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# PALEOMAGNETIC AND ROCK MAGNETIC PROPERTIES OF THE LOWER PALEOZOIC METAMORPHIC COMPLEX OF THE RUDAWY JANOWICKIE (WEST SUDETES, POLAND)

MARIA JELEŃSKA[1*], TOMASZ WERNER[1] and STANISŁAW MAZUR[2]

[1]Institute of Geophysics, Pol. Ac. Sc., Ks. Janusza 64, 01-452 Warsaw, Poland; *bogna@igf.edu.pl
[2]Institute of Geological Sciences, University of Wrocław, Pl. Borna 9, 50-204 Wrocław, Poland

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**Abstract:** The Lower Paleozoic Rudawy Janowickie Metamorphic Complex represents the eastern part of the Izera-Karkonosze Massif in the West Sudetes (NE Bohemian Massif). It comprises a nappe pile overthrust towards the NW onto the pre-Variscan continental basement of the Saxothuringian Basin. The complex consists of three units: (1) Leszczyniec Unit composed of metabasites and gneisses, (2) Izera-Kowary Unit consisting of gneisses and mica schists and (3) the South Karkonosze (Niedamirów) Unit consisting of greenstones and phyllites. These rocks underwent multi-stage deformation mostly accompanied by epidote-amphibolite grade metamorphism of the Late Devonian to Early Carboniferous age. Rock magnetic study revealed magnetite and hematite as carriers of remanence accompanied by maghemite and sometimes by goethite. Several high stability components of characteristic remanent magnetization (ChRM) of predominantly reversed polarity were found. The shallow directions of remanence were interpreted as Carboniferous overprint on the basis of the similarity of their pole position to the Carboniferous segment of the Apparent Polar Wander Path (APWP) for Baltica. The position of paleopoles derived from the steep directions corresponds well with the Silurian segment of the APWP for Baltica assuming the anticlockwise rotation of the Rudawy Janowickie Complex by the angle of ca. 90°. The paleolatitude derived from these directions after averaging corresponds well to the Silurian data for the Bohemian Massif. The possibly Early Paleozoic directions were found in different rock types: metabasites, gneisses and limestones from the Leszczyniec and Izera-Kowary Units. However, the scatter of the Kmax and ChRM along similarly oriented girdles may suggest that the deformation influenced the NRM directions.

**Key words:** Paleozoic, metamorphic complex, paleomagnetism, rock magnetism.

## Introduction

The West Sudetes lying on the NE margin of the Bohemian Massif shows complex geology consisting in a mosaic of distinct, fault bounded, pre-Permian basement units. Several recent interpretations invoke a number of variously defined tectonostratigraphic terranes in the West Sudetes, either showing close affinities to the major tectonic zones of the Variscan Orogen (e.g. Matte et al. 1990) or, at least in part, exotic with respect to the Variscan belt (e.g. Cymerman et al. 1997). The space for conflicting tectonic hypothesis partly emerges from the scarcity of paleomagnetic data for the pre-Permian, mostly metamorphosed rock complexes of the West Sudetes. The preliminary studies generally revealed the paleomagnetic poles representing Carboniferous and Permian overprints (e.g. Jeleńska et al. 1995; Kądziałko-Hofmokl & El-Hemaly 1997; Edel et al. 1997). Some other results (Nawrocki & Żelaźniewicz 1996; Kądziałko-Hofmokl et al. 1998) suggest the presence of characteristic directions with their poles located on the Early Paleozoic segment of the Apparent Polar Wander Path (APWP) for Baltica and Eastern Avalonia. The latter data, however, seem to be not fully consistent with the available geological evidence (e.g. Aleksandrowski et al. 2000). The paleomagnetic study of non-metamorphosed Devonian olistoliths from Early Carboniferous wild-flysch succession (Jeleńska et al. 2001) documented pre-folding remanence component corresponding to the paleolatitude characteristic for the southern margin of Baltica in the Devonian. It dates back, however, only to Middle-Late Devonian times that is to the interval contemporaneous with the initial accretion of the Variscides. Consequently, preceding results are still very insufficient and require additional verification through more specific investigations in particular units of the Variscan basement of the Sudetes.

This paper discusses the results of the paleomagnetic study in the Rudawy Janowickie Metamorphic Complex, being a part of the Karkonosze-Izera Massif in the West Sudetes. The present work is a continuation of magnetic anisotropy and structural investigations of that area carried out by Werner et al. (2000). It also refers to the earlier paleomagnetic results of Kądziałko-Hofmokl et al. (1998) which were only limited to the Paczyn gneisses (locality LPC in this paper). The aim of the study is to put new constraints on the tectonic evolution of the metamorphic complex of the Rudawy Janowickie on the basis of paleomagnetic data and analysis of relationships between deformation, tectonic and magnetic anisotropy and paleomagnetic directions.

## Geological setting

The Rudawy Janowickie Complex belongs to the Karkonosze-Izera Massif which occupies the south-central part of the West Sudetes on the NE margin of the Bohemian Massif (Fig. 1). The massif comprises the Early Carboniferous Karkonosze granite pluton surrounded by its Neoproterozoic-

