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Paleomagnetism and remagnetization of Upper Devonian synorogenic clastic sediments from the Pogorzala Formation (Świebodzice Depression, West Sudetes, Poland)

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Abstract The Upper Devonian highly polymict conglomerates (site 26) and sandstones with clasts (site 27) of the Pogorzała Formation in the synorogenic Świebodzice Depression, West Sudetes, are hydrothermally altered and show signs of penetration by mineralized fluids. Nearly all the magnetic minerals present (mainly Fe-oxides and pyrrhotite accompanied by Fe-hydroxides) are of secondary origin. Rocks from each site carry multicomponent natural remanence composed of Mesozoic/post-Mesozoic and Palaeozoic components. In the conglomerates (site 26) two Palaeozoic components, labelled P and C, occur in the matrix and pebbles, whereas in the sandstones with large clasts (site 27) only one Palaeozoic component labeled C1 occurs. This means that the results of the conglomerate test for both sites are negative and the studied rocks were remagnetized during several remagnetization episodes. The overprints present in site 26 closely fit the reference data for the Baltica Plate for the Early Permian component (P) and Viséan component (C). The overprint present in site 27 is slightly shifted from the Westphalian (C1) segment of the reference path. The P component is also close to the path of polar wander for Variscan Europe.

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INTRODUCTION

This paper is the continuation of the paleomagnetic and rock-magnetic study of Sudetic Palaeozoic rocks performed by Polish and French paleomagnetologists (Westphal *et al.*,1987; Jeleńska *et al.*, 1995; Edel *et al.*, 1997).This, and other paleomagnetic studies of Sudetic rocks (Kądziałko-Hofmokl & El-Hemaly, 1997; Kądziałko-Hofmokl *et al.*, 1998; Nawrocki & Żelaźniewicz, 1996; Nawrocki, 1998) show an overall presence of Carboniferous and Permo-Carboniferous overprints. The ages of isolated remanences are estimated by comparison of the obtained results with the reference Apparent Polar Wander Path (APWP) for Baltica, compiled after the data of Torsvik & Smethurst (1992). This paper presents the results obtained for the Upper Frasnian–Famennian polymictic conglomerates and sandstones with large clasts from the Pogorzała Formation (PF) of the Świebodzice Depression (SD). The application of the conglomerate test to these rocks helped to answer the question whether the studied sediments retained primary remanence or whether their remanence is an overprint (or a resultant of several overprints) due to remagnetization processes.

GEOLOGICAL FRAMEWORK

The Świebodzice Depression is one of the smallest (c. 100 km^2) synorogenic sedimentary basins in the West Sudetes (Fig. 1). It is filled with c. 4 km thick coarse-grained to shallow marine clastic sediments of Late Devonian to Early Carboniferous age, representing a fan-delta system mostly supplied by detritus coming from basement uplifts to the south and southwest. This infill was taken into large-scale, E–W trending upright to inclined folds. The boundaries of the Świebodzice Depression are tectonic. The northeastern boundary is one of the most important tectonic features of the Sudetes - the Sudetic Marginal Fault, of normal character, which probably originated in late Carboniferous or earlier times (Żelaźniewicz *et al.*, 1997). In the southwest, the depression is in fault contact with the Upper Carboniferous through to Lower Permian intra-montane fluvial to marine clastic sediments of the Intra-Sudetic Basin (ISB). The reverse boundary fault is referred to as the Struga fault (J. Teisseyre, 1962) along which the crystalline basement rocks, equivalent to the Kaczawa complex, locally cut up to the surface. This may be an offset of the Main Intra-Sudetic Fault (MIF) - a dextral strike-slip feature during early Carboniferous times. In the north the Świebodzice Depression is partly brittlely overthrust by the Góry Kaczawskie unit (GK), and to the south it has a normal fault contact with the Góry Sowie Block (GSB). The initiation of the Świebodzice Depression was triggered by and connected with the onset of the uplift of the Góry Sowie Block (Bederke, 1929; H. Teisseyre, 1956) at 370-360 Ma (Van Breemen *et al.*, 1988) and ever since these two units have occurred together in the Sudetic template, sharing the same palaeogeographic position. The sedimentary infill of the Świebodzice Depression was probably deformed in two phases - folding and uplift during the Late Tournaisian was followed by southward thrusting of the Kaczawa unit onto the depression, and then subsequent refolding toward the end of the Viséan (H. Teisseyre, 1956). The dextral strike-slip tectonic activity connected with the Main Intra-Sudetic Fault may have influenced sedimentation in the depression (Porębski, 1990).

At 325-330 Ma two-mica granite intrusion and at 280 Ma granite and granodiorite intrusions formed the Strzelin-Sobótka (SS) massif (Puziewicz & Oberc-Dziedzic, 1995), separated from the Świebodzice Depression by a several km wide belt of the Kaczawa complex (see Fig. 1). Both the granitoid intrusions and the Permian volcanic activity in the Intra-Sudetc Basin might have caused remagnetization processes in the Świebodzice rocks.

