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# A realistic approach to explanation of the normal and reversed remanent magnetization of rocks: Application for submarine volcanics

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**Abstract:** The results of the magnetic measurements and mineralogic data of the submarine basalts and peridotites have been compared with the original model to explain the origin of the normal and the reversed remanent magnetization (RM) of volcanics. According to the author the Ti-rich titano-magnetite (Ti-Mt) bearing rocks (without the secondary magnetic phase) and the magnetite are always the carriers of only normal RM. The low-temperature oxidized Ti-Mt bearing rocks and those of the ilmenite-hematite bearing rocks of the deutheric oxidation origin (of the defined composition) are the carriers of dominantly reversed RM of the self-reversal origin. This idea have been approved by many results of submarine volcanics, mostly basalts.

**Key words:** Ti-rich Ti-Mt and magnetite the carriers of normal RM, the low-temperature oxidized Ti-Mt and the ilmenite-hematites the carriers of reversed RM of rocks

## 1. Introduction

So far, in the interpretation of the marine magnetic anomalies the field-reversal hypothesis has been applied. The sea-floor spreading conception has been taken into account. The results of a study of magnetic properties of submarine rocks have been explained with respect to the mentioned hypotheses. For a long time I have applied the self-reversal hypothesis to explain an origin of the reversed RM of volcanics. A completely new approach for the explanation of the sources of normal and reversed RM of rocks has been proposed by *Orlický (2006, 2009, 2010)*, which is supposed to be the dominant one for the realistic interpretation of normally and reversally magnetized rocks. According to this approach the reversed RM of volcanic rocks is not a reflection of some reversally oriented geomagnetic field during formation of the rock, but it has a self-reversal origin. The results of physical analyses and complex laboratory works allowed to reveal the different magnetic behaviour and to select the basic types of Fe-Ti magnetic minerals, which carry either normal or the reversed RM in the rocks. The mentioned idea was derived using the results of continental and submarine volcanics. I am preparing now a compilation of suitable results from available publications of other authors from large amount of localities and places of continental volcanics from the Globe, to broadly confront my idea with the published results. Because the field-reversal theory has been so far very conceivably accepted for the explanation of marine magnetic anomalies, including the results of rock's magnetic properties, I would compare first of all my idea with the published results of the submarine volcanics. Experimental results have supported the idea that submarine rocks of the igneous oceanic crust often have very different magnetic properties from those interfered from studies of magnetic anomalies near spreading centers, or from rock magnetic studies of oceanic extrusives dredged near spreading centers. The results of many studies show that the stable inclinations are often anomalous (usually shallow) relative to those expected from a geocentric axial dipole field. Frequently reversals are observed in the vertical column in a single hole. Furthermore, the relatively low intensities of NRM which are usually observed imply that a magnetic layer several kilometers thick is required to produce the observed anomalies.

In this work only basic suitable data will be used to characterize the place, the respective volcanic structure or the body, as well as magnetic data from the works of other authors. The following characteristics or data will be applied to make a comparison: The geographical coordinates ($\varphi_L$, $\lambda_L$, if they are available), petrographical description of rock, the age in million of years, bulk magnetic susceptibility ($\kappa$) of the rock, compositional parameter x of the titanomagnetite (Ti-Mt, $Fe_{3-x}Ti_xO_4$), z - oxidation parameter, Curie temperature $T_C$ of magnetic Fe-Ti mineral, polarity of NRM and RM, special comments concerning the results. Generally, the gathered data of other authors were realized in different laboratories and different methodic procedures were used. E.g. the measurements of the Curie temperatures of magnetic minerals is not uniform. In many laboratories a change of saturation magnetization with temperature was used (in air, or within the noble gasses), a change of $\kappa$ with temperature was used by others. But what is not useful, many authors have applied very high speed of heating of the sample (e.g. 40 or 100° C/min) which is not in agreement with the basic principle that the sample must be thoroughly warmed up to provide a correct result concerning the change of respective parameter. So, the compiled results cannot be considered in a detailed form. Of course, this work has not been considered as the final one. I will continue with the study of other actual submarine volcanics from other places which were published so far.

