Mineralogy and magnetism of Fe–Cr spinel series minerals from podiform chromitites and dunites from Tąpadła (Sudetic ophiolite, SW Poland) and their relationship to palaeomagnetic results of the dunites

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SUMMARY

This paper presents the mineralogy and magnetic properties of two varieties of chromitite, sampled in the same exposure of a serpentinite massif regarded to be a fragment of the Sudetic ophiolite. The varieties differ mineralogically and magnetically. One of them, labelled TaA and altered to a low degree according to scanning electron microscope (SEM) and microprobe results, comprises an unaltered Al-Cr spinel core, some secondary chromite and less abundant Cr-magnetite. It has a high magnetic susceptibility and natural remanence (NRM), and its dominating magnetic phase is ferrichromite with $T_{\rm b}/T_{\rm c}$ of about 530 °C occurring in grains in the single domain (SD) + pseudo-single domains (PSDs) and superparamagnetic (SP) states. The second variety, labelled TaB, is highly altered and comprises, apart from Al spinel, two kinds of secondary chromites that do not differ much from the primary Al spinel and no Cr-magnetites. This chromitite variety does not reveal one well defined $T_{\rm b}/T_{\rm c}$, but a series ranging between 200 and 450°C, their grain sizes correspond to the SD + SP domain states. The same pattern was observed in chromitite TaA after annealing in air at a temperature of 700 °C. Dunites associated with the chromitites contain, apart from magnetite, chromite grains. The majority of specimens reveal magnetic characteristics similar to the TaA-like variety, but in some specimens TaB-like characteristics were also observed. A standard palaeomagnetic study performed earlier on the dunites showed that their NRM has three components-Lower Devonian carried by magnetite, Permian and Tertiary-Recent. The results presented here lead us to conclude that the latter two are carried by ferrichromites similar to those found in the TaA and TaB chromitites.

Key words: Magnetic mineralogy and petrology; Palaeomagnetism applied to geologic processes; Remagnetization; Rock and mineral magnetism.

INTRODUCTION

In a previous paper (Kadziałko-Hofmokl *et al.* 2006b), we discussed the mineralogy and palaeomagnetism of ultramafic rocks from the Góry Sowie Block (GSB) and the Jordanów-Gogołów Serpentinite Massif (JGSM), the latest supposed to be fragment of a dismembered Sudetic ophiolite. Dunites (labelled Ta dunites) exposed at Tapadła Pass in the JGSM, contain magnetite and grains of chromite (Cr-bearing spinel minerals). The purpose of the present paper is to show that chromite grains present in Ta dunites are partly altered to ferrichromites of a similar type to those found in associated chromitites, and are carriers of Permian and Tertiary-Recent components of natural remanent magnetization natural remanence (NRM) (see Kądziałko-Hofmokl *et al.* 2006a). The oldest, Lower Devonian, component of NRM isolated in Ta dunites and labelled A3 (see Kądziałko-Hofmokl *et al.* 2006b) is carried by magnetite, formed probably during an initial stage of oceanic serpentinization of the Sudetic ophiolite.

Cr-bearing spinel minerals are common minor components of basic, ultrabasic and metamorphic rocks of the crust and the upper mantle, for example, gabbros, peridotites, dunites, kimberlites, basalts, serpentinites, etc. and are also present in meteorites and as detrital material in some sedimentary rocks (e.g. Stevens 1944; Coleman 1977; Dick & Bullen 1984; Fernandes 1999; Höfer *et al.* 2001; Barnes & Roeder 2001; Yu *et al.* 2001; Proenza *et al.* 2004; Maher & Hallam 2005). Occasionally, Cr-bearing spinels concentrate to form chromitites which are the commonest chromium ore. Traditionally chromitites are subdivided into two types (based on morphological and genetic characteristics): stratiform—associated with Proterozoic layered mafic–ultramafic intrusions located within

continental crust, and podiform—connected with Phanerozoic ophiolites which are remnants of ancient oceanic crust (Coleman 1977).

The cores of the Cr-bearing spinels present in podiform chromitites are very stable over a wide range of metamorphic conditions and tend to preserve their primary magmatic composition. However, alteration processes, such as serpentinization and regional metamorphism, usually modify the chemical composition of their external parts (Evans & Frost 1975; Burkhard 1993; Barnes 2000; Mellini et al. 2005; Arai et al. 2006; Kapsiotis et al. 2007). Depending on the degree of alteration, secondary magnetite, Cr-magnetite or other Fe-Cr spinel phases (e.g. chromite, 'ferrichromite') develop on the primary phases. These new phases usually form narrow alteration rims surrounding the primary Cr spinel core or develop along cracks. Their formation is attributed to low or medium grade metamorphism, up to mid-amphibolite facies (Thalhammer et al. 1990; Barnes 2000; Hartman & Chemale-Junior 2003). Lee (1999) suggests that Cr spinel alters into Fe-Cr spinel during amphibolite (over 500 °C) and greenschist (300-500 °C) facies metamorphism, whereas alteration to Cr-magnetite takes place at lower temperatures. The Cr/Fe³⁺ ratio within the rims is a function of either the abundance and availability of Cr and Fe in the environment or the ambient temperature (Evans & Frost 1975). Usually the amount of both Fe²⁺ and Fe³⁺ increases toward the grain margin. Similar changes of the spinel's chemical composition also take place during chloritization and hydrothermal processes (Shen et al. 1988).

