Geologie en Mijnbouw **76:** 97–104, 1997.

Paleomagnetism of Carboniferous sediments from the West Sudetes (SW Poland)

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Received 10 May 1996; accepted in revised form 30 July 1997

Key words: Intra-Sudetic Basin, remagnetization, Variscides

Abstract

The studied Carboniferous flysch and molasse sediments from the Intra-Sudetic Basin correspond to the period from Middle Visean to Early Autunian. Main magnetic minerals carrying the natural remanent magnetization (NRM) are goethite, magnetite, maghemite and hematite, all usually secondarily formed and/or remagnetized due to several tectonometamorphic events. In most samples several NRM components were isolated. One of them is usually a Jurassic-Triassic overprint. Some others define the Westphalian-Early Permian segment of the declination and inclination trajectory for the Sudetes calculated according to the reference apparent polar wander path for the Baltica plate. The Sudetic path is slightly shifted to the east compared to the reference path, suggesting the possibility of independent movements of the Sudetes during this time. The majority of isolated NRM components are secondary and related to the Sudetic orogenic phase and later tectonometamorphic activity.

Introduction and geological setting

The West Sudetes lie at the northeastern periphery of the Bohemian Massif, a tectonic unit in the eastern part of the European Variscan Belt (inset in Figure 1). They originated together with the European Variscides due to the collision of the Gondwana and Baltica plates. The Sudetes form a mosaic of small blocks of varying stratigraphy and tectonic history, that is as yet not fully understood. The authors discussing problems of the geotectonic evolution of the Sudetes (e.g. Van Breemen et al. 1988, Cymerman & Piasecki 1994, Franke et al. 1993) are of the opinion that the major tectonometamorphic activity took place during Late Devonian to Late Carboniferous times. In order to contribute to the knowledge of the evolution of the Sudetes we have performed paleomagnetic investigations of paleontologically dated Carboniferous and Lower Permian sediments in the Intra-Sudetic Sedimentary Basin. This basin lies in the central part of the West Sudetes and is the largest of the Sudetic sedimentary basins, being 65 km long and 25 km wide. It is separated from the neighbouring units by tectonic boundaries (Figure 1). The basin was formed due to the gravitational collapse connected with the uplift of the eastern metamorphic cover of the Karkonosze block during the Late Devonian and Early Carboniferous. The sedimentation in the basin began in the Early Carboniferous and lasted till the Cretaceous.

According to Bossowski & Ihnatowicz (1994), the most important tectonic activity that affected this area is related to the Sudetic orogenic phase that took place in two pulses: during the Late (but not latest) Visean and the Early Namurian. The same authors state that the influence of the Erzgebirge (Middle Namurian) orogenic phase was rather weak in the Intra-Sudetic Basin, although not negligible. The Asturian orogenic phase took place during the Stephanian and was accompanied by volcanic activity. Early Permian volcanic activity in the northern part of the basin also contributed to the metamorphic alterations of the sampled sediments. Peak metamorphic temperatures in the basin are estimated to range between 200 and 300°C, nev-