At the first stage the applied works of other authors have been selected on a simple principle - "the availability" of the respective title on the internet. I have focused my interest on the volcanics containing the Ti-rich titanomagnetites, the low-temperature oxidized titanomagnetites and the magnetites. Further elaboration of works of other authors will be more comprehensive, which will adopt the available results not only from the internet, but also from libraries and archives. Clearly, as in this work, the respective authors will be precisely quoted.

## 2. The description of the basic idea concerning the carriers of normal or reversed RM of rocks

### A. The dominant carriers of normal (positive) remanent magnetization (RM) in the rocks

1. **The titanium-rich titanomagnetite (Ti-Mt; $Fe_{3-x}Ti_xO_4$) bearing rocks.** If only the Ti-rich Ti-Mt with a high compositional parameter $x \geq 0.6$ is present in the rock, low oxidation parameter $z \approx 0.0$, very low Curie temperature $T_C \leq 150\,°C$, without a secondary low-temperature or high-temperature oxidized magnetic phase the volcanics (mostly basalts) have possessed only **normal polarity** of RM in the normally oriented geomagnetic field during their origin, regardless the age of the rock. These Ti-Mt-es are of primary origin. The RM of rocks containing these types of Ti-Mt-es is of primary thermoremanet magnetization (TRM). The basaltic rocks are usually characterized with high bulk magnetic susceptibility ($\kappa$ mostly 40 000 to $100\,000 \times 10^{-6}$ SI Units).

2. **The pure or of very low non-stoichiometry magnetite ($Fe_3O_4$) bearing rocks.** If the magnetite is present dominantly in the rocks, only **normal polarity** of RM is acquired in the normally oriented geomagnetic field. The RM of such rocks is dominantly of the chemical (CRM) origin, but partly also the RM of the TRM origin may be present. In such types of rocks very low content of ilmenite, rarely also ilmenite-hematite, in intrusive rocks also Fe-sulphides, may be present. More frequent occurrence of such types of magnetic minerals concerns the volcanics of intrusive origin, or ultra-maffic rocks, but also effusive or extrusive rocks.

**B. The dominant carriers of reversed (negative) remanent magnetization (RM) in the rocks**

1. **The low-temperature oxidized Ti-Mt - the titanomaghemite-(Ti-Mgh) bearing rocks (mostly basalts, basaltic andesites, andesites).** These types of titanomaghemites (Ti-Mgh-tes) originated during low-temperature oxidation of Ti-rich Ti-Mt-tes - either during initial cooling of basalt magma, during an additional heating of the volcanic body, exceptionally during existence of volcanics on the Earth's surface at atmospheric temperature in post-volcanic time. The process of alteration of original Ti-Mt-tes is very heterogeneous, which is accompanied by extreme decrease of magnetic susceptibility, the increase of $T_C$ and the creation of a secondary, so-called inversion, magnetic phases in the volcanics. The Ti-Mgh itself is of the ferrimagnetic state with the two A and B sub-lattices. The alteration of Ti-Mt to Ti-Mgh-te is accompanied by the transformation of original, probably of a ferromagnetic behaviour, Ti-Mt to ferri-magnetic behaviour through ionic reordering of magnetic Fe ions in the sub-lattices of the Ti-Mgh-te. The respective rock has acquired the **reversed polarity** of RM of the CRM origin, induced in the normally oriented geomagnetic field. I suggested a model this process in *Orlický (2006)*. The mentioned self-reversal acquirement of the reversed CRM was approved for continental volcanics but it is probably valid also for the sub-marine basalts.
2. **The ilmenite-hematite (Ilm15-20 Hem85-80, or of similar Il-Hem composition) bearing basalts and intermediate volcanics.** The Ilm-Hem-es are produced by high-temperature oxidation of Ti-Mt-

es. They carry the **reversed polarity** of RM, mostly of the TRM and rarely of the CRM origin. This process is quite frequent in continental volcanics, but very rare in sub-marine volcanics.