The structure of Fe-Cr spinels (chromite series) is based on a nearly ideal cubic close-packed array of oxygen atoms with tetrahedral and octahedral cavities. The tetrahedral sites (A sites) are usually occupied by divalent cations, for example, Mg, Fe²⁺, Ni²⁺, Zn, etc. and the octahedral sites (B sites) by trivalent cations, for example, Al^{3+} , Fe^{3+} , Cr^{3+} . The chromite end-member (FeCr₂O₄) has a normal spinel structure where each type of cation is situated in a dedicated site: the Fe²⁺ cations are situated in the tetrahedral sites and the Cr³⁺ cations in the octahedral sites. Its magnetic structure is ferromagnetic (collinear spins of the same directions in A and B sites), but spins in the octahedral sites are canted against the tetrahedral ones, forming a cone-spiral magnetic spin structure. The mineral is ferromagnetic below its Curie temperature T_{c} equal 71 K (Ziemniak & Castelli 2003). The magnetite end-member, Fe²⁺Fe³⁺₂O₄ has an inverse spinel structure, where all tetrahedral sites are occupied by trivalent cations but half of the octahedral sites are substituted by divalent cations (e.g. Lenaz et al. 2004). This cation ordering can be attributed to the temperature of spinel crystallization (Sack & Ghiorso 1991). The magnetic structure of magnetite is ferrimagnetic, where spins in both sites are collinear, but have reversed directions. Its Curie temperature is about 575 °C. Binary mixed Fe–Cr spinels are described as $Fe^{2+}(Fe_{1-n}Cr_n)_2O_4$ where 0 < n < 1 denotes the mole fraction of chromite; n = 1 describes pure chromite, whereas magnetite has n = 0. The physical properties and structure of the spinel series depend on the contributions from normal and inverse spinels, as, for example, the Curie temperatures T_c and magnetic moments μB shown in Figs 1(a) and (b) (Robbins et al. 1971; Ziemniak & Castelli 2003). Both parameters decrease with an increasing amount of Cr. Fe-Cr binary spinel phases with n < 0.55-0.6 here called ferrichromites may influence the magnetic properties and the palaeomagnetic results of the rocks. In naturally formed Fe-Cr spinels, apart from Cr and Fe, cations of Al, Mg, Mn, Ni, Ti are also usually present and may influence the magnetic properties, although experiments by Chhaya et al. (1999) on chromites with minor admixtures of Al and Ni did not significantly modify the T_c –*n* relation.



Figure 1. (a) Curie temperature (T_c) dependence on mole fraction of chromite (n). (b) Magnetic moment (μB) dependence on mole fraction of chromite (n). n = 0—magnetite, n = 1—chromite.

Number of papers that deal with palaeomagnetism of Fe–Cr spinels is not high: Schmidbauer 1971; Kumar & Bhalla 1984; Fernandes 1999; Yu *et al.* 2001; Weiss *et al.* 2002; Yu & Gee 2005. This paper presents new data concerning the importance of magnetic Fe–Cr spinels ('ferrichromites') in palaeomagnetic investigations. As papers dealing with mineralogy and petrology of chromities and chromites use various terms for phases occurring within chromite grains, we append here Section Nomenclature explaining terms that are used in further parts of the paper.

NOMENCLATURE

The nomenclature of spinel group minerals is complex because of extensive solid solutions between many end-members. The term 'chromite' is applied to the Cr end-member ($Fe^{2+}Cr_2O_4-Fe^{2+}Fe^{3+}_2O_4$). However, Stevens (1944) proposed the name 'chromite' for spinels containing Cr as a major trivalent component (1–2 Cr per formula unit, pfu) and Fe^{3+} and Al as minor ones. On the other hand, the name 'chromite' is traditionally used for a wide variety of spinel compositions containing more than 15 wt per cent of Cr_2O_3 (Loferski & Lipin 1983). In the part of this paper concerning mineralogy of spinels, we consider as a 'Alchromite' the primary Cr-bearing spinel containing approximately equal amount of Cr and Al (about 1 pfu each) and less than 0.1 Fe³⁺



Figure 2. Geological sketch map of the middle part of the Jordanów-Gogołów Serpentinite Massif and locality of chromium ore mine near the village of Tapadła (modified from Delura 2001). Inset map shows position of the Jordanów-Gogołów Massif, Sudetes Mts., on the northern border of Góry Sowie Block.

pfu—(Mg,Fe²⁺)[Al,Cr,Fe³⁺]₂O₄. For spinel varieties that form alteration rims that progressively replace primary Al-chromite and are enriched both in Cr (over 1 Cr pfu) and Fe³⁺ (over 0.1 Fe³⁺ pfu), we use the names 'chromite', 'chromite 1' and 'chromite 2' instead of the widely used 'ferrichromite' or Spangenberg's (1942) 'ferritchromit'. We use 'Cr-magnetite' to describe a group of Cr-bearing spinel minerals close to the magnetite (Fe²⁺Fe³⁺₂O₄) end-member. The name 'ferrichromite' will be used in the part of the paper concerning magnetic properties of the spinels in the ores and dunites to describe magnetic Fe–Cr spinels. Preliminary results concerning mineralogy and magnetic properties of Tapadła chromities are shown in Kądziałko-Hofmokl *et al.* (2006a).

Geological setting of the Jordanów-Gogołów Serpentinite Massif

The geological setting and tectonic structure of the JGSM (SW Poland) have been described by several authors (e.g. Majerowicz 1979; Narebski et al. 1982; Dubińska 1995). The JGSM is an arcshaped body, ca. 12 km long and 3-5 km wide (Fig. 2-inset). It is the largest of the three serpentinite massifs considered to be dismembered fragments of the Sudetic ophiolite (e.g. Dubińska & Gunia 1997) and situated adjacent to the GSB. The JGSM mainly comprises completely serpentinized ultramafic rocks that were formed at the expense of harzburgites, lherzolites and dunites. Fresh or slightly altered ultramafic rocks are scarce. Most of the JGSM rocks are considered to be mantle tectonites (e.g. Majerowicz & Pin 1994; Dubińska & Gunia 1997). Their initial serpentinization was directly dated at 400 + 4/-3 Ma based on an integrated study of hydrothermal zircon from the rodingite blackwall (Dubińska et al. 2004). Palaeomagnetic studies suggest that the JGSM together with GSB has become the part of West Sudetes not earlier than 390 Ma (Kadziałko-Hofmokl et al. 2006b).

The serpentinites from the middle part of the JGSM, adjacent to the village of Tapadła, may represent the transition zone of the Sudetic ophiolite sequence (Delura 2001). They host small podiform (lens-shaped) chromitite bodies (Fig. 2), mined as chromium ore till 1945 (Birecki 1962). Unfortunately, the chromitites are now available only as rock debris forming waste dumps located on the slopes of Czarna Góra hill. The primary Al-chromites from this locality are usually altered; their alteration rims were described for the first time by Spangenberg (1942) as a 'ferritchromit'. Dunites outcrop close to the abandoned chromitite mine. Their mineralogy, magnetic properties and palaeomagnetic results have been already discussed in Kądziałko-Hofmokl *et al.* (2006a, b). Here we will show that magnetic varieties of chromite grains in the dunites contribute to their NRM.