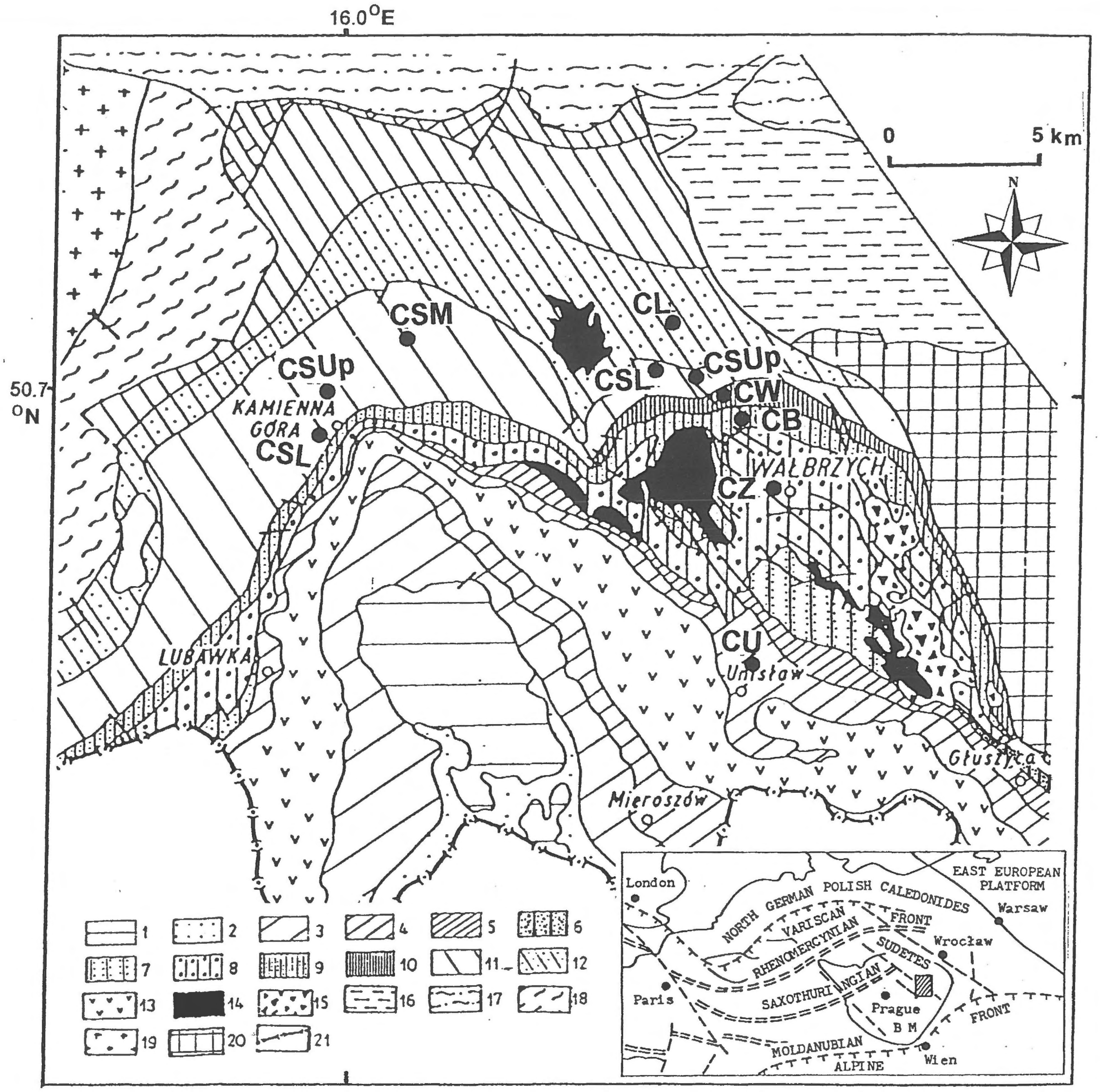

Figure 1. Schematic geological map of the Intra-Sudetic Basin with sampling localities. Inset shows situation of Sudetes within European Variscan Belt (BM – Bohemian Massif). 1 – Upper Createaceous, 2 – Lower Triassic, 3 – Radków Formation (Fm), 4 – Słupiec Fm, 5 – Krajanów Fm, 6 – Ludwikowice Fm, 7 – Glinik Fm, 8 – Zacler Fm, 9 – Biały Kamień Fm, 10 – Wałbrzych Fm, 11 – Szczawno Fm, 12 – Lubomin Fm, 13 – Lower Permian volcanites, 14 – Westphalian-Stephanian rhyodacites, 15 – Westphalian-Stephanian rhyolites and intrusives, 16 – Świebodzice Depression, 17 – Kaczawa Mts, 18 – eastern metamorphic cover of Karkonosze granitoid, 19 – Karkonosze granitoid, 20 – Sowie Góry Mts, 21 – state boundary. ● – sampling localities: CL - Lubomin Fm, CSUP, CSM, CSL – upper, middle and lower parts of Szczawno Fm, CW – Wałbrzych Fm, CZ – Zacler Fm, CB – Biały Kamień Fm, CU – Unisław beds of Ludwikowice Fm.

er exceeding the higher value (A. Bossowski and J. Siemiatkowski, private communication).