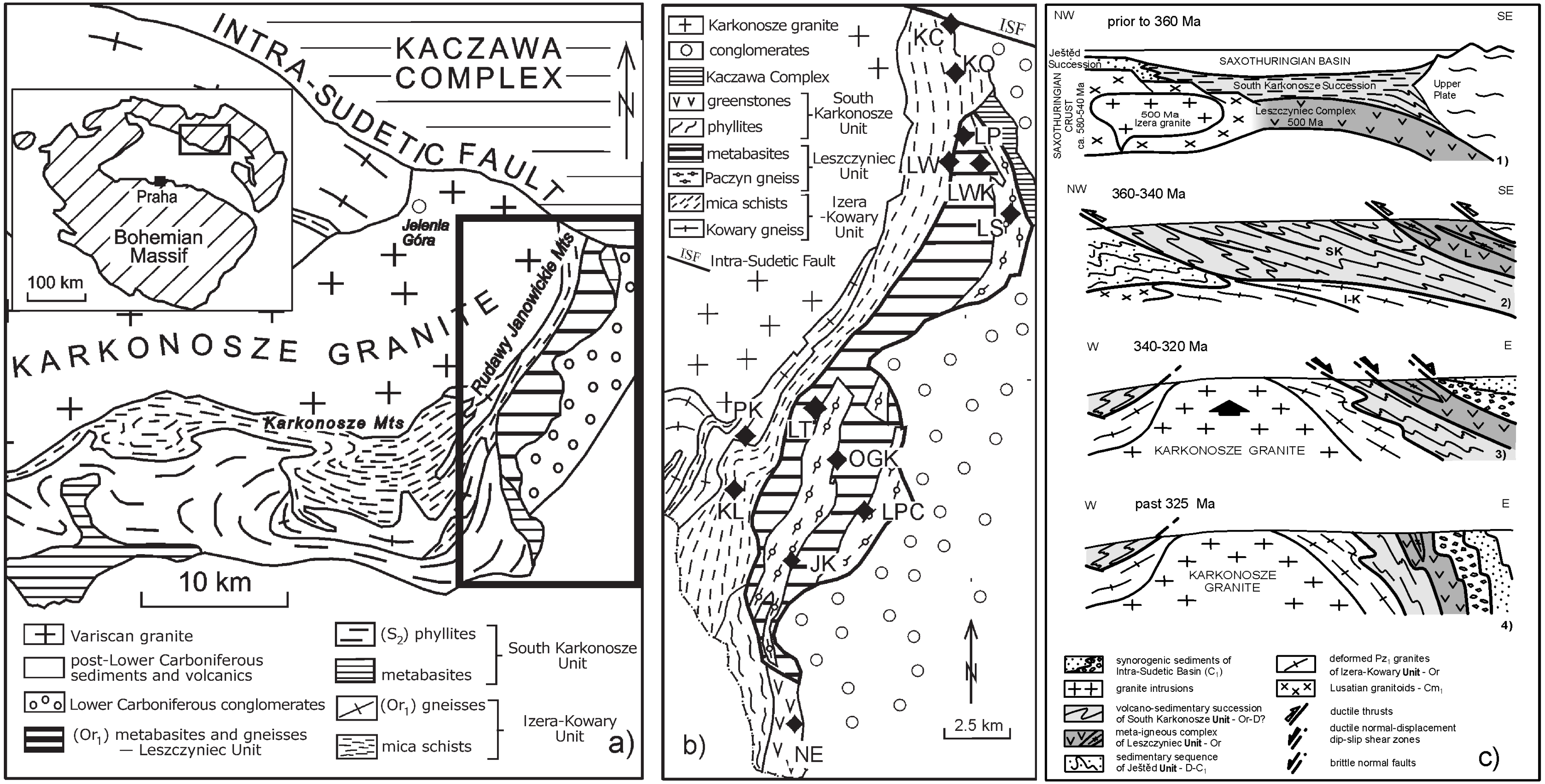


**Fig. 1. a —** Geological sketch map of the Karkonosze-Izera Massif with inset map to show tectonic location within the Bohemian Massif. Inset: hachure— pre-Permian crystalline rocks. **b —** Geological sketch map of the Rudawy Janowickie Mts (Leszczyniec, Izera-Kowary and South Karkonosze Units). Diamonds indicate the location of sampling sites. **c —** Late Devonian to Carboniferous structural evolution of the Karkonosze-Izera Massif modified after Mazur & Aleksandrowski (2001) (vertically exaggerated schematic model). (1) Schematic palinspastic restoration of the Karkonosze-Izera nappe units prior to the main overthrusting event inspired by Wolfgang Franke's reconstructions of the Saxothuringian belt. (2) NW-ward overthrusting event. (3) Top-to-ESE extensional collapse followed by intrusion of the Karkonosze granite. (4) Development of the East Karkonosze monocline. **I–K** — Izera-Kowary Unit, **J** — Ještěd Unit, **SK** — South Karkonosze Unit, **L** — Leszczyniec Unit.

Paleozoic metamorphic envelope. The latter consists of several structural units showing different lithostratigraphy and metamorphic evolution (Mazur & Aleksandrowski 2001). From base to top these units are: (1) the Izera-Kowary, (2) Ještěd, (3) South Karkonosze and (4) Leszczyniec. The Izera-Kowary Unit is mainly composed of the ca. 500 Ma old (Oliver et al. 1993; Kröner et al. 2001) Izera granite, most of it transformed by a subsequent deformation into the Izera (or equivalent Kowary) gneiss, and of mica schists representing remains of its Neoproterozoic(?) envelope. These rocks underwent medium-pressure (MP) metamorphism under upper greenschist–lower amphibolite facies conditions (Kryza & Mazur 1995; Oberc-Dziedzic 1987). The mica schists are in places associated with bands of stripe metabasites characterized by within-plate geochemical signature (Winchester et al. 1995). The Ještěd Unit comprises shelf and continental slope sediments of Devonian to Early Carboniferous age only subjected to lower greenschist facies conditions. The South Karkonosze Unit consists of Lower Paleozoic variegated metasediments and MORB (Mid-Ocean Ridge Basalt) type metabasites. These rocks bear record of blueschist facies metamorphism overprinted by the medium-pressure greenschist facies event. The Leszczyniec Unit comprises a differentiated suite of mafic and felsic rocks of volcanic and plutonic origin. The most widespread rock type is fine-grained MORB-type schistose metabasite associated with minor medium-grained massive varieties and with thin intercalations of felsic metavolcanics (Kryza et al. 1995; Winchester et al. 1995). Their age is estimated as Early Ordovician, ca. 500 Ma through preliminary U-Pb zircon dating (Oliver et al. 1993). The metabasites include several large sill-like bodies of the Paczyn gneiss. The latter comprise a wide range of rock types from felsic to hornblende-bearing gneisses (Kryza et al. 1995). The Leszczyniec Unit underwent relatively high pressure (HP) metamorphism reaching the epidote-amphibolite facies.

The N-S trending Rudawy Janowickie Mts represent the eastern margin of the Karkonosze-Izera Massif sandwiched between the Karkonosze granite on the west and Carboniferous to Lower Permian sediments of the Intra-Sudetic Basin on the east. The metamorphic complex of the Rudawy Janowickie Mts comprises the eastern margin of the Izera-Kowary Unit, the entire Leszczyniec Unit and a small fragment of the South Karkonosze Unit (Fig. 1).

The structural study of the eastern margin of the Karkonosze-Izera Massif, carried out by Mazur (1995), revealed three main deformation events $D_1$, $D_2$ and $D_3$ of regional extent. The $D_1$ episode, comprising NW-directed ductile thrusting, produced the main foliation $S_1$ and mostly NW-SE trending stretching lineation $L_1$ with local relics of top-to-the NW shear indicators. The $L_1$ stretching lineation in the Leszczyniec Unit is NNE-SSW-oriented and, thus, it differs from the general trend of $L_1$ in the neighbouring units. The NW-ward nappe stacking was followed by SE-directed Visean extensional collapse $D_2$. The $L_2$ stretching lineation trends WNW-ESE throughout the entire Karkonosze-Izera Massif. Numerous kinematic indicators consistently show a top-to-the ESE sense of shear. The important reorientation of the regional foliation on the eastern margin of the Karkonosze-Izera Massif has been attributed to the $D_3$ rotation around a NNE-SSW trending axis of the so-called East Karkonosze monocline (Oberc 1960).

The South Karkonosze and Leszczyniec Units are interpreted as nappes, which emplaced blueschist facies rocks and MORB-type meta-igneous complexes on top of a continental passive margin (Mazur & Aleksandrowski 2001). Outcrops of these two nappes are considered to delineate a Variscan suture zone separating the Saxothuringian passive margin to the NW, represented by the Izera-Kowary and Ještěd Units, and the concealed hypothetical active margin of the Tepla-Barrandian terrane to the SE (Mazur & Aleksandrowski 2001).

The timing of the collision recorded by the Karkonosze suture zone is approximately constrained by the Ar-Ar age of white micas from the HP rocks of the South Karkonosze Nappe (Maluski & Patocka 1997). The blueschist facies metamorphism, at least partly preceding the collisional event, was dated at ca. 360 Ma (a minimum age), whereas the age of the subsequent MP overprint was estimated at ca. 340 Ma. The time span between 360 and 340 Ma roughly corresponded to the period of nappe emplacement, since the decompression of the HP rocks was mostly related to the overthrusting event (Mazur & Kryza 1996). The final emplacement of the previously metamorphosed nappes must have post-dated the early Visean cessation of sedimentation in the Ještěd Succession, as this weakly metamorphosed sedimentary sequence is overridden by the South Karkonosze Complex. The subsequent extensional collapse took place at around 340 Ma and must have ceased before the intrusion of the little deformed, mostly post-orogenic Karkonosze granite, dated at ca. 330–325 Ma (Duthou et al. 1991). The origin of the East Karkonosze monocline post-dated the $D_2$ event and the emplacement of the Karkonosze granite, since the rotation affected, apart from the metamorphic complexes of the Rudawy Janowickie Mts, also the Upper Visean conglomerates of the Intra-Sudetic Basin.

A total of 145 hand samples and 52 drilled cores (Fig. 1) were collected in 12 localities from the Rudawy Janowickie Complex:

8 within the Leszczyniec Unit: LP — metabasite and limestone, LW — metabasite, LWK — metabasite and metaryolite, LS — metabasite and gneiss, LT — metabasite and gneiss, OGK —metabasite and gneiss, LPC — gneiss, JK — gneiss.

4 within the Izera-Kowary Unit: KC — schist, KO — stripe metabasite, PK — gneiss, KL — schist.

1 within the South Karkonosze Unit: NE — greenschist.

Several cylindrical specimens were cut from each hand sample and one or two cores were obtained from each drilled core.