I can comment very shortly that in the nature, the physical and geological environments are generally of heterogeneous character. It means that the respective volcanic units or a body are not characterized strictly by only one type of pure magnetic mineral, but they contain mostly the assemblage of several types of the Fe-Ti oxides, in which the one type would be dominant. With such, or similar idea the above mentioned main respective magnetism carriers of normal or reversed RM in the rocks were nominated.

## 3. The selected results published by other authors

**The pillow basalts from the FAMOUS AREA and the LEG 37 Ti-rich Ti-Mt bearing rocks**: *Prévot et al. (1979)* have presented the results of pillow basalts collected from the Rift Valley near 37° N under French American Mid-Ocean Undersea Study (FAMOUS). Fission-track ages indicate that these rocks are less then 0.1 m.y. old. Within the FAMOUS Rift Valley the mean inclination of magnetization fits the dipole inclination of normal polarity. The nine samples broadly distributed within the median valley, are normally magnetized. The mean inclination is equal to +56°, which corresponds to the expected inclination for an axial centered dipole at this latitude. The mean $T_C$ is $159 \pm 9\,°C$, $z = 0.2$. Comparison of electron-microprobe and thermomagnetic data indicates that the FAMOUS pillow basalts contain only slightly oxidized titanomagnetites (Ti-rich Ti-Mt-es). These types of the Ti-Mt-es contain also the pillow basalts collected as far as 4 km West of the axis. They have $T_C$ of about 150 °C, which is very near to the mean value of rocks at the axis. The samples are of the normal polarity NRM. The FAMOUS area pillow basalts with the Ti-rich Ti-Mt-es are the carriers of only normal polarity RM. If there are also individual reversally magnetized samples present, they must be tested for a presence of the secondary - inversion phase which can carry self-reversal CRM.

**Low-temperature oxidized Ti-Mt bearing rocks**

Other studied group of the pillow basalts comes from the Leg 37, sites 332A and 332B. Site 332 is located at 37° N, only 30 km West of the present-day plate boundary. Estimated age of the crust at this site is about 3.5 m.y. The works were performed under Deep Sea Drilling Program (DSDP). According to *Prévot et al. (1979)* in the Leg 37 cores the data from the holes 332A and 332B are considered, the nearest site to the ridge axis, for comparison with FAMOUS results. Anomalously shallow inclinations are commonly observed at DSDP and Integrated Program of Ocean Drilling (IPOD) sites from the Mid-Atlantic Ridge Crest. From the FAMOUS area to DSDP 332 site, the mean intensity of NRM decreases by a factor of 4. Magnetic polarity is mostly reversed in accordance with interpretation of sea surface magnetic profiles suggesting that site 332 is within the 3.32–3.78 m.y., old negative polarity block. There is an agreement between intensities of remanence measured and intensities calculated from direct modelling of near-bottom magnetic anomalies at 37° N for 3.5 m.y. old crust. The mean inclination is shallower by as much as $25° - 30°$ from the expected dipole value. The Leg. 37 pillow basalts are largely maghemitized (the high mean Curie point ($294 \pm 14\,°C$), $z = 0.7 \pm 0.04$. The Curie temperatures corresponded to a presence of low-temperature oxidized Ti-Mt-es (titanomaghemites, Ti-Mgh-es) in these pillow basalts. Due to lack of data it was not possible to compare the inclinations of individual samples. We see that if there are the low-temperature oxidized Ti-Mt-tes in the rocks of the higher $T_C$ present, the reversed polarity of RM of rocks appear.

*Dunlop and Hale (1976)* dealt with the Leg. 37 pillow basalts. They presented four typical thermomagnetic curves of samples for Hole 332B and Site 335. Except for one curve, the three curves showed the secondary magnetic phases (in the interval $350 - 400\,°C$), commonly present in the low-temperature oxidized basalts. The initial Curie point (160 °C) is lower than any of the others, which range from 212 to 570 °C. Curie temperature near 570 °C indicates that also high-temperature oxidation of Ti-Mt-es was present. It is apparent from thermomagnetic analysis that many samples may be at least partially oxidized, and that both Ti-Mt and Ti-Mgh may be present. Polarity of NRM of 12 measured samples was normal for 2 samples (of very shallow inclination), but other samples from the holes 332 and 335 were reversed.

