Geological Quarterly, 2011, **55** (3): 223–234

Palaeomagnetic age constraints on folding and faulting events in Devonian carbonates of the Kielce Fold Zone (southern Holy Cross Mountains, Central Poland)

Rafał SZANIAWSKI, Andrzej KONON, Jacek GRABOWSKI and Petr SCHNABL

Szaniawski R., Konon A., Grabowski J. and Schnabl P. (2011) – Palaeomagnetic age constraints on folding and faulting events in Devonian carbonates of the Kielce Fold Zone (southern Holy Cross Mountains, Central Poland). Geol. Quart., **55** (3): 223–234. Warszawa.

The results of numerous palaeomagnetic studies performed in the last three decades in Devonian carbonates of the Holy Cross Mountains (HCM) have documented the occurrence of several episodes of remagnetisation. This knowledge was applied in this study to determine the temporal relationships between the acquisition of particular secondary palaeomagnetic components and the formation of tectonic structures. This made it possible to estimate the timing of several episodes in the multistage tectonic evolution of particular folds and faults. We show that the westernmost part of the southern HCM was rotated clockwise after the early Permian. Detailed palaeomagnetic analysis documented also shape modifications in some map-scale and minor folds. This tectonic overprinting of originally Carboniferous folds postdated the early Permian. It was furthermore shown that the N–S trending dextral strike-slip faults studied were active between the early Permian and the Permo/Triassic. Our recent data show also the post-early Permian age of breccia that covers the deformed Devonian strata.

Rafał Szaniawski, Institute of Geophysics, Polish Academy of Science, Ks. Janusza 64, PL-01-452 Warszawa, Poland, e-mail: rafsz@igf.edu.pl; Andrzej Konon, Institute of Geology, University of Warsaw, Żwirki i Wigury 93, PL-02-089 Warszawa, Poland, e-mail: andrzej.konon@uw.edu.pl; Jacek Grabowski, Polish Geological Institute – National Research Institute, Rakowiecka 4, PL-00-975 Warszawa, Poland, e-mail: jacek.grabowski@pgi.gov.pl; Petr Schnabl, Institute of Geology AS CR v.v.i., Rozvojova 269, 165 00 Praha 6, Czech Republic, e-mail: schnabl@gli.cas.cz *(received: December 23, 2010; accepted: September 11, 2011).*

Key words: remagnetisations, palaeomagnetic components, fold tests, tectonics.

INTRODUCTION

Recognition of the age of magnetic remanence and its relation to geological events constitutes the principal issue in most of palaeomagnetic studies. In the early years of the palaeomagnetic method, two powerful techniques were developed to distinguish time relationships between magnetisation and the formation of folds and conglomerates: the fold test and conglomerate test (Graham, 1949). Both methods were systematically improved and used most commonly for constraining the age of magnetisation in relation to folding and erosional events. It was recognized that sedimentary rocks were commonly remagnetised either by thermoviscous or by chemical processes (e.g., McCabe and Elmore, 1989) and that acquisition of secondary magnetisation might happen at any stage of rock deformation (e.g., Lewandowski, 1981; McWhinnie *et al*., 1990; Stamatakos *et al*., 1996; Enkin *et al*., 2000; Grabowski *et al*., 2009). Correct age recognition of a secondary component together with understanding the complex and multistage nature of tectonic processes constituted the basis for numerous palaeomagnetic studies constraining the age of deformation events (e.g., Sandberg and Butler, 1985; Stewart, 1995; Szaniawski *et al*., 2003; Cederquist *et al*., 2006; Pueyo *et al*., 2007).