## Magnetic mineralogy

Magnetic mineralogy was determined by examination of thin and polished sections under ore microscope and by a set of thermomagnetic experiments. Several samples were examined under scanning electron microscope JSM-35 and by means of microprobe (EDS) LINK-ISIS. The range of magnification used was between 80 and 2500 times.

The thermomagnetic methods used to identify magnetic minerals comprised: thermomagnetic analysis which consists of continuous thermal demagnetization of saturation isothermal remanence (SIRM), the Lowrie test — step by step thermal demagnetization of three components IRM (Lowrie 1990), changes of magnetic susceptibility during heating-

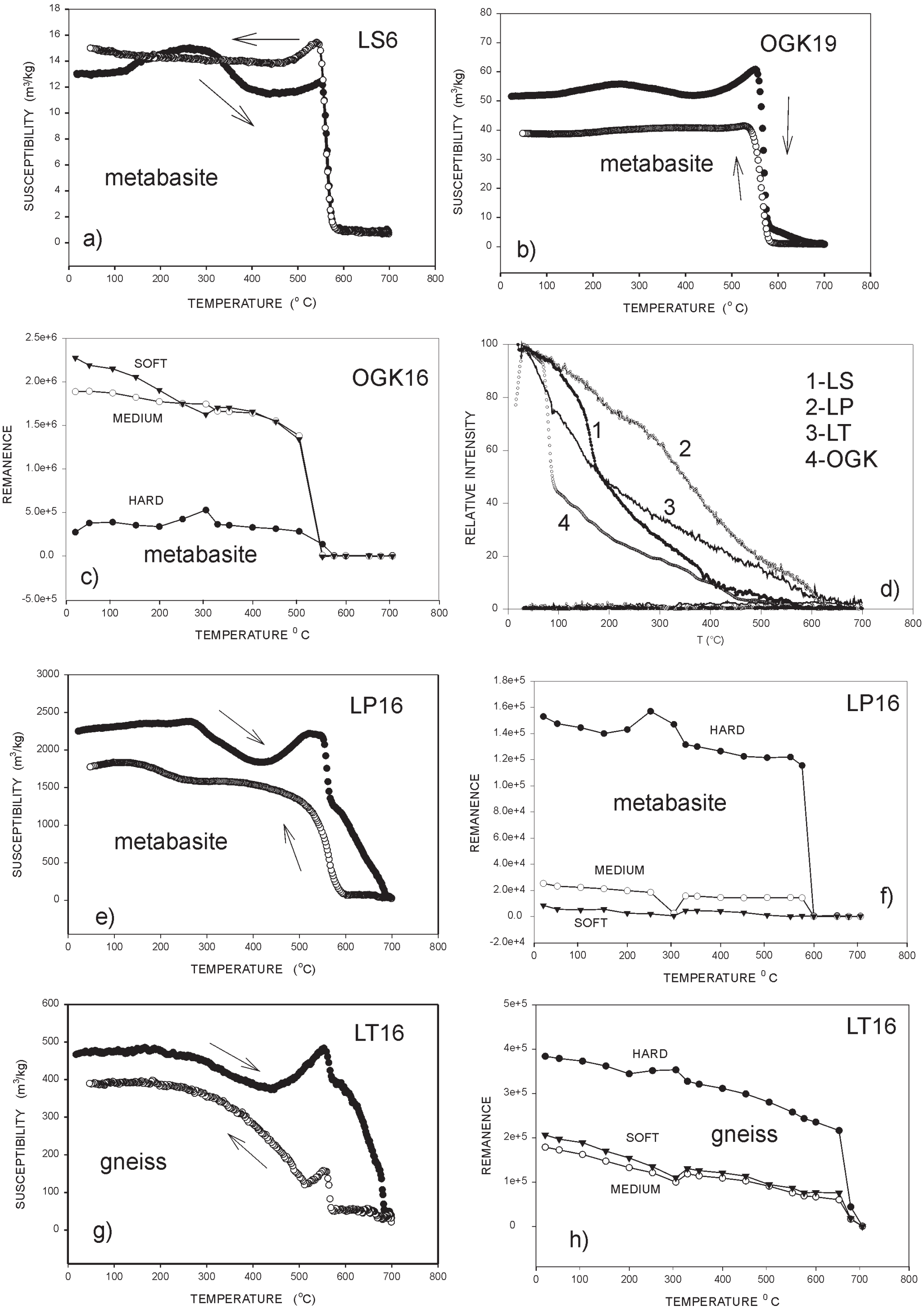


**Fig. 2.** Examples of susceptibility during heating K(T) (Figs. a,b,e,g); thermal demagnetization of three-axial IRM (Lowrie test; Figs. c,f,h); decay of saturation IRM (SIRM) during continuous heating (Fig. d) curves showing magnetite, hematite and goethite for metabasites and gneisses from the Leszczyniec Unit.

cooling cycle (K(T)) and changes of room temperature susceptibility $K_m$ after step by step heating. The structure of the magnetic minerals were examined by determination of IRM and anhysteretic remanent magnetization (ARM) acquisition curves and hysteresis loop parameters.

Thermomagnetic analysis was made using a home-made device. A specimen was magnetized in a field of 1 or 9 T using MMPM10 of Magnetic Measurements (Liverpool, UK). Then remanence was measured in a field free space during rotation of a specimen. Three perpendicular components of remanence used for Lowrie test were acquired in fields of 3 T, 0.5 T and 0.12 T, respectively. Remanent magnetization was measured by means of 2G SQUID cryogenic magnetometer and by a JR4 Czech spinner magnetometer (Agico, Brno).

