Khain) (~2.6 Ga) has been reconstructed based on geological data only.

Noteworthy, paleomagnetic data on Archaean rocks are rather unreliable and contradictory. It may be linked to the fact that the nature of the geomagnetic field at different stages of the Earth's evolution is still unclear. Presumably, it was toroidal, and not dipole at that time. However, we know that the surface of supercontinents was covered by glaciers in the time range of 2.5-2.4 Ga, which is known in literature as the Huronian Glaciation. Therefore, if there were a supercontinent, its central areas should be covered by glaciers. Finds of tillites and tilloids of the time help to reconstruct the shape of the required supercontinent. However, the Archaean-Proterozoic boundary is marked by powerful collisions between crustal domains. They predetermined the mosaic-like appearance of ancient formations, which was also used to reconstruct Monogea. Figure 3 shows the obtained results.

Analysis of the paleo-geodynamic reconstructions shows that the above stated conclusion can be enhanced. Thus, we can assume that the present-day location of continental areas formed under greater overheating of the Earth's mantle reflects the location of the paleo-equator in the Archaean (Fig. 3). It is clearly seen that in most cases parameters of high temperature formation of komatiites [after 3] coincide with their great amounts in sections. Thus, komatiites in greenstone belts of the Yilgarn Craton (Western Australia) compose most part of the section, and the temperature of their

formation ranges from 1790 to 1850 °C. It clearly indicates their formation under considerable overheating of the mantle. Unfortunately, we have no sufficient data on Antarctica, except the fact that late Archaean greenstone belts of this region are not rich in komatiites in sections compared to basic volcanites. Hence, we suggest that they were formed under rather “cold” settings of the mantle at that time.

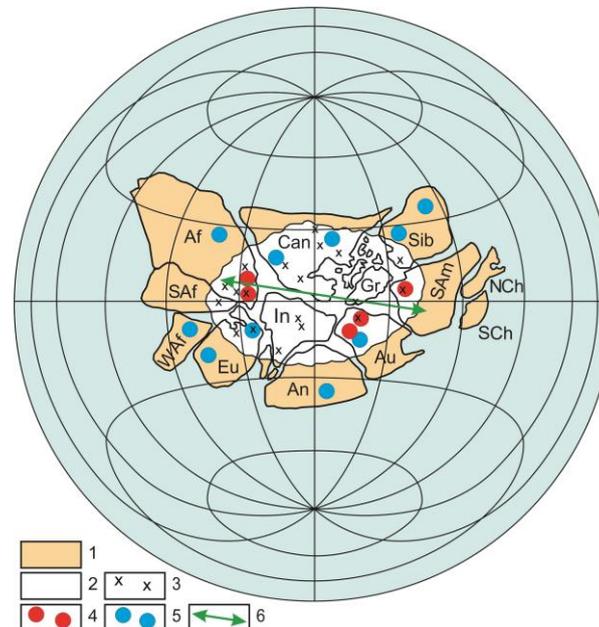


Figure 3. *The supercontinent of Monogea 2.5-2.4 G ago [6]. 1 – areas of the continental crust, 2 – area covered by the Huronian glaciation, 3 – present-day finds of tillites and tilloids, 4 – areas of the crust formed under greater overheating of the mantle, 5 – areas of the crust formed under lesser overheating of the mantle, 6 – line of the reconstructed Paleoarchaean equator (3.0-2.8 Ga)*

According to the suggested concept, the northern and southern periphery groups of microcontinents should have formed in similar and rather “cooler” tectonic and thermal conditions. Meanwhile, continental-crustal formations in the equatorial area evolved simultaneously under temperate overheating of the mantle and, as a result, enrichment with some ore elements. Thus, they can be united in two major types. We should take into account that the geodynamic bimodal symmetry of the continental plates separation, which is common today, formed back in the Archaean. The present-day symmetry seems to have formed in the late Proterozoic. It is marked by two groups of continents, i.e. Gondwana and Laurasia. Certainly, they could not exist in their modern concept in the Archaean. However, two geodynamic types of the continental crust were still regularly arranged in space.