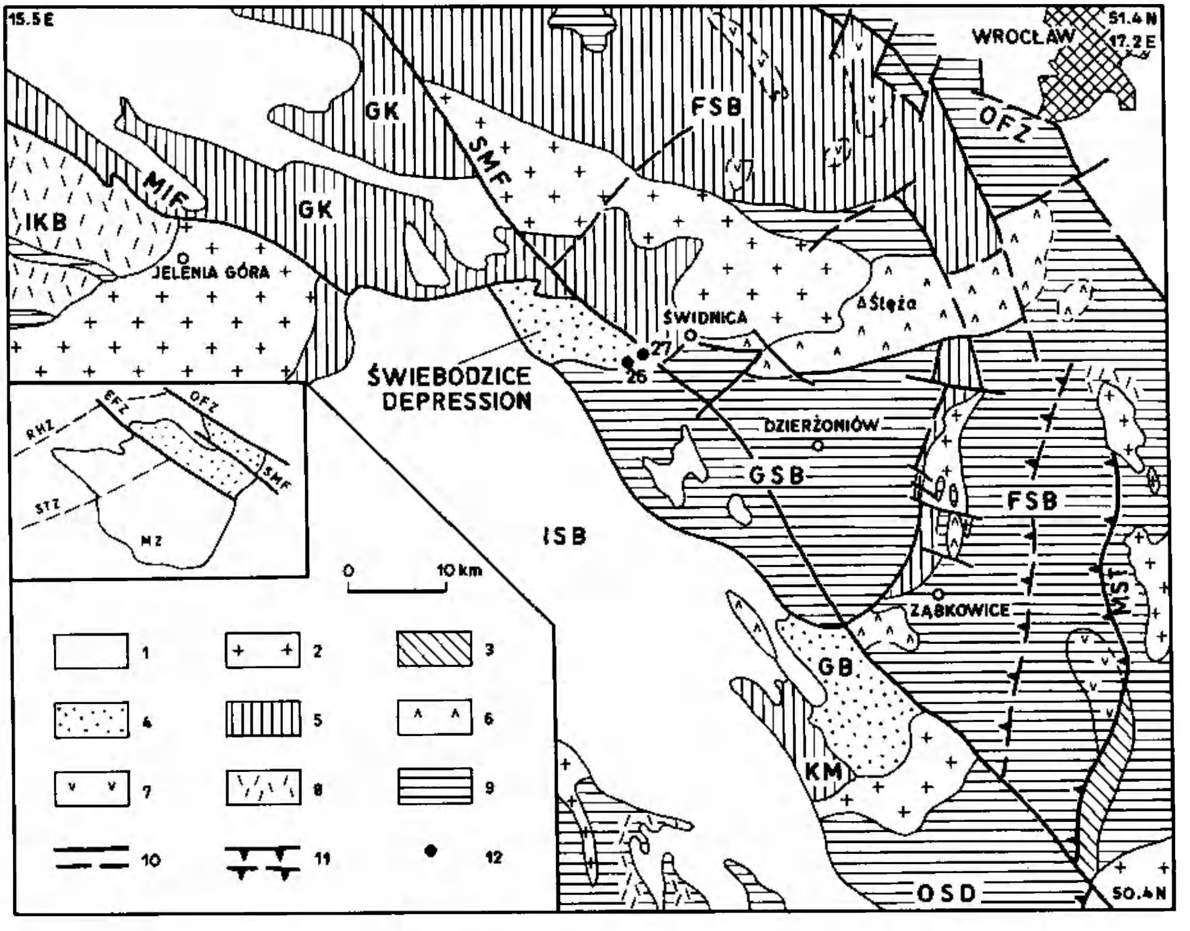

Fig. 1. Geological map of the West Sudetes with the location of the sampling sites. Inset: the Sudetes (stippled) in the Bohemian Massif. *1* - Upper Carboniferous-Mesozoic cover; *2* - Variscan granitoids; *3* - Devonian of the Moravo-Silesian Zone; *4* - unmetamorphosed synorogenic deposits of Late Devonian-Early Carboniferous age (in the Góry Bardzkie with allochtonous Upper Ordovician-Devonian rocks); *5* - Ordovician-Lower Carboniferous metamorphic succession; *6* - Sudetic ophiolite; *7* - other metabasites; *8* - Lower Ordovician granitoids; *9* - Neoproterozoic-Lower Cambrian metamorphic succession; *10* - faults; *11* - thrusts; *12* - sampling sites. EFZ - Elbe Fault Zone; FSB - Fore-Sudetic Block; IKB - Izera Karkonosze Block; ISB - Intra-Sudetic Depression; SD - Świebodzice Depression; GB - Góry Bardzkie; GSB - Góry Sowie Block; KM - Kłodzko metamorphic unit; MIF - Main Intra-Sudetic Fault; MST - Moldanubian Thrust Zone; MZ - Moldanubian Zone; OFG - Odra Fault Zone; OSD - Orlica-Śnieżnik Dome; RHZ - Rhenohercynian Zone; SMF - Sudetic Marginal Fault; STZ - Saxothuringian Zone; SS - Strzelin-Sobótka granitoid massif.

The lithostratigraphy of the Świebodzice Depression embraces four formations differing in age and source areas (Porębski, 1981, 1990). The lowermost part of the succession is occupied by the 1300–1500 m thick Pogorzała Formation (PF), which consists mostly of upper Frasnian–Famennian polymict conglomerates and sandstones, and northwards contacts laterally with the mudstones of the Pelcznica Formation of late Famennian–early Tournaisian age. The upper part of the succession consists of the laterally equivalent Chwaliszów Formation and Książ Formation, both containing mostly conglomerates and sandstones but sourced from different areas. The c. 2000 m thick Książ Formation is almost exclusively composed of detrital material derived from the Góry Sowie Block.

This paleomagnetic study was performed on clastic rocks from the Pogorzała Formation, the southeastern part of the Świebodzice Depression (Fig. 1). They are represented by polymict conglomerates mixed with coarse sandstone bodies, with packets of mudstones, fine lithic arenites and wackes. Pebbles in the conglomerates include quartzites, spilites, slates and some granites – all probably coming from the hypothetical "southern massif" that has since disappeared. The palaeocurrent directions, deduced from imbricated clasts, trended NE to E, but localized palaeoflow from the south was also observed (Porębski, 1981, 1990).

Two sites numbered 26 and 27 were sampled within the Pogorzala Formation; both are situated close to the Sudetic Marginal Fault, some 7 km from the Strzegom–Sobótka granitoid massif. The site 26 conglomerate consists of matrix and pebbles of different derivation. From this site 3 hand samples were taken from the matrix, and 2 hand samples and 6 drill-cores from pebbles of variable size, shape and origin. Site 27 is dominated by sandstones with subordinate larger clasts. 4 hand samples and 14 drill cores were taken from the fine grained sandstones, and 2 hand samples and 8 drill cores from the clasts. Standard specimens were cut from these samples for paleomagnetic and rock-magnetic studies.

The sampling sites are situated close to each other. The attitude of the bedding planes in the two cases are similar (dip azimuth/dip angle), being 326/41 in the site 26 and 334/43 in the site 27. This similarity and lack of smaller scale folds prevented the execution of the fold test.

MINERALOGY AND ROCK-MAGNETIC STUDY

A study of the magnetic minerals of all the rock types concerned was performed with microscopic and magnetic study methods.

An analysis of polished sections performed in Polish[1] and French[2] laboratories with ore microscopes revealed the presence of fine grained Fe-hydroxides (goethite, lepidocrocite and/or other) of mostly post-pyrite origin in all rock types from both sites. Titanites and automorphic pyrites were observed in some sections. Fine grains of pyrrhotite and 1 μm automorphic grains of magnetite and hematite are present but very rare. In all the sections studied there are clear signs of alterations due to penetration by mineralized fluids, responsible for the chloritisation of biotites and garnets, the transformation of plagioclase into zoisite, the sericitization of feldspar, the formation of Fe-hydroxides, and the alteration of feldspar. This activity is responsible for the formation of a cherry-red or brown film coating consisting of either Fe-hydroxides or hematite often observed on the surfaces of rock fragments and minerals. Some alterations (sericitization of feldspar) may have been due to hydrothermal metasomatism (*sensu* Ryka & Maliszewska, 1991). Several investigated sections exhibit an alignment of rock fragments and minerals. Some of them possess the above described brown or cherry red coating.

Thermomagnetic analysis (Warsaw) performed in the non-magnetic space consisted of continuous thermal demagnetization of isothermal remanence Ir acquired in the field of 1T or 1.7 T using a home-made device (Kądziałko-Hofmokl & Kruczyk, 1976). Specimens were heated in the air up to 670°C. The curve of the thermal decay of Ir for a fresh specimen (Fig. 2, curve 1 on the Ir-T diagram) gives the blocking temperatures (Tb) of the magnetic minerals present in it. The same procedure repeated for the heated specimen (curve 2 on the Ir-T diagram) shows the Tb's of magnetic minerals remaining after annealing and produced during annealing. Changes of Ir intensities after the first heating also give information about mineralogical changes within the heated specimen. The Ir-T results obtained for the fresh Pogorzala Formation rocks reveal the presence of magnetite with a Tb of about 570°C (Fig. 2c) or maghemite (hematite?) with a Tb between 600°C and 650°C (Fig. 2a and 2b). They are sometimes accompanied by traces of phase with a Tb about 200°C (goethite?, Fig. 2a) and around 320–340°C (pyrrhotite, Fig. 2c). Hematite with a Tb about 670°C is rarely seen. The curves of the second heating show large increase of Ir (from several to several thousand times) due to the presence of new magnetic phases formed during annealing.

Thermomagnetic analysis of composite isothermal remanence IRM (Warsaw), invented by Lowrie (Lowrie, 1990), was performed for five specimens. This method consists of thermal demagnetization of three components of IRM imparted on a sample in such a way that different coercivity fractions of IRM are magnetized in successively smaller fields along three orthogonal directions. The thermal demagnetization of each orthogonal component plotted separately gives the Tb of magnetic minerals carrying

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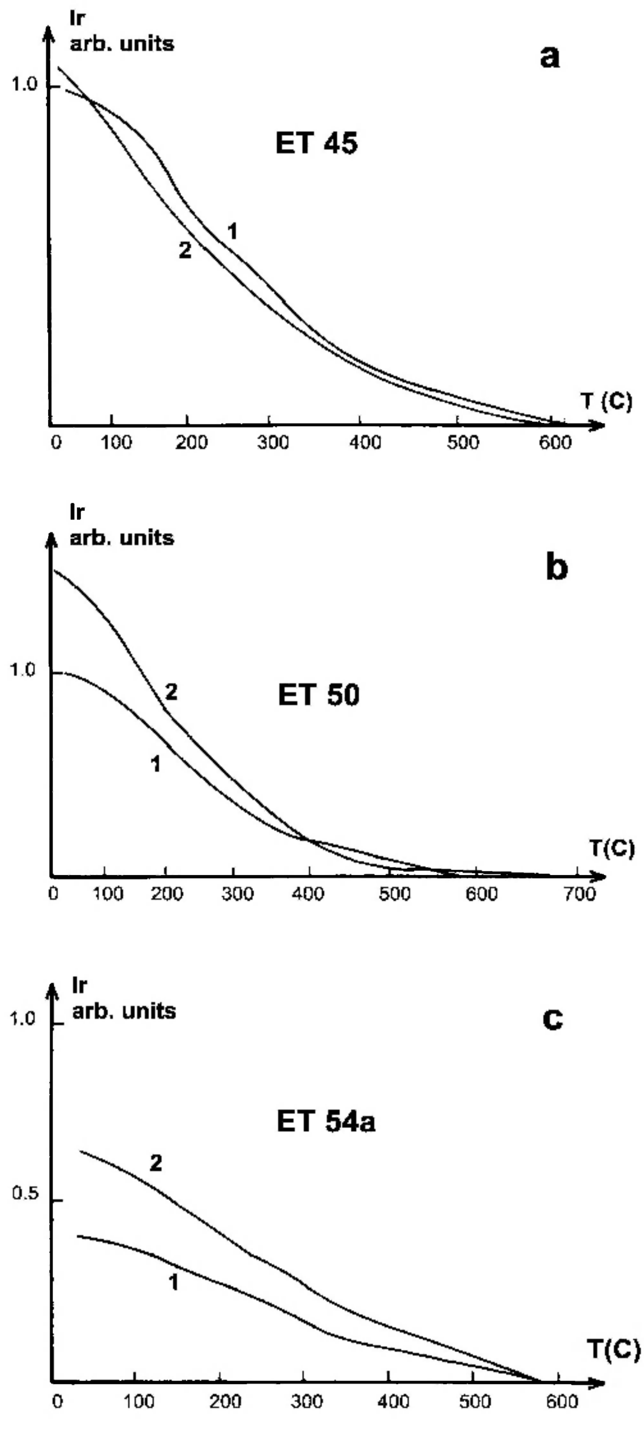