Generally, the Leg 37 basalts contain highly cation-deficient Ti-Mt-es, a feature which is likely to influence strongly their magnetic properties including acquiring the self-reversed CRM.

*Sempere et al. (1988)* studied magnetic properties of some young basalts from the East Pacific Rise. The basalts were recovered from the axis and from 0.7 m.y. old crust at 21° N and 19° S on the East Pacific Rise, as well as from the 9° 03′ N overlapping spreading centers (OSC). Nine samples from the axis and ten samples from the reversal area were studied. Three dredge hauls were recovered at 19° 30′ S. D-8 was recovered from the axis while D-6 and D-7 were obtained from two small volcanoes in the reversal area. The value of NRM, and susceptibility are always higher at the axis than at the reversed area. This is similar also for the 9° 03′ N OSC. Samples in the Hole 8 (at the axis) have high NRM and $\kappa$, and normal polarity of RM, but samples from the reversal area (Hole D-6 and D-7) possess the lower NRM and $\kappa$. Several of the samples show new phases appearing after 300 °C as a result of the inversion of Ti-Mgh-tes. The primary magnetic carrier in young submarine basalts are Ti-rich Ti-Mt-tes of composition ($x = 0.62 \pm 0.04$) in $Fe_{3-x}Ti_xO_4$. The thermomagnetic curves of samples from the ridge axis at 21° N are reversible and with respect to mean $T_C = 176$ °C they contain probably unaltered Ti-rich Ti-Mt-tes. The thermomagnetic curves of the older samples show an initial Curie temperature from 250 and 450 °C (350 °C in average). I suppose again that the samples of basalts with the Ti-rich Ti-Mt-es of low $T_C$ have carried normal RM and those with the low-temperature oxidized Ti-Mt-es of higher $T_C$ have carried the reversed CRM of the self-reversal origin.

*Bina (1990)* studied magnetic properties of basalts under the Ocean Drilling Program (ODP) Hole 648B from the Mid-Atlantic Ridge near 23°. Seventeen samples from pillow or massive fresh basalts of the present age from ODP Legs 106 and 109 (from the hole; the depth of 8.62 to 47.0 m) were studied. The samples from 14 depth intervals are of the positive stable inclination of NRM in the range of $33-84°$. But from 3 intervals there were detected the reversed inclinations of NRM (15.48 m: $I_s = -57°$, $\kappa = 12\,000$, $T_C = 150$ °C, $x = 0.66$, $z = 0.45$; 16.49 m: $I_s = -48°$, $\kappa = 10\,500$, $T_C = 140$ °C; 28.18 m: $I_s = -23°$, $\kappa = 9\,000 \times 10^{-6}$ SI units, $T_C = 153$ °C, $x = 0.62$, $z = 0.40$). The Curie temperatures with $T_C$ from 127 to 220 °C are with reversible heating and cooling curves. Unfortunately, the thermomagnetic curves were measured up to 250 °C, so we cannot exclude the presence of secondary inversion phases, which may be responsible for the self-reversal of RM. The mean $z = 0.3$ was derived using $T_C$ and electron microprobe results ($z$ values have shown that some Ti-Mt-es have been oxidized. $J_n/J_S$ ($J_n$ - natural magnetization, $J_s$ - saturated magnetization) decreases and $\kappa/J_s$ increases slightly from pillow to massive basalts.