Schematic locations of the sampling localities are indicated in Figure 1. At each locality several sites were sampled; those that have the same bedding orientations are listed as one common entry in Table 1. This table also gives a stratigraphic overview with bedding expressed in the form of azimuth of dip direction/dip. Unfortunately, bedding orientations are not sufficiently different for a fold test to be performed, with the exception of the Stephanian-Autunian CU formation. The Carboniferous sediments sampled for this study are generally of fluvial and lacustrine origin. The 127 independently oriented hand samples collected in 34

Table 1. General characteristics of sampled formations.

Formation		Paleontol. age	S	N	Lithology	Bedding
Ludwikowice		E. Autunian	1	3	limestones	217/29
(Unisław beds)	CU	L. Stephanian	2	12	sandstones and mudstones	140/34
Zacler	CZ	Westphalian B	2	6	sandstones	180/25
		Westphalian A	3	9	sideritic sandstones and mudstones	130/22
Biały Kamień	CB	Westphalian A	2	10	sandstones	178/15
Wałbrzych	CW	E. Namurian	3	9	sandstones	155/12
			3	9	sandstones and conglomerates	140/15
Szczawno		Late Visean				
upper part	CS UP		2	7	sandstones	130/37
			2	8	sandy shales	156/36
			2	8	limestones andturbidites	170/35
middle part	CS M		1	5	sandstones	114/17
			1	3	sandstones	140/32
			1	5	sandstones	124/27
lower part	CS L		2	7	sandstones	141/35
			3	11	sandstones	185/47
Lubomin	CL	Middle Visean	1	5	sandstones	151/45
			2	7	sandstones	171/36

S and N: numbers of sites and samples, respectively. Bedding: bedding parameters: azimuth of dip direction/dip (°). The lithostratigraphic division is based on Mastalerz et al. (1993) and Bossowski & Ihnatowicz (1994).

sites are sandstones and mudstones, partly turbiditic, and rarely limestone varieties. According to paleontological dating, their ages vary from the Middle Visean to the Stephanian-Autunian boundary. From each hand sample four to ten specimens were cut for measurements.

Magnetic mineralogy

Magnetic minerals were identified with microscopic and thermomagnetic methods. Microscopic investigations performed with classical optical microscopy, scanning electron microscopy (SEM) and microprobe reveal the presence of goethite which is a main magnetic mineral. It is of hydrothermal origin or a weathering product. It occurs in various forms: as grain clusters, as coatings on grains of other minerals, sulphides or silicates, or as precipitates from hot fluids filling voids between minerals. Some pigmentary hematite within cracks was also observed. Among rarely visible relicts of highly altered detrital titanomagnetite, a martitized hematite was identified together with titanite and rutile (anatase) grains. Often, the matrix was brownish or cherry-red coloured, probably related to the presence of pigmentary goethite or hematite.

Thermomagnetic analysis consisted of thermal decay in a non-magnetic space of the isothermal remanence (Ir) acquired in a 1-T or 1.7-T field in (non-heated) fresh specimens and in the same specimens annealed to 600–700 °C (Figure 2, see Kadziałko-Hofmokl & Kruczyk 1976). The results reveal the presence of components with low unblocking temperature (Tb), ranging from 150 to 250 °C. We assume, that these components of Ir are related to goethite (or hydrogoethite?). The Néel temperature of goethite, sometimes identified with the maximum blocking temperature, is 120 °C (e.g. Strangway et al. 1968, Dekkers 1988, 1990), especially in grains of acicular form (Bagin et al. 1988). According to the latter authors the Tb of goethites, or of hydrogoethites that are more common in nature than goethite, depends very strongly on the morphology of the grains. They show that goethites of cloddy or sinter varieties loose their remanence at temperatures of 200 to 350 °C. Blocking temperatures higher than 120°C were also observed by these authors in acicular grains crushed to smaller sizes. Goethite dehydrates and transforms into

