Transmagmatic fluids and magmatogenic ore formation. A problem of mantle ore sources

D.S. KORZHINSKII, N.N. PERTSEV and I.A. ZOTOV

Institute of Ore Deposit Geology, Petrography, Mineralogy and Geochemistry, Moscow (USSR)

With 2 figures

Abstract: It is supposed that large magmatogenic ore deposits and ore fields are generated by flows of transmagmatic mantle fluids.

Magmatogenic ore deposits as magmatic ones and postmagmatic (scarn, porphyric, rare metallic, greisen and massive sulphide) deposits are closely connected in space with magmatic bodies. The composition and genetic type of ores of these deposits naturally depend on the composition of magmatic masses. It is considered that the sources of ore-mobilizing and ore-forming fluids are volatiles released during magma crystallization, i.e. residual magmatic fluids and to some degree solutions of wall rock suites.

Admitting the participation of these fluids in the genesis of ore deposits, we consider that they do not make the main contribution to the formation of large and unique ore fields and deposits at least because there is no direct connection between the size of ore deposits and ore productive magmatic bodies. Besides, there is no strict dependence of the size of ore units on the contents of ore components in magmas. Usually on large deposits magmatic bodies are not of big size and the contents of ore elements in them are often below clark quantities (Ljakhovich, 1968; Tauson, 1977). Ore productivity of magmatic massifs does not strictly depend on the contents of ore components in wall rock suites and their lithology.

For the last ten years there have appeared some publications aimed at overcoming the difficulties in magmatogenic hypotheses. In these papers the geologists offer an idea of forming the ore mineralization by mantle fluids connected paragenetically (through a common source) with one or another type of magmatism (Barsukov et al., 1975; Ovchinnikov, 1973; Ozerova, 1978; Ostrovski et al., 1977; Favorskaja & Ljakhovich, 1977; and others). A considerable age and space separation between mantle fluids and magmas is allowed.

The hypothesis in question also offers the connection between ore masses at least some of magmatogenic mainly large deposits and mantle fluids of different levels. According to this hypothesis there is a tight space compatibilitiy of mantle fluid flows and magmas. It is assumed that fluids and magmas have a common source and magma columns ascending from the depth serve as fluid conductors. The interaction of these going through magma transmagmatic fluids with magma and wall rocks in changing physico-chemical medium results in the formation of ore concentrations.

The basis of this hypothesis constitutes the following statements: 1) Saturation of mantle by some fluid components; 2) Presence in magma of independent fluid phase causing magmatic replacement process, 3) Higher fluid permeability of magmas as compared with pressed solid rocks of lower parts of the Earth's crust and of the mantel; 4) High reduction character of mantle fluids in which metals are readily dissolved.

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Now we shall look into these statements in detail.

1) The research of mantle rock xenoliths in abyssal magmas and magmatic masses themselves carried out in different countries convincingly shows that the mantle contains a considerable quantity of volatiles the evidence of which is the inclusions of phlogopite, carbonates and sulphides in mantle rocks as well as the presence of admixture of nitrogen in diamonds. The above statements are also proved by active fluidic changes of kimberlite and peralkaline magmas, by mantle source of isotopes of carbon and oxygen incarbonatites. It is absolutely evident that a considerable part of the mantle gases accounting for no less than 0.5–1.0 wt/% of lava material are of mantle origin. Many investigators are inclined to consider that there is a convection of fluid phase in mantle (Sobolev, 1978; Anonymous, 1980); stenosphere appears to be rich of carbon dioxide gas (Green, 1972; Schulling, 1979); metasomatism is developed in solid rocks of the mantle (Anonymous, 1980) and metallic hydrids are present in the mantle (Marakushev & Perchuk, 1972; Stevenson, 1977). The ground facts of these assumptions cannot be explained without an active participation of volatiles in the mantle processes.

Gas inclusions in minerals of mantle magmatic rocks testify to fluid saturation of magmas too. The analyses of the contents of these fluid inclusions give a large variety of gas relations, very frequently with sharp predominance of reduced gas forms (H_2, CO) and considerable share of nitrogen, against oxidized ones (H_2O, CO_2). From these gases only H_2O and in alkaline melts CO_2 as well dissolve highly in magmas. A considerable share of hardly soluble gases in magma phenocrysts and volcanic emanations of primary stages of eruptions (Menjailov et al., 1980) testify to the usual presence in abyssal magmas of fluid bubbles enriched by components insoluble in silicate melts.