Samples and experimental methods

Two hand samples of chromitite, labelled TaA and TaB, were collected from a waste dump of the abandoned chromitite mine near the village of Tapadła; the dunites (seven hand samples, see Kądziałko-Hofmokl et al. 2006b) were sampled nearby. For our study, we prepared three cylinders for standard palaeomagnetic measurements and about a dozen (as many specimens as was necessary for respective experiments, often repeated on fresh sister-specimens) from each chromitite hand sample. Specimens were crushed in a ceramic mortar, when needed (K_b-T method). Crushing did not change their susceptibility in an important way: specific susceptibility of the ore TaA before crushing was $4015 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}$, whereas after crushing was $4074 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}$; for the ore TaB respective values were: before crushing 294×10^{-9} m³ kg⁻¹ and after crushing 335×10^{-9} m³ kg⁻¹. Petrological and mineralogical studies of the chromitites were performed on natural and thermally treated specimens. Polished sections were examined with transmitted- and reflected-light polarizing microscopy.

Mineral compositions were determined using a CAMECA SX 100 electron microprobe equipped with wavelength-dispersive spectrometers (15 kV and 20 nA, PAP correction procedure) at



Figure 3. Microphotographs of sample TaA and TaB chromitites; polarizing microscope; reflected light, one polar. (a) TaA chromitite sample; Al-chromite (Al-Chr) occupies inner part of the spinel grains and is surrounded by chromite alteration rims (Chr); Cr-chlorite (Chl) fills the cracks and the spaces between spinel grains and also forms minute grains inside the chromite rims. Large primary pyroxene inclusion (Px) is visible within Al-chromite. Note the narrow extent of chromite alteration rims, the sharp boundary between Al-chromite and chromite, the small number of Cr-chlorite inclusions within the alteration rims and minute Cr-magnetite grains located along the cracks (Mag). (b) Serpentinized TaA chromitite with primary Al-chromite grains surrounded by wide chromite alteration rims. The rims contain more abundant Cr-chlorite, Cr-magnetite and rare millerite (Ml) inclusions, are located inside the chromite alteration rims. (c) Serpentinized TaB chromitite containing strongly altered spinel grains within Cr-chlorite mineral mass (Chl); Al-chromite (Al-Chr) occupies only the narrow inner part of the spinel grain, and it is surrounded by wide chromite alteration rim. Chromite 1 (Chr1) is the first alteration phase whereas chromite 2 (Chr2) is the second phase, forming outer alteration rim; both are located along grain edges. Note isometric dolomite (Dol), Cr-chlorite (Chl) and serpentinite (Srp) inclusions within chromite 1 and minute Cr-chlorite inclusions in chromite 2. (d) Strongly altered spinel grain from TaB sample; Al-chromite is absent; chromite 1 occupies inner part of grains, and it contains huge Cr-chlorite and tiny heazlewoodite (Hzl) inclusions. Chromite 2, located along the grain margins and cracks, surrounds chromite 1 and hosts smaller Cr-chlorite inclusions. The boundary between chromites 1 and 2 is indistinct, but it is underlined by a rapid rise of reflectance and loss of big chlorite inclusions.

the Electron Microprobe Laboratory, Faculty of Geology (Warsaw University) as well as by JEOL JXA-840A microprobe equipped with NORAN Voyager energy-dispersive spectrometer (15 kV and 35 nA, ZAF correction procedure) at the Institute of Geological Sciences, Polish Academy of Sciences (Warsaw). Synthetic silicate glasses and natural minerals were used as analytical standards. In the microprobe analysis of spinel, Fe is reported as total FeO, and Fe²⁺ and Fe³⁺ were recalculated by assuming ideal spinel stoichiometry. Backscattered electron (BSE) images and X-ray composition maps were recorded using a CAMECA SX 100 electron microprobe. The diameter of an excitation area was not less than 5 μ .

The magnetic study performed on both chromitite hand-samples fragments had, as a main goal, to find out whether they possess stable NRM and to identify the magnetic minerals responsible for the measured magnetic characteristics. The intensity of their NRM and its stability in the alternating field (AF) was studied with 2G SQUID, USA, with AF demagnetizer. Identification of magnetic minerals was performed by means of three thermomagnetic methods: (1) Analysis of the thermal decay curve of saturation remanence (SIRM) acquired in the field of 7 T, during heating in the field-free space in the air (TUS, Warsaw, Poland) to various temperatures, the highest being 700 °C. This method yields values of blocking temperatures (T_b) of minerals present in the rock sample in its natural state and $T_{\rm b}$ of new phases appearing due to previous heating. Heating to temperatures 150-600 °C with heating steps of 50 °C was done to find the temperature at which the magnetic properties of the specimen begin to change. (2) Lowrie analysis where specimens were magnetized in perpendicular directions in 0.12 mT, 0.4 mT and 1.5 T and then demagnetized thermally, together with saturation acquisition curve (IRM acquisition). This method reveals the presence of phases differing in T_{b} and in coercivity (Lowrie 1990). (3) Measurements of low-field bulk magnetic susceptibility $(K_{\rm b})$ during continuous heating from room temperature (r.t.) to 700 °C and in the low-temperature range between -194 °C and r.t. This method is often applied for estimation of Curie temperature $(T_{\rm c})$ with the two-tangent Grommé et al. (1969) method, very popular in estimating T_c from M_s -T curves and highly recommended by Tauxe (2002) for this purpose. This way of interpretation of $K_{\rm b}-T$ plots was lately questioned by Petrovsky & Kapička (2006) who argue that the two-tangent method applied to these plots does not

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			TaA						TaB			
Sample	Natural		Heated			Natural			Heated			
Phase	Al-chromite	Chromite	Al-chromite	Chromite	Cr-magnetite	Al-chromite	Chromite 1	Chromite 2	Al-chromite	Chromite 1	Chromite 2	Cr-magnetite
Al	0.96	0.61	0.96	0.59	0.01	0.98	0.76	0.44	0.99	0.76	0.44	0.04
V	0.01	0.01	I	I	I	0.01	I	I	I	I	0.01	I
Cr^{3+}	0.98	1.14	0.96	1.08	0.07	1.00	1.24	1.51	1.02	1.24	1.52	0.20
Fe^{3+}	0.05	0.24	0.08	0.33	1.90	0.02	I	0.04	I	I	0.03	1.72
Mg	0.71	0.68	0.76	0.69	0.04	0.56	0.48	0.42	0.51	0.52	0.42	0.13
Mn	I	0.01	I	0.01	I	I	0.01	0.01	0.01	0.01	0.01	I
Fe^{2+}	0.28	0.30	0.24	0.29	0.94	0.44	0.50	0.57	0.47	0.46	0.57	0.86
Ni^{2+}	Ι	0.01	Ι	0.01	0.01	Ι	I	I	Ι	I	I	Ι
Sum	3.00	3.00	3.00	3.00	2.97	3.00	3.00	3.00	3.00	3.00	3.00	2.95