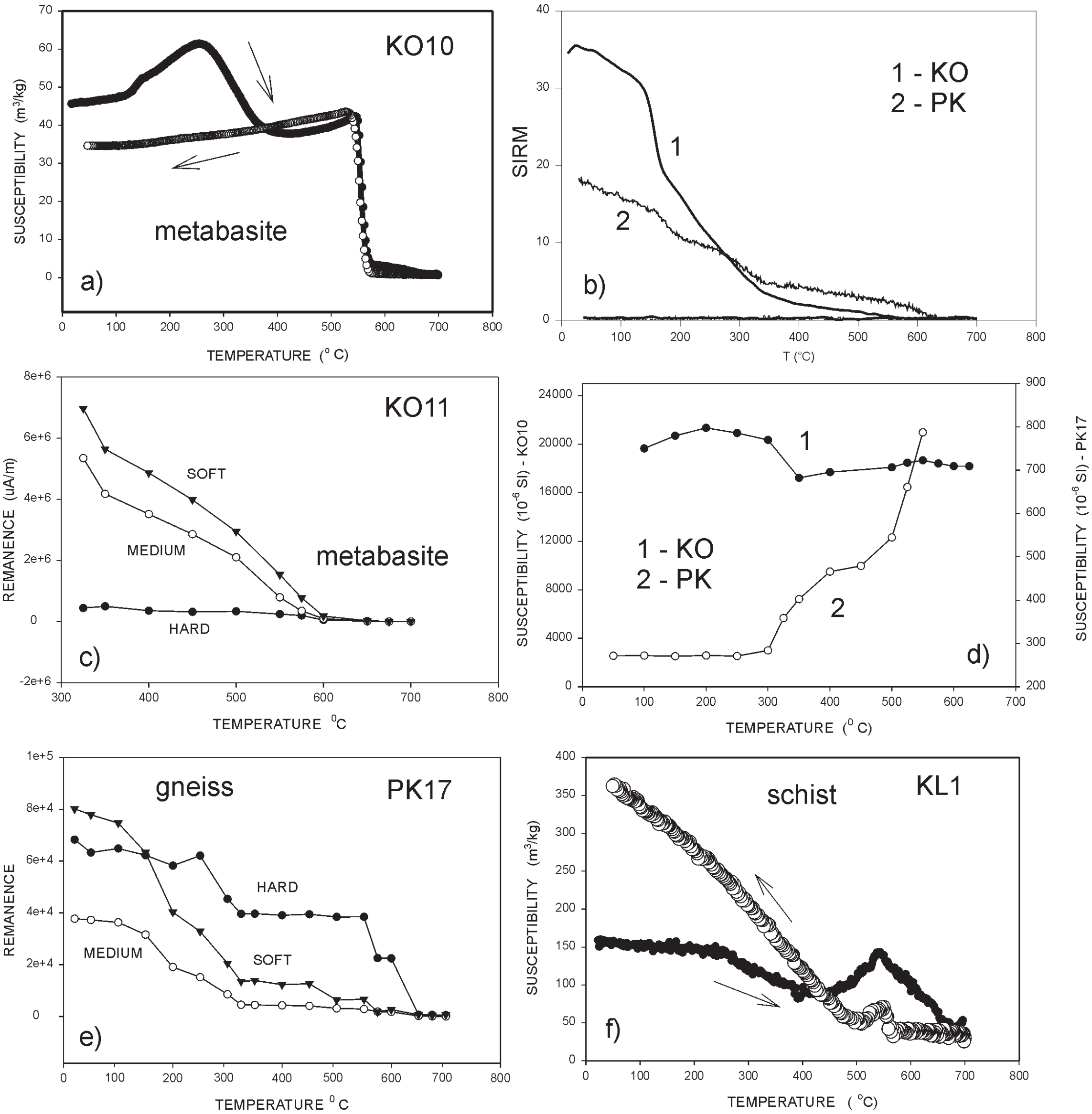


**Fig. 3.** Examples of susceptibility during heating K(T) (Figs. a,f); thermal demagnetization of three-axial IRM (Lowrie test; Figs. c,e); decay of saturation IRM (SIRM) during continuous heating (Fig. b) and changes of room temperature susceptibility $K_m$ after step by step heating (Fig. d) curves showing magnetite, hematite and goethite for schists and gneisses from the Izera-Kowary Unit.

Heating was performed in a non-magnetic oven of Magnetic Measurements (Liverpool, UK). ARM was acquired in a steady field of 0.05 or 0.1 μT and a peak alternating field increasing up to 100 mT in a Czech device LDA1/AMU (Agico, Brno). The bulk susceptibility measurements were conducted using KLY-2 Kappabridge (Agico, Brno). Changes of magnetic susceptibility during heating were performed with use of a KLY-3/CS-3 device (Agico, Brno). Hysteresis loop was measured using vibrating magnetometer VSM of Molyneaux, UK.

*Leszczyniec Unit*

In the metabasites (OGK, LS, LW, LWK, LP, LT) examination of thin and polished sections revealed the presence of automorphic magnetite sometimes with thick ilmenite lamellae. Often magnetite underwent martitization. In the LS pseudomorphs after Fe-oxides and sulphides were observed. In the LWK and LP hydrooxides after sulphides were seen. Everywhere magnetite is accompanied by tabular or flaky hematite. In the gneisses (OGK, JK, LS, LT, LPC) aggregate of hematite or tabular hematite were observed under a microscope. In LPC pseudomorphs after magnetite and hydrooxides were seen. Under the scanning electron microscope, in LS and LW, two generations of magnetite and flaky hematite were detected.

In the metabasites from the Leszczyniec Unit the main magnetic mineral detected by K(T) curves, thermomagnetic analysis and Lowrie test (Fig. 2) is magnetite. Sometimes magnetite is accompanied by some amount of hematite (Fig. 2b). In the LS and LW metabasites goethite was seen on the thermomagnetic curve (Fig. 2d). In the LP, the thermomagnetic and K(T) curves (Fig. 2d,e) show hematite not seen on Lowrie test curves (Fig. 2f). We explained this behaviour as due to oxida-

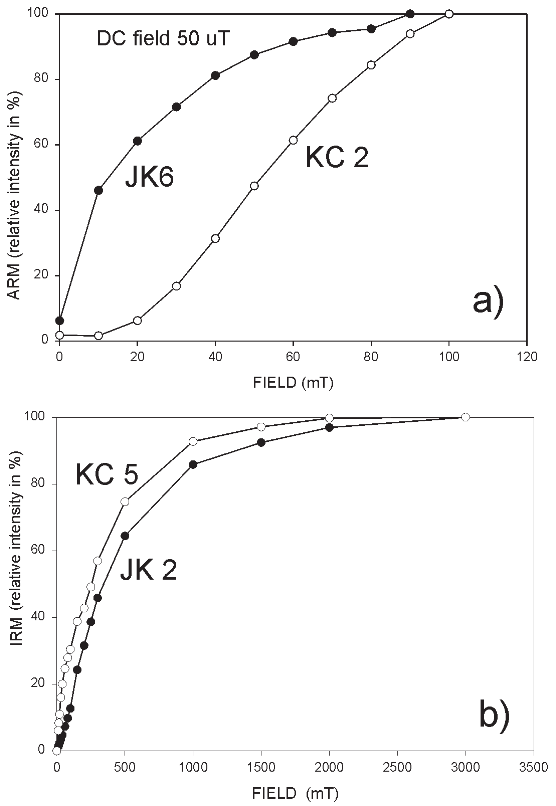


**Fig. 4.** Examples of ARM (a) and IRM (b) acqusition curves.

tion of maghemite to hematite after heating above 300 °C demonstrated by decrease of susceptibility (Fig. 2e).

In the gneisses mainly hematite was observed (Fig. 2g,h), sometimes with magnetite (Fig. 2g) and the phase with unblocking temperature ($T_{ub}$) about 300 °C (Fig. 2h). In the OGK and JK gneisses, thermomagnetic analysis (Fig. 2d) revealed the presence of goethite.

*Izera-Kowary Unit*

In the mica schists and metabasites of the Izera-Kowary Unit, magnetite was seen under miscroscope only in KL. In the KO magnetite is replaced by amphibole. In the KL and PK sulphides and hydrooxides were observed. Under scanning microscope hematite, hydrooxides and sometimes magnetite were observed in the KO.

The thermomagnetic analysis and K(T) curves showed magnetite in the KO, KL and KC (Fig. 3a,b). The Lowrie test confirmed the presence of magnetite in these localities (Fig. 3c). Sometimes K(T) curves revealed magnetite, an increase of susceptibility from a temperature of 150 °C followed by a decrease from 300 °C and some hematite. Such behaviour often observed on the K(T) curves (Fig. 3a) can be interpreted as dehydration of goethite to maghemite followed by oxidation of maghemite to hematite. The thermomagnetic analysis (Fig. 3b) revealed the presence of mineral with low unblocking temperature ($T_{ub}$) seen on all components with $T_{ub}$ between 150 and 200 °C which can be a goethite as well.

In the PK and KL gneisses the Lowrie test showed hematite, magnetite and the phase with $T_{ub}$ of 200 °C (goethite?), and sometimes the phase with $T_{ub}$ of about 320 °C, which can be related to pyrrhotite (Fig. 3e). The curve of room temperature susceptibility changes after step by step heating shows increases of susceptibility after heating to 325 °C and after 500 °C, which can be related to dehydration of non-magnetic hydrooxides and to oxidation of pyrite, respectively (Fig. 3d). The K(T) curves confirmed the presence of hematite (Fig. 3f) in the PK and KL.

In KC all experiments revealed the presence of magnetite.

For selected samples IRM and ARM acquisition curves were determined (Fig. 4). The IRM and ARM acquisition curves are evidence for high coercivity material, although the coercive force and coercivity taken from hysteresis loops are not very high (Werner et al. 2000, Table 1). It suggests that the field of 0.1 T used for hysteresis loop measurements is not sufficient for saturation and we are still dealing with partial loops.

*South Karkonosze Unit*

In the NE greenschists all experiments pointed to hematite as the magnetic mineral. The hysteresis parameters and IRM/ARM acquisition curves showed high coercivity material (10).

Summing up the main magnetic carriers of remanence are magnetite, hematite and sometimes goethite and maghemite. Magnetite is often cut by ilmenite lamellae, partly oxidized to martite or replaced by amphibole. This magnetite is likely to be primary. Hematite seen under the microscope occurs in the tabular form or flakes often inside the veins. The tabular or flaky form can be related to the primary origin. Hematite placed inside the veins should be of secondary origin.