Fig. 2. Examples of thermomagnetic analysis: continuous thermal demagnetization of isothermal remanence Ir. 1 – first heating curve; 2 – second heating curve.
a – matrix from site 26, magnetizing field 1T, Ir2/Ir1 = 60; b – sandstone from site 27, magnetizing field 1T, Ir2/Ir1 = 200; c – clast from the site 27, magnetizing field 1.7T, Ir2/Ir1 = 2. Ir1 – isothermal remanence before the first heating; Ir2 – isothermal remanence after the first heating.

respective fractions of coercivity. Fields of intensities of 0.1T, 0.4T and 2.7T were applied for the purpose of this study. Figures 3 a, b, and c present the results obtained for three specimens that are the sister specimens of those for which the Ir-T curves are shown in Figure 2. The distinct Tb of about 680°C on the thermal decay curves of the hard coercivity fractions (0.4–2.7T) are evidence of the presence of hematite in all the specimens. Pyrrhotite with Tb of about 320–340°C appears in all three specimens on curves corresponding to the soft (.1T), medium (0.1–0.4T) and hard coercivity fractions. This result suggests that this mineral occurs in different grain sizes – from fine to coarse. Lowrie (1990) and Muttoni (1995) using this method documented the presence of pyrrhotite carried by soft and hard fractions of coercivity in pyrrhotite bearing limestones from Italy (Muttoni) and sandstones from Canada (Lowrie). The presence of some amount of magnetite/maghemite are evidenced by a Tb of about 580°C on the curves corresponding to the soft and medium coercivity fractions in all the specimens and on the curve of the hard fraction in a clast from site 27 (Fig. 3c). A Tb of about 150°C seen on the hard fraction curve of the matrix from site 26 (Fig. 3a) testifies to the presence of goethite. It seems that pyrrhotite is much more abundant in samples from the site 27 than in those from the site 26. The results obtained from the Ir-T (Fig. 2) curves seem to be less informative than the results of the Lowrie method, mainly because they were acquired from much smaller specimens with the application of a lower magnetizing field (0.8 cm^3 and 1 or 1.7T) than the latter one (8 cm^3 and 2.7T).

Curves of IRM acquisiton (Fig. 4a) measured with a field increasing to 1T using a Brucker BE10 electromagnet (Rennes) show the presence of two magnetic phases of different coercivities in the matrix specimens from site 26 (plot (a)) and a high coercive phase in clasts and sandstones from site 27 (plots (b) and (c)). Curves of acquisition of anhysteretic remanence ARM (Warsaw) measured using an alternating field up to100 mT in the presence of a steady field of 0.05 mT reveal the presence of phases with lower and higher coercivities in clasts from sites 26 and 27, and also the sandstones from site 27 (Fig. 4b). On the basis of the results of microscopic and thermomagnetic tests, the low coercivity minerals are interpreted as magnetite/maghemite, while the high coercive ones as hematite and/or goethite. Pyrrhotite may contribute to both coercivity fractions.

Hysteresis parameters were measured (Warsaw) with a VSM Molspin device with the highest available field of 1T. The measured values of saturation magnetization Ms, saturation remanence Mrs, coercivity Hc and coercivity of remanence Hcr, together with the ratios of Mrs/Ms and Hcr/Hc, are summarized in Table 1. In three specimens (ET47A1, ET54C1 and ET54aC1) Hcr is very high suggesting that goethite or hematite dominate in them. In four specimens (ET47A2, ET52B2, ET54A2, ET54aB2) the ratio Hcr/Hc is higher than 1.0 and lower than 2.0. According to Dekkers (1988) such low values of this ratio are characterisitc of pyrrhotite with grain sizes between several to several tens of μm. In view of the results of other methods this mineral is believed to dominate in the investigated specimens.

Monitoring the influence of heating on the the low-

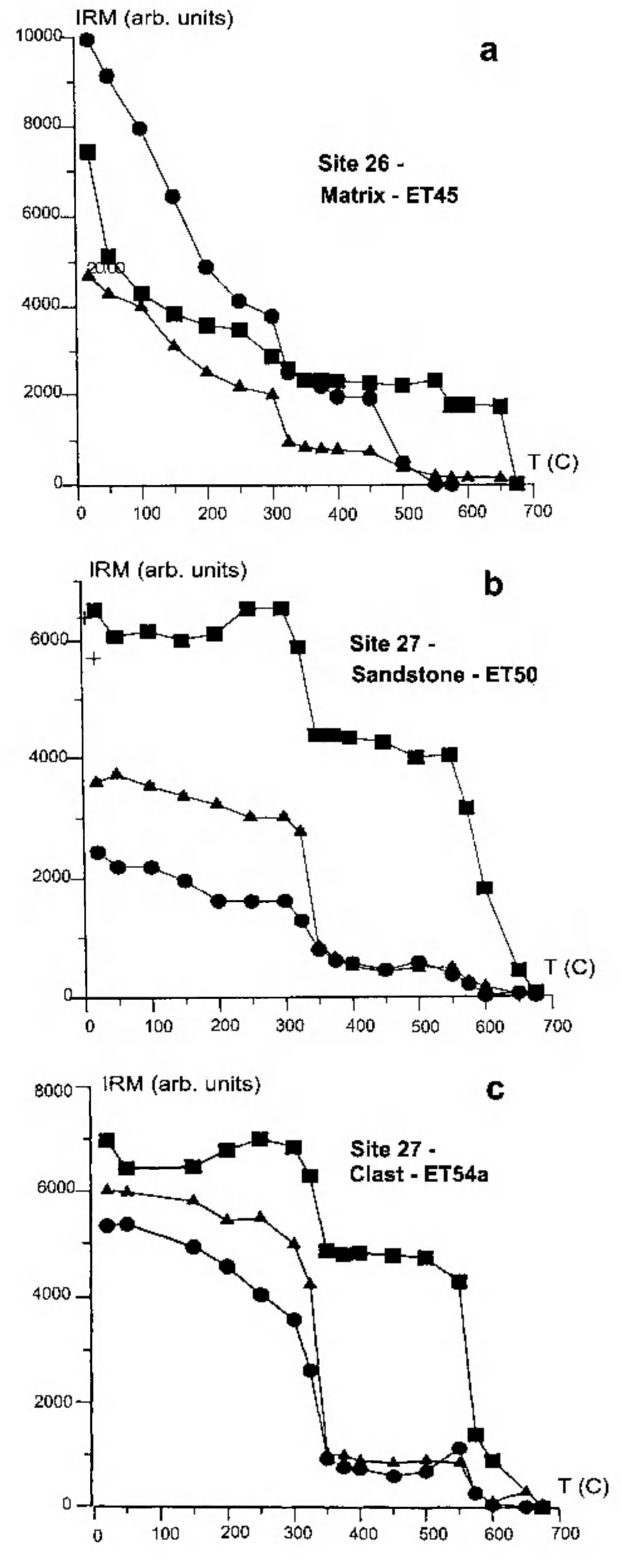


Fig. 3. Thermal demagnetizations of composite isothermal remanence IRM: **a** – matrix specimen from site 26; **b** – sandstone specimen from site 27; **c** – clast specimen from site 27. 1 – soft component imparted in the field of 0.1 T; 2 – intermediate component imparted in the field of 0.4 T; 3 – hard component imparted in the field of 2.7 T.