Our studies focus on Devonian carbonates from the southern part of the HCM (SHCM – Kielce Fold Zone) where the age of particular tectonic structures is frequently unclear and debated (synsedimentary and Variscan deformations *versus* a Maastrichtian-Paleocene overprint, see Kutek and Głazek, 1972; Lamarche *et al*., 1999, 2002, 2003). These rocks were chosen since their magnetic record had been recognized by previous studies (Lewandowski, 1981, 1999; Grabowski and Nawrocki, 1996, 2001), revealing mostly secondary magnetisations. Three major episodes of remagnetisation in the Kielce Fold Zone were distinguished by Zwing (2003) and Szaniawski (2008) from fold tests applied to map-scale folds from the entire area of the SHCM. They resulted in the early syn-folding Visean component B, and post-folding components of early Permian (component A) and late Permian/Early Triassic age (component C).

The present paper shows new results of integrated palaeomagnetic and structural studies carried out in the SHCM and their application to dating and to restoring the evolutionary stages of both major and minor tectonic structures as well as related sedimentary breccias.

GEOLOGICAL SETTING

The HCM represent an exposed fragment of the Trans-European Suture Zone (TESZ) that forms a transition between the Precambrian East European Craton (EEC) and Paleozoic mobile belts of Central and Western Europe (Fig. 1). These studies have been carried out in the southern region of the HCM (SHCM) that belongs to the Małopolska Block, that constitutes a tectonostratigraphic terrane derived from Gondwana and accreted to the EEC in the Cambrian (Bełka *et al*., 2000, 2002; Nawrocki, 2000; Winchester *et al*., 2002; Nawrocki *et al*., 2007).

Sedimentation of late Paleozoic carbonates in the SHCM started in the Eifelian and continued during the Mid and Late Devonian (e.g., Czarnocki, 1919). At that time the carbonate platform developed progressively and subsequently drowned in an extensional tectonic regime (see Szulczewski, 1989, 1990; Racki, 1992; Szulczewski *et al*., 1996). At the beginning of early Carboniferous times, the basin was progressively deepening, as reflected by uniform deep-water clayey deposition. This was followed by clayey-sandy sediments in the Visean, indicative of general shallowing of the basin and representing the youngest Carboniferous deposits in the area (e.g., Szulczewski, 1995). The rock succession described is folded and covered discordantly by upper Permian strata which set an upper time limit on the folding.

The Devonian carbonates studied underwent a multi-stage tectonic evolution. At the beginning these rocks were affected by significant synsedimentary deformation in a generally extensional setting (Szulczewski, 1971, 1989; Racki and Narkiewicz, 2000). A significant episode of tectonic activity occurred in the late Paleozoic when the HCM constituted the foreland of the Variscan Orogen (Pożaryski *et al*., 1992; Dadlez *et al*., 1994; Szulczewski, 1995; Krzemiński, 1999; Jaworowski, 2002; Mazur *et al*., 2006). In the HCM, the Variscan folding started after Visean times due to N–S to NNE–SSW-directed shortening (e.g., Czarnocki, 1957; Tomczyk, 1988; Mizerski, 1995; Lamarche *et al*., 1999, 2002; Konon, 2006, 2007; Szaniawski, 2008). The late Variscan compression terminated prior to late Permian times (Czarnocki, 1919), resulting in map-scale folds defining a fold belt comprised of the Kielce (=SHCM) and Łysogóry fold zones (as defined by Konon, 2008).

Another active tectonic episode occurred during the Maastrichtian-Paleocene uplift, when the rocks studied were affected by mostly brittle deformation accompanied by modification of shapes of the earlier formed folds (Jaroszewski, 1972; Kutek and Głazek, 1972; Lewandowski, 1985; Kutek, 2001; Krzywiec, 2009). The latter deformation was particularly intense at the contact zone of the Paleozoic substratum and its Mesozoic cover (Gągol *et al*., 1976; Głazek *et al*., 1981; Lamarche *et al*., 2002, 2003).