*Sager et al. (2008).* The paleomagnetic and rock magnetic study of basaltic samples of the Hole U1301B was done. During Integrated Ocean Drilling Program (IODP), 235 m of upper igneous crust was cored in Hole U1301B, in the area of hydrothermal circulation on Juan de Fuca Ridge. 3.5 m.y. age crust was drilled on the flank of the Juan de Fuca Ridge at Site U1301, located at 47° 45.2′ N, 127° 45.8′ W. The pillow and massive basalts are dominated. The Hole is located at the anomaly of normal polarity. The results have shown that unregulated interchange of positions of positive or negative polarity of stable RM have appeared. E.g. in the interval 471.55 mbsf (meter below sea floor) and 476.00 mbsf are the following positions: 3 reversed, 2 normal, 1 reversed, 5 normal and 3 reversed RM. It concerns the 4.55 m thickness of the massive basalts. Similar interchanges are also in the pillow basalt positions. E.g. in the interval of 536.19 to 551.29 mbsf, 3 positions are of reversed RM, 1 normal, 2 reversed and 4 normal RM. The authors considered the reversally magnetized samples as spurious ones. From the thermomagnetic data it is evident that 10 samples showed low $T_C$ in the range 128 to 190 °C. Nine of these samples have normal polarity with $I = 38.1$ to 86.2°. They have relatively high NRM. The Ti-rich Ti-Mt-tes are the carriers of magnetic properties in these massive basalts. One sample of this type is of reversed polarity. Further samples of the $T_C$ in the range 219 to 380 °C (mostly around of 360 °C), nine of 21 tested samples have shown the reversed RM, 12 of them showed the normal RM.

Again, the Ti-rich Ti-Mt bearing basalts carry the normal RM of the thermoremanent origin and the basalts with the low-temperature oxidized Ti-Mt-tes frequently carry the reversed RM of the chemical remanent magnetization (CRM) of the self-reversal origin.

*Petersen (1979)* studied paleomagnetic properties of basalts from Site 396B, LEG 46. The rocks of the Hole 396B were studied also by *Kirkpatrick (1979).* Paleomagnetic and rock magnetic properties were analyzed for 112 samples from Hole 396B, Leg 46 (Mid-Atlantic Ocean). The age of rocks is about 13.0 m.y. The Hole is situated at 22° 59.14′ N, 43° 30.90′, about 150 km east of the ridge. The rock samples were oriented with respect to vertical axis. Four polarity groups or magnetic units were distinguished. Within the individual magnetic units, the stable magnetic inclination values are remarkably consistent (apart from magnetic Unit IV). Only the center part of lithologic Unit 3 (the basalt flow or sill in lithologic Unit 4 have higher susceptibility values. Apart from magnetic Unit II, the measured magnetic inclinations of the rocks are distinctly shallower, with mean values of $4 - 20.8°$ and $-60°$ for magnetic Units I and III, respectively. In these rocks the Ti-Mt grains have been altered by low temperature oxidation. The Curie temperatures of 3 samples of basalts were in the range $165 - 195\,°\mathrm{C}$, $240 - 560\,°\mathrm{C}$ (64 samples). Polarity zones: 0.62 m to 75.43 m (normal); 76.95 to 93.48 m (reversed); 95.08 m to 164.43 m intermediate with a tendency for reversed RM; 170.42 m to 200.06 m (normal). Lithologic Unit 1 - sparsely phyric, pillow basalts with carbonate cemented palagonite breccias ($I = 20°$), $\mathrm{T}_C = 308\,°\mathrm{C}$); lithologic Unit 2 - breccias ($I = -70\,°\mathrm{C}$), $T_{Cav} = 274\,°\mathrm{C}$; lithologic Unit 3 - basalt flow or sill ($I = -65°$), $T_{Cav} = 239\,°\mathrm{C}$); lithologic Unit 4 - phyric, pillow basalts ($I = -8°$), $T_{Cav} = 300\,°\mathrm{C}$). Only rarely there have been detected the primary Ti-rich Ti-Mt-tes in respective rocks. Mostly low-temperature oxidized Ti-Mt-tes are the carriers of RM, in above named magnetic units also of reversed polarity, of the self-reversal origin. There are quite good relations between lithologic units and the polarity of RM. It is noticeable that the Unit 3 of the flow and sills is of very high reversed polarity of RM. Evidently, low-temperature oxidized Ti-Mt-es of basalts are the carriers of the reversed CRM.