reveal real $T_{\rm c}$. According to Petrovsky & Kapička , the $T_{\rm c}$ may be obtained either as temperature of the onset of $1/K_{\rm b}-T$ linear segment or as temperature of Hopkinson peak, if it is sharp enough. But none of these methods determines the exact Curie temperature: $T_{\rm c}$ estimated from $1/K_{\rm b}-T$ curve is slightly higher than the exact one (Morrish 2001). T_c estimated from Hopkinson peak is slightly lower than the exact one, because it determines the temperature of disappearance of energy barriers and not spontaneous magnetization as does T_c. Lattard et al. (2006) discussing application of inverse susceptibility method for Fe-Ti-O system express the opinion that the inversion susceptibility method does not work for magnetically heterogenous specimens. So we decided to apply the two-tangent method to the sharply descending segments of $K_{\rm b}-T$ plots and label the obtained temperatures as 'temperatures of susceptibility decrease' T_{sd} . T_{sd} obtained by his method also slightly overestimates real T_c , because it reflects end of curvature of $1/K_b$ -T plots just above $T_{\rm c}$. We argue that the two-tangent method may be satisfactory applied for specimens containing several magnetic phases where several segments of T_b –K plot of different curvatures represent different magnetic phases of different $T_{\rm sd}$ close to $T_{\rm c}$. According to Gendler (private communication 2006), $T_{\rm sd}$ are close to $T_{\rm c}$ in specimens that were not changed during heating; in case of important changes (oxidation/reduction), T_{sd} often do not reflect initial magnetic phases.

The K_b-T experiments above the r.t. were performed in air and in argon to check influence of heating processes on studied specimens. Experiments performed in the low temperatures could show low-temperature transitions, if present, and bring some information about domain state of the studied material.

To estimate composition of ferrichromites (mole fraction of chromite *n*) from the T_c –T plot (Fig. 1a), we used T_b instead of T_c —temperature that we could not measure due to the lack of appropriate equipment, as both temperatures are usually very close.

Heating of specimens to various temperatures from 150 to 700 °C was performed in the air to determine temperature at which the specimen starts to alter (Hrouda *et al.* 2003), (KLY-3S/CS-3/CS-L, Agico, Brno, Czech Republic). Measurements at r.t. of K_b after consecutive heating steps with a highest temperature of 700 °C were also performed (susceptibility bridge KLY-2, Geofyzika-Brno, Czech Republic).

Measurements of the parameters of hysteresis (VSM, Molspin, UK) concerned $M_{\rm rs}$ —saturation magnetization, $M_{\rm r}$ —saturation remanence, $H_{\rm c}$ —coercivity. Coercivity of remanence ($H_{\rm cr}$) was measured as well. The $M_{\rm rs}/M_{\rm s}$ and corresponding $H_{\rm cr}/H_{\rm c}$ ratios were compared with the Day plot for magnetite (Dunlop 2002), which helped us to speculate upon the domain state of the samples in their natural state as well as after consecutive annealings. A study of the anhysteretic remanence (ARM) was performed for the same purpose (LDA – 3 AF demagnetizer, AGICO, Czech Republic). It consisted in demagnetizing by AF (peak amplitude 140 mT) of ARM imparted to the studied specimens in a steady field of 100 μ T and AF decreasing from 100 mT. An inflected shape of the ARM–H(AF) curve reveals presence of grains in single domain (SD) state, whereas an exponential shape indicates MD state (Bailey & Dunlop 1983).

EXPERIMENTAL RESULTS

Petrology of chromitites

Chromitites from the Tapadła mine typically occur as two varieties, each of them represented by one hand sample. From each hand



Figure 4. (a) Ternary plots of trivalent cation contents in Al-chromite, chromite, chromites 1 and 2 and Cr-magnetite from both natural (white symbols) and thermally treated (black symbols) samples TaA (left-hand side) and TaB (right-hand side); note the sharp separation between primary and altered (secondary) spinels. Samples TaA and TaB seem to reveal two different alteration trends. (b) $Cr/(Cr + Al) \times 100$ (#Cr) versus $Fe^{2+}/(Fe^{2+} + Mg) \times 100$ (#Fe) plots for both natural (white symbols) and thermally treated (black symbols) samples TaA (left-hand side) and TaB (right-hand side); note that there is nearly no difference in #Fe between primary Al-chromite and secondary chromite in sample TaA, and the slight difference in #Fe between primary and secondary phases in sample TaB. Cr-magnetites in both samples have visibly higher #Fe than other phases. #Cr rises from Al-chromite to Cr-magnetite due to Al loss during alteration. (c) $Fe^{3+}/(Fe^{3+} + Cr + Al) \times 100$ (#Fe) plots for both natural (white symbols) and thermally treated (black symbols) samples TaA (left-hand side) and TaB (right-hand side); note the generally rising Fe³⁺ content and decreasing #Mg from primary (Al-chromite) to secondary (chromite and Cr-magnetite) phases at sample TaB, Fe³⁺ content is generally constant and associated with decrease in #Mg.

sample, we prepared as many specimens (about 20) as were necessary for respective experiments. The first variety (denoted TaA) is composed of large spinel grains (up to 2 cm in diameter) hosted by a Cr-chlorite matrix (Figs 3a and b). The main primary mineral, Al-chromite, forms cores of large spinel grains. Other primary minerals, olivine and minor pyroxene, are preserved as relicts within Al-chromite cores. The cores are surrounded by narrow alteration rims composed of light-grey opaque secondary chromite (higher reflectance than Al spinel). The boundary between both spinel phases is distinct. Within chromite rims numerous lath-shaped grains of Crchlorite are entrapped, as well as minute scarce Cr-magnetite and millerite (NiS) inclusions. The large spinel grains are frequently fractured and the edges of the cracks are usually altered.