## Magnetic anisotropy

The results of the anisotropy of magnetic susceptibility (AMS) study, presented in the paper by Werner et al. (2000), confirmed that magnetic foliations in both the Izera-Kowary and the Leszczyniec Units display, besides the minor differences in dip, approximately similar NNE-SSW striking subvertical orientations. The Kmin axes correlate well with poles to the $S_1$ foliation at the scale of a single locality and the entire area (Fig. 5a,c). This is only the northernmost edge of the Izera-Kowary Unit where the structural and magnetic foliation strikes E-W (localities KC and KO).

Werner et al. (2000) demonstrated that the magnetic lineation Kmax and structural stretching lineation $L_1$ (Fig. 5b,d) are steep, mostly WNW-ESE oriented over the Izera-Kowary Unit. In contrast, the majority of exposures in the Leszczyniec Unit display distribution of the Kmax along a great circle, corresponding to the mean attitude of the magnetic foliation. There is a full spectrum of transitional orientations between the NNE-SSW horizontal and WNW-ESE steep structural trends (L1) characteristic of the Leszczyniec and the Izera-Kowary Units (Fig. 5d), respectively. A scatter of the magnetic lineation, detected at the scale of individual exposures (i.e. LPC), precludes rotation of magnetic fabric on the limbs of map-scale folds. It must have resulted, therefore, from a continuous change of strain geometry. Consequently, the AMS data support previous structural observations showing a different structural pattern in the Leszczyniec Nappe in comparison to the underlying tectonic units.

**Table 1:** Hysteresis parameters for selected samples of different lithology (modified after Werner et al. 2000).

| Unit | Sample | Mineral | Lithology | $K_b$ $10^{-6}$ S.I. | $K_{par}$ $10^{-6}$ S.I. | $K_{par}/K_b$ % | $M_s$ μA $m^2$ | $M_{rs}$ μA $m^2$ | $H_c$ mT | $H_{cr}$ mT | $H_{cr}/H_c$ | $M_{rs}/M_s$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KOWARY | KC5 | mgt | schist | 1069 | 821 | 76.8 | 4.86 | 1.45 | 21.5 | 67.0 | 3.12 | 0.30 |
| | KO4 | mgt + goethite | metabasite (actinolite, chlorite) | 30728 | 1418 | 4.6 | 622.5 | 139 | 21.0 | 60.0 | 2.86 | 0.22 |
| | PK21 | mgt + hem goethite? | gneiss | 73 | 60 | 81.6 | 0.32 | 0.06 | 17.5 | ? | - | 0.19 |
| | Kl5 | mgt + hem goethite | schist | 19290 | 1543 | 8.0 | 1159 | 33.5 | 3.0 | 26.0 | 8.67 | 0.03 |
| LESZCZYNIEC | LP17 | mgt + hem | metarhyolite | 153 | 109 | 71.3 | 0.52 | 0.10 | 19.5 | 40? | 2.05 | 0.19 |
| | LW11 | mgt + hem goethite | metabasite | 21835 | 969 | 4.4 | 1243 | 102 | 8.5 | 40.0 | 4.70 | 0.08 |
| | LWK4 | mgt + hem | metarhyolite (actinolite, chlorite) | 432 | 432 | 100.0 | - | - | - | - | - | - |
| | LS6 | mgt + hem goethite | metabasite | 4321 | 624 | 14.4 | 129 | 19 | 15.5 | 59.0 | 3.81 | 0.15 |
| | LT16 | hematite | gneiss | 177 | 172 | 97.5 | 0.42 | 0.12 | 29.0 | 40? | 1.38 | 0.28 |
| | LT17 | mgt | metabasite | 28880 | 1383 | 4.8 | 1108 | 76 | 5.0 | 28.0 | 5.60 | 0.07 |
| | OGK2 | mgt + hem goethite | gneiss | 140 | 104 | 74.1 | 2.04 | 0.25 | 17.0 | 42.0 | 2.47 | 0.12 |
| | LPC31 | mgt + hem | gneiss | 846 | 846 | 100.0 | - | - | - | - | - | - |
| | LPC15 | mgt + hem | gneiss | 543 | 517 | 95.2 | 0.65 | 0.09 | 4.0 | - | - | 0.14 |
| | JK2 | hematite + goethite | gneiss | 576 | 358 | 62.0 | 20.06 | 1.51 | 9.0 | 60.0 | 6.67 | 0.07 |
| NIEDAMIRÓW | NE5 | hem | greenstone | 66 | 26 | 39.1 | 1.92 | 0.94 | 109 | 950 | - | - |

$K_b$, $K_{par}$ are the bulk susceptibility and paramegnetic susceptibility; $M_s$, $M_{rs}$ are saturation magnetization and saturation remanence; $H_c$, $H_{cr}$ are coercive force and coercivity.

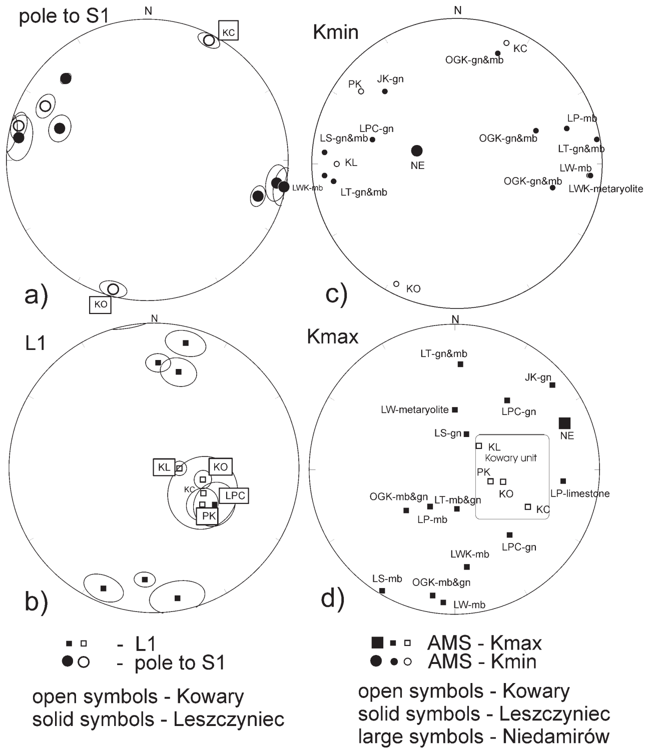


**Fig. 5.** Mean values of S1 and poles to L1 (a,b); counting means for Kmin (c) and counting means for Kmax (d) for localities (modified after Werner et al. 2000).

The AMS data of Werner et al. (2000) are completed in this paper with measurements of magnetic remanence anisotropy (AARM), carried out by imposing anhysteretic remanence (ARM). The anhysteretic remanence was acquired on a sample using a commercial AMU-1/LDA-1 device made by Agico Czech Republic. The ARM acquisition curves made for two values of DC field: 50 and 100 μT allow us to choose values of the DC and AF field for ARM acquisition and orientation scheme for anisotropy determination. We used the DC field of 100 μT and AF field of 90 mT. The 6-directions scheme along face-diagonals was selected as a fast robust method of the AARM tensor determination with sufficient accuracy. This scheme was employed by Agico for AREF software, which we used for AARM tensor calculation (Jelinek 1981).