**The volcanics containing dominantly the magnetite**

*Kelso et al. (1996)* studied the peridotites from Site 895, Hess Deep, under the Ocean Drilling Program (ODP) Leg 147 at 2.5° N and 101.25° W. There were collected hard-rock samples from the intrarift ridge of Hess Deep in the central East Pacific Ocean. The samples from Site 895 were dominated by serpentinized peridotites likely from the uppermost mantle. Their age is less than 10.0 m.y. The measured peridotite samples have Curie temperatures in the range between 560° and $585\,°\mathrm{C}$, with a median value of $578\,°\mathrm{C}$. The dominant magnetic mineral is nearly pure magnetite of $\mathrm{T}_C = 585\,°\mathrm{C}$. But also some portion of Ti-products is present in the rocks. The serpentinization at Site 895 occurred at $350 - 450\,°\mathrm{C}$. Due to serpentinization a new magnetization of CRM origin may be acquired in the rocks. So, the magnetization of the samples is partly of thermoremanent (TRM) and partly of the chemical remanent origin (CRM). The samples have always resided near the equator in a shallowly inclined magnetic field ($< 20°$). So, the inclination of RM of rocks should also be shallow. From the results of the Hole 895D (Leg 147) unregularly interchanged 15 positions with normal polarity also unregularly interchanged 12 positions of reversed polarity of RM were detected. It was in the interval of 16.2 to 85.4 mbsf (meter below seafloor) of the serpentinized harzburgite and exceptionally dunite rocks. In the interval of 0.47 to 80.82 mbsf of dominantly present dunites of the Hole 895E (Leg 147), 49 individual gradual positions with normal inclination of RM and only 7 individual reversed positions were detected. All inclinations are variable and inconsistent. They do not reflect precisely the inclination of the geomagnetic field at the respective geographical altitude. The inclinations of RM are dominantly normal. As mentioned above, the serpentinized peridotites contain the magnetite. The presented results have approved (not fully) my idea that the magnetites are the carriers only of normal RM in the rocks. The reversed inclinations of CRM in several samples were probably acquired by self-reversal process of the low content of ilmenite-hematites, which could be present in the rocks due to the high-temperature oxidation. The authors explained variability of inclinations of peridotites by tectonic tilting and by rotations of some parts of peridotite bodies.

## 4. Discussion and conclusions

In my previous works I focused my interest on the continental volcanics. On the basis of my experimental works, a new idea about the specified mineralogical carriers of normal and reversed RM of volcanic rocks has been established. It is quite natural that I need to test my idea with the large collections of rocks from different places of the globe, including the submarine rocks. At the first stage I selected the results from the places and locations as described above. E.g the young basalts from the FAMOUS area, mostly with the Ti-rich titanomagnetites, but also 0.7 m.y. old basalts. Basalts with the low-temeprature oxidized Ti-Mt-es from the Sites 332A,B area of the Leg 37, about 3.5 m.y. old. These basalts have dominantly reversed RM of self-reversal CRM origin. Young basalts from the Mid-Atlantic

Ridge dominantly of normal polarity and with Ti-rich ti-Mt bearing basalts. Further basalts were studied from the Juan de Fuca Ridge from the Hole U1301B in the very young axis systems but also within the older basalts. As in the massive basalts there are the Ti-rich Ti-Mt-tes present. But there are also the low-temperature oxidized Ti-Mt-es in most of basalts. Again, the Ti-rich Ti-Mt bearing basalts carry normal RM of the thermoremanent origin and the basalts with the low-temperature oxidized Ti-Mt-tes frequently carry the reversed RM of the chemical remanent magnetization (CRM) of the self-reversal origin.

From the Mid-Atlantic Ocean there were studied 13.0 m.y. old basalts from the Site 396B, Leg 46. The primary Ti-rich Ti-Mt-tes in these rocks have been detected only rarely. Mostly low-temperature oxidized Ti-Mt-tes are the carriers of RM of reversed polarity, of the self-reversal origin.