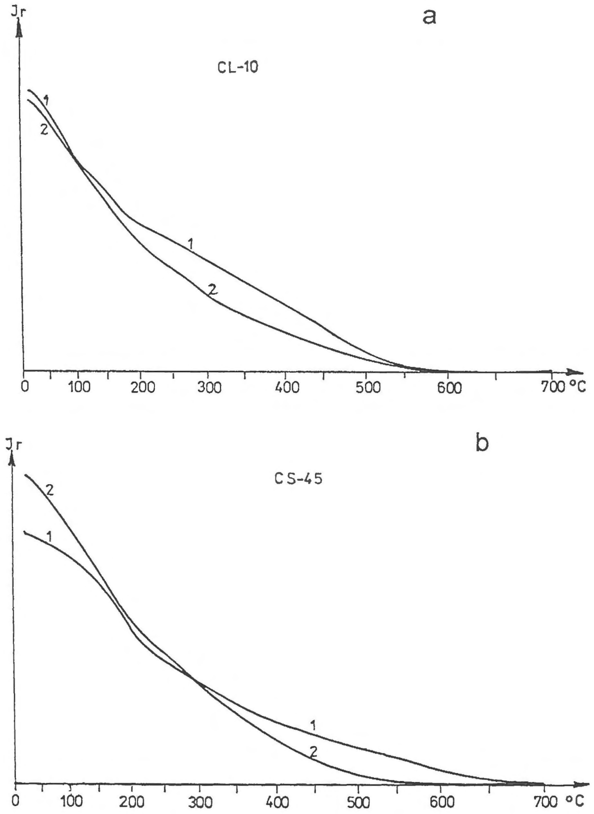

Figure 2. Typical thermal demagnetization curves Ir-T: a) specimen from CL formation, ratio Ir2/Ir1 = 2.3, b) specimen from CS formation, Ir2/Ir1 = 14.5. (Ir1: Ir of unheated specimen, Ir2: Ir of the same specimen after annealing). Ir in arbitrary units.

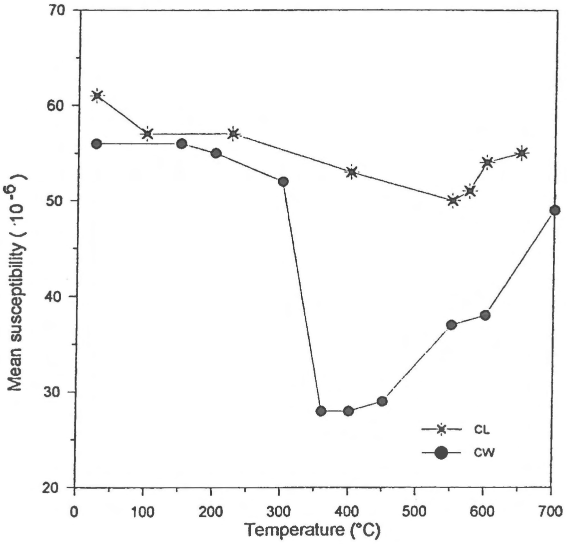

Figure 3. Changes of low-field susceptibility (in SI units) after consecutive heating steps for specimens from the CL and CW formations. The plots are characteristic for the studied rocks.

hematite in the temperature range of about 180–350 °C, and it is possible that kinks observed on the Ir-T (isothermal remanence versus temperature) curves are related to this process. In the higher temperature segments, thermomagnetic curves show the presence of Fe-oxides: magnetite and/or maghemite and hematite (Figure 2). The presence of maghemite in some specimens is shown by the drop of their susceptibility measured at room temperature after consecutive heating steps between 300 and 450 or 500 °C. These specimens differ significantly from others, that carry mostly goethite and magnetite and/or hematite, and that have no or much smaller susceptibility changes in this temperature range (Figure 3). Measurements of susceptibility were performed with the KLY-2 bridge of Geofyzika in Brno. In all specimens investigated, heating in air to temperatures higher than 450–550 °C causes an increase of the amount of magnetite (probably in majority formed at the expense of non-magnetic clay minerals). This was deduced from observed increases of susceptibility and high-field remanence. In particular, the distinct Tb characteristics in the Ir-T curves of the second heating (Figures 2 and 3) point to magnetite. The presence of goethite and Fe-oxides (mostly fine-grained) was additionally inferred from cumulative frequency curve analysis of IRM (isothermal remanence) acquisition curves according to Robertson & France (1994), performed by one of the authors (El-Hemaly) during his stay at the Liverpool University. The coercivities of remanence B_{cr} obtained by him clustered around the following values: 20, 45, and 65 mT characteristic of single-domain (SD) and pseudo-single-domain (PSD) magnetite and/or maghemite, 400–580 mT characteristic of hematite, and about 2700 mT characteristic of goethite (e.g. Dunlop 1972, Robertson & France 1994).