2) The existence of fluid flows in magmas is confirmed by some geological phenomena which can be observed in contacts of many magmatic bodies. One of them is a magmatic replacement of exocontact rocks which are subjected to metasomatism with the changes of their contents getting closer to magma and subsequent melting. This process is impossible without the participation of transmagmatic fluids. It cannot be identified with anatexis because melts formed in the place of changing rocks are uniform in composition and refined from impurities of replaced rocks. Magmatic replacement phenomena are known in connection with magmas of wide range composition forming small and large bodies in abyssal and subvolcanic conditions. At the same time these massifs are often characterized by evident features of intrusion of magmas.

Magmatic replacement accompanied by metasomatism of magmatic stage is clearly revealed in contacts with wall rocks the content of which greatly differs from magmas. Thus, the replacement of magnesian marbles by granite magmas is carried out by means of preliminary conversion of marbles into zonal magnesian scarns.

3) A swift rise of diamond-bearing kimberlite magmas from the mantle to the surface is obviously carried out along deeply penetrating fault zones. The pressure in fault zones goes down which gives rise to magma and independent fluid phase at some levels of the mantle. To the surface free gases ascend along the melts filling fault zones as the permeability of solid rocks is low at these depths. In crystal rocks pore fluids are oversaturated because of high pressure and must mineralize any large cavities. The calculations showed (Epelbaum, 1980) that gases will, apparently, move quicker along magmatic melts than even along friable sedimentary rocks.

The experiments carried out by Letnikov et al. (1978) proved that the speed of gas bubbles passing through silicate melts is high due to the appearance of convection flows and concentration of fluids in cord-like cavities (Fig. 1).

The ratio of gases in fluid bubbles must considerably differ from the ratio of volatiles dissolved in magma. The fluid phase is enriched by hardly soluble gases and lacks gases

Fig. 1. Experimental quenched structure with $H_2O + CO_2$ blowing through the granite melt. Foto from Letnikov et al. (1978, Fig. 15).

readily soluble in magma. The distribution of gases between magma and fluid depends on the temperature and pressure. Thus as fluid phase moves upwards along magma column, the phase composition must change because of redistribution of volatile components between fluid and magma. Oxidation of fluids in upper parts of the magmatic column may cause the increase of water share in fluid as well as in magma.

4) It is generally accepted that more reduced conditions exist in the mantle than in sedimentary layers of the Earth's crust. Divalent chrome in mantle silicate minerals and predominant nitrogen-hydrogen gas in mantle xenoliths from kimberlites testify to the above statement. Hydrogen inclusions in minerals of abyssal xenoliths from Kamchatka basalts (Kutiev & Kutieva, 1975) is another evidence of this point of view.

Mantle gases are apparently more reduced than crust fluids. In connection with this problem two questions arise. What is the solubility of ore metals in reduced gases and how do they move to upper levels of the Earth's crust?

The information on metal solubility in anhydrous and reduced gaseous medium is very limited in geological literature. One knows from available data on general and analytical chemistry that in the above conditions exist a large variety of easy volatile compounds of ore and non-ore elements which are stable at high temperatures. Some hetero-organic compounds and some of carboxides, cyanides, rhodanates, chlorides, nitrides belong to such gases. Without going into detail, it is worth mentioning that similar compound may transport useful metals to the Earth's crust for the formation of ore deposits.

At the same time it is evident that these volatile compounds cannot move through the Earth's crust rocks as relatively high oxidation and water saturation of the rocks prevent the stability of these gases. But such fluids are stable in magmas which generated in reducing mantle environments or under the influence of reduced mantle fluids. They can move up the magmatic columns to upper layers of the Earth's crust without oxidation or hydration. Magmas protect fluids from oxidating by crust material because small endocontact portions of magmatic body melt only interacting with wall rocks.

Thus the transmagmatic fluid flows mentioned above can transport ore metals for formation of deposits. We may suppose that only some gases, which are water and oxygen inert, such as mercury vapor, inert gases, carbon dioxide, and similar compounds can move through the Earth's crust avoiding magmas.

Theoretical research (Korzhinskii, 1970) and experiments (Kuznetsov & Epelbaum, 1978) have shown that while temperature goes down, acidity of fluids increases because of partial condensation of easy vapouring components of strong acids. It results in leaching bases out of magma and changing the composition of eutectic melts. Magmas undergo debasification and disseminated liquid sulphides are generated in basic and ultrabasic magmas with low contents of alkali metals (Korzhinskii, 1979). Similar processes of changing magma composition as a result of fluid-melt interactions have been named by D.S. Korzhinskii as metamagmatism.

