The contribution to the solution of the source of marine magnetic anomalies

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Abstract: The examples of possible source of intense marine magnetic anomalies have been presented on the basis of study of continental basalts from Slovak volcanic fields. According to experimental works when the oxidation of the titanomagnetites in basalts has taken place below 150° C with the presence of ambient magnetic field, basaltic rocks acquired low intensity CRM, mostly lower than their original RM. But when the oxidation (low, or high-temperature oxidation) takes place over 150° C, the VRM (the chemico-viscous RM) of basalts is several times more intense than the RM of rocks before their oxidation. This VRM is always of positive direction. Such model can be applied to the explanation of different intensities of marine magnetic anomalies. Basaltic magma of the central part of rift system preserved its temperatures at higher level and cooled a longer time than the thin lava flows on the flanks of the system. So, the alterations of the Ti-Mt-es took place at higher temperatures in the central sizable body comparing it with the thin lava flows when the temperatures are supposed to be expressively lower. These different temperature oxidation conditions resulted also in the acquisition of different intensity of VRM (or CRM) of basaltic rocks and thus resulted in the generation of different intensities of marine magnetic anomalies.

Key words: oxidized titanomagnetites, basalts, the sources of magnetic anomalies

1. Introduction

Total magnetic field anomalies observed on crossing the mid-ocean ridges show three essential features according to Vine-Matthews crustal model (*Vine and Matthews, 1963*): there is always a pronounced central anomaly, associated with the median graben, whilst over the rugged flanks short wavelength anomalies are observed. The central anomaly can be reproduced by a block of material very strongly magnetized in the present direction of the

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earth's magnetic field. Measurements of the magnetic properties of dredged rocks demonstrate the predominance of remanent magnetization (RM) over the magnetic susceptibility (κ) (*McElhinny, 1973*). The results concerning dredged basalts from the mid-Atlantic ridge at 45° N have been summarized by *Butler (1973)*. According to the results a 90% decrease in normal remanent magnetization (NRM) intensity was found as the sample localities moved from the median walley to the ridge flanks. According to *Irving (1970)* the changes in magnetic properties could be due to oxidation of original titanomagnetites (Ti-Mt-es) to a cation-deficient titanomaghemite (Ti-Mght). The NRM decrease would then be caused partly by viscous demagnetization of low-coercive grains and partly by oxidation of Ti-Mt to Ti-Mght. *Marshall and Cox (1972)* proposed that the decrease of NRM with distance from the ridge is entirely due to maghemitization. An intrinsic decay mechanism due to ionic diffusion of Fe^{2+} ions in quenched Ti-Mt-es may lead to a decrease in remanence coercivity with increasing age. This could produce a decrease in NRM intensity that would add to the decrease due to oxidation (*Banerjee, 1971*). *Readman and O'Reilly (1972)* revealed that Curie temperature of synthetic Ti-Mt-es was increased with increasing oxidation parameter z, whereas cell edge and σ_s decreased. They found a strong decrease anisotropy constant K_1 with increasing oxidation. According to *Butler (1973)* rotational hysteresis date will lead to an additional decrease in NRM intensity by causing a significant portion of Ti-Mt grains, when they are unoxidized, are stable single-domain grains, to become superparamagnetic (SP) as they are oxidized to Ti-Mght. Thus low-temperature oxidation of oceanic basalts could cause a significant portion of the originally stable carriers of natural remanence to become SP. This mechanism could aid in explanation of the large NRM intensity decrease of dredged basalts with distance from the mid-Atlantic ridge. *Johnson and Merrill (1973)* revealed that the oxidation of Ti-Mt produced two separate types of behaviour. At the temperature of 135° C or above, oxidation produced an increase in the intensity of the original remanence and a chemical remanence (CRM) that was stronger than the original one in the sample. At the temperatures below 135° C, oxidation produced a decrease in the intensity of the initial remanence and the CRM component was less intense than the original remanence. The increase in RM intensity at the higher oxidation temperatures is shown to be associated with the unmixing of the Ti-Mght that forms during oxidation. An exhaustive review on the alterations of Ti-Mt-es and the sources of marine magnetic anomalies has been presented by *Pechersky et al., (1981)*. According to *Özdemir (1987)* low-temperature oxidation takes place below about 350° C in mild hydrothermal environments (in the upper oceanic crust near active rifts). The metastable Ti-Mght inverts to a multiphase intergrowth when heated above 250-300° C. Decrease in the ratio J_{RS}/J_S and in H_C and an increase in magnetic viscosity after inversion reflect the subdivision of originally single-domain (SD) homogeneous Ti-Mght grains into SP or nearly SP-size subgrains. The spinel phase in the intergrowth was near-stochiometric Ti-Mt or magnetite, and other phases included ilmenite, hematite, anatase, and/or pseudobrookite. *Beske-Diehl (1990)* have shown that the intensity of NRM of Ti-Mt-es decreased throughout low-temperature oxidation. The coercivities increased in moderalety oxidized basalts until Curie temperature reached 250° C and then decreased with increasing Curie temperature in many of the more highly oxidized, very fine-grained samples. An increased proportion of SP grains most likely caused the decreasing of coercivity. Viscous remanent magnetization (VRM) was present in moderately oxidized medium-grained samples and in some highly oxidized, very fine-grained samples.