The anisotropy of the remanence axes Amax (Fig. 6) are approximately similar to the AMS axes (Fig. 5) for the Leszczyniec and the Izera-Kowary Units. The subhorizontal NE-SW orientation of the Amax of the Leszczyniec Unit is better pronounced than for the AMS. The foliation planes of the AARM (Figs. 5 and 6) are subvertical and more scattered than those for the AMS data. The scatter observed for the anisotropy of remanence could be caused by the hardness of the rocks often containing goethite or hematite. The orientation of the ARM foliation planes in the Izera-Kowary Unit are almost perpendicular to those in the Leszczyniec Unit. The E-W strike of the structural and AMS foliation planes in the KO and KC localities are considered by Werner et al. (2000) as an effect of their rotation due to a sinistral displacement along the adjacent Intra-Sudetic Fault. The N-S oriented Amin directions are, however, well-documented by AARM data not only in these localities, but also in this part of the Izera-Kowary Unit (KL and PK) which crops out far away from the fault. This situation indicates that a growth of ferromagnetic minerals, responsible for the anisotropy of remanence took place in different time than the structural and AMS foliations were created. The subhorizontal NE-SW Amax found in the Leszczyniec Unit is probably related to the oldest fabric created during NW-directed ductile thrusting and associated with the N-S trending foliation plane. The steep WNW-ESE structural and magnetic fabrics well pronounced in the Izera-Kowary Unit were produced during the extensional deformation $D_2$, super-

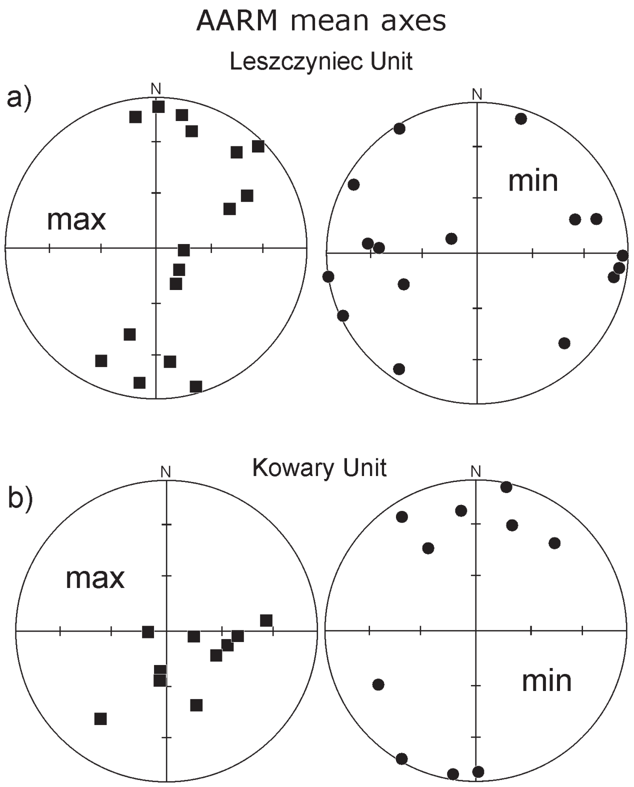


**Fig. 6.** AARM axes for Leszczyniec unit (upper) and Kowary Unit (lower). AARMmax (left) and AARMmin (right). Axes for individual samples.

imposed on the original $D_1$ fabric in the Leszczyniec Unit. Ferromagnetic minerals which are responsible for E-W trending remanence foliation of the Izera-Kowary Unit were probably produced in the extensional regime $D_2$ demonstrated by well developed magnetic lineation overprinted in the Izera-Kowary Unit on the previously developed N-S trending foliation.

## Palaeomagnetic experiments

Paleomagnetic measurements were performed by means of 2G SQUID and associated AF demagnetizer. Thermal demagnetization was carried out in the non-magnetic oven produced by Magnetic Measurements, U.K. The measurements were performed in the cage (Magnetic Measurements, U.K) compensating about 95 % of the ambient magnetic field.

AF and thermal demagnetization were performed for pilot samples from each locality. For part of samples thermal demagnetization was not possible to temperatures higher than 500–575 °C (Fig. 7). Above that temperature heating caused chemical changes in the magnetic minerals and an increase of remanence was observed. Sometimes chemical changes occurred at low temperature (200–300 °C) which preclude thermal demagnetization. When thermal demagnetization was impossible AF demagnetization was applied. AF demagnetization did not remove the remanence completely for the majority of samples, but the demagnetization path is usually directed to the beginning of the coordinate frame (Fig. 7a,d,f,g). When the path is not directed to the beginning (Fig. 7c,e) we loose the final direction. In spite of such difficulties we were

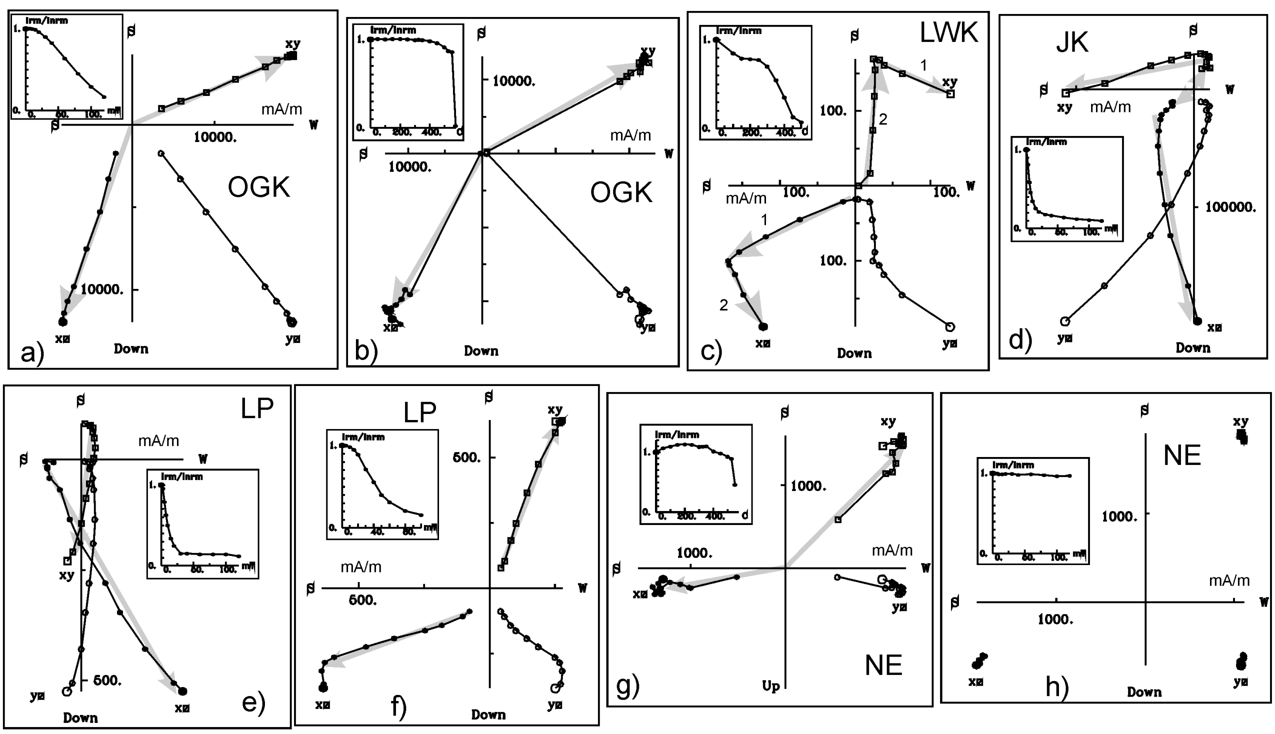


**Fig. 7.** Examples of thermal and AF demagnetization of specimens. Lines represent directions calculated by PDA software of Lewandowski et al. (1997). Directions are plotted in geographical coordinate system by means of the PDA software.

able to isolate directions of characteristic remanence (CHRM) of high stability. Characteristic remanence components were calculated using the PAD package (Lewandowski et al. 1997) which includes principal component analysis (Kirschvink 1980). Linear segments of demagnetization curves were accepted for maximum deviation (MAD) of less than 10°. More than 4 points were used to define a line. Isolated components were usually removed between 20 and 80–120 mT or at a temperature about 500–575 °C suggesting magnetite as magnetic carrier. In the case of some samples it is not possible to determine blocking temperatures as we are not able to complete thermal demagnetization and only AF treatment was applied. However, we suppose that the high stability component not removed completely by 120 mT field during AF demagnetization is carried by hematite.