The second variety of Tapadła chromitite (TaB) consists of large spinel grains (up to 2 cm in diameter) macroscopically similar to TaA chromitite (Figs 3c and d). The spinel grains are also hosted by a Cr-chlorite matrix, but dolomite is a minor matrix phase. Primary Al-chromite is rare and may form small relict cores within strongly altered spinel grains (Fig. 3c). It is gradually replaced by secondary chromite rims. The TaB spinel grains are usually composed of two generations of secondary chromite. Secondary chromite 1 forms the inner part of spinel grains and forms intergrowths with large irregular Cr-chlorite grains as well as with serpentine, dolomite and scarce heazlewoodite (Ni₃S₂). Narrow outer rims are composed of spongy chromite 2 intergrowths with minute lath-shaped Crchlorite. Secondary chromite 2 also forms narrow alteration zones developed along spinel grain fractures. The boundary between the chromite varieties is gradual and irregular. Microscopic studies of TaB sample did not reveal the presence of Cr-magnetite.

Mineral chemistry of chromitites

Over 200 microprobe analyses were performed on natural and thermally treated specimens of chromitite. Representative spinel analyses are listed in Table 1.

Analyses representing relict (primary) Al-chromite are similar in both chromitite samples. The trivalent cation composition #Cr [Cr/Cr + Al] is nearly identical for both chromitite varieties, whereas the divalent cation composition (i.e. Mg^{2+} and Fe^{2+}) is slightly different: #Fe [$Fe^{2+}/(Fe^{2+} + Mg^{2+})$] values of TaA vary between 20 and 37, while TaB is 30–50 (Fig. 4a). A representative chemical formula for Al-chromite from TaA and TaB samples can be written as follows: $Fe^{2+}_{0.23}Mg_{0.77}Al_{0.96}Cr_{1.04}O_4$.

Analyses of chromite alteration rims in samples TaA and TaB differ significantly. TaA chromite compositions form two distinct groups. The first is characterized by nearly constant Cr^{3+} content and decreasing contents of Al^{3+} ; it also forms a compact set of points showing a strong linear correlation between #Cr and #Fe, depicting a



Figure 5. (a) Fe, Cr, Al, Mg and Si contents in Al-chromite grain surrounded by narrow chromite alteration rim from natural sample TaA chromitite; BSE image and X-ray compositional maps (K α lines); note strong Al, Fe and slight Cr, Mg zoning. (b) Fe, Cr, Al, Mg and Si contents of Al-chromite grain surrounded by narrow chromite alteration rim from thermally treated sample TaA chromitite; BSE image and X-ray compositional maps (K α lines); numerous Cr-chlorite inclusions in the chromite alteration rim are responsible for higher Si content; note that there are no visible differences in compositional trends of Fe, Cr, Al and Mg between the natural and thermally treated samples. (c) Fe, Cr, Al, Mg and Si contents in spinel grain from natural sample TaB chromitite; BSE image and X-ray compositional maps (K α lines); Al-chromite is surrounded by wide chromite 1 and narrow chromite 2 alteration rim; note strong Al, Cr and Mg whereas Fe zoning is only slight; there is a distinct compositional difference between chromites 1 and 2 (Al and Fe). (d) Fe, Cr, Al, Mg and Si contents in spinel grain from thermally treated sample TaB chromitite; BSE image and X-ray compositional maps (K α lines); Al-chromite is used and X-ray compositional maps (K α lines); Al-chromite is a distinct compositional difference between chromites 1 and 2 (Al and Fe). (d) Fe, Cr, Al, Mg and Si contents in spinel grain from thermally treated sample TaB chromitite; BSE image and X-ray compositional maps (K α lines); small relics of Al-chromite are surrounded by Cr-chlorites and wide chromite 1 and narrow chromite 2 alteration rim; note that there are no visible differences in compositional trends of Fe, Cr, Al and Mg between the natural and thermally treated samples.



Figure 5. (Continued.)

concurrent increase of Fe²⁺ content with decrease in Al³⁺ (Fig. 4b). The distribution of analytical points for the second group suggests an increase in Cr^{3+} content associated with a constant Al^{3+}/Fe^{3+} ratio. The relationship between #Cr and #Fe is not clear; the analyt-

ical points are scattered. #Mg decreases with increasing Fe content (Fig. 4c).

TaB chromites generally are Fe^{3+} -free, except for a few points. They also form two separate groups that differ in Cr^{3+} content and



Figure 6. Magnetic properties of TaA chromitite sample (a) SIRM–*T* plot for sample during first and second heatings in air to 700 °C, SIRM acquired in 7 T, the inset shows ferrichromite (ferrichr) with T_b of 530 °C and magnetite (mgt), (b) SIRM–*T* plot for sample annealed at 700 °C for 45 min., (c) Lowrie plot showing the predominance of a low-coercivity component with T_b of 530 °C, (d) IRM acquisition curve, (e) K_b-T plot during continuous heating to 550 °C and consecutive cooling to r.t. in the air, (f) K_b-T plot during continuous heating in the air to 700 °C K_b and consecutive cooling to r.t. performed in argon, (h) K_b-T plot for sample in natural state in the low-temperature range from –196 °C to r.t., (i) the same for sample heated previously to 700 °C in the air.

#Fe value. Chromite 1 is Al^{3+} and Mg^{2+} enriched while chromite 2 contains more Cr^{3+} and Fe^{2+} (Figs 4a–c).

Cr-magnetites form a randomly distributed group varying from Cr^{3+} rich to nearly pure magnetite. Cr-magnetite was very rare in the investigated chromitites. During microprobe studies, only a few magnetite grains were found in the TaA sample and in TaB only one magnetite grain was found (Fig. 4a).

Composziational maps were made for determination of element distribution within mineral grains as well as for the investigation of reactions in the solid state during heating. In spinel grains in natural sample TaA (Fig. 5a), the Fe_{tot} content is insignificantly variable across primary Al-chromite and distinctly higher in the chromite alteration rim. These two spinel phases are clearly distinct from each other. The Cr^{3+} content is less variable; the chromite rim is slightly richer in Cr than Al-chromite. A high Al³⁺ content is limited to Al-chromite while chromite rims are impoverished in this element. Mg distribution is opposite to Fe. High Si content represents the presence of Cr-chlorite around and within spinel grain. Compositional maps of thermally treated TaA sample show similar behaviour of major elements as seen in natural sample

Table 2. Hysteresis parameters of specimens from chromitite TaA and TaB in natural state and after annealings.