Another case of metamagmatic interaction is connected with oxidation of reduced transmagmatic fluids when penetrating into the endocontact melts of intrusives. It was already mentioned, the melts of these parts of massifs with the fluid flows are formed by means of magmatic replacement of wall rocks from which magma usually inherits high oxidizing features. As a result of mantle fluid oxidation and decay of gas complexes of metals, endocontact magmas are enriched by ore compounds sometimes to economic levels. Sulphides in trap intrusions and probably rare metal mineralization in alkali granites are the examples of the above statement. Apparently it accounts for frequent enrichment by ore metals of endocontact rocks of ore productive massifs and increase of metal dispersion there.

Magma liquid segregations caused by fluid oxidation can provoke stratification in gently sloping contacts of some granitic massifs.

During fluid oxidation heat must excrete which delays crystallization of magmas and provides fuller completion of their crystal gravity differentiation. The differences in morphology, matter composition, and internal structure of magmatic bodies are connected with irregular treatment of massifs of single magmatic complex by fluid flows.

The above described processes are clearly displayed in basaltic trap intrusions of copper-nickel sulphide deposits of the Eastern Siberian platform (Zotov, 1979, 1980). The Talnakh and Norilsk ore fields which have very much in common are located here. The sulphide-bearing complex of these ore fields is composed of three type intrusions (from older to younger): Lower Talnakh, olivine-bearing leucogabbro, and Upper Talnakh. Intrusive types in question undoubtedly belong to the single sulphide-bearing complex which is confirmed by their tight space connection, equal geostructural position, and presence of liquation sulphides in all three types. The mean compositions of Lower and Upper Talnakh intrusions are very close (wt/%): SiO_2 43.40 and 43.95; Al_2O_3 13.10 and 14.03; FeO 2.54 and 4.23; Fe_2O_3 9.24 and 8.88; MgO 14.93 and 10.40; leucogabbro is enriched by SiO_2 3 %, Al_2O_3 6 %, CaO 2 %, at 1 % of each K_2O and Na_2O, and is unpoverished by the sum of iron oxides on 4 %, MgO 6–10 % in comparison with Talnakh massifs.

All magmatic bodies are localized in periclinal closing of large syncline filled with basalt (trap) lavas. The intrusions slope down at an angle not more than 10° towards the centre of the syncline. Magmatic bodies have sill-like form, they lie subcordantly with sedimentary and volcanic rocks. The width of the bodies does not exceed 1.5 km having the length of some kilometers. The thickness of the intrusions is no more than 450 m and leucogabbro 70 m.

In respect of composition, geological position and interrelationship with wall rock suites the bodies of Lower Talnakh and Upper Talnakh types have very much in common. These intrusions are respectively located one under the other at a distance of not more than 100 m, but practically do not adjoin each other. Contact metamorphic aureoles, thicker in roof in comparison with the floor of intrusions, are developed near magmatic bodies of both types. Asymmetry of aureoles thickness show that metamorphism of wall rocks was caused by magmatic fluids penetrating chiefly into the roof of the massifs. Besides, in the Upper Talnakh intrusions fluids actively moved to the front of replacement.