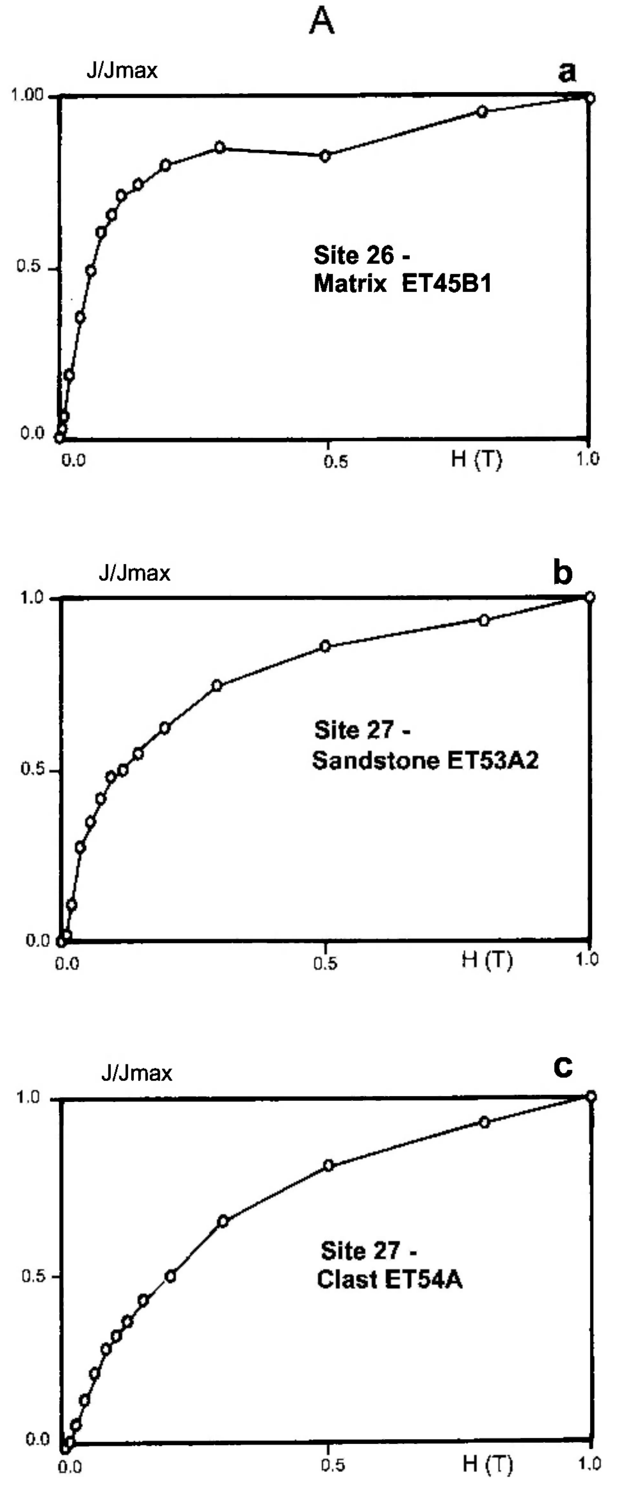
Table 1

Hysteresis parameters for the Pogorzała Formation

Specimen	Lithology	Ms $\mu A/m^2$	Mrs $\mu A/m^2$	Mrs/ Ms	Hc mT	Hcr mT	Hcr/ Hc
site 26							
ET 45.2	matrix	0.53	0.10	0.19	11.5	55	4.78
ET 49.1	matrix	0.27	0.08	0.29	25	62	2.48
ET 47A1	pebble	0.63	0.08	0.13	16	210	13.12
ET 47A2	pebble	0.53	0.12	0.23	20.5	30	1.46
ET 47B1	pebble	0.83	0.16	0.19	–	13	–
ET 47B2	pebble	1.21	0.21	0.17	8.5	45	5.29
ET 48.1	pebble	0.90	0.11	0.12	9	50	5.55
ET 48.2	pebble	3.2	0.14	0.28	7	34	4.86
site 27							
ET 52.1	sandstone	0.73	0.07	0.09	17.5	60	3.42
ET 52B2	sandstone	0.35	0.11	0.31	26.5	27	1.02
ET 54C1	sandstone	0.99	0.09	0.09	33	110	3.33
ET 54C2	sandstone	0.28	0.12	0.43	33.5	80	2.39
ET 54aC1	clast	0.77	0.23	0.29	30.0	290	9.67
ET 54a1	clast	0.85	0.22	0.25	24.5	60	2.45
ET 54a2	clast	1.24	0.38	0.31	22	38	1.78
ET 54aB1	clast	1.56	0.56	0.36	24	54	2.25
ET 54aB2	clast	1.71	0.59	0.35	21.5	34	1.58

Ms – saturation magnetization; Mrs – remanence saturation; Hc – coercivity; Hcr – coercivity of remanence

field magnetic susceptibility Km also helped in the identification of magnetic minerals. The Km was measured with the susceptibility bridge KLY2 of Geofyzika Brno (Warsaw, Rennes) in fresh specimens and after each consecutive heating step for all specimens demagnetized thermally. In nearly all of the matrix specimens from site 26 the mean susceptibility Km ranges from 120 to 175x 10^{-6} SI, while in two specimens it reaches 515–525x10^{-6} SI. One sample (three specimens measured) containing mostly goethite according to the thermomagnetic analysis, has a Km of 60 x10^{-6} SI. In pebbles from this site Km ranges from 160 to 660x10^{-6} SI. According to this pattern the distribution of magnetic minerals is more homogenous in the matrix than in the pebbles. At site 27 values of Km remain in the range between 125 and 250x10^{-6} SI in sandstones (only in one sample reaching 330x10^{-6}SI), and from 95 to 250x10^{-6} SI in clasts. Characteristic thermal changes of Km are shown in Figures 5a and 5b. In most of the specimens Km does not change up to 450–500°C and begins to increase after annealing in higher temperatures; in some specimens the increase is preceeded by a decrease of Km characteristic for the oxidation of maghemite into hematite (lower plot for a clast from site 27, Fig. 5b). In some specimens the changes in Km begin after heating to 400°C or even 250–300°C which is characteristic for the transformation of pyrrhotite into magnetite (upper plot for a



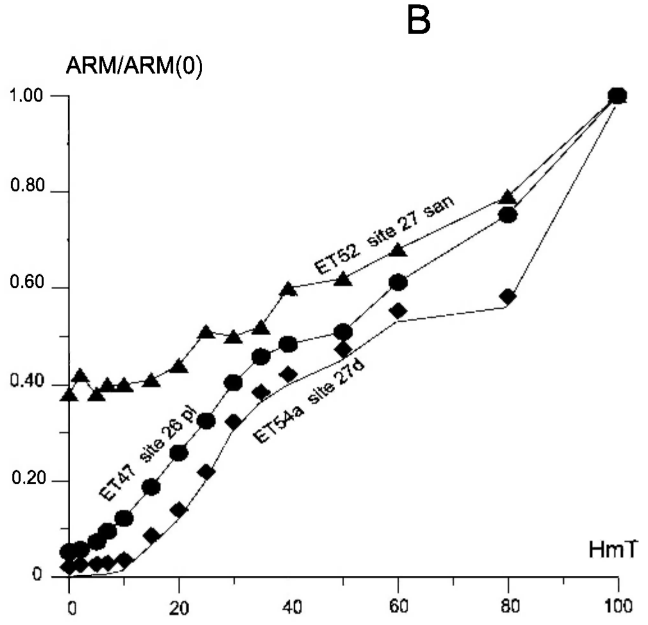


Fig. 4. IRM and ARM acquisition curves. a – IRM acquisition curves: (a) – matrix from site 26; (b) – sandstone from site 27; (c) – clast from site 27; J/Jmax – remanence/ highest remanence of the experiment; b – ARM acquisition curves for one pebble from site 26 (circles), one clast from site 27 (triangles), and the sandstone from site 27 (squares).

clast from site 27, Fig. 5b; Roberts & Turner (1993) and van Velzen *et al.* (1993)).