Previous geological investigations (Bossowski & Ihnatowicz 1994) and our microscopic study reveal the presence of siderite in the CZ formation. Being paramagnetic (Tarling & Hrouda 1993) it does not contribute to NRM, but to susceptibility. As siderite converts into magnetite at temperatures exceeding 300 °C (Ellwood et al. 1989), its presence indicates that the rocks in question likely did not pass this temperature during any of the metamorphic events.

Summarizing, we conclude that the studied sediments contain goethite and Fe-oxides that are in majority of secondary origin and could have been formed and/or remagnetized during several tectonometamorphic or volcanic events that took place in the Intra-Sudetic Basin, i.e. during both pulses of the Sudetic

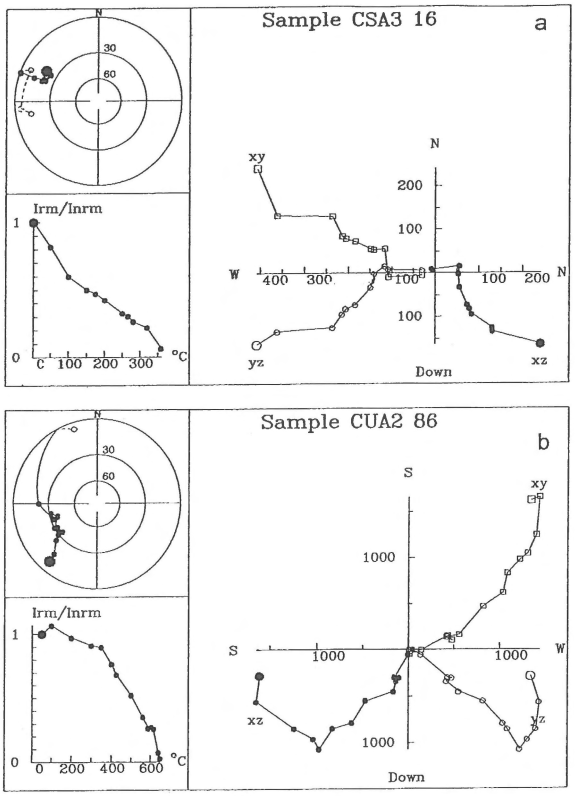

Figure 4. Examples of demagnetization results: a) specimen from CS formation, b) specimen from CU formation. Upper left: equal-angle stereographic projection of the direction of NRM; ●: projection on lower hemisphere, ○ – projection on upper hemisphere. Lower left: intensity decay curve Irm/Inrm: intensity of NRM after consecutive heating steps/intensity before demagnetization. Right: Zijderveld plot in three perpendicular planes, ●: XZ plane, ○: YZ plane, □: XY plane. Numbers on the axes denote intensity in 10^{-3} mA/m.