The map-scale folds in the HCM are dissected by numerous longitudinal faults as well as by those striking at high or low angles to their axes (i.e. transverse and oblique faults; Czarnocki, 1919, 1957; Samsonowicz, 1934; Konon, 2007). Most faults in both the Kielce and Łysogóry fold zones are characterized by combined strike-slip and either normal or reverse-slip components (e.g., Czarnocki, 1957; Jaroszewski, 1972; Mastella and Mizerski, 2002; Konon, 2007).

SCIENTIFIC TARGETS AND SAMPLING STRATEGY

The present study is focused on reconstructing the formation of selected tectonic structures using palaeomagnetic methods, a task important for understanding the overall tectonic evolution of the SHCM. Studies reported in this paper were performed within map-scale folds near to the southern and western edge of the SHCM where Maastrichtian-Paleocene modification of fold shapes (e.g., Głazek and Kutek, 1970; Kowalczewski, 1971; Kutek and Głazek, 1972; Kowalski,

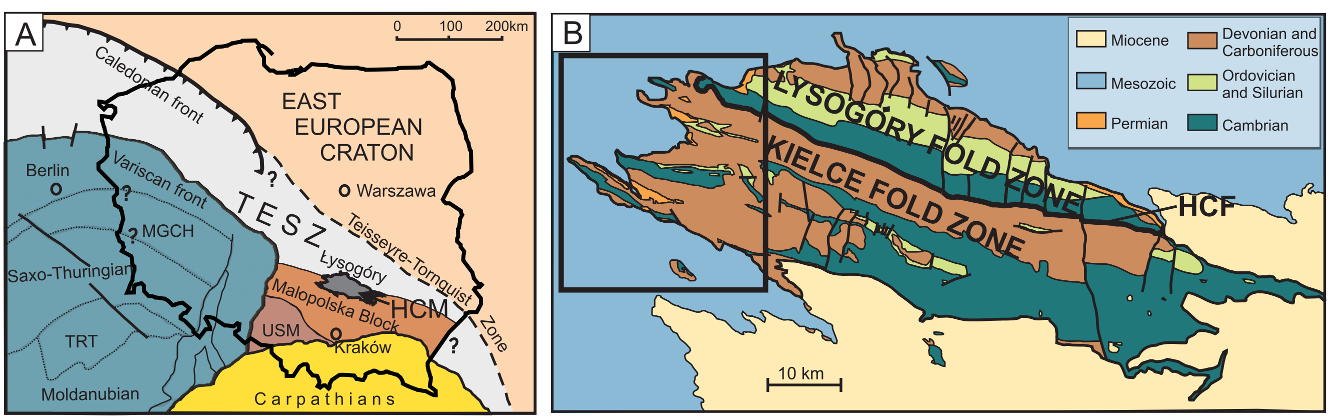

Fig. 1A – tectonic map of Poland (modified after Bełka *et al*., 2000); B – geological map of the Holy Cross Mountains (after Czarnocki, 1938)

HCF – Holy Cross Fault, HCM – Holy Cross Mountains, MGCH – Mid-German Crystalline High, TESZ – Trans-European Suture Zone, TRT – Tepla–Barrandian Terrane, USM – Upper Silesian Massif, black rectangle marks the study area shown in detail in Figure 2