The applied methods combined indicate the presence of goethite, maghemite, hematite and pyrrhotite as secondary minerals. The magnetite identified by all methods is also assumed to be mostly of secondary origin. Some of it was probably formed through the transformation of goethite. According to Dekkers (1990) this may happen in temperatures lower than 400°C under reducing conditions created, for instance, by the decomposition of traceable amounts of organic matter. The presence of some of the maghemite may be explained by the transformation of non-magnetic hydroxides, like lepydocrocite, which is also present in the studied material. In the laboratory, lepydocrocite dehydrates to maghemite at temperatures between 200 and 300°C (Mc Clelland & Goss, 1994). At higher temperatures it transforms into hematite, but under reducing conditons it may transform to magnetite as goethite does (J. Siemiątkowski, pers. com.). The presence of pyrrhotite supports the assumption about an episode of reducing conditions. The results of the magnetic methods used in this study suggest that pyrrhotite occurs in quite a number of specimens, probably in very fine grains. The grain sizes of several tens of μm suggested by the Hcr/Hc values may be erroneous due to the presence in the rocks of not only pyrrhotite but also other magnetic minerals (magnetite) that influence the measured values of bulk coercivities.

Taking all the described results into account the magnetic minerals present in the Pogorzała Formation rocks are concluded to be mostly secondary pyrrhotite, hematite, very fine grained magnetite and maghemite, accompanied by low quantities of goethite.

PALEOMAGNETIC STUDY

Natural remanent magnetization NRM was measured and demagnetized independently using different devices in three laboratories: Warsaw (2G cryogenic magnetometer SQUID), Rennes (CTF cryogenic magnetometer and Schoenstedt flux-gate magnetometer) and Strasbourg (DIGICO flux-gate magnetometer). Most specimens were demagnetized thermally; the alternating field demagnetization (AF) was rarely used, because specimens responded better to thermal cleaning. The analysis of demagnetization results was performed with the PDA software package (Lewandowski *et al.*,1997). For pebbles from site 26 and clasts from site 27 the conglomerate test was performed. Preliminary results from the Pogorzala Formation are in Edel *et al.* (1997).

Site 26

From this site 18 specimens from the matrix and 14 from pebbles were demagnetized. The matrix consists of fragments of older rocks of various shape and lithology. Intensities of NRM of specimens cut from the same hand sample are often different and they behave in a different way when demagnetized. Generally, the intensity of the NRM of matrix specimens ranges from 600 to 12000 μA/m. Figures 6a and 6b present thermal demagnetization plots for two specimens cut from the same hand sample; the differences between them reflect the inhomogeneity of the material. Analysis of the demagnetization results revealed the presence of two magnetization components in most of specimens. The unblocking temperatures Tub of the medium temperature component (MT) range between 200 and 350°C. The Tub of the high temperature component (HT) range in most cases between 450 and 550°C, in some rare cases they are higher. Components with a Tub lower than 200°C (LT) occur only rarely. In several specimens NRM consists of only one component, in several others three components of remanence were isolated.

In specimens from pebbles the intensity of NRM remains between 200 and 2000 μA/m. Demagnetization plots differ from one specimen to another, generally one or two components of NRM were isolated with Tub ranging usually from 200 to 350°C (MT) and from 450 to 550°C (HT), in rare cases to 600°C (Fig. 6c).

Stereographic plots of the *in situ* directions of components isolated from matrix and pebbles are presented in Figures 7a, 7b. The group of directions present in the first quadrant, isolated in matrix and pebbles in the MT and LT ranges may be either the Mesozoic overprint (see the reference directions for Europe in Besse & Courtillot, 1991), or not completely cleaned Recent viscous component. Notwithstanding its origin it will not be discussed further. The remaining remanence directions obtained in matrix and pebbles have southern (SSW) declinations and shallow to moderate positive and negative inclinations. The results obtained for matrix form two groups. The first group of directions, with negative inclinations isolated in the MT range in three specimens, is represented by the component labeled Pm. The other group of directions, with positive inclinations isolated in ten specimens in the MT and HT ranges, is represented by the component labeled Cm. Their mean directions *in situ* and after tectonic correction together with parameters of the Fisher statistics and appropriate pole positions are summarized in Table 2. The corresponding results obtained for the pebbles became subject of the conglomerate test described in the next section.

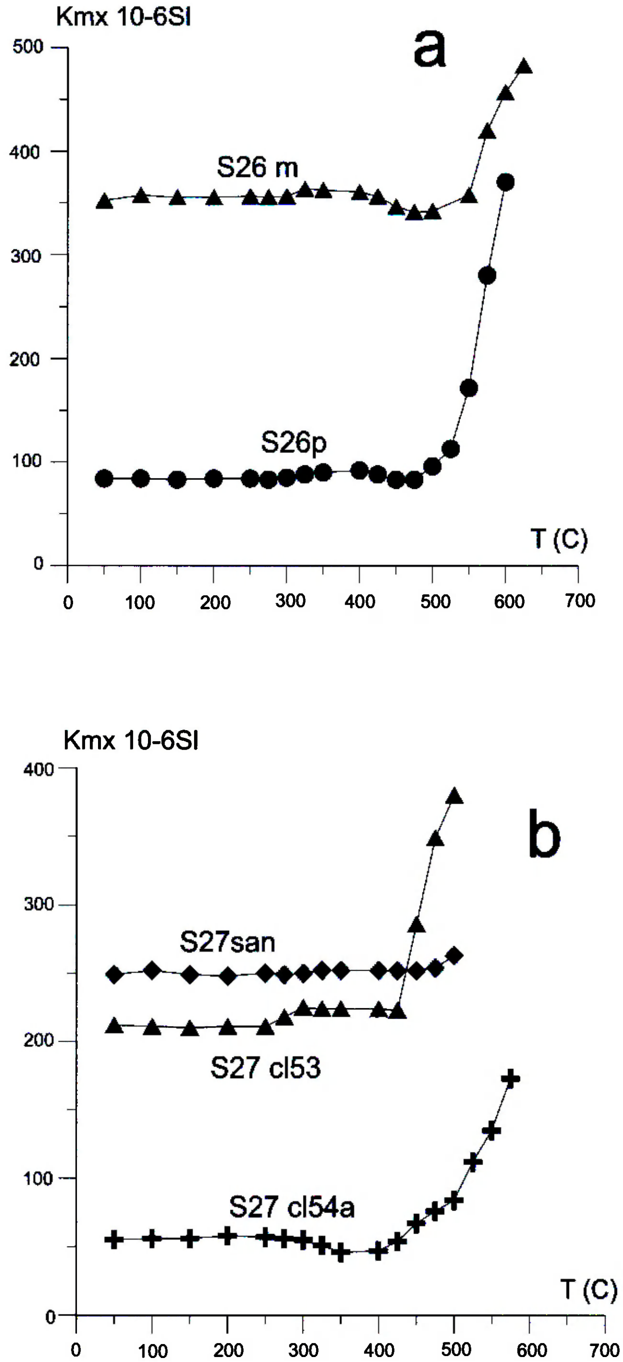


Fig. 5. Mean susceptibility Km measured after consecutive heating steps. a– pebble (p) and matrix (m) specimens from site 26; b– sandstone (san) and clast (cl) specimens from site 27.

