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MAGNETITE AND ILMENITE SERIES OF THE WESTERN CARPATHIAN GRANITODIS

(2 Figs.)

Abstract: In the submitted paper the author analyses results of field and laboratory measurements of magnetic properties of the Western Carpathian granitoids. These measurements were a decisive criterion which made it possible to divide the granitoids into two contrast series – high-magnetic "magnetite" and low-magnetic "ilmenite". The magnetite series includes magnetic phase of granitoids of the Hodruša-Štiavnica Intrusive Complex, Rochovce, Turčok and Čierna hora Mts. area. The ilmenite series consists of granitoids of the Gemericum, Bratislava Massif, Inovec Mts., Suchý Mts. as well as substantial parts of the Nízke Tatry Mts. and Veporicum.
Because of insufficient amount of measurements, for the time being, we cannot assign granitoids of the Vysoké Tatry Mts., Malá Fatra Mts. and Modra Massif along with Čierna hora Mts. into a certain outer zone of increased magnetic susceptibility.
The employed classification has a genetic importance because it indicates some types of mineralization. High efficiency of field as well as laboratory measurements and possible application of earlier geophysical measurements are a great advantage of the employed method.

Резюме: В предлагаемой статье автор разделил гранитоиды Западных Карпат в главном на основе их магнитных свойств на две серии – высокомагнитную „магнетитную" и слабомагнитную „ильменитовую". В магнетитную серию входит магнитная фаза гранитоидов Годрушско-Штьявницкого интрузивного комплекса и области Роховце, Турчок, Черная гора. В ильменитовую серию входят гранитоиды Гемерикума, Братиславского массива, Иновца, Сухого, значительной части Низких Татр и Вепорикума.
Включить гранитоиды Высоких Татр, Малой Фатры, Модранского массива вместе с гранитоидами Черной горы в внешнюю зону с повышенными данными магнитной восприимчивости нам пока не позволяет низкое количество измерений.
Использованная классификация имеет генетический смысл и показывает на некоторые связи с оруденением. Преимуществом использованной методики является высокая эффективность полевых и лабораторных измерений с возможностью использования существующих геофизических данных.

Introduction

Granitoid rocks have always attracted significant attention of geologists because of their great variability resulting from varied source materials of granitoid magmas, variability of geotectonic settings and origins as well as from wide range of processes giving rise to or affecting differences in composition and possible ore-potential of granitoid bodies in time and space.

This variability is reflected also in a number of various classifications which more or less successfully classify granitoids. Division of granitoids into two genetically different types

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– I (igneous) and S (sedimentary) resulting from partial melting of different source materials has recently become very popular. These two types have been distinguished by Chappel – White (1974) within Australian Paleozoic granitoids on the basis of mineralogical, chemical, physical, field and other criteria.

One of the physical parameters employed by the two authors was magnetic susceptibility. This criterion for division of granitoids was earlier used by Pechersky (1964) and Sukhorada (1972). Later, the criterion was employed also by Romanovsky (1976), Ishihara (1977), Dubinchik – Rozental (1980) and Dortman et al. (1984). Of the above-mentioned classifications, mainly Ishihara's (1977) division of Japanese Mesozoic – Tertiary granitoids into magnetite and ilmenite series has undoubtedly a genetic character.

At present, the granitoid division into I and S-types is being gradually abandoned because its validity is not general, mainly as regards ore potential of granitoids. In the magnetite/ilmenite classification, the relationship between mineralization and the both petrographic series has been studied in much more detail (Ishihara, 1981). Those are the reasons why our contribution is focused on the study of magnetic properties of the Western Carpathian granitoids with their possible assignation into the magnetite or ilmenite series.

Magnetic susceptibility of granitoid rocks

Although magnetic susceptibility ($\varkappa$) values vary substantially in different granitoids and range from values close to zero to values exceeding $100\,000 \times 10^{-6}$ SI units, numerous authors have demonstrated significant regularities in the distribution of these values.