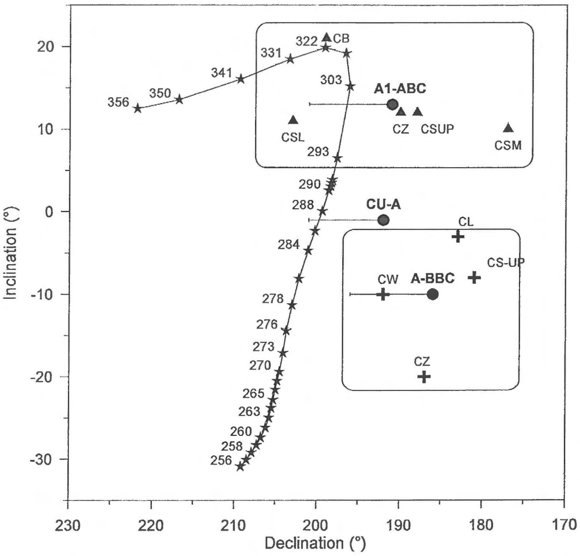

Figure 5. Results of the present paper compared with the declination/inclination path (★) expected for the Sudetes calculated after the Apparent Polar Wander Path for Baltica (Torsvik et al. 1990). Numbers denote ages in Ma. ▲ mean A1 directions after bedding correction for formations CB, CZ, CSUP and CSM. ● A1-ABC is the mean A1 direction for the Intra-Sudetic Basin calculated from the enframed data together with the error bar. ● CU-A is the mean direction obtained for the CU formation after partial correction (see text and Table 2) together with the error bar. + mean A directions before bedding correction for formations CL, CSUP, CW and CZ. ● A-BBC is the mean A direction for the Intra-Sudetic Basin calculated from the enframed data together with the error bar. Formations labelled as in Figure 1 and Table 1.

phase, but also during the Erzgebirge phase, the Asturian phase, or the Late Carboniferous and Early Permian volcanic activity, or in later times.

Methods and instrumentation

The natural remanent magnetization (NRM) was measured with a 2G Enterprises cryogenic magnetometer equipped with RF SQUIDs. The NRM intensity ranges from 0.1 to 4.5 mA/m, remaining in most cases below 1 mA/m in all formations. Only in the CU formation the NRM ranges from 2 to 18 mA/m. Three to six specimens from each hand sample were demagnetized. They were demagnetized thermally in a Magnetic Measurements furnace and with alternating fields (AF) with an apparatus of the 2G Enterprises. Magnetometer and demagnetization devices are installed in a Magnetic Measurements low-field-environment coil system. Thermal demagnetization was used more often because the presence of goethite or haematite in numerous specimens precludes complete AF demagnetization. Specimens from the CZ formation, containing siderite, were demagnetized thermally up to 270 °C followed by AF treatment. This procedure was adopted in order to avoid bias of the NRM behaviour due to mineralogical changes by the conversion of siderite into magnetite. All demagnetization results were analysed with stereographic and Zijderveld plots. NRM components were calculated according to the procedure described by Kirschvink (1980).

Paleomagnetic results and discussion

The NRM of nearly all specimens is composed of two or three components that very often differ from one specimen to the other (Figure 4). This is in agreement with the presence of various magnetic minerals formed and/or remagnetized at various times. The analysis of the obtained results generally revealed the presence of four to five components within each formation. The Upper Visean CS formation, especially its lower part CS L, showed eight groups of components.

The component labelled T has the direction D = 33°, I = 58°, α_{95} = 6°, k = 69 which is close to the Triassic and Jurassic field directions expected for the Sudetes, viz. D = 31°, I = 56° for the Late Triassic, and D = 27°, I = 61° for the Early Jurassic (Westphal et al. 1986). Apart from the T component, there are two other components suitable for interpretation, labelled A and A1. Their SSE-SSW declinations and low to intermediate inclinations are characteristic for the Late Carboniferous and Early Permian segment of the path of expected declination and inclination for the Sudetes calculated after the reference apparent polar wander path (APWP) for Baltica (Figure 5; Torsvik et al. 1990). Their directions before and after bedding correction (bbc and abc respectively) are presented in Table 2 together with statistical parameters and corresponding virtual pole positions.

