УДК 550.382.3:550.382.8 DOI: https://doi.org/10.24028/gj.v47i2.322474

Magnetization of the lithosphere and the upper mantle based on magnetic-mineralogical data

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According to numerous studies, sources of magnetic anomalies in the lithosphere and mantle can have a magnetic-mineralogical nature due to magnetic minerals at mantle depths. The minerals include native iron, which can be brought up from significant depths by mantle melts or formed under the influence of reducing fluids. Mantle plumes play a leading role in these processes as conduits of matter (and energy) from the Earth's outer core to its surface, according to some authors. Metallic iron has been identified in oceanic basalts, traps, and hyperbasites. In subduction zones, the magnetization and increased magnetic susceptibility of lithospheric plates can persist at mantle depths for a long time due to the Hopkinson effect, with the highest value observed for pure native iron. Phase transitions of magnetite, hematite, native iron, and iron-cobalt alloy can occur at mantle depths ranging from 25 to 700 km depending on their Curie temperatures under different thermodynamic regimes of hot and cold lithospheric plates.

Key words: mantle, magnetization, lithosphere, native iron, magnetic minerals.

Citation: Shestopalova, O.Ye., & Drukarenko, V.V. (2025). Magnetization of the lithosphere and the upper mantle based on magnetic-mineralogical data. *Geofizychnyi Zhurnal*, *47*(2), 141—145. https://doi.org/10.24028/gj. v47i2. 322474.

Introduction. Magnetic anomalies of large tectonic structures have wavelengths of several thousand kilometers. Analysis of the induction module of the Earth's Main Magnetic Field (IGRF-12) allowed us to identify its «core» (related to the Earth's core) and «crust-mantle» (lithospheric) components [Orlyuk et al., 2017]. The latter has intermediate wavelengths (between the core and crust anomalies) of 2500—4000 km and suggests sources at mantle depths. More than fifteen stable anomalies have been identified on the Earth's surface. Given the constancy of these anomalies' locations and the slight temporal changes in their intensity, a magneto-mineralogical nature of the sources may be preferred over a current-induced origin.

Discussion. Potential sources of upper-mantle magnetic anomalies may include iron oxides, particularly hematite (α-Fe_2O_3, Curie temperature T_c=700 °C), which is the dominant oxide in subduction zones at depths of 300 to 600 km, magnetite Fe_3O_4 (T_c=585 °C), native iron α-Fe (T_c=760 °C), iron-cobalt alloy (T_c=1121 °C), and iron alloys with nickel and copper formed under highly reducing conditions. The transformation of iron minerals can occur due to reactions of reducing fluids with various iron compounds and rocks according to the generalized scheme: $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$. Changes in the magnetic properties of these minerals may be the reason for contemporary temporal changes in the long-wavelength magnetic anomalies [Orlyuk et al., 2020].

Transformations of magnetic minerals can occur in specific tectonic zones of the Earth's upper mantle, particularly at the junctions of different types of lithospheric slabs, rifts, plumes, and zones of tectono-thermal activation, etc. [Ferré et al., 2014, etc.]. Experimental studies have shown that in zones of lithospheric plates' subduction to mantle depths, their magnetization can be preserved for a long time, and an increase in magnetic susceptibility can be observed due to the Hopkinson effect [Kupenko et al., 2019] near the Curie temperature of magnetic minerals. Magnetic areas of the upper mantle are characterized by temperatures below the Curie temperature of magnetite (for example, in subduction zones, cratons, and areas with ancient oceanic lithosphere). Naturally, pure native iron is characterized by the highest values of the Hopkinson effect.

According to the thermodynamic regime of hot and cold lithospheric plates, the Hopkinson effect in subduction areas can manifest at significantly different depths for the iron-containing substances, depending on their Curie temperatures. In particular, the minerals can undergo phase transitions at mantle depths ranging from 25 to 700 km. They may coincide with the depths of phase transitions of crust-mantle material [Orlyuk et al., 2020]: plagioclase lherzolite to pyroxene (25—40 km); pyroxene to garnet (85—100 km); recrystallization of olivine to the spinel phase (400—420 km); decomposition of silicates into simple oxides (650—690 km).