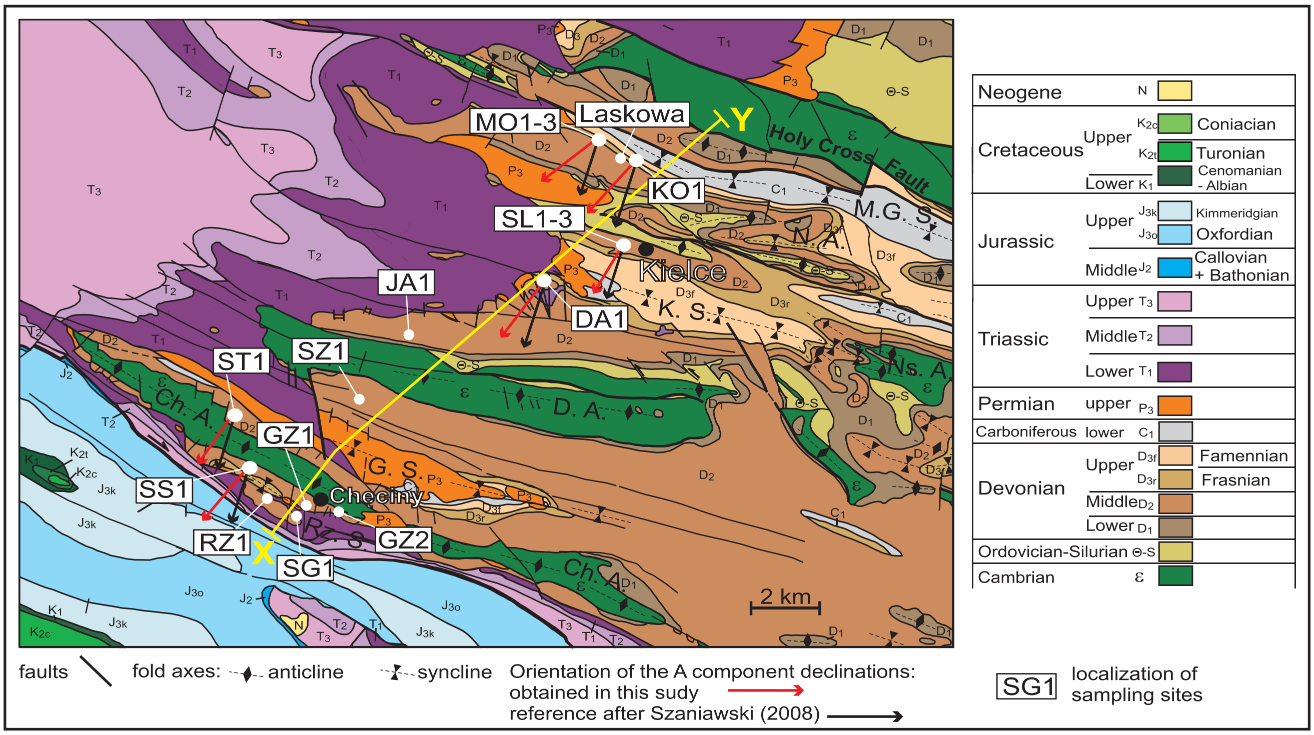

Fig. 2. Geological map of the western part of the Holy Cross Mountains (after Czarnocki, 1938 and Konon, 2007; modified) showing location of palaeomagnetic sampling sites, orientations of the A component declinations and position of the cross section X–Y

Ch. A. – Chęciny Anticline, D. A. – Dyminy Anticline, G. S. – Gałęzice Syncline, K. S. – Kielce Syncline, M.G. S. – Miedziana Góra Syncline, N. A. – Niewachlów Anticline, Ns. A. – Niestachów Antykline, Rz. S. – Rzepka Syncline

1975) and reactivation of faults has been suggested (e.g., Gągol *et al*., 1976; Głazek *et al*., 1981). Sampling sites were chosen along a transect cutting the western part of the SHCM from the area of Niewachlów in the north to that of Rzepka in the south (Figs. 2 and 3). Samples were collected from limbs of map-scale folds, avoiding locations close to smaller, lower-order folds, from the following sites: MO3 (Mogiłki Quarry) and KO1 (Kostomłoty Quarry) from the northern limb of the Niewachlów Anticline; site SL1 (Śluchowice Quarry) from the southern limb of the Niewachlów Anticline; DA1 (Dalnia Quarry) and JA1 (Jaworznia Quarry) from the northern limb of the Dyminy Anticline; SZ1 (Szewce Quarry) from the southern limb of the Dyminy Anticline; ST1 (Stokówka Quarry) situated on the northern limb of the Chęciny Anticline. Detailed analyses were performed close to the southern edge of the HCM Paleozoic core, where three sites were sampled in the southern limb of the Chęciny Anticline (SS1 – Sosnówka Hill; GZ1 and GZ2 – Zamkowa Hill) and two other sites in the southern limb of the relatively small Rzepka Syncline (RZ1 – Rzepka Quarry plus SG1 – Sułtańskie Górki).