Specimen	$M_{\rm rs}~(\mu{\rm A~m^2})$	$M_{\rm s}$ ($\mu \rm A~m^2$)	$H_{\rm cr}~({\rm mT})$	$H_{\rm c}~({\rm mT})$	$M_{\rm rs}/M_{\rm s}$	$H_{\rm cr}/H_{\rm c}$
TaA(1) natural state	98.4	342.7	20	11	0.29	1.82
After 1st heating to 700 °C	116.6	276.5	27	18.5	0.42	1.46
After. 2nd heating to 700 °C	114.0	266.1	27	19	0.43	1.42
After. 3rd heating to 700 °C	101.8	236.2	27.5	19	0.43	1.45
TaA(2) natural state	118.9	401.7	20	13	0.30	1.54
After. 1st heating to 700 °C	120.8	276.5	26	19	0.44	1.37
After. 2nd heating to 700 °C	114.1	263.2	27	19	0.43	1.42
After. 3rd heating to 700 °C	107.1	243.6	27	19	0.44	1.42
TaB(1) natural state	0.89	1.95	10	6	0.46	1.67
After. 1st heating to 700 °C	2.71	7.93	35	13	0.34	2.69
After. 2nd heating to 700 °C	2.42	8.9	37	10.5	0.27	3.5
After. 3rd heating to 700 °C	2.31	6.74	25	13	0.34	1.92
TaB(2) natural state	1.36	3.12	9	6	0.43	1.5
After. 1st heating to 700 °C	3.35	8.44	32	17	0.40	1.88
After. 2nd heating to 700 °C	2.81	9.02	25	13	0.31	2.17
After. 3rd heating to 700 °C	12.68	7.2	28	16	0.37	1.75

(Fig. 5b). There is no microscopic evidence for redistribution of the elements (recrystallization of the spinel) during sample heating.

Natural sample TaB spinel grains (Fig. 5b) reveal the presence of three spinel phases: primary Al spinel located in the grain centre (rich in Al³⁺ and Mg²⁺) and secondary chromite 1 which forms an intermediate zone around Al spinel whereas the outer zone is composed of chromite 2. Chromite 2 is significantly enriched in Cr^{3+} and slightly in Fe_{tot} and impoverished in Al³⁺ and Mg²⁺ compared to Al-chromite and chromite 1. The boundary between Al-chromite and chromite 1 is distinct while the chromite 1–chromite 2 transition is gradual. A high Si content underlines the presence of Cr-chlorite (abundant inclusions in chromites 1 and 2 and rock matrix). As in sample TaA, natural and thermally treated samples TaB demonstrate an analogous distribution of the elements (Fig. 5d). It suggests a lack of microscopically visible solid state reactions during heating.

The differences in spinel chemical compositions between natural and thermally treated samples are negligible in sample TaB and probably represent original variations in composition. Nevertheless, the differences are not significant which suggests that heating does not influence spinel composition in the large scale observations. Due to the large excitation area (see above), analyses cannot represent either the real mineral composition or its changes on the microscale.

Magnetic study of chromitites

Chromitite TaA

The intensity of the natural remanent magnetization NRM measured at r.t. reaches about 15000 mA m⁻¹. The amplitude of the AF of about 60 mT demagnetizes it completely, and the median destructive field (MDF) is about 25 mT. Values of bulk low-field susceptibility attain about 12 000 × 10⁻⁶ SI. Thermomagnetic analysis SIRM–*T* performed on at least five specimens from this hand sample revealed the prevalence of a phase with T_b of about 530 °C, traces of T_b at around 200 °C and around 580 °C— the blocking temperature of magnetite (Fig. 6a), 1st heating curve and the inset. The phase with T_b of 200 °C is easily removed during heating, but important changes in the SIRM–*T* plot begin to show only after heating to 550–600 °C. Consecutive heatings to 600, 650 and 700 °C result in consecutive lowering of T_b of the predominant

component to 470, 440 and 400 °C; the appearance of the last is seen on the curve of 2nd heating in Fig. 6(a). After about 40 min of annealing at 700 °C, the SIRM-T curve corresponds more to a series of $T_{\rm b}$ than to a well defined one, with the highest $T_{\rm b}$ of about 350 °C (Fig. 6b), and remains so during further annealings. The Lowrie plot and IRM acquisition curve (Figs 6c and d) show a predominance of a low-coercivity phase with T_b of about 530 °C, and traces of other components with $T_{\rm b}$ of about 170, 350 and over 550 °C. The observations of bulk susceptibility $K_{\rm b}$ changes against the temperature give more information about the composition of chromitite and about influence of the heating in air on it. Kb values measured at r.t. after consecutive heating steps do not change up to 300 °C, where they start to increase slowly. The heating-cooling branches of $K_{\rm b}$ -T plots obtained during continuous heating in air, show in some cases T_{sd} of about 50–70 °C. Both branches remain reversible during a heating-cooling cycle up to 550 °C (Fig. 6e). During heating to 700 °C, K_b -T plots clearly show pronounced T_{sd} at 530 °C and about 600 °C (Fig. 6f). The cooling branch reveals a lowering of the T_{sd} of the prevailing phase to about 470 °C and the beginning of formation of a 'hump' between 100 and 300 °C. Further heating to 700 °C results in lowering the temperature of the prevailing phase, eventually to 370-400 °C; at the same time, the 'hump' becomes more pronounced. After prolonged annealing, the heating and cooling branches become nearly reversible. Heating in argon reveals the presence of the phases with T_{sd} about 530, 580 °C (Fig. 6g), very close to $T_{\rm b}$.

The experiments performed at low temperature on specimens in the natural state show an increase of K_b with increasing temperature, which is characteristic of superparamagnetic (SP) grains. The experiment repeated on the same specimen heated previously to 700 °C shows a hump-like behaviour on the K_b-T plot (slow increase followed by decrease in K_b) indicating the increasing influence of paramagnetic grains (Figs 6h and i).

The results obtained from thermomagnetic methods reveal the presence in the TaA chromitite, apart from a very small amount of magnetite, of at least two magnetic Fe–Cr spinel phases: a decidedly prevalent phase with T_b of about 530 °C which corresponds to *n* of about 0.05–0.1, and, sometimes, a small amount of the phase with T_b of about 50–70 °C which corresponds to *n* of about 0.50–0.55 mol fraction of chromite (Fig. 1a). T_{sd} are of similar values. Annealing decreases both characteristic temperatures of the high temperature phase to about 350–400 °C, corresponding to *n* about 0.2–0.25 and



b)

AF (mT)

Figure 7. (a) Hysteresis ratios M_{rs}/M_s and H_{cr}/H_c measured for two specimens from TaA variety and two samples of TaB variety in natural state and after consecutive annealings at the Day–Dunlop plot for magnetite (after Dunlop 2002). SD—single domain, PSD—pseudo-single domain, SP—superparamagnetic, MD—multidomain. Other symbols as in the legend. (b) Normalized AF demagnetization plots of ARM imparted on samples TaA and TaB in DC of 100 μ T and AF decreasing from 100 mT. ARMo–ARM before demagnetization.

the formation of phases with lower T_b/T_{sd} corresponding to n < 0.4. All can be named 'ferrichromite' because of their high magnetic moment (Fig. 1b) and ability to acquire magnetic remanence.