Having studied 1600 granitoid massifs in the northeastern U.S.S.R., Pechersky (1964) divided them into three groups: nonmagnetic ($\varkappa < 630 \times 10^{-6}$ SI units), slightly magnetic ($630-5650 \times 10^{-6}$ SI units) and magnetic ($\varkappa > 5650 \times 10^{-6}$ SI units). He also noted that this division is not based entirely on the chemical composition of the rock and its magnetite content, but also on geotectonic conditions of rock formation, the fact related to some mineralization types. Tin is associated with nonmagnetic-group granitoids, whereas gold accompanies those of the magnetic group.

Sukhorada (1972) studied magnetic properties of Ukrainian shield granitoids and found that their magnetic susceptibility has bimodal distribution, with the minimum value of some 1000×10^{-6} SI units.

Romanovsky (1976), who studied granitoids of the Soviet Far East (700 granitoid massifs), divides them into tin-bearing ones with magnetic susceptibility values below 1200×10^{-6} SI units and granitoids of gold-bearing areas whose magnetic susceptibility exceeds 3600×10^{-6} SI units.

Dubinchik – Rozental (1980) statistically treated magnetic susceptibility values of granitoids from various parts of the U.S.S.R. and classify these rocks as slightly magnetic and magnetic, with the boundary separating these two groups amounting to 500×10^{-6} SI units. The former are assigned by the two authors into the group of batholithoid plutonic granitoids formed at the end of middle and beginning of late stages of tectonomagmatic cycles, whereas the latter are formed at the end of late stages of tectonomagmatic cycles or during the period of tectonomagmatic activation, often located in volcanotectonic zones. The both groups differ from one another in their relationship to mineralization. The group of slightly magnetic granitoids is associated with tin and tungsten, whereas the group of magnetic granitoids is accompanied with gold, zinc, copper and lead.

On the basis of magnetic susceptibility, Dortman et al. (1984) classify individual granitoid formations, according to their source, as upper crustal and lower crustal ones. Much attention has been aroused by Ishihara's (1977) classification dividing Japanese Mesozoic and Neogene granitoids into two contrast series – slightly magnetic "ilmenite" and magnetic "magnetite", the two series being separated by the magnetic susceptibility value of 3600×10^{-6} SI units (Ishihara, 1989, pers. comm). The both the series differ from each other mainly because lower crustal to mantle magmas quickly ascend in a tension setting (subduction zone) with little contamination by crustal rocks and at high oxygen and sulphur fugacities, which is typical of "magnetite" series granitoids. In contrast, "ilmenite" series granitoids originated from upper crustal magmas in a compressive setting, at low oxygen fugacity and were considerably contaminated by surrounding rocks. The different formation conditions also gave rise to different types of associated mineralization.

"Magnetite" series granitoids are associated with gold, silver, copper, zinc, lead and tungsten (scheelite) deposits, whereas "ilmenite" series granitoids are associated with cassiterite, wolframite, beryl and fluorite deposits (Ishihara, 1981).

Applied methods

Analysed samples of the Western Carpathian granitoids have been collected within a regional petrophysical research (Gregor, 1987) and within some partial projects in cooperation with workers of other organizations. During regional research, rocks typical of individual granitoid massifs have been collected (360 samples). The samples have been petrophysically, geochemically and petrographically studied in detail. Magnetic susceptibility has been measured by an apparatus MA-21 at the Kiev State University.

The regional research has been later supplemented by local measurements, mainly in the Malé Karpaty, Tribeč and Nízke Tatry Mts. as well as Veporic/Gemeric contact. These measurements have been carried out by a field apparatus KT-5 (over 2000 measurements) and laboratory apparatus KLY-2 (423 samples), both produced by Geophysics, State company, Brno.

Our interpretations of measured data have been based on the assumption of Dubinchik – Rozental (1980) that each intrusive phase has a small statistical dispersion of magnetic susceptibility values. This allowed us to divide individual granitoid massifs or granitoid intrusive phases of the Western Carpathians, on the basis of their magnetic susceptibilities, into two groups–series (magnetite and ilmenite) separated from one another by the value of 3600×10^{-6} SI units (Ishihara, 1989, pers. comm). In addition, we have taken into account also geological position, petrography, geochemical composition and further petrophysical properties of the investigated granitoids. Thousands of new data, mostly geochemical and petrophysical ones, have been mathematically treated.

In this paper figures showing measured values are not given because they have been published earlier (Gregor, 1987, 1988).