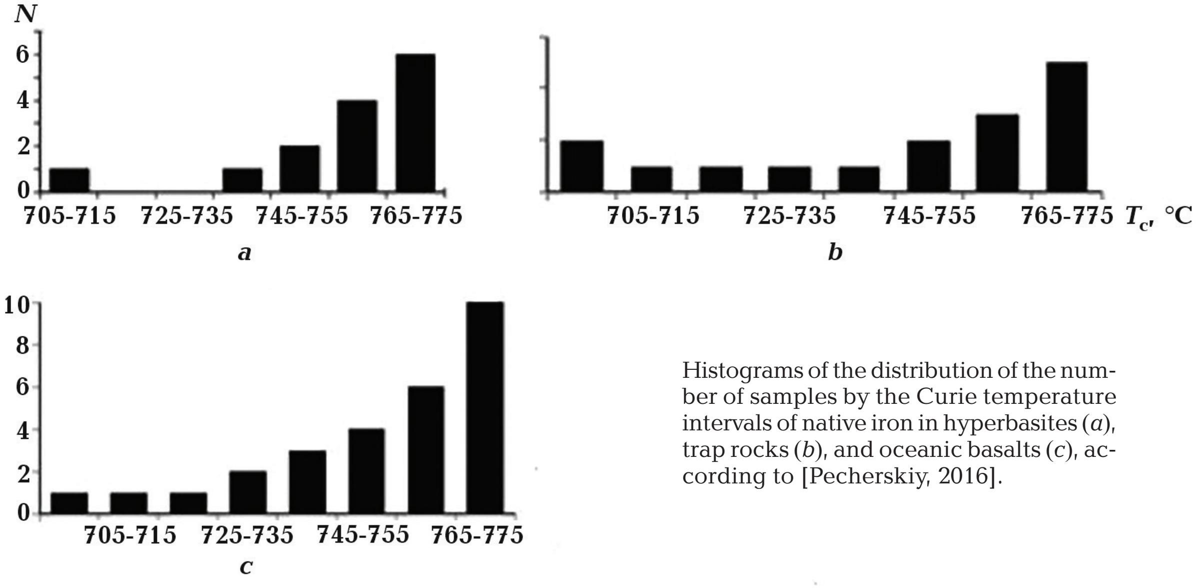
Studies by [Ishii et al., 2019] showed the lower boundary of the upper mantle at a depth of 660 km to be determined by the reaction ringwoodite — ferropericlase+bridgmanite, which is considered a result of the post-spinel transition. The seismic discontinuity occurs within only 2 km, corresponding to a pressure difference of just 0.1 GPa. The obtained results can explain this sharp boundary, and it should be assumed that the distribution of adiabatic vertical flows between the upper and lower mantle can be reflected based on the sharpness of this boundary.

The study of mineral inclusions in superdeep diamonds showed [Kvasnytsa, 2018] that, depending on the composition of the initial substrate, silicates of the upper mantle and transition zone in the lower mantle transform into two mineral associations: juvenile ultramafic (bridgmanite, CaSi-perovskite, ferropericlase) and mafic (bridgmanite, CaSi-perovskite, SiO_2, and Al-phases). The Fe content of the ultramafic mineral association increases with depth, reflecting an increase of iron in the bulk composition of the lower mantle in general [Kaminsky, 2017]. The mafic mineral association is likely formed locally during the recrystallization of subducted lithospheric plates.

According to existing hypotheses [Shestopalov et al., 2018, etc.], the iron in erupted rocks (basalts and hyperbasalts) is brought up from significant depths by mantle plumes that rise from the core-mantle boundary and reach the base of the lithosphere, carrying basic composition melts. Alternatively, it is formed (reduced) in magma under the influence of reducing fluids – hydrogen, carbon, or organic matter, captured by the melts during intrusion. Thus, reducing fluids are derivatives of the deepest horizons of the geosphere (outer core — «D» layer — lower mantle). Mantle plumes lead in degassing processes, acting as conduits of matter (and energy) from the Earth's outer core to its surface and determining the location of the largest metallogenic and oil and gas provinces.

According to seismic tomography [Shestopalov et al., 2018], the uneven distribution of heated zones and flows (plumes) of core-mantle material in the mantle (up to the core boundary) is postulated. These are located at different levels, including reaching the lithosphere. The roots of the plumes are in the liquid core, and their main sources are associated with the «D» layer. The global processes of heat accumulation in the «D» layer are superimposed by ascending hydrogen flows, occluding in practically unlimited quantities by the solid iron-nickel core (with impurities of other metals). A complex chemical composition of the «D» layer is assumed, in which the entire periodic table is present against the background of the predominance of Fe, C, Si, and S, including the incoherent elements. Indicators of the regime of deep degassing processes of the Earth and the composition of superdeep fluids propose the allocation of a new genetic type of natural mineral formation, the so-called prigozhinites, which can form, among other things, in the zones of crushing of crystalline rocks.