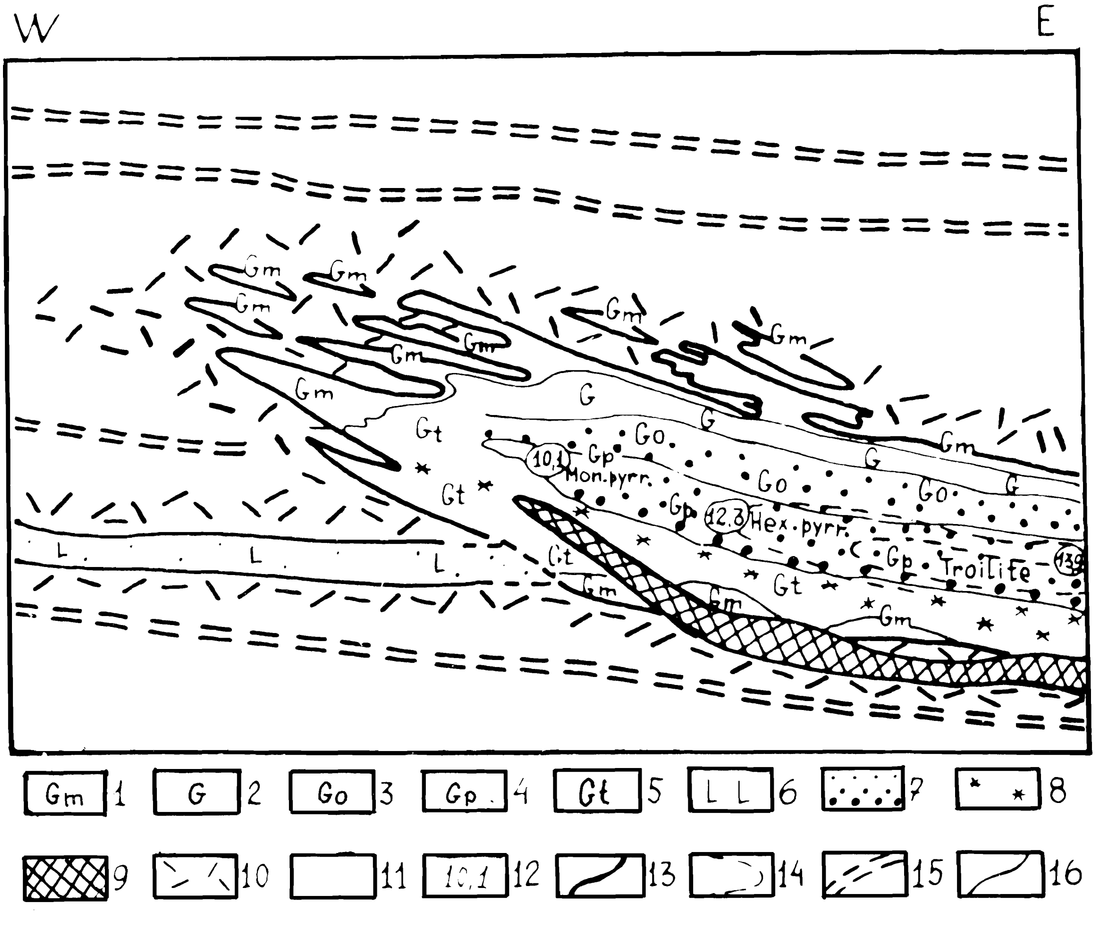

Fig. 2. Schematic section along the Upper Talnakh intrusion (its Kharaelakh branch). Data on the composition of ferrous sulphides and sulphur isotopes in disseminated liquation ores are shown too. 1–5 = gabbro-dolerites: 1 = fine-grained, free of olivine and sulphides; 2 = medium-grained, free of olivine and sulphides; 3 = olivine-bearing; 4 = picritic; 5 = taxitic, olivine-bearing; 6 = leucogabbro; 7–8 = disseminated liquation sulphides: 7 = fine, interstitial and coarser drop-like aggregates (approximate sizes of sulphide drops are shown); 8 = sideronitic aggregates; 9 = massive sulphide ores; 10 = hornfels; 11 = unmetamorphosed wall rock suites; 12 = mean sulphur isotope composition of liquation sulphides (^{34}S in %); 13–16 = contours of: 13 = intrusions and massive ores; 14 = sulphide assemblages with different types of ferrous sulphides 15 = stratigraphic units; 16 = differentiates of intrusions.

In spite of this similarity the compared types of intrusions greatly differ in respect of morphology, crystal gravity differentiation, sulphide content and ore productivity. All economic types of sulphide copper-nickel ores: disseminated liquation sulphides in magmatic rocks, magmatic massive ores and metasomatic ores of exocontacts of intrusions – are connected in space and genesis only with the intrusions of the Upper Talnakh type.

The form of the Upper Talnakh intrusions is very complicated in its front and flank parts because of many apophyses (Fig. 2). Apophyses' compounds differ from composition of Upper Talnakh intrusions as to the absence of liquation sulphides and olivine. Apophyses are not typical of Lower Talnakh intrusions.

The Upper Talnakh intrusions are evidently stratified. Their upper layers are formed by gabbro-dolerites without olivine and sulphides. Below they are replaced by olivine-bearing dolerites and then by picritic gabbro-dolerites. Disseminated liquation sulphides appear in rocks together with olivine. In the upper level they are represented by few small sulphide crystals. Lower sulphides are joined into droplets which are at the beginning rare and small (0.3–0.5 cm in diameter), and then increase in quantity and size (up to 3–5 cm). Some large drops are flat. Most of the large drops are divided on horizontal surface into pyrrhotite in the lower part and chalcopyrite in the upper part. The structural peculiarities of the observed part of the through section of the Upper Talnakh intrusion are undoubtedly caused by sedimentation of liquid sulphide drops and olivine crystals in silicate magma.