2. The contribution to the solution of the problem

Recently I presented the results of continental basalts from Slovak volcanic fields, and from localities from abroad (*Orlický, 2005*). The dominant magnetism carriers in submarine pillow basalts are the Ti-Mt-es of prevailing composition about $Fe_{2.4}Ti_{0.6}O_4$, but also more oxidized Ti-Mt-es were found. Similar composition of the Ti-Mt-es has been detected also in continental basalts (*Orlický, 2004*). But all volcanics, including basalts are mostly of very heterogeneous development. In some parts of individual basaltic body a complete unoxidized Ti-Mt-es can be found, but in other positions there are present also the low-temperature, but in some bodies also high-temperature oxidation magnetic phases except of the original unoxidized forms. This different state of the Ti-Mt-es has been reflected also in different values of volume magnetic susceptibility (κ). The secondary low-temperature oxidation phase (SLTOPh) can be detected either by the measurements of the change of κ during continual heating of the sample, or by the measurements of the change of κ of the sample, after its step-wise heating to discrete temperature and its cooling to laboratory temperature.

The Ti-Mt-es and forms of basalts with low intensity of NRM: We see in Fig. 1 that the sample of Ti-Mt Mašková - 2 is thermally unstable magnetic mineral. The Curie temperature $T_C \approx 130°$ C. There is sharp decrease of κ on the left site of the curve - from the peak at 70° C down to -196° C. We see from the thermal demagnetization results of the sample Mašková 2-2 that the dominant carrier (about 90 %) of the reversed RM is the Ti-Mt of low T_C. The reversed RM of the sample was not removed after attaining the temperature of low T_C of the Ti-Mt, but it survived till the temperature of 550° C. Similar behaviour was detected by the thermal demagnetization of the sample Mašková - 1 with the well developed SLTOPh (Fig. 1). The sample Ma-2-2 (locality Mašková, Fig. 1) of olivine basalts with unoxidized Ti-Mt (Curie temperature T_C= 130° C) has $\kappa = 63553 \times 10^{-6}$ SI units, but the sample of olivine basalt Mašková 1-1 with the developed SLTOPh from the same quarry (Fig. 2) has $\kappa = 33421 \times 10^{-6}$ SI units (the difference in κ between these two samples is 30132×10^{-6} SI units). Such high differences in κ can be found very frequently in the samples of basalts with Ti-rich Ti-Mt-es from the same volcanic body. In some cases the SLTOPh can develop very intensely, which is detected by an extreme low value of volume κ of the sample and very intensely increased κ at the inversion temperatures (Fig. 2, Šomoška - 3a). On the basis of results of large collections of basaltic rocks the unoxidized Ti-rich Ti-Mt-es (without SLTOPh) attained very high values of volume κ (60000×10^{-6} to 100000×10^{-6} SI units). Such types of Ti-Mt-es behave as SP particles (*Orlický, 2004*). On the other side the Ti-rich Ti-Mt-es with a well developed SLTOPh attained relatively low values of κ. The samples of basalts in-situ-state with the developed SLTOPh have the lower, or extremely lower volume κ than those of the same type of basalt which have not possessed the developed SLTOPh. The above discussed samples of basalts come from thin lava flows. After a thin lava flow was formed, there was no chance for the larger grains of minerals, including the Ti-Mt-es, to develop during very quick cooling of magma. Experimental evidence has proven that the SLTOPh in these types of rocks was developed during low temperatures, which have not attained more than 150° C (according to *Johnson and Mer-*