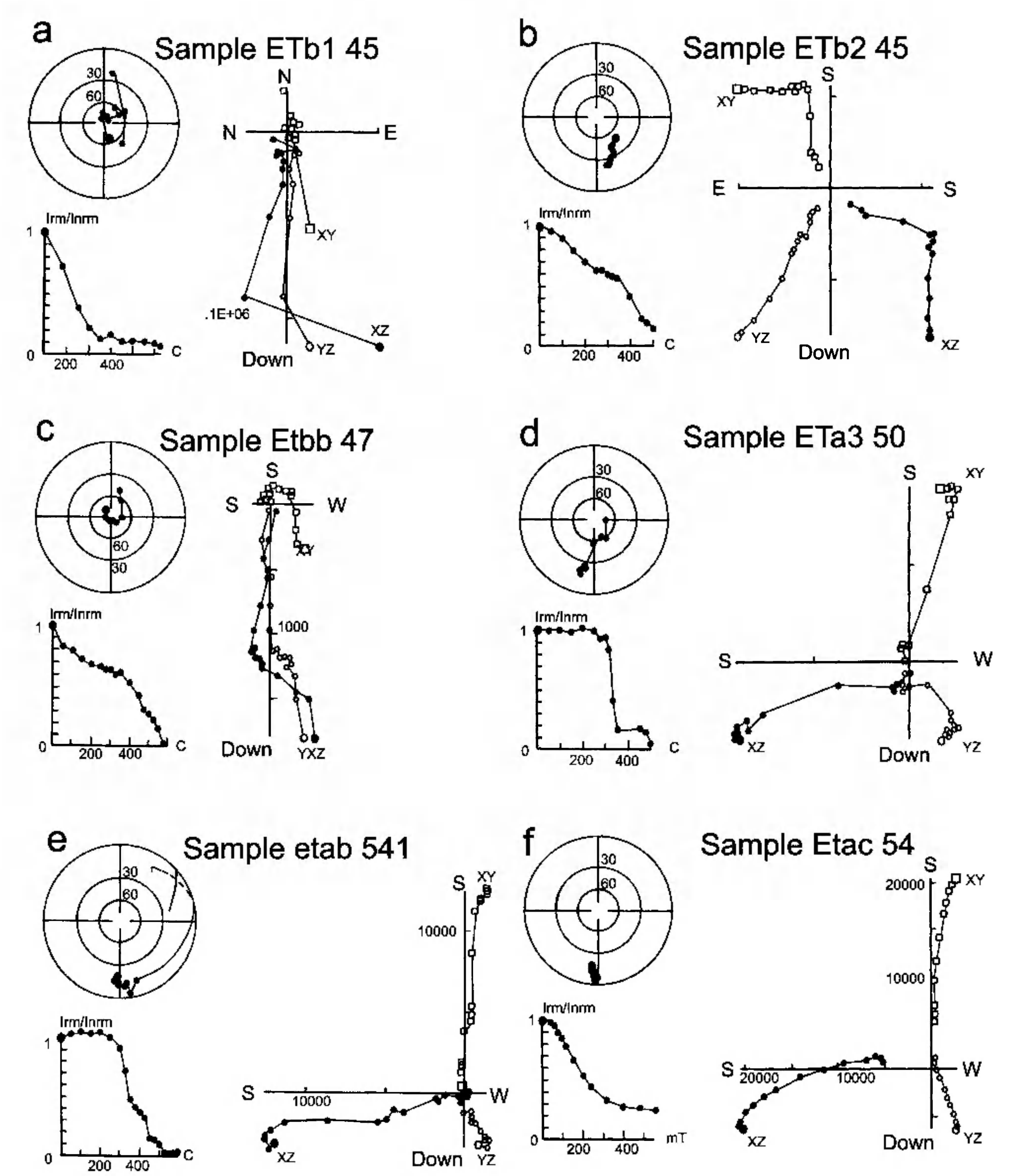


Fig. 6. Examples of the demagnetization plots. Irm/Inrm – intensity of the natural remanence after consecutive cleaning steps/intensity of natural remanence before cleaning; Zijderveld plots are constructed in three planes. a and b – thermal demagnetizations of two specimens from the matrix of the same sample, site 26; c – thermal demagnetization of a pebble specimen from site 26; d – thermal demagnetization of a sandstone specimen from site 27; e and f – thermal demagnetization of two specimens from a site 27 clast; g – alternating field demagnetization of a specimen from the same clast sample as in e and f. Values of intensity in μA/m.

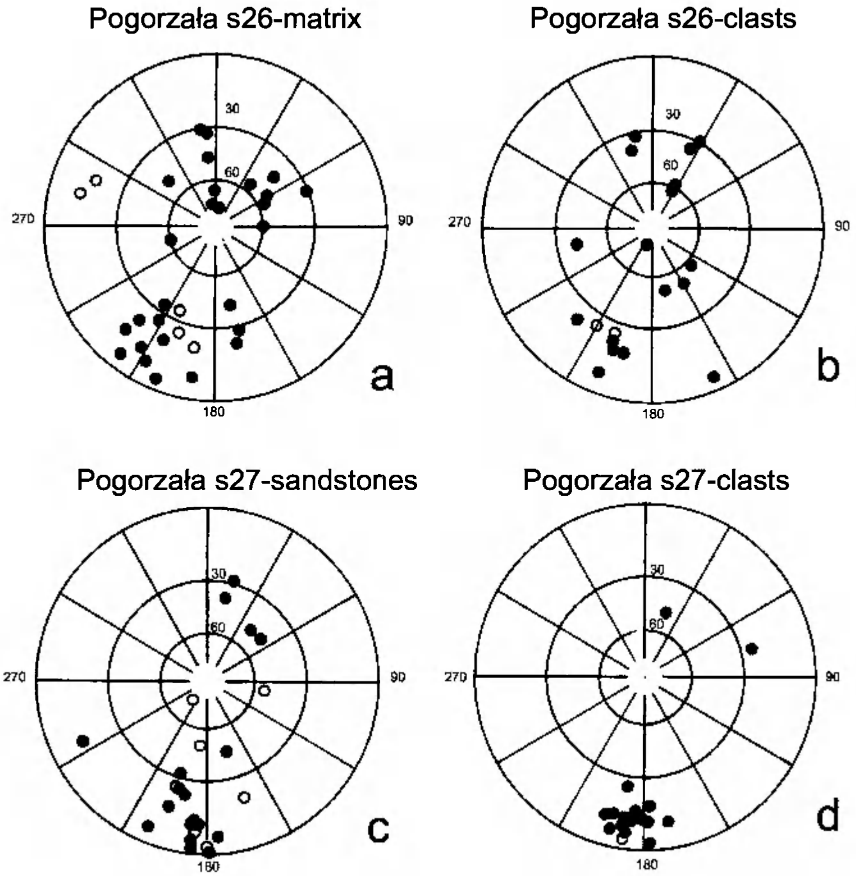


Fig. 7. Stereographic plots of directions of all isolated components of NRM before bedding correction. A – matrix from site 26; b – pebbles from the site 26; c – sandstones from site 27; d – clasts from site 27; open circles – negative inclination, full circles – positive inclination.

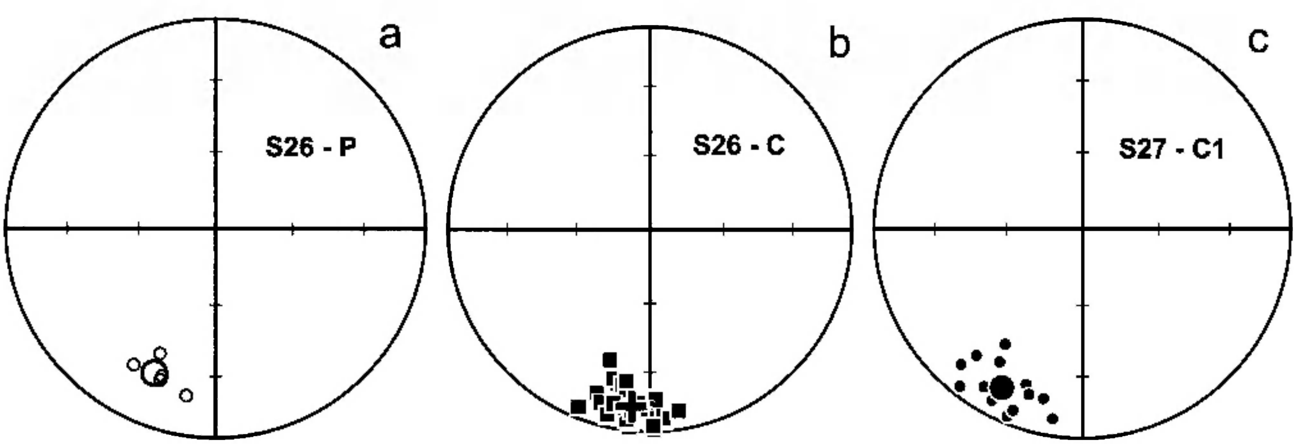


Fig. 8. Stereographic plots of directions before bedding correction forming clusters representing overprints. a – direction P obtained from site 26, small open circles – directions for specimens, large open circle – mean direction; b – direction C obtained from site 26, squares – directions obtained from specimens, cross – mean direction; c – direction C1 obtained from site 27, small full circles – directions for specimens, large full circle – mean direction.