The layer of the so-called taxitic gabbro-dolerites is located below the layer of picritic dolerites. The taxites may be described as coarse-grained olivine-bearing dolerites with large star-like aggregates of liquation sulphides which are abundant in the upper part of the layer and disappear towards the bottom. There are no taxitic dolerites beyond the bodies of Upper Talnakh intrusions. In relation to the upper picritic layer the taxites are considered to be younger. In our opinion taxitic gabbro-dolerites have been partly formed as a result of metamagmatic sulphurization of crystallizing trap magmas and partly by magmatic replacement of the exocontact metamorphic rocks. Thus the taxitic dolerites are the result of working of transmagmatic fluids.

Vertical differentiation of the Lower Talnakh intrusions is not as perfect as in ore productive ones. In former olivine crystals are present already in the upper contact of the bodies. In Lower Talnakh intrusions there is no layer of taxitic dolerites. Few sulphides are observed mainly in differentiates enriched by olivine.

The above typomorphic peculiarities of ore productive intrusions of the Upper Talnakh type are directly connected with the genesis of economic mineralization. A detailed petrological research (Zotov, 1979, 1980) has shown that ore productive intrusions differ from other types in intensive work of transmagmatic fluid flows. They account for all geological, petrographic and geochemical peculiarities of the massifs (Fig. 2).

The directed movement of fluid determines the thickness (up to 500 m) of metamorphic aureoles on the front of replacement of the Upper Talnakh intrusions. Many apophyses formed mainly by magmatic replacement are also concentrated there. During this process the first smeltings in rocks of high basicity are presented by low temperature magmas of olivineless dolerites. The terrigenous rocks are replaced by granophyric smeltings of anatectic type on the fore-front. That is why compositions of apophyses naturally differ from mean compositions of the main bodies of the Upper Talnakh intrusions. Genkin et al. (1977) have discovered a change in the sulphur content of sulphides composing the disseminated liquation ores in the Upper Talnakh magmatic rocks. From central and root parts of magmatic bodies to endocontact, front and flank parts the meagre sulphur sulphides (troilite, talnakhite, mooihoekite) give place to sulphides enriched by sulphur, firstly hexagonal pyrrhotite and then monoclinic pyrrhotite, both associated with normal chalcopyrite. This regularity is caused by the increase of the oxidizing potential in these directions. Sulphides are not stable and replaced by magnetite in magmas of apophyses because of low sulphur chemical activity, high temperature and high oxidizing potential there. Abundance of disseminated liquation sulphides in the Upper Talnakh intrusions is connected with the oxidation of transmagmatic fluids near the contact parts of the bodies. Components of dissociated gas complexes caused sulphurization of melts with the formation of liquid sulphide drops which were enriched by Co, Ni, and Cu from fluids. The heat released during fluid oxidation increased the period of crystallization of magma and made more complete gravity crystal differentiation of ore productive intrusions. Kovalenker et al. (1973) have discovered that sulphides of the near-front parts of the Upper Talnakh intrusions are enriched by sulphur light isotope ^{32}S in comparison with sulphides of the root parts of magmatic bodies (Fig. 2). Thus isotope differentiation has taken place in liquid magmas and cannot be explained without flows of fluids going through magmas.

Massive sulphide ores of the Talnakh and Norilsk fields have been formed by ore melts which intruded from depth. Apparently these ore magmas concentrated in the bottom of the intermediate basin of trap magma as a result of sulphurization and sedimentation of the liquid sulphide drops. A similar process has been described above. It has been supposed (Zotov & Pertsev, 1978) that metasomatic ores located in the exocontacts of the Upper Talnakh intrusions have been formed by fluids isolated by sulphide melts.

Certainly the participation of transmagmatic fluids in the formation of magmatogenic ore deposits is not confined by the above example. Shabinin (1969) has shown that some parts of magnetite ores in magnesian scarn deposits were undoubtedly formed by metal from transmagmatic fluids.

There comes to light a perspective of application of this hypothesis to understanding the genesis of some other types of magmatogenic ore deposits. As possible examples we mention the apatite ores in ultra alkali and alkali-ultramafic magmatic massifs, chromites in ultramafic intrusions, rare metal mineralization in carbonatites, etc.

The possibility of application of this hypothesis to postmagmatic ore deposits has been already supposed by Zotov (1980). There is some experience (Zhabin & Gladkih, 1982) in explanation of the genesis of the massive sulphide deposits in the terms of the hypothesis.

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