rill, 1973 not more than 135° C). In these types of basalts either with the extreme high κ and SP behaviour, or in those with the described SLTOPh, there are mostly low intensities of NRM, and they have not generated the intense geomagnetic anomalies.

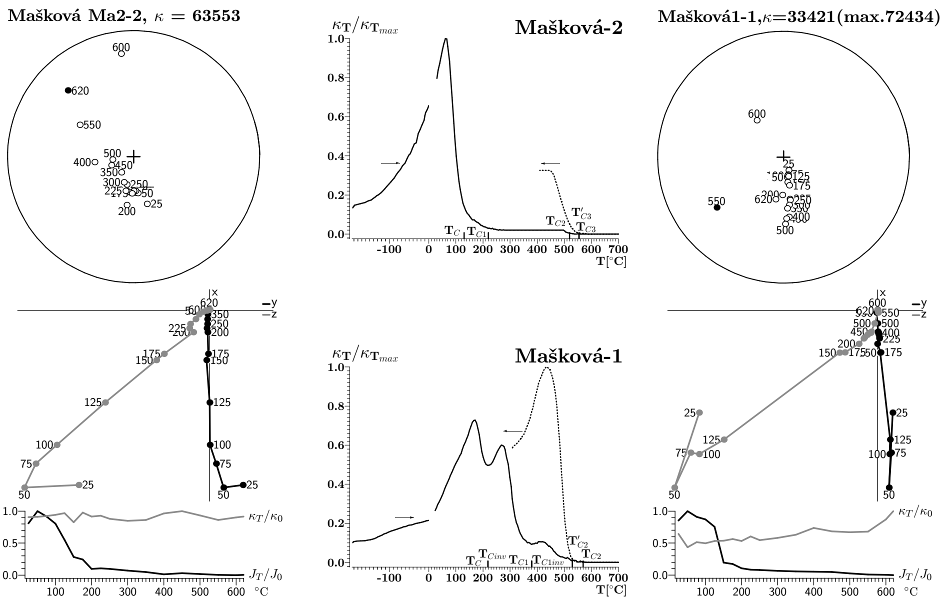

Fig. 1. Thermomagnetic curves of Mašková-2, Mašková-1 samples (the measurements of the change of κ: during heating of the sample - full line, and after heating to 700° C and cooling–dotted line; $T_{C,C1}$–Curie temperatures, T_{inv}–inverse temperature). Thermal demagnetization of samples Mašková M2-2 and Mašková 1-1 - stepwise heating to 600° C; Zijderveld diagrams and stereographic projections; • (○) - positive (negative) polarity of RM; κ - magnetic susceptibility: κ_T at T, κ_0 - at 25° C; J_T (J_0) - remanent magnetization at T and at 25° C.