Additionally a number of sites were selected for studies of minor tectonic structures and of sedimentary breccia. In Mogiłki Quarry two sampling sites (MO1 and MO2) were situated at the opposite limbs of a metre-scale chevron fold (Fig. 4C). The minor fold studied belongs to the northern limb of a the map-scale Niewachlów Anticline. Further studies were performed to clarify the age of N–S trending dextral strike-slip faults from Śluchowice Quarry, whose age and importance were comprehensively discussed elsewhere (Konon, 2007, 2009; Świdrowska and Lamarche, 2009). For this purpose, samples were taken from two sites (SL2 and SL3), from rock layers dragged by a strike-slip fault (Fig. 4A). A palaeomagnetic study of a post-tectonic breccia was carried out in Laskowa Quarry (Fig. 4D). This breccia is composed of slightly rounded clasts of Devonian carbonates within red fine-grained indurated matrix. The breccia rests in a horizontal position and discordantly covers deformed and folded Devonian strata. For this study five clasts of the breccia were sampled.

LABORATORY METHODS

At a typical sampling site, six to seven hand samples were taken. Samples were subsequently drilled in the laboratory in order to obtain specimens 24 mm in diameter. Most palaeomagnetic experiments were performed at the Palaeomagnetic Laboratory, Institute of Geophysics, Polish Academy of Sciences. Laboratory measurements started with studies on acquisition of isothermal remanent magnetisation (IRM) and with the Lowrie test (Lowrie, 1990), using a *2G SQUID* cryogenic magnetometer plus a *Magnetic Measurements MM-1* furnace and pulse magnetizer. The same laboratory equipment was applied in investigations of natural remanent magnetisation (NRM). Collections from two localities (SZ1 and breccia from Laskowa Quarry) were investigated in the palaeomagnetic laboratories of the Polish Geological Institute – National Research Institute in Warsaw (*JR6A* magne-