The in situ mean directions of high stability for localities are shown in Fig. 8 and listed in Table 2. For localities: LP, OGK and LPC two directions were found. Three directions were re-

**Table 2:** ChRM directions for Rudawy Janowickie.

| | | Locality | $D^0/I^0$ | $\alpha_{95}$ | k | N | $\Lambda^0/\Phi^0$ | Corr. 1 $D_c^0/I_c^0$ | Corr 1 $\Lambda_c°/\Phi_c°$ | Corr. 2 $D_{cc}^0/I_{cc}^0$ | Corr 2 $\Lambda_{cc}°/\Phi_{cc}°$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Leszczyniec Unit | metabasites | LP1 | 205/14 | 10.4 | 16.7 | 13 | –28/347 | 206/14 | –28/347 | - | - |
| | | LP2 | 9/69 | 12.5 | 20.6 | 8 | 84/84 | 82/55 | 31/87 | 92/7 | 1/103 |
| | | LW | 195/15 | 13.6 | 32.4 | 5 | –30/359 | 197/10 | –32/357 | - | - |
| | | LWK1 | 188/28 | 6.8 | 28.3 | 17 | –24/8 | 184/17 | –31/12 | - | - |
| | | 2 | 243/47 | 15.7 | 13.2 | 8 | 6/324 | 207/60 | 4/357 | 144/39 | –10/50 |
| | | 3 | 32/17 | 16.6 | 21.9 | 5 | –40/332 | 49/8 | –28/318 | 44/-20 | –18/330 |
| | metabas.-gneiss | LS | *314/25 | 10.9 | 23.4 | 9 | 37/258 | - | - | - | - |
| | | LT | 214/31 | 16.1 | 18.2 | 6 | –16/342 | 202/33 | –19/355 | 177/25 | –26/25 |
| | | OGK1 | 231/49 | 6.6 | 25.0 | 20 | 2/334 | 196/54 | –4/4 | 149/32 | –17/48 |
| | | 2 | 300/58 | 13.6 | 17.4 | 8 | 47/294 | 52/84 | 57/34 | 99/36 | 10/87 |
| | gneiss | LPC1 | 33/-17 | 8.9 | 27.0 | 11 | –24/340 | 30/-21 | –23/344 | - | - |
| | | 2 | 314/74 | 12.0 | 9.2 | 18 | 63/323 | 101/70 | 34/61 | 104/20 | 0/90 |
| | | JK | 196/31 | 11.3 | 17.3 | 11 | –21/359 | 188/23 | –27/8 | - | - |
| Kowary | schists | KC | 187/-8 | 15.7 | 18.9 | 6 | 43/186 | 243/14 | –11/312 | 218/45 | –6/343 |
| | | KO | 183/54 | 7.5 | 24.9 | 16 | –5/13 | 269/75 | 42/337 | 112/54 | 14/68 |
| | gneiss | PK | 7/19 | 10.8 | 32.0 | 7 | 49/185 | 30/23 | –44/334 | - | - |
| | schists | KL | 263/49 | 11.2 | 25.4 | 8 | 18/311 | 222/72 | 23/353 | 128/46 | 0/61 |
| | | | *303/40 | 13.5 | 13.8 | 10 | 38/275 | 22 | | | |
| Nied. | green st. | NE | 212/3 | 7.8 | 23.1 | 16 | –31/337 | 218/9 | –26/334 | - | - |
| Mean of LP2, LWK2, OGK2, LPC2, KO, KL after corr 1 and 2 | | | 111/35 | 20.2 | 11.8 | 6 | 2/78 | | | | |

**D, I** — declination, inclination of the ChRM; $\alpha_{95}$, **k** — Fisher statistics parameters; **N** — number of directions used; $\Lambda^0$, $\Phi^0$ — latitude and longitude of the south paleopole; "-" for south hemisphere. **Corr 1** — rotation of all direction except KC and KO around the axis 205°/15° about 35° clockwise. For KC and KO the axis 100°/65° and angle 60° was used. **Corr 2** — rotation of steep directions around the axis 15°/0° about the angle 50°. * — the direction was not considered for further analysis

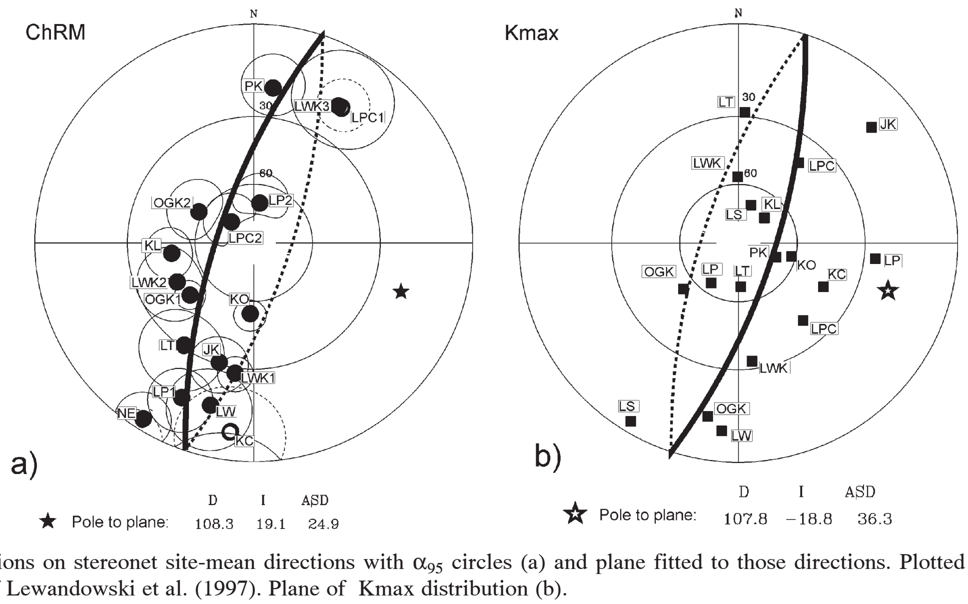


**Fig. 8.** Distributions on stereonet site-mean directions with $\alpha_{95}$ circles (a) and plane fitted to those directions. Plotted by means of the PDA software of Lewandowski et al. (1997). Plane of Kmax distribution (b).