Analysis of the obtained data provides another important conclusion on the geodynamic settings. Since the late Archaean at least, the formed continental lithospheric plates have been regularly shifted along the Earth and remained relatively stable around centers of their accretion (Fig. 3, 4). We believe that the lithospheric plates marked in red were formed under the anomalous overheating of the Archaean mantle. They still occupy the subequatorial area. The lithospheric plates marked in blue rim them along the margin and reflect conditions of the “colder” environment of the Earth’s asthenosphere of the time.

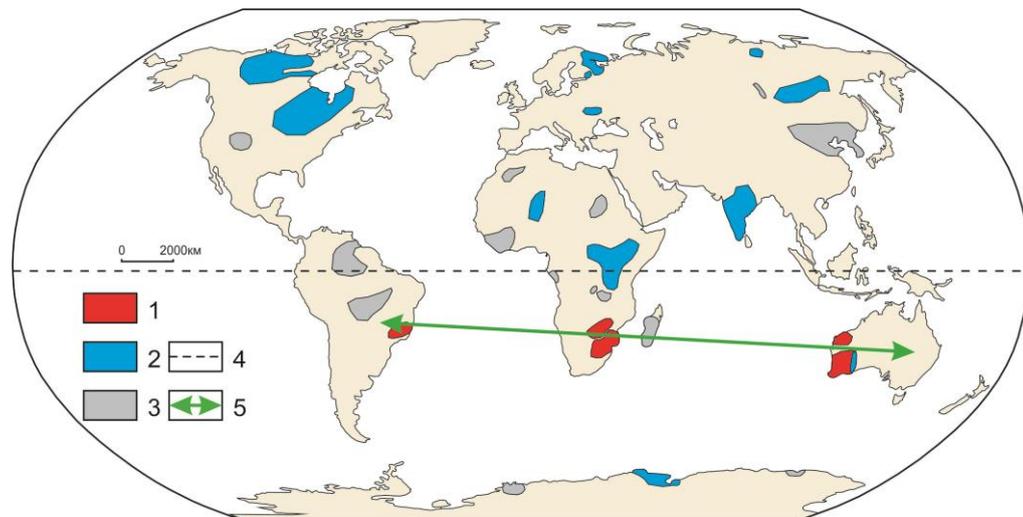


Figure 4. Present-day location of lithospheric plates with a marked line of the Neoproterozoic paleo-equator. Types of greenstone belts (1-3): 1 – formed under conditions of maximal overheating of the mantle matter; 2 – formed under conditions of the relatively “colder” mantle, 3 – unidentified type; 4 – the present-day location of the equator; location of the Neoproterozoic paleo-equator at the moment of the Earth’s first supercontinent formation

3. Conclusions

If you refer to the state strategic planning documents for the development of the Arctic of these five countries, you can see that, in general, the declared goals, objectives and principles of the Arctic states in their generalized presentation coincide (Table 1).

The study of regular features of the Earth’s mantle evolution in the Archaean shows that convective flows produce a chemically homogenous medium, when the Earth’s substance is intensively mixed. More heated areas, which are therefore rich in certain ore components, could occur in this medium. The mantle was regularly enriched with siderophile and chalcophile elements at the periphery of the ever-expanding mantle lens of the Earth, since the actual contact of two media was there. However, it inevitably resulted in cooling of the medium, since the transition of the matter into the melt was accompanied by endothermic processes. On the other hand, more heated areas in the zone similar to the proto-equatorial one should have had high clarkes of protocristallization elements. Therefore, these areas should be characterized by lower clarkes of concentrations and, thus, by greater amount and genetic diversity of types of their deposits in these areas, which is typical of komatiites of different structures [1].

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