Table 2 contains values of hysteresis parameters and H_{cr} obtained for natural and annealed specimens. For an interpretation of domain state, we used a Day plot evaluated for magnetites and titanomagnetites (Dunlop 2002). The M_{rs}/M_s versus H_{cr}/H_c values obtained for the TaA chromitite in the natural state lie on this plot along the line characteristic of a mixture of SD + MD (PSD, pseudo-single domain), close to its SD-rich end, Fig. 7(a). The values of M_s/M_{rs} obtained for TaA specimens (Table 2) are slightly lower than 0.3, whereas for the pure SD state, its value should reach 0.5. According to Dunlop & Prévot (1982), the grain sizes for magnetite, corresponding to the values of M_s/M_{rs} observed here, should not exceed 0.5μ and we assume that the same is valid for ferrichromite rich in magnetite. Already a single heating to 700 °C shifts the domain state of the samples closer to SD, M_s/M_{rs} increases to above 0.4 and remains so despite several consecutive annealings. These experiments show the resultant behaviour of the bulk specimens, implying that the prevalent amounts of ferrimagnetic Fe–Cr spinels present in the TaA ore are very fine grained with a dominance of grains in the SD state. SP grains are also present, as indicated in the results of the low-temperature experiments.

The ARM imparted on the TaA specimen in the steady field DC of 100 μ T and AF of 100 mT was demagnetized in AF with a peak field of 140 mT. The corresponding curve (Fig. 7b) has an inflected shape, supporting the conclusion about the presence of grains in the SD state.



Figure 8. Magnetic properties of the TaB chromitite (a) SIRM–*T* plot for sample in natural state during heating in the air to 700 °C, (b) the same after annealing for 45 min in 700 °C, (c) Lowrie plot, inset shows presence of low-coercivity phase with T_b of about 450 °C and presence of high-coercivity phase with T_b over 600 °C (haematite), (d) IRM acquisition curve, (e) wasp-waist hysteresis plot, (F) K_b –*T* plot during consecutive heating steps, (g) K_b –*T* plot during continuous heating to 700 °C in air and cooling to r.t., (h) K_b –*T* plot for natural sample in the low-temperature range from –196 °C to r.t., (i) the same for sample heated previously to 700 °C in air.

Chromitite TaB

Sample TaB behaves differently to sample TaA. It has a much lower intensity of NRM (200 mA m⁻¹) and magnetic susceptibility (only about 1000 × 10⁻⁶ SI). AF demagnetization of NRM reveals the presence of carriers with lower coercivity (up to 20 mT) and another, with a different direction and higher coercivity. The bulk MDF is low—it reaches only 10 mT. The SIRM–*T* curves reveal the presence of a spectrum of T_b ranging between 100 and 350 °C, rather than a well pronounced T_b value. It is accompanied by a phase with

 $T_{\rm b}$ of about 670 °C, probably haematite (Fig. 8a). In some specimens, heating in air results in shifting the $T_{\rm b}$ range to slightly higher temperatures, but most often they remain in the same or slightly lower temperature range, even after prolonged annealing (Fig. 8b). The Lowrie method shows the prevalence of low-coercivity phases with a series of $T_{\rm b}$, where $T_{\rm b}$ of 200, 300, 450 °C and a small amount of 530 °C are discernible. The high-coercivity curve reveals the presence of a high $T_{\rm b}$ phase—haematite (Fig. 8c). The presence of haematite is supported by the IRM acquisition curve and by the wasp-waist shape of the hysteresis loop (Figs 8d and e).



Thermomagnetic properties of Ta dunites

Figure 9. SIRM–*T* (left-hand side) and K_b-T (right-hand side) plots of two samples of Tapadła dunites containing TaA-like and TaB-like ferrichromites. (a) Dunite TaA-like, inset in the left plot shows SIRM–*T* dependence between 400 and 600 °C, (b) Dunite TaB-like, curve for 2nd heating lies on the curve of the 1st heating, inset in the left plot shows SIRM–*T* dependence between 300 and 600 °C.

Bulk K_b does not change during consecutive heatings except for the relatively large peak between about 350 and 450 °C (Fig. 8f). It corresponds to the results of the study of K_b during continuous heating in air—the K_b –T plots show, in the majority (but not all) cases, an important increase of K_b in the temperature range of 300– 580 °C, with a peak at about 450 °C. This phase disappears during further heating. During cooling, K_b increases slowly and attains values higher than the initial ones (Fig. 8g). Changes of K_b during heating in the air begin in TaB sample after heating to 500 °C, heating and cooling branches of K_b –T plots in lower temperatures are reversible. The behaviour of K_b in the low-temperature range shows paramagnetic-like behaviour in the natural state, and para + SP-like after heating to 700 °C (Figs 8h and i).

As was shown in Fig. 8(e), the hysteresis loop has a wasp-waist shape, proving presence of two components with different coercivities, but values of hysteresis parameters included in Table 2 are more characteristic of the low-coercivity component. On the Day–Dunlop plot for magnetite (Fig. 7a), points for the natural specimens of TaB ore lie close to the SD + SP trend of magnetite, with a very small amount of SP and very close to the SD range (M_s/M_{rs} is above 0.4). Consecutive annealings change the ratios of SD/SP grains, but after several heatings to 700 °C domain state seems to go back to the SD area. The presence of grains in the SD state is supported by the inflected shape of the ARM demagnetization curve (Fig. 7b).

Summarizing, the thermomagnetic methods reveal the presence in the TaB sample of a series of T_b of low-coercivity phases, rather than one well pronounced value of T_b . We assume that in the TaB sample numerous phases of ferrichromite with T_b between about 100 °C (*n* about 0.5) and 450 °C (*n* about 0.2) dominate, accompanied by haematite. This pattern (series of T_b) does not change during annealing. The K_b-T plots show the presence of a series of T_{sd} on the heating branch, often (but not always) together with the rapid appearance and break-up of an unindentified phase, and a series of T_{sd} beginning at about 400 °C on the cooling branch. The Day plot and study of ARM demagnetization curve suggest that ferrichromites occur in SD and SP grains.