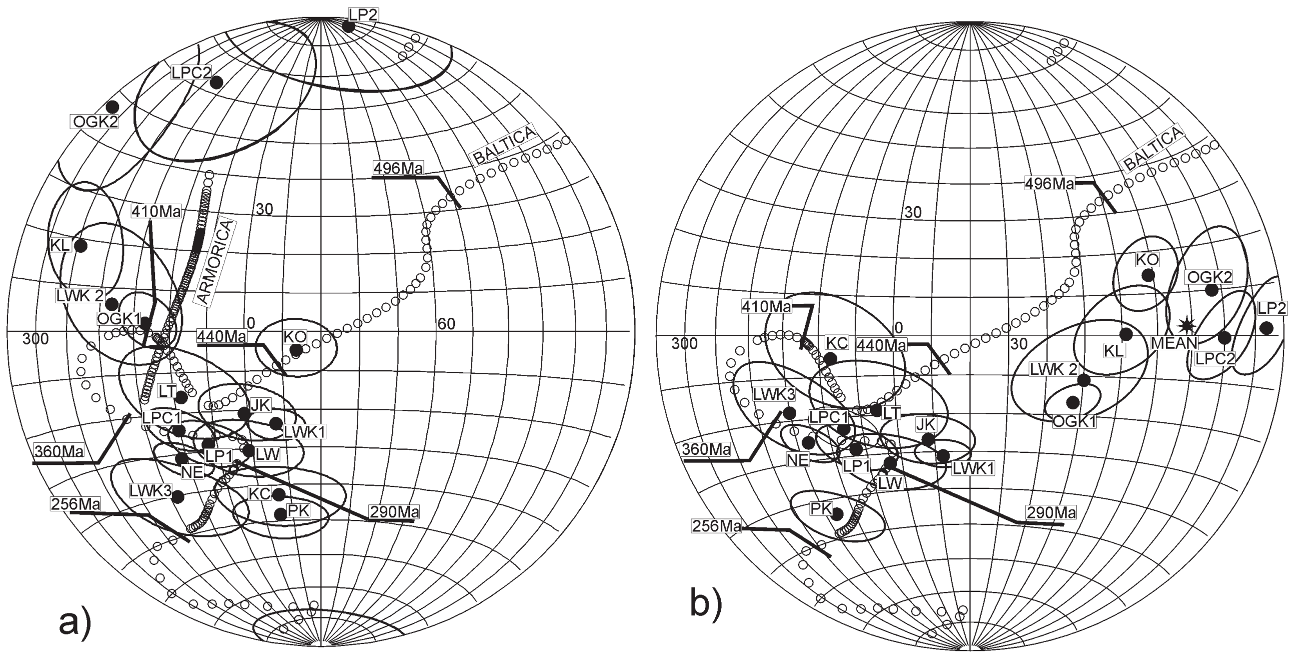


**Fig. 9.** APWP for Baltica on equal area projection (after Torsvik et al. 1992) shown with paleopoles for the Rudawy Janowickie Complex. (a) in-situ paleopole positions; (b) tilt corrected paleopoles: LW, LP1, LWK1, PK, LPC1, LT, JK and NE — pole positions derived from directions after correction 1 (Table 2); LP2, LWK2, LWK3, OGK1, OGK2, LPC2, KC, KO and KL — pole positions derived from directions after correction 1 and 2 (Table 2). Plotted by means of the GMAP software of Torsvik & Smethurst (1994).

vealed in LWK. The in situ mean directions lie along NE-SW great circle (Fig. 8). Shallow directions of reversed polarity trending SSW (NE, LP1, LW), slightly steeper directions (LT, JK, LWK1) and shallow direction of normal polarity trending NNE (LPC1) are similar to the Late–Middle Carboniferous directions previously reported for Sudetes (Westphal et al. 1987; Edel et al. 1997; Kądziałko-Hofmokl & El-Hemaly 1997). The paleopoles derived from these in situ directions (Fig. 9a, Table 2) are placed in the Carboniferous segment of Apparent Polar Wander Path (APWP) for Baltica constructed by Torsvik et al. (1992). The paleopoles derived from the directions KC, PK and LWK3 can be easy interpreted as Permian overprint, although they do not fit exactly the APWP. The steep directions trending to the N-NW (directions LP, LPC, OGK) or to S-SW (directions KL, KO, LWK2, LT, OGK1) gave the pole positions to the north from the Devonian-Silurian boundary, close to the APWP for Armorica (N-NW directions, LPC2, OGK2, KO, LP2,) and close to the Early Devonian poles for Baltica (SW directions, LWK2, OGK1, KL). The directions belonging to the particular groups do not differ in stability, which is always very high or by magnetic carrier. They were carried by magnetite and hematite as well.

## Interpretation and discussion

The tectonic evidence from the Rudawy Janowickie Complex indicates its twofold tilting. The SE-directed extensional collapse $D_2$ resulted in a steep ESE-ward dipping of the regional foliation. The subsequent important reorientation of the regional foliation was attributed to the rotation $D_3$ around a NNE-SSW trending axis of the East Karkonosze monocline. Its development must have post-dated the emplacement of the Karkonosze granite dated at 330–325 Ma and the origin of the Upper Visean conglomerates of the Intra-Sudetic Basin. Consequently, we corrected all directions to restore their position before rotation induced by the East Karkonosze monocline. Furthermore, we took into account that the northernmost edge of the Izera-Kowary Unit (locatities KC and KO) was rotated anticlockwise due to a sinistral movement along the Intra-Sudetic Fault. The correction applied (correction 1) and corrected directions were listed in Table 2. After the correction, the N-NW directions yielded poles (LPC2, OGK2, LP2), which lie close to the 500 Ma poles for Baltica (Table 2). The SW directions (LWK2, OGK1, KL) and KO yielded poles between the Late Ordovician poles of Baltica and Armorica. The LT pole lies in the vicinity of the Lower Silurian and KC in the Middle Devonian. The changes of the Carboniferous poles are insignificant. Because the regional foliation produced by the $D_1$ event was strongly tilted during the $D_2$ Early Carboniferous extensional collapse, the position of poles earlier than Carboniferous should be additionally corrected. After correction for the $D_2$ deformation (correction 2 in Table 2), the LWK3 pole fell in the Late Devonian segment of the APWP for Baltica (Fig. 9b). The KC pole was placed at about 415 Ma. The KO, LP2, OGK2, LPC2, KL, OGK1 and LWK2 poles form a cloud close to the equator beneath the Ordovician segment of the APWP for Baltica. The mean of these poles: 2°N, 78°E gives the paleolatitude 19°S which is the value characteristic for the Llandoverian up to Emsian position of the southern margin of Baltica. It suggests the position of the Rudawy Janowickie adjacent to the southern margin of Baltica and large-scale anticlockwise rotation of about 90°. This is in agreement with the Late Silurian pole obtained for the Bohemian Massif by Tait et al. (1994a). These authors reported the Silurian paleolatitude of the Bohemian Massif of 23°S and 140° anticlockwise rotation. The rotation of the Rudawy Janowickie Complex should have taken place between the Middle–Late Silurian and Early Devonian as the KC pole falls in the 415 Ma part of the APWP. The rotation of about 10° brought the KC pole to the Early Devonian position. The previously reported data (Kądziałko-Hofmokl et al. 1998) from the LPC gneisses after twofold correction gave the following pole positions: 11°N, 103°E (BE2); 7°S, 62°E (CN) yielding the mean: 2°N, 84°E very close to the mean of the Rudawy Janowickie: 2°N, 78°E. The corrected pole A2 from the previous data: 53°N, 54°E gives the paleolatitude of 67°S close to the rest of Armorica in the Ordovician and well compared with the 76°S of the Bohemian Massif obtained by Tait et al. (1994b).

Despite the similarity of the paleopole position of the NW directions to the Ordovician and Silurian poles for Baltica we treat these directions with caution. There is some evidence supporting the possibility that the old directions can be preserved despite significant Early Carboniferous metamorphism. The old directions were found in the rocks of different lithology: metabasites, gneisses and limestones within the Leszczyniec Unit and metabasites (KO) and gneisses (KL) of the Izera-Kowary Unit. The presence of primary magnetite suggests that such old directions may have been preserved in spite of the high metamorphism which affected the rocks. On the other hand, some directions were carried by secondary hematite as well. The age of the NW directions was not constrained by any test applied in paleomagnetism. The close position of the plane of Kmax distribution and the plane of ChRM distribution (Fig. 8) allows us to suspect that deformation has influenced the NRM directions. The magnetic remanence fabric carried by the ferromagnetic minerals copies the structural and AMS fabric, which is evidence of the secondary origin of the majority of magnetic carriers. On the other hand the structural and AMS data indicate that the deformation of the Leszczyniec Unit partly preceded the deformation of the Izera-Kowary Unit. In spite of the different deformation pattern, however, similar paleomagnetic directions were found in both units.

## Conclusions

1. Magnetic mineralogy study shows magnetite and hematite as the main carriers of NRM associated with maghemite. Sometimes goethite is recognized. The presence of magnetite cut by thick lamellae indicates the preservation of primary magnetite. Magnetic minerals display high coercivity.

2. Demagnetization treatment revealed high stability components which fall into two groups. The first group is interpreted as a Carboniferous overprint based on the similarity of their pole position to the Carboniferous segment of the APWP for Baltica. The second group comprises the steep directions. The position of paleopoles derived from those directions after tectonic correction corresponds well to the Silurian segment of the APWP for Baltica, assuming the anticlockwise rotation of the Rudawy Janowickie Complex by the angle of ca. 90°. The paleolatitude derived from these directions correspond well to the Silurian data obtained by Tait et al. (1994a) for the Bohemian Massif.

3. The steep potentially Early Palaeozoic directions were found in different lithologies: metabasites, gneisses and limestones within the Leszczyniec and Izera-Kowary Units. However, the scatter of Kmax and ChRM along similarly oriented girdles may suggest that the deformation influenced the NRM directions.

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