Site 27

From this site 25 specimens of sandstones and 20 of clasts were demagnetized. The intensity of NRM of the sandstones ranges between 70 and 800 μA/m. In most specimens NRM has only one component which demagnetizes in the temperature range of 350–400°C (MT) (Fig. 6 d). In two specimens only components with high unblocking temperatures HT were observed and in four specimens components with unblocking temperatures in

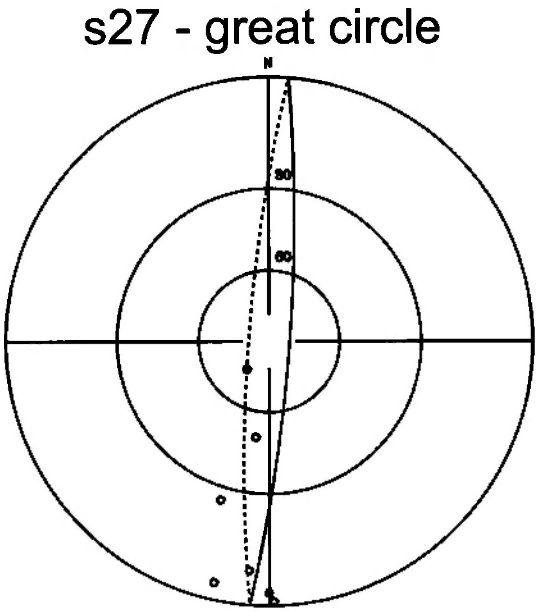


Fig. 9. Great circle passing through the directions of components with negative inclications isolated in sandstones from site 27.

the LT range accompanied the main HT component. In specimens from clasts the intensity of NRM is very variable and ranges from about 1100 μA/m in one specimen to 20000 μA/m in another. Thermal demagnetization shows that NRM in most specimens has two components (Fig. 6e), one with a Tub of about 350°C (MT) and another with a Tub of about 550°C (HT), often both of the same directions. The AF demagnetization plots show a smooth decrease of single component NRM up to 140mT, but about 25% of NRM intensity remains after demagnetization (Fig. 6 f).

Figures 7c and 7d present the stereographic distribution of directions of components isolated in the sandstones and clasts, respectively. In the first quadrant lie directions of components isolated in the LT range in four specimens from the sandstones and one from clasts. They probably represent either the Mesosoic overprint or an uncleaned Recent viscous component and will not be discussed any more as in the case of site 26. The majority of the isolated directions in the sandstones from site 27 have a southern declination and negative and positive inclinations. Directions with negative inclination lie along the great circle (Fig. 9) showing that they may not be well cleaned and do not reflect the direction of the magnetizing field. The directions with southern declination and positive inclination form a group labelled C1san (Table 2). This group was isolated in nearly all the sandstone specimens in the MT range, in one it was obtained in the HT range and in one by AF cleaning. Its mean direction *in situ* and after tectonic correction together with parameters of the Fisher statistics and appropriate pole positions are listed in Table 2. The remanence directions with southern declination isolated in clasts became subject of the conglomerate test which is described in the next section.

Table 2

Paleomagnetic results obtained for sites 26 and 27 before and after correction for bedding together with the results of the F-test. Geographic position of the Pogorzała Formation: lon:16.3°E, lat:50.8°E

Site	Lithology S/N	dir	n1/n2	D/Ibbc	α_{95}	K	PLatN	PLonE	Plat	D/Iabc	PlatN	PlonE
s26	matrix 3/18	Pm	3/3	198/-27	15	66	-51	348	-14	191/1	-38	3
		Cm	5/10	210/15	8	35	-26	343	8	226/28	-13	331
	pebble 8/14	Pcl	2/2	206/-26	–	–	-48	338	-14	197/-2	-38	354
		Ccl	5/5	202/18	11	52	-27	351	11	222/36	-11	336
	mat+peb 11/32	P	**5/5**	**201/-26**	**8**	**85**	-49	**344**	-14	193/0	-38	360
		C	10/15	207/16	6	39	-27	345	6	225/31	-12	333
s27	sandst. 18/25	C1san	14/17	187/14	5	49	-32	8	7	205/47	-8	354
	clasts 10/20	C1cl	11/17	185/12	4	92	-33	10	6	201/46	-10	357
	san+clas 28/45	C1	**25/34**	**186/13**	**3**	**65**	**-32**	9	**6**	203/47	-8	356

Site and direction	F calculated (Butler, 1992)	F tabulated for 95% confidence limit (Fisher *et al.*, 1993)
Site 26 – P	0.710	9.552
Site 26 – C	1.146	3.806
Site 27 – C1	0.576	3.295

mat+peb – matrix + pebbles; sandst. – sandstones; san+clasts – sandstones + clasts; dir – direction; S/N – number of samples taken in the field/number of specimens demegnetized; n1/n2 – number of independently oriented samples in which the respective direction was found/number of specimens in which respective directions were found; α_{95}, k – parameters of Fisher statistics; D/Ibbc – declination and inclination in degrees before correction for bedding; D/Iabc – declination and inclination in degrees after correction for bedding; PLatN, PLonE – latitude and longitude of the north paleomagnetic pole; plat – paleolatitude

Table 3

Paleomagnetic results obtained for Permian rocks in the Sudetes by other authors

Region	Number in Fig. 10	Lithology	D/I	α_{95}	k	PlatN	PlonE	Reference
ISB	1	sediments	186/-10	10	89	-44	8	Kądziałko-Hofmokl & El-Hemaly (1977)
ISB	2	sediments	192/-1	9	185	-39	0	Kądziałko-Hofmokl & El-Hemaly (1977)
ISB	3	sediments	191/13	10	60	-32	3	Kądziałko-Hofmokl & El-Hemaly (1977)
ISB	4	volcanites	192/-2	11	27	-39	1	Westphal *et al.* (1987)
ISB	5	volcanites	190/-19	18	18	-48	1	Westphal *et al.* (1987)
ISB+NSB	6	sed+volc	199/-11	5	122	-42	351	Nawrocki (1997)

ISB – Intra-Sudetic Basin; NSB – North Sudetic Basin; sed+volc – sedimentary and volcanic rocks combined; others symbols as in Fig. 2

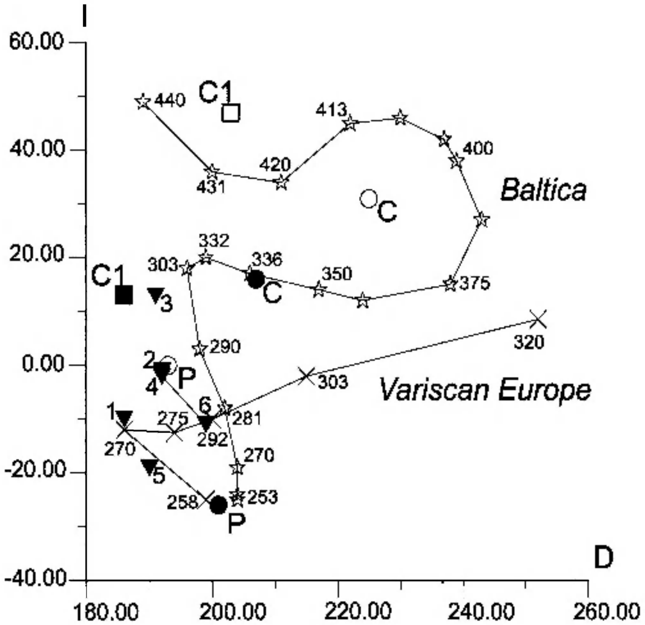


Fig. 10. Directions of isolated components of NRM obtained for the Pogorzała Formation: before bedding correction (squares) and after bedding correction (triangles) against the reference D-I curve constructed according to the data of Torsvik & Smethurst (1992) for Baltica (stars) and the curve obtained by Edel & Duringer (1997) for Variscan Europe (crosses). Full circles – directions for site 26 before bedding correction; open circles – directions for site 26 after bedding correction; full squares – directions for site 27 before bedding correction; open circles – directions for site 27 after bedding correction; triangles – directions obtained for Carboniferous and Permian rocks from the Intra- and North Sudetic Basins: 1, 2, 3 (Kądzialko-Hofmokl & El-Hemaly, 1997), 4, 5 (Westphal *et al.*, 1987), 6 (Nawrocki, 1997).