Magnetic susceptibility of the Western Carpathian granitoids

Magnetic susceptibility (induced-to-remanent magnetization ratio) of the Western Carpathian granitoids depends on the amount of dia-, para- and ferromagnetic minerals, the decisive role being played by the latter (Fe-Ti minerals, mainly magnetite, less frequently Fe-sulphides – pyrrhotite). Principal rock-forming minerals, quartz and feldspar, are diamagnetic and therefore affect magnetism only passively: if abundant, they leave little space for para- and ferromagnetic minerals. E. g., correlation between $\varkappa$ and quartz equals to -0.63.

Paramagnetic minerals, biotite and amphibole, absorb iron from melt thus decreasing probability that ferromagnetic minerals will crystallize. In this case, magnetic susceptibility is only slightly increased. On the other hand, however, under certain conditions (mainly increased oxygen fugacity), paramagnetic minerals may become the source of secondary magnetite, as has been proved also by experimental works:

$$Bi^{Fe} + (O_2) = Bi + Ort + Mt + (H_2O)$$

(Wones – Eugster, 1965), where Bi – biotite, Ort – orthoclase, Mt – magnetite.

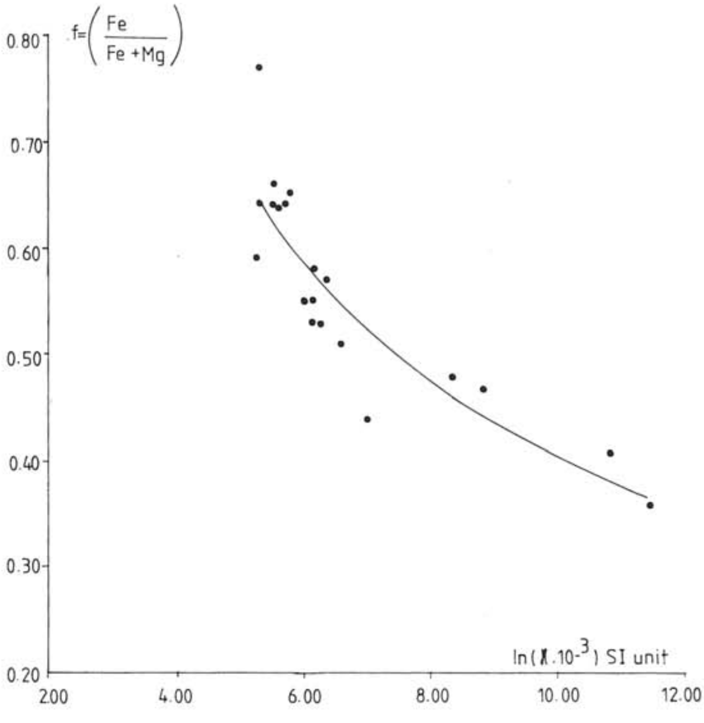

Fig. 1. Relationship between magnetic susceptibility and iron content in biotites from selected samples of the Western Carpathian granitoids.

Magnetite formed in this manner substantially increases magnetism of the rock. Relationships of iron content in biotites of some Tatric, Veporic and Gemeric granitoids measured by Petrík (1985) as well as Hodruša-Štiavnica Intrusive Complex granitoids investigated by Šulgan (1986) to their magnetic susceptibilities measured by Gregor (1987) have been evaluated by us and confirm the above assumption. Mutual relationship between these two parameters can be mathematically expressed by the equation $\ln \varkappa = 2.15 \times f^{-3/4}$ (Fig. 1) where $\varkappa$ – magnetic susceptibility, f – ratio of biotite.

Tatric and Veporic granitoids

Magnetic susceptibilities of most Tatric and Veporic granitoids are fairly low, what attests to low contents of ferromagnetic minerals (Fig. 2). The regional research (Gregor, 1987) has found that only granitoids from the Čierna hora Mts., Rochovce and some samples from the Vysoké and Nízke Tatry Mts. as well as the Malá Fatra Mts. have high magnetic susceptibility. These researches, however, must be supplemented by more detailed ones, as has already been done in the Malé Karpaty, Nízke Tatry Mts. and Veporic/Gemeric contact.

Malé Karpaty granitoids occur in the Bratislava and Modra Massifs. On the basis of their magnetic properties, Vilinovič (1985) has divided them into two series.