The components labelled A1 have positive inclinations which in situ (bbc) are higher than the Permo-Carboniferous ones expected for the Sudetes (Figure 5). The mean A1 bbc direction: D = 199°, I = 36°, α_{95} = 13°, k = 35, does not fit the reference curve. After correction for the bedding the mean A1 direction (A1 abc): D = 191°, I = 13°, α_{95} = 10°, k = 60, is shifted closer to the reference curve, and has less scattering than before correction. This suggests the pre-tilting origin of this component. By comparison with the reference declination and inclination curve we estimate its age as Westphalian (290–320 Ma) which is the age of the CZ formation. The A1 component is secondary in the CS and CB formations, whereas in the CZ formation it is either primary or early diagenetic.

The component labelled CU-A was obtained only in the CU formation which is the youngest one and which comprises Upper Stephanian sandstones and Lower Autunian limestones. The rocks are badly exposed and only nine hand samples from three sites could be collected. The best grouping of the directions of the CU-A component was obtained when we calculated the mean CU-A, taking pre-tilt (abc) directions for the Upper Stephanian, and applying partial tilt correction to the directions for the Lower Autunian rocks. The consecutive trials indicate that the CU-A component was acquired by the Lower Autunian limestones when they were tilted by 9° instead of the 29° measured now in the field. The mean CU-A direction calculated in the described way: D = 192°, I = −1°, α_{95} = 9°, k = 185, is situated close to the Early Autunian segment of the reference declination and inclination path. This result could imply that the CU-A is a syntectonic component (Ka działko-Hofmokl & El-Hemaly 1996).

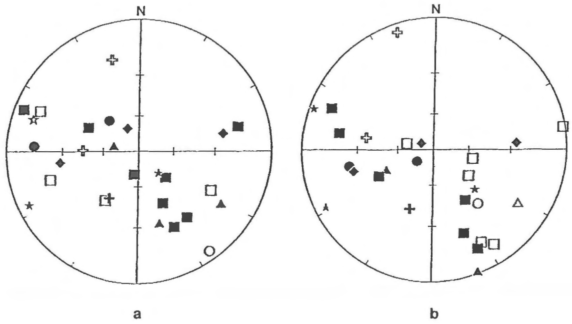

Figure 6. Stereographic equal-angle projections of unidentifiable mean directions (i.e. with exception of the T, A and A1 means) per formation: a) before, b) after bedding correction. Triangles – CU, stars – CZ, diamonds – CB, crosses – CW, squares – CS, circles – CL formation. Full (open) symbols denote projection on the lower (upper) hemisphere.

The directions of the component labelled A have negative inclinations. They were isolated in rocks from the CL, CS, CW and CZ formations. Their *in situ* directions with the mean direction Abbc: D = 186°, I = −10°, α_{95} = 10°, k = 89, fit the reference curve much better than the direction after correction (Aabc) although the precision parameters remain similar in both cases: D = 191°, I = −32 °, α_{95} = 11°, k = 71 (Figure 5) . We therefore conclude that the A component is a post-tilt overprint of 270–280 Ma age (Early Permian).

The above described mean results obtained for the Intra-Sudetic Basin are summarized in Table 3, together with the data obtained for Carboniferous rocks from other regions of the Sudetes.

The directions of the other isolated NRM components resemble neither Carboniferous nor post-Carboniferous field directions expected for the Sudetes. Their stereographic projections before and after bedding correction are shown in Figures 6a and b. They are all rather well identified with α_{95} ranging between 6 and 20° and k between 13 and 95, both before and after bedding correction. Nevertheless they cannot represent the geomagnetic field of any epoch because they do not resemble the expected directions for the Sudetes for either Carboniferous or post-Carboniferous times. It is likely that they represent

Table 2. Mean Permo-Carboniferous directions and virtual pole positions for the Intra-Sudetic Basin.