The peridotites of the age about 10.0 m.y. from the East Pacific Ocean were studied. They have been intensively altered by serpentinization. The magnetite is a dominant carrier of magnetic properties in these rocks. The inclinations of RM are dominantly normal. They do not reflect precisely the inclination of the geomagnetic field at the respective geographical altitude. The presented results have approved (not fully) my idea that the magnetites are the carriers only of normal RM in the rocks. The reversed inclinations of CRM in several samples were probably acquired by self-reversal process of the low-content ilmenite-hematites which could be present in the rocks due to the high-temperature oxidation.

The low-temperature oxidation Ti-Mt (Ti-Mgh) bearing volcanics are present in the submarine layers most frequently. They are preferably the carriers of the reversed CRM of the self-reversal origin. But I need to comment that we can find also the normally magnetized samples within the volcanic submarine systems. This problem has not been solved so far. I have proposed the mechanism of self-reversal acquiring of the reversed CRM of volcanics in a normally oriented field (*Orlický, 2009*), but there have not been considered all the possible conditions which are able to influence and modify a direction of the RM in the rocks. Because the low-temperature oxidized Ti-Mt-es (Ti-Mgh-es) are the product of alteration of Ti-rich Ti-Mt-tes, we need to know the magnetic state and properties of these primary magnetic minerals. It is necessary to know more about the micro-structure, atomic and ionic structure of this complicated mineral. The effective method for this purpose is the neutron diffraction. Unfortunately, such an instrument is not accessible in our laboratory nor in laboratories of the associated institutes. In the past I contacted the responsible specialists abroad, but I did not receive any answer. I have gathered the knowledge about the Ti-rich Ti-Mt in *Orlický (2010)*. But the knowledge about the Ti-rich Ti-Mt structure and its behaviour have not been completed. Each additional knowledge about the micro-structure, composition and properties are very useful. In the past a new approach – X-ray magnetic circular dichroism – was applied to solve Fe site occupancy in magnetite-ulvöspinel solid solution (*Pearcel et al., 2010*). It is as follows: Ordering of $Fe^{3+}$ and $Fe^{2+}$ cations between octahedral and tetrahedral sites in synthetic members of the magnetite-ulvöspinel ($Fe_3O_4$- $Fe_2TiO_4$) solid-solution series was determined using Fe L2,3-edge X-ray magnetic circular dichroism (XMCD) coupled with electron microprobe and chemical analysis, Ti L2,3-edge and Fe K-edge X-ray absorption spectroscopy (XAS), and unit-cell parameters. Microprobe analyses, cell edges, and chemical FeO determinations showed that bulk compositions were stoichiometric magnetite-ulvöspinel solid solutions. XMCD showed that the surface was sensitive to redox conditions, and samples required re-equilibration with solid-solid buffers. Detailed site-occupancy analysis gave $Fe^{2+}/Fe^{3+}$ XMCD-intensity ratios close to stoichiometric values. L2,3-edge XAS confirmed that $Ti^{4+}$ was restricted to octahedral sites. XMCD showed that significant $Fe^{2+}$ only entered the tetrahedral sites when Ti content was $> 0.40$ atoms per formula unit (apfu), whereas $Fe^{2+}$ in octahedral sites increased from 1 apfu in magnetite to a maximum of 1.4 apfu when Ti content was 0.45 apfu. As Ti content increased, a steady increase in $Fe^{2+}$ in tetrahedral sites was observable in the XMCD spectra, concurrent with a slow decrease in $Fe^{2+}$ in octahedral sites. Calculated magnetic moments ($\mu_B$) decreased rapidly from magnetite ($4.06\mu_B$) to USP45 ($1.5\mu_B$), then more slowly toward ulvöspinel ($0\mu_B$). Two synthesized samples were maghemitized by re-equilibrating with an oxidizing buffer. XMCD showed that $Fe^{2+}$ oxidation, with concomitant vacancy formation, restricted to octahedral sites. This new approach will be considered to make a more complete model for the Ti-rich Ti-Mt bearing rock properties.

Once the magnetic structure of the Ti-rich Ti-Mt and its magnetic behaviour is known, also the so-far accepted model of the self-reversal acquiring of the reversed CRM of low-temperature oxidized Ti-Mt-es can be refined.

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