The Ti-Mt-es and forms of basalts with high intensity of NRM: The lava necks and the lava penetrations of basalts were investigated. An example of the lava penetration with the transition to thick lava flow is the basalt from Šomoška locality - Fig. 2, Basalt Šomoška-2, Šomoška SM2-3. This basalt contains two basic Ti-rich Ti-Mt-es. One with T_C = 130° C and the second one with T_C = 220° C. There is present also the third component with SLTOPh (more oxidized Ti-Mt) with an inversion temperature 380° C and T_C = 580° C (Fig. 2, Basalt Šomoška-2, Šomoška SM2-3). Cooling of such large lava flows (large neck basaltic bodies) took longer time

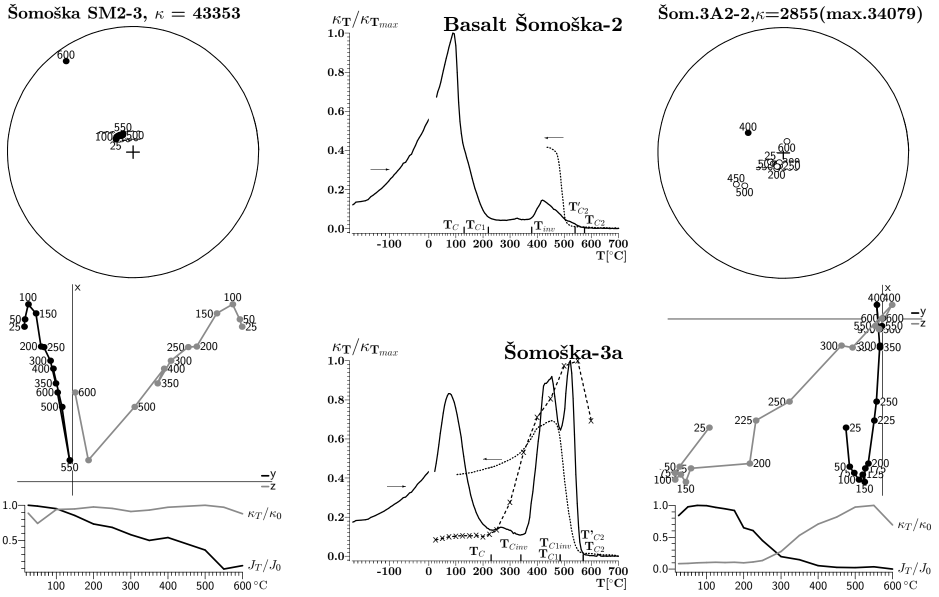

Fig. 2. Thermomagnetic curves of Šomoška-2, Šomoška-3a samples and thermal demagnetization of samples Šomoška SM2-3 and Šom. 3A2-2. Other explanations see below Fig. 1.

and at higher temperatures; the grains of magnetic minerals of larger sizes were developed in such basalts. The heterogeneity of magnetic properties throughout the larger basaltic body is typical. The basaltic body as a whole was magnetized in the normal (positive) direction. But there are variable declinations and inclinations of RM of the samples from different places of the body (depending on whether SLTOPh has or has not developed in the sample). The declination varied from 320° to about 350°. The intensity of NRM of 9 samples is in the range of 9565 nT to 17710 nT and κ is in the range of 43353×10^{-10} SI units to about 62123×10^{-10} SI units. There are the larger intensities of NRM which could contribute to the value of effective κ of the rock and they can generate the intense magnetic anomalies. The basaltic lava necks, dykes or the larger lava flows from 12 different localities from central and southern Slovakia have shown anomalous directions of RM, regardless of the polarity of RM (the declinations have varied in the range 83 to 285° for the rocks with normal polarity and 232 to 346° for the rocks with reversed polarity of RM). The total anomalous direction of RM