Differences noted by us in magnetic susceptibilities of both these massifs (average susceptibility is higher in the Modra Massif) may be caused by different compositions due to partial melting of the source(s) and fractional crystallization (Cambel – Vilinovič, 1988). In the Bratislava Massif, magnetic susceptibility considerably increases with increasing basicity (leucocratic granites: $\varkappa < 312 \times 10^{-6}$ SI units, two-mica and biotite granites: $\varkappa < 640 \times 10^{-6}$ SI units, two-mica and biotite granodiorites: $\varkappa < 892 \times 10^{-6}$ SI units).

As regards granitoids of the Pezinok-Pernek crystalline, we have found higher susceptibilities in granitoids taken from mine workings ($\varkappa_{max} = 3210 \times 10^{-6}$ SI units). In our opinion, higher $\varkappa$ values in granitoids from mine workings suggest that they were enriched in magnetic minerals by secondary processes related to the formation of the mineral deposit and/or their relationship to Modra Massif granitoids.

An interesting anomaly has been found by us in the Tríbeč Mts. where, apart from low magnetic granitoids, there occur also high magnetic ones located in enclaves of dioritic rocks (Petrík – Broska, 1989). In comparison with the surrounding granitoid rocks, the enclaves always have higher susceptibilities amounting up to $16\,000 \times 10^{-6}$ SI units. Nízke Tatry granitoids occur largely in the Ďumbier Massif whose composition is very heterogeneous. Their heterogeneous genesis is reflected also in the distribution of magnetic susceptibility. The lowest values characterize the Králička-type granitoids, the fact related to their genesis and leucocratic character. Fairly low $\varkappa$ values (below 450×10^{-6} SI units) occur also in acid granitoid varieties of the Chopok area. Magnetic susceptibilities of the Prašivá- and Ďumbier-type granitoids are mutually similar ($\varkappa < 1000 \times 10^{-6}$ SI units). Susceptibility values hardly allow to distinguish both these types, although $\varkappa$ values of the Prašivá-type are slightly higher than particularly those of the Latiborská hoľa-type granitoids.

We have found an interesting magnetic susceptibility anomaly on the Nízke Tatry ridge above the village Magurka where gold and antimony had been mined in the past. The anomaly was not continuous, but consisted of separated zones with 5 to 50 times higher susceptibility values in comparison with the surrounding rocks. Fairly high $\varkappa$ values ($< 3000 \times 10^{-6}$ SI units) occur also in granitoids from a mine working at the Dúbrava mine in the Nízky Tatry Mts.

As regards Veporic granitoids, the more basic Sihla type attains higher values ($650 < \varkappa < 1100 \times 10^{-6}$ SI units) than the more acid Vepor type ($150 < \varkappa < 880 \times 10^{-6}$ SI units) and granitoids of the Sinec Massif ($230 < \varkappa < 450 \times 10^{-6}$ SI units). Veporic granites located at the Veporic/Gemeric contact show lower $\varkappa$ values than they should have because of their material composition relative to the other Veporic granitoids.

In contrast, the Rochovce granites which contain up to 5 kg/t magnetite (Klinec et al., 1980; Határ et al., 1989) show high magnetic susceptibilities ($\varkappa < 30\,000 \times 10^{-6}$ SI units). These acid granites have been intersected by drilling in the centre of a high magnetic anomaly (Filo et al., 1974) near the village Rochovce. In addition to their high magnetic susceptibility, another interesting feature of these rocks is also high anisotropy of their magnetic properties (Gregor, 1989).

Fig. 2. Magnetic susceptibilities of the Western Carpathian granitoids and their areal distribution. 1 – Tatric and Veporic granitoids; 2 – Gemeric granitoids; 3 – metamorphic envelope of Tatric and Veporic granitoids; 4, 5 – metamorphic and sedimentary rocks of Gemericum; 6 – Hodruša-Štiavnica Intrusive Complex – HŠIK; 7 – samples of Tatric granitoids; 8 – samples of Veporic granitoids; 9 – samples of Gemeric granitoids; 10 – samples of HŠIK granitoids.