RESULTS OF CONGLOMERATE TEST

The conglomerate test, invented by Graham (1949), is one of the most powerful field tests used in palaeomagnetic research of rocks containing conglomerate clasts. It helps to answer the question whether such fragments of earlier rocks after having been emplaced into sediments still retained their primary remanence or whether their remanence is an overprint (or a resultant of several overprints) due to remagnetization processes postdating the deposition. The test makes use of the remanence directions in clasts residing in conglomerates or other deposits (Van der Voo, 1993). If clasts, emplaced after transport and possible rotations, have retained their original remanences, the measured remanence directions are random between them – the test is positive. On the other hand, if the measured remanence directions in clasts are similar to each other, it means that they have become remagnetized after deposition – the test is negative. If the common direction found in the clasts is similar to the remanence direction found in the matrix it means that both conglomerate components have been subjected to remagnetization at the same time.

Taking this into account we have decided that the conglomerate test will help to answer the question whether the studied clasts and pebbles retained their original magnetizations or became remagnetized after deposition. The test was applied for the remanence directions isolated in pebbles of site 26 characterized by southern declination and negative and positive inclinations and for the remanence directions isolated in clasts of site 27 characterized by southern declination and positive inclinations. Other isolated directions were interpreted in the previous section.

Site 26 – pebbles

The results of the conglometrate test applied to pebbles from this site are illustrated by Fig. 7b. The isolated remanence directions are not randomly scattered but reasonably grouped indicating that pebbles did not retain any old remanence. It proves that the conglomerate test for this site is negative. Here, as in the matrix (see previous section), we were able to find two groups of directions. One of them, with negative inclination isolated in two specimens in the MT range, represents the component labeled Pp. The other, with positive inclination isolated in five specimens in the MT range, represents the component labeled Cp. Their directions *in situ* and after tectonic correction together with the parameters of Fisher statistics and appropriate pole positions are shown in Table 2.

Site 27 - clasts

In 17 specimens taken from the clasts only one remanence component was isolated: in six specimens it appeared within the HT range, in one it was found due to the AF cleaning, and in the remaining ten specimens it occurred within the MT range. This component, which has southern declination, is shown in Fig. 7d where it forms a tight cluster indicating that the conglomerate test also in this case is negative. The component was labeled C1cl and its mean directions *in situ* and after tectonic correction together with parameters of Fisher statistics and appropriate pole positions are shown in Table 2.

DISCUSSION OF THE PALEOMAGNETIC RESULTS

According to the negative conglomerate test the components of NRM isolated in pebbles (Pp and Cp in site 26) and clasts (C1cl in site 27) are overprints. There are two important types of remagnetization processes that may lead to stable remanences which may remain preserved through long period of time. These are: preheating which gives partial thermal remagnetization (with thermoviscous remanence as its modification) and chemical alterations that lead to chemical remagnetization.We believe that remagnetization processes resposible for the P, C and C1 components had chemical nature. Our conclusion is based on the presence of secondary minerals as magnetic carriers (see section concerning rock-magnetic research). The hydrothermal activity recognized in the sampled rocks and their magnetic mineralogy consisting of secondary minerals supports this conclusion. Now the question arises whether the matrix and clasts in site 26 and the sandstones and clasts from site 27 became remagnetized at the same time. In order to find an answer, the F-test (Butler, 1992) was performed for the following pairs of the directional data sets: Pm, Pp and Cm, Cp from site 26 and C1san, C1cl from site 27. In all three cases the calculated values of the parameter F are much lower than the tabulated values (Table 2) for the confidence parameter of 95% (Fisher *et al.*, 1987). This means that in all three cases the two respective pairs of directional data sets belong to the same population. According to this conclusion we calculated the appropriate means for the matrix and clasts and combined from site 26 labelled **P** and **C** (Fig. 8 a, b), and for the sandstones and clasts combined from site 27 labelled **C1** (Fig. 8c). The results included in Table 2 indicate that:

- rocks from site 26 were subjected to remagnetization twice, whereas the rocks from site 27 only once,
- each overprint was acquired at different times.

THE AGE OF THE RESPECTIVE COMPONENTS OF NATURAL REMANENCE

In order to assign proper ages to the isolated components of natural remanence the results obtained before (*in situ*) and after tectonic correction were compared (Table 2) with the reference curves for the Baltica plate (Torsvik & Smethurst, 1992) and for Variscan Europe (Edel & Duringer, 1997) and also with the results obtained for the Carboniferous and Upper Permian rocks from the Intra-Sudetic Depression (Westphal *et al.*, 1987; Kądziałko-Hofmokl & El-Hemaly, 1997) and from the North Sudetic Depression and Intra-Sudetic Depression combined by Nawrocki (1997) (Table 3 and Fig. 10).

The locations of respective pre-tectonic (abc) directions, the hollow symbols on Figure 10, are as follows: Pabc - the Carboniferous–Permian boundary, Cabc and C1 abc - far away from the expected segment of the D/I reference path for the Devonian. According to H. Teisseyre (1956) and Porębski (1990) tectonic activity ceased in the Świebodzice Depression by the end of the Visean. It may therefore be surmised that the P overprint, if pretectonic, was acquired earlier than the Early/Late Carboniferous boundary. Consequently, it seems to be rather post-tectonic

The Cabc and C1abc components appear older than the rocks that carry them, therefore they should also be post-tectonic. None of the isolated components fit the Upper Devonian segment of the path proving that the Pogorzała Formation rocks did not retain their primary remanence.

The *in situ* directions shown as the filled symbols, are situated in the following segments of the D/I reference paths:

- component **P** lies in the Late Permian segment of the D/I reference path calculated after data for Baltica and for Variscan Europe;
- component **C1** lies close to the Westphalian segment; it fits component 3 obtained for the Intra-Sudetic Depression and assumed to be of Westphalian age (Kądzialko-Hofmokl & El-Hemaly, 1997);
- component **C** fits the Early Namurian–Late Visean segment;
- components **C** and **C1** fit the reference curve for Baltica, rather than that for Variscan Europe.

Despite the above conclusion an alternative solution has to be mentioned: the directions of the Sudetic Early Permian components cited in Table 3 for comparison, and the present results lie on the same side of the reference path. Therefore, some authors make suggestions about small (not greater than about 20°) rotations of the Sudetic units against the Baltica plate during Westphalian–Early Permian times (Kądziałko-Hofmokl & El-Hemaly, 1997; Jeleńska *et al.*, 1997; Nawrocki, 1998). If this is true, all the results concerning Sudetic remanences older than Permian should be verified. As this hypothesis is not properly verified, and bearing in mind that since Late Carboniferous times all the Sudetic units have generally kept their positions with respect to each other, its consequences will not be discussed in the present paper.

CONCLUSIONS

1. The main carriers of magnetic properties in the studied Pogorzała Formation rocks are secondary submicroscopic Fe-oxides (magnetite-maghemite), fine-grained pyrrhotite, hematite and a small amount of goethite.

2. The rocks studied did not retain their primary remanence as shown by negative results of the conglomerate test.

3. Rocks from both sites carry a Mesozoic/post-Mesozoic overprint.

4. Rocks from both sites were most probably remagnetized after tectonic activity ceased, during three different episodes:

- the rocks of site 26 acquired the remanence **C** close to the Visean–Namurian boundary shortly after the cessation of tectonic activity that may have been connected with the first episode of the Strzegom–Sobótka granitoid intrusion, and the remanence **P** may have been due to the Early Permian volcanic activity in the Intra-Sudetic Depression.
- the rocks of site 27 acquired the remanence **C1** during the Westphalian.

The stated differences in times of remagnetization episodes in the two studied localities are probably due to their different lithologies.

5. The results obtained better fit the reference data for the Baltica Plate than for Variscan Europe and show that the Świebodzice Depression has not moved against Baltica since at least the end of the Viséan. By virtue of their closeness the same has also held true for the Góry Sowie Block since late Devonian times.

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