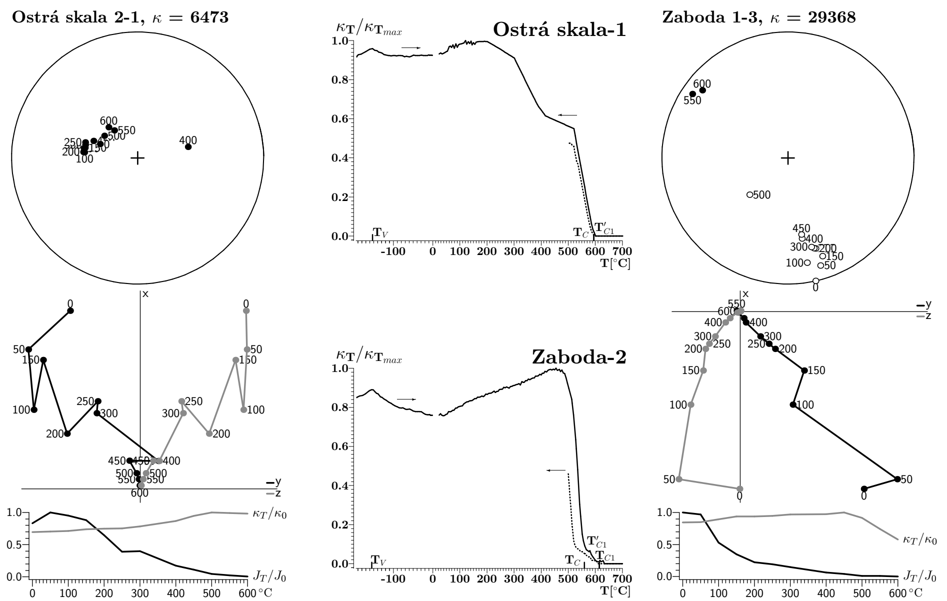

Fig. 3. Thermomagnetic curves of Ostrá skala-1 and Zaboda-2 samples (T_V–Verwey temperature) and thermal demagnetization of samples Ostrá skala 2-1 and Zaboda 1-3. Other explanations see below Fig. 1.

of the rock is influenced by the VRM which cannot be easily removed during AF or thermal demagnetization. In highly oxidized, fine grained samples, a hard VRM is thought to be acquired by grains or portions of grains near the SP to single-domain boundary. Both types of VRM could be termed a chemicoviscous remanent magnetization (a term which should be limited to VRM affected by chemical process, *Beske-Diehl, 1990*).

There is the third type of basalts which survived the high and low-temperature oxidation conditions (Fig. 3, Ostrá skala-1, Ostrá skala 2-1; Zaboda-2, Zaboda 1-3). The low and high-temperature oxidation follow by multi-phase alteration and unmixing of Ti-Mt. The phases with larger portion of magnetite (with T_C near to 580° and the Verwey temperatures of about - 155°) were detected in the oxidized Ti-Mt. These types of basalts are characterized by lower values of κ but high intensities of NRM, attaining the values of 20000 to 30000 nT. The form of these types of basalts are either the lava necks or very large thick lava flows. The high intensities of NRM of these basalts may expressively contribute to the total magnetic effect of basaltic bodies and so it can generate the intensive magnetic anomalies.

3. Discussion and conclusions

It has been noted above, that the dominant magnetism carriers in oceanic basalts are the Ti-rich Ti-Mt-es ($x \approx 0.6$). I suggested previously that the titanomagnetites with Ti-rich contents behave similarly to the SP particles in which there is the absence of domain structure, so they are completely thermally unstable. The low and high-temperaature oxidation of the Ti-Mt-es plays a decisive role in alteration of magnetic properties of the Ti-Mt-es. The mechanism of the low-temperature oxidation of the Ti-Mt-es has been described by *Orlický (2005)*. According to experimental works when the oxidation has taken place below 150° C, with the presence of ambient magnetic field, basaltic rocks acquired low intensity CRM, mostly lower than their original RM. But when the oxidation (low, or high-temperature oxidation) takes place over 150° C, the VRM (the chemico-viscous RM) of basalts is several times more intense than the RM of rocks before their oxidation. This VRM is always of positive direction. Such explanation can be applied to a different intensities of marine magnetic anomalies. Basaltic magma of the central part of a rift system preserved its temperatures at higher level and cooled a longer time than the thin lava flows on the flanks of the system. So, the alterations of the Ti-Mt-es took place at higher temperatures in the central sizable body comparing it with the thin lava flows when the temperatures are supposed to be expressively lower. These different temperature oxidation conditions resulted also in the acquisition of different intensity of VRM (or CRM) of basaltic rocks and so with the generation of different intensity of marine magnetic anomalies.

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