Com.	Fm.	n	D bbc	I bbc	α_{95}	k	PlaN bbc	PloE bbc	D abc	I abc	α_{95}	k	PlatN abc	PloE abc
A1	CSL	7	217	53	17	13	0	346	20	11	16	16	−30	349
	CSM	9	191	30	9	36	−25	5	177	10	10	30	−34	19
	CSUp	6	196	41	10	43	−14	1	188	12	12	42	−33	6
	CB	10	202	35	10	27	−17	354	199	21	10	27	−26	355
	CZ	8	196	22	10	33	−25	358	190	12	10	33	−32	4
		5	*199*	*36*	*13*	*34*	*−17*	*357*	*191*	*13*	*10*	*60*	*−32*	*3*
CU-A	CU	27	196	14	16	59	−31	358	191	− 7	19	45	−42	1
CU-A*									*192*	*− 1*	*9*	*185*	*−39*	*0*
A	CL	8	183	−3	11	27	−40	12	189	−38	11	27	−60	359
	CSUp	10	181	−8	11	32	−42	15	186	−36	11	19	−59	5
	CW	14	192	−10	9	20	−43	359	195	−19	9	20	−47	354
	CZ	7	187	−20	10	37	−49	5	195	−33	13	23	−55	350
		4	*186*	*−10*	*10*	*89*	*−44*	*8*	*191*	*−32*	*11*	*71*	*−55*	*358*

Com.: component; Fm.: formation, n: number of specimens used for calculations in the case of formations and number of entries in the case of means for whole Intra-Sudetic Basin; α_{95}, k: Fisher parameters; D, I: declination and inclination (°); PlaN/PloE: latitude/longitude of the virtual paleomagnetic poles (°); bbc/abc: data before/after bedding correction. Means for formations are in roman script, means for the Intra-Sudetic Basin are in *italics*. Mean CU-A$*$ is the best grouping obtained after partial correction for the tilt of the Autunian rocks and full correction for the tilt of the Stephanian rocks (see text).

Table 3. Mean paleomagnetic directions and pole positions for the Intra-Sudetic Basin, geographical position 16.2°E, 50.7°N and corresponding results from other Sudetic areas.

Comp./Ref.	Age of remanence	N	α_{95}	k	D	I	PlaN	PloE	plat
ISB A (bbc)	L. Autunian	4	10	89	186	−10	−44	8	−5
ISB CU−A	E. Autunian	3	9	185	192	−1	−39	0	0
ISB A1 (abc)	Westphalian	5	10	60	191	13	−32	3	7
^{1} – granites and granitoids, 305–281 Ma	Late Carboniferous	4	13	–	202	−12	−42	346	−6
^{2} – volcanites L. Carbonif. and Permian	Late Carboniferous	8	11	27	192	−2	−39	1	
	Permian	5	18	18	190	−19	−48	1	

Comp./Ref.: Component/References; ^{1} – Halvorsen et al. (1989), ^{2} – Westphal et al. (1987). N: number of entries; plat: paleolatitude (°); L: Late Autunian, E: Early Autunian; other symbols as in Table 2.

mixed contributions of several components, a possibility suggested by great-circle analysis of the directions. Taking the above facts into account we assume that these components are artefacts resulting from the multiple remagnetizations that affected the studied deposits (Mertanen & Pesonen 1995). An important feature of the analysed material is the absence of components representing the Visean and Namurian fields. The formations deposited during these periods turned out to be fully remagnetized. Apart from identifiable components (A1, A and T) they carry more unidentifiable components of unknown age, acquired due to remagnetization processes, than the other formations (Figure 6). This points to the important role of the Sudetic orogenic phase in the processes of remagnetization of the studied deposits.

Conclusions

- The investigated sediments are strongly altered and remagnetized; nevertheless the Westphalian-Permian segment of the APWP for the Sudetes could be isolated in some cases.

- The obtained path is shifted slightly to the east compared to the reference path for Baltica, suggesting some small movements of the Sudetic block with respect to the Baltica plate during Westphalian Early Permian time.
- The results obtained for the Visean and Namurian sediments indicate that the Sudetic orogenic phase influenced the sediments to a substantial degree.
- All studied sediments carry a Jurassic-Triassic magnetic overprint.

Acknowledgements

The study was supported by the Polish National Committee for Scientific Research, project no. 6P20102404. The authors express their thanks to M. Jeleǹska and K. Mastalerz for help in the field work. Thanks are also due to J. Siemiątkowski, B. Kazimierska and P. Łącki for microscopic investigations, as well as to J. Shaw and J. Share from the University of Liverpool for help in performing the IRM-acquisition curves and their analysis.

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