Gemeric granitoids

Southwest of the Rochovce granites there is exposed a narrow belt of the Turčok granites that are assigned among the Gemeric granites by In Ončáková (1955), J. Kamenický – L. Kamenický (1955). The granites are acid, strongly tectonically disturbed. Their magnetic susceptibility is high, similar to that of the Rochovce granites ($< 30\ 000 \times 10^{-6}$ SI units). The Turčok and Rochovce granites resemble each other also in their microelement composition and anisotropy of magnetic susceptibility. That is why we do not rule out the possibility of their mutual relationship.

The other Gemeric granites are characterized by very low magnetic susceptibilities. In addition to their mutually similar magnetic susceptibilities (Betliar granites: $\varkappa < 420 \times 10^{-6}$ SI units; Hnilec granites: $\varkappa < 420 \times 10^{-6}$ SI units; Poproč granites: $\varkappa < 440 \times 10^{-6}$ SI units; Čučma granites: $\varkappa < 420 \times 10^{-6}$ SI untis), these granites resemble each other also in other physical and geochemical properties.

According to the Ishihara's classification (1977), this type belongs to the ilmenite series of granitoids formed from upper crustal material in a compressive setting, at low oxygen fugacity and with considerable contamination by the surrounding rocks. This granitoid type should be characterized by tin mineralization, which is consistent with the fact that the Gemeric granites are tin-bearing (Baran et al., 1970; Tauson et al., 1977 and others).

Young granitoids of the Hodruša–Štiavnica Complex

The highest magnetic susceptibility values have been noted in the samples of young granitoids of the Hodruša-Štiavnica Intrusive Complex. The samples have been collected by Šulgan (1986) and on the basis of mineralogical criteria have been assigned by him into the magnetite series. Detailed study of magnetic properties of granitoids from a new dewatering adit as well as data by Bujňáková – Marušiak (1989) suggest that in the area of the Hodruša-Štiavnica Intrusive Complex there exist, apart from high magnetic granitoids, also low magnetic ones. This may be partly due to secondary alterations of the investigated samples as well as existence of another intrusive phase or changed oxygen pressure.

According to the Ishihara's classification (1977), the high-magnetic granitoids of the Hodruša-Štiavnica Intrusive Complex quickly ascended in a tension setting from relatively great depths, with a minimum contamination by the surrounding rocks and at high oxygen fugacity. This would correspond to magmatic intrusion ascending from fairly great depths along fractures formed by crustal tension which, in turn, was caused by a rising diapir in the Pannonian Basin area. Similarly, the type of mineralization related, according to Ishihara (1981), to this series corresponds to mineralization known and mined in the Hodruša-Štiavnica region, one of the richest ore districts in Slovakia which, e.g. in the 14th century accounted for one quarter of the world's silver mining along with great quantities of gold and copper.

Conclusion

Magnetic properties employed to divide granitoids into two contrast series allow us to make some assumptions concerning oxygen fugacity during granitoid formation in a given region and this factor is likely to play an important role in ore-forming processes.

On the basis of magnetic susceptibilities, the magnetite series includes magnetic phase of granitoids of the Hodruša–Štiavnica Intrusive Complex and granitoids of the Rochovce, Turčok and Čierna hora areas, whereas the ilmenite series comprises granitoids of the

Gemericum, Bratislava Massif, Inovec, Suchý as well as extensive tracts of the Nízky Tatry Mts. and Veporicum.

Because of insufficient number of measurements, we cannot assign Vysoké Tatry, Malá Fatra, Modra Massif and Čierna hora granitoids into a certain outer zone of increased magnetic susceptibility.

Relationship between magnetic susceptibility values and mineralization is indicated by occurrences of magnetic granitoids in the Hodruša-Štiavnica Intrusive Complex, Rochovce and partly also the Dúbrava and Pezinok areas and nonmagnetic ones in the Gemericum. Despite the fact that not all magnetic granitoids are associated with Au, Ag, Cu, Pb, Zn, Mo and W ores and not all nonmagnetic ones are accompanied with tin deposits, we can employ magnetic susceptibility as an indicator of some genetic and/or ore-forming processes.

Great advantages of the employed method are high efficiency of field as well as laboratory measurements, possible usage of earlier geophysical measurements and solution of some special problems, e. g. using anisotropy of magnetic properties.

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