[Pecherskiy, 2016] determined that particles of metallic iron are present in xenoliths of upper mantle hyperbasites, oceanic basalts, and trap formation basalts. Most particles have the same shape regardless of origin, indicating uniform primary magmatic conditions for their formation. The global distribution of native iron without nickel impurities but with silicon, aluminum, and magnesium impurities is associated with upper mantle and crustal rocks. The main contribution to the magnetization of hyperbasites is made by iron-containing paramagnetic minerals, such as olivine and pyroxene. The Curie temperature of iron was obtained for 14 samples out of 50, with a concentration of 0.0001—0.0003 %. In trap-formation rocks, metallic iron is present in subintrusive bodies. Its concentration varies from 0.0001 to 0.0055 %. The distribution of Curie points is similar to their distribution in hyperbasites and ranges from 705—775 °C, with a maximum in the range of



Histograms of the distribution of the number of samples by the Curie temperature intervals of native iron in hyperbasites (*a*), trap rocks (*b*), and oceanic basalts (*c*), according to [Pecherskiy, 2016].

765—775 °C. The distribution of metallic iron in oceanic basalts does not differ from other terrestrial rocks; however, iron particles form before the lava eruption under conditions like those for hyperbasites and traps. Metallic iron was identified in half of the samples studied with a 0.0002—0.0018 % concentration. An increase in the number of samples with a Curie temperature (T_c) from 700 to 770 °C and a maximum within the range of pure iron is observed. Pure iron in oceanic basalt samples was identified in 31 % of cases, in traps — 36 %, and in hyperbasites — 75 % (Figure).

By the precise mineralogical studies of foreign authors, rims of other iron-containing minerals are often observed around grains of native iron. For example, iron droplets from Ovifak (Greenland) have ilmenite shells. In Mellemfjord (Disko Island), complex structures of iron growth with magnetite are known [Shestopalova, Drukarenko, 2024]. In gabbro-dolerites (Siberian Traps), grains of native iron have several different shells; this indicates frequent changes in the geochemical environment of mineral formation. In our opinion, this is highly relevant in studying ore minerals and requires further studies using precise research methods.

Conclusions. 1. Sources of magnetic anomalies in the lithosphere and mantle can have a magnetic-mineralogical nature due to magnetic minerals at mantle depths, including native iron. Native iron can be brought up from significant depths by mantle melts or formed under the influence of reducing fluids. Mantle plumes lead in these processes as conduits of matter (and energy) from the Earth's outer core to its surface. 2. In subduction zones, the magnetization and increased magnetic susceptibility of lithospheric plates can persist at mantle depths for a long time due to the Hopkinson effect, with the highest values observed for pure native iron. 3. Metallic iron is present in oceanic basalts, traps, and hyperbasites. 4. Native iron often has shells of other iron-containing minerals requiring precise research methods for further study.

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Намагніченість літосфери та верхньої мантії за магнітно-мінералогічними даними

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Згідно з численними дослідженнями джерела магнітних аномалій літосфери та мантії можуть мати магнітно-мінералогічну природу за рахунок існування на мантійних глибинах магнітних мінералів, зокрема самородного заліза, яке може виноситися зі значних глибин мантійними розплавами або утворюватися під дією відновлювальних флюїдів. Мантійні плюми як провідники речовини (та енергії) від зовнішнього ядра Землі до її поверхні відіграють провідну роль у цих процесах на думку деяких авторів. Присутність металічного заліза визначено у зразках океанічних базальтів, трапах і гіпербазитах. У місцях занурення літосферних плит на мантійних глибинах тривалий час може зберігатися їх намагніченість, а також може спостерігатися підвищення магнітної сприйнятливості за рахунок ефекту Гопкінсона з максимальними величинами цього ефекту для чистого самородного заліза. За різних термодинамічних режимів гарячих і холодних літосферних плит фазові переходи магнетиту, гематиту, самородного заліза та сплаву заліза та кобальту залежно від їх температур Кюрі можуть відбуватися на мантійних глибинах в інтервалі 25—700 км.

Ключові слова: мантія, намагніченість, літосфера, самородне залізо, магнітні мінерали.