DISCUSSION

Our results show that both ore varieties, although coming from the same locality, are different; the variety TaA carries large amount of secondary, highly magnetic, Fe-Cr spinels with a composition close to that of magnetite (Cr-magnetites) of very fine grain size (PSD + SD + SP), which makes its identification by mineralogical methods difficult. A similar situation was observed by Mellini et al. (2005) in retrograde serpentinites where the 'ferritchromite' appeared as nanoscale intergrowths. Heating procedures influence much more the magnetic than mineralogical characteristics. When mineralogical data do not show much change, magnetically they are drastic; the $T_{\rm b}$ and $T_{\rm sd}$ of the dominant phase decrease, due to annealing, from well defined at 530 °C to a series of temperatures ranging from about 100 to 350 °C. This behaviour is probably due to a miscibility gap observed in the Fe-Cr series (Cremer 1969; Ziemniak & Castelli 2003). The dominant ferrichromite (Crmagnetite) phase with n of about 0.1-0.05 begins to unmix at temperatures exceeding 550-600 °C and, passing through the solvus



Figure 10. Thermal demagnetization plots of three samples of Ta dunites containing TaA-like and TaB-like ferrichromites. Left plots present normalized changes in intensity of NRM after consecutive heating steps, NRMo—intensity of NRM in room temperature. Right plots present Zijderveld diagrams. Values of intensity labelled on the axes—in μ A/m². (a) Ta15 dunite containing R, A1 and A3 components, (b) Ta13 dunite contains A1 component, (c) Ta14 dunite contains A1 and R components.

temperature during cooling, forms two phases: one with n about 0.25–0.3 at the magnetite-rich end of the series and another close to the chromite-rich end, non-magnetic above r.t.. Consecutive annealings result in the formation of a series of ferrichromite phases.

According to our mineralogical study, it does not seem that the TaB variety carries magnetic phases of the Fe–Cr spinel series. Nevertheless, thanks to the magnetic study, we found the presence in this ore of magnetic carriers with a series of T_b in the range 100–450 °C, occurring in the SD and SP states. This composition does not change much due to heating. As annealing of the TaA variety brings its magnetic composition to the initial composition of TaB, we assume that the TaB variety became altered and acquired its thermodynamic equilibrium due to processes that did not touch some areas of the chromitite body, leaving the TaA variety unaltered.

Our results for chromitite have enabled us to interpret better

palaeomagnetic data obtained by Kądziałko-Hofmokl *et al.* (2006b) for the Ta dunites associated with chromitite. As was shown in Kądziałko-Hofmokl *et al.* (2006b), the dunites contain chromite grains identified microscopically, as well as several generations of magnetite, some haematite and maghemite (figs 7 and 8 in Kądziałko-Hofmokl *et al.* 2006b). Magnetic methods used for the identification of magnetic minerals indicate the presence in majority of specimens magnetic phases with T_b/T_c of about 530 °C (TaAlike ferrichromite) and 580 °C in the majority of studied specimens. Heating in air to 700 °C shifts T_b/T_c of the former to slightly lower temperatures, in a similar way to that observed in chromitite TaA (Figs 9a and b), but in some other specimens, SIRM–*T* plots correspond more closely to SIRM–*T* plots obtained for TaB (Figs 9c and d). It is possible that all Ta dunites comprise Fe–Cr spinels of both types, but TaB-like types are not easily observable because they are



Figure 11. Stereographic plot of components of natural remanence of TaA dunites carried by ferrichromites; component A1—Permian, component R—Tertiary-Recent. Other symbols are in the legend.

magnetically weaker than TaA-like types and become covered by them on the appropriate plots.

Kadziałko-Hofmokl et al. (2006b) showed that the Ta dunites, together with other ultramafic rocks from the JGSM and GSB, carry three palaeomagnetic components: the oldest, labelled A3, dated as Lower Devonian according to the Apparent Polar Wander Path for the West Sudetes, Jeleńska et al. (2003), Permian (labelled A1) and Tertiary-Recent labelled R. Thermal demagnetization showed that in dunites the component A3 appeared at the unblocking temperatures of magnetite, whereas A1 and R components appeared in a broad range of demagnetizing temperatures from 200 to 550 °C, and we could not precisely identify their carrier. Now, comparing the magnetic results of TaA and TaB chromitites with those of dunites, we can say that they contain the TaA-like and TaB-like 'ferrichromite' phases. Analysis of thermal demagnetization plots of dunites revealed that in a number of specimens, component A1 is carried by a mineral which demagnetizes at 525-530 °C-the TaA ferrichromite—but in some it appears at lower unblocking temperatures. The same is true for component R (Figs 10a-c). We therefore assume that components A1 and R are carried mainly by ferrichromites of various compositions. Distribution of their directions obtained in various ranges of unblocking temperatures and during AF cleaning are presented in Fig. 11.

The alterations of initial Al spinel that leads to 'ferrichromite' formation probably took place at rather low temperatures, during serpentinization and hydrothermal episodes. The newly formed ferrichromites and, perhaps, magnetites, are responsible for the Permian and Tertiary-Recent palaeomagnetic components found in numerous places in the Sudetes.

CONCLUSIONS

The studied Palaeozoic chromitites and dunites exposed in the JGSM fragment of the Sudetic ophiolite carry various phases of 'ferrichromite'; from highly magnetic Cr-magnetite with $T_{\rm b}/T_{\rm c}$ of

530 °C to less magnetic phases with T_b/T_c ranging from about 100 to 450 °C. The magnetic phases are very fine grained (mostly in the SD, PSD and SP domain state), which made identification with microscopic methods impossible. Microprobe data show some areas of Cr-magnetite composition in the highly magnetic TaA ore variety, whereas in the TaB one, they do not. This can be ascribed to the different degrees of alteration that affected TaA and TaB varieties. The presence of ferrichromite rich in magnetite has not been recognized before in any paper concerning palaeomagnetic investigations of rocks containing minerals of the Fe–Cr spinel series.

Ferrichromites similar to those identified in the chromitite are present also in the associated dunite where they are the main carriers of the Permian and Tertiary-Recent components of NRM. It has been suggested (Dubińska *et al.* 2004) that the dunites are of Lower Devonian age, the age of initial oceanic serpentinization of the JGSM ophiolite fragment. Ferrichromites, which carry much younger NRM components, formed during Permian and later times, due to the alteration of initial Al spinel. Alteration did not homogenously change either the whole chromitite or the whole dunite bodies.

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