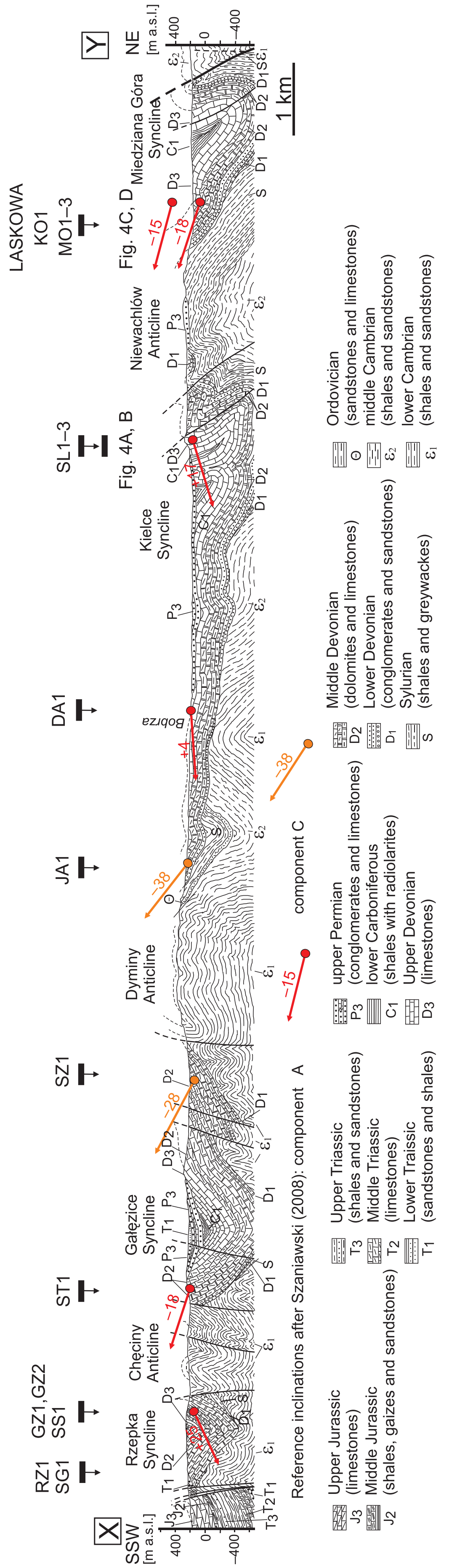

Fig. 3. Geological cross section X–Y (after Filonowicz, 1973; Hakenberg, 1973; Konon, 2006) showing location of sampling sites and values obtained of palaeomagnetic inclinations of A (red) and C (orange) components

tometer and *MMTD1* thermal demagnetizer) and at the Institute of Geology of the Academy of Sciences of the Czech Republic in Prague (*2G* cryogenic magnetometer and *MAVACS* thermal demagnetizer system).

The thermal demagnetisation technique was utilized for investigations of the NRM composition since this method has turned out to be the most effective for separating the palaeomagnetic components of the rocks studied (e.g., Grabowski *et al*., 2006). After each step of thermal cleaning, the magnetic susceptibility was monitored applying the *KLY-3* kappbridge. Separation of palaeomagnetic directions was performed using the principal component analysis method (PCA; see Kirschvink, 1980) and software by Chadima and Hrouda (2006). Palaeomagnetic site mean directions were calculated as a mean of hand sample directions, whereas the direction for every sample was determined as a mean of specimen directions obtained by PCA.

PALAEOMAGNETIC RESULTS

The IRM acquisition experiments reveal that the majority of the rock samples investigated contain an important contribution of low-coercivity magnetic minerals that manifest themselves by a rapid increase of magnetisation after applying magnetic fields below 160 mT (Fig. 5A). Most samples were almost completely saturated in fields over 400 mT indicating negligible content of high-coercivity minerals. Results of Lowrie tests are in agreement with IRM studies since most magnetisation was carried by low-coercivity minerals showing maximum unblocking temperatures (Tub) of 450–500°C (Fig. 5A). The observed low-coercivity magnetic minerals characterized by moderate Tub represent most likely nonstoichiometric magnetite or maghemite. These results are generally in line with previous reports showing comprehensive rock magnetic and SEM studies (Zwing, 2003; Grabowski *et al*., 2006). Different magnetic properties were noted only in a few of the rocks studied (sites JA1, SL3 and SZ1), which are characterized by an important content of hematite, as distinguished by its high coercivity and Tub above 600°C (Fig. 5B). These hematite-bearing rocks are easily recognizable by their characteristic reddish shade.

The NRM shows a relatively low initial intensity, ranging typically between 0.1 and 5 mA/m. At those sites where rock analyses uncover a lack of hematite, the magnetic record shows comparable structure. The lowest temperatures of demagnetisation (up to 255°C) effectively remove soft, components, directed along the present-day geomagnetic field direction of the area. Some of the sites studied (GZ1, GZ2, RZ1, SG1), which display very low values of NRM intensity, reveal the occurrence of only this soft, component, interpreted as recent viscous remanent magnetisation (VRM).

After VRM removal a gradual migration of the NRM vector toward the third quarter of the hemisphere is observed, accompanied by a small increase in the remanence intensity (Fig. 6A, B). On subsequent demagnetisation steps, just one component of the characteristic remanent magnetisation (ChRM) typically occurs, being recognized as the A component known from previous studies (Zwing, 2003; Szaniawski, 2008). It was distinguished by a Tub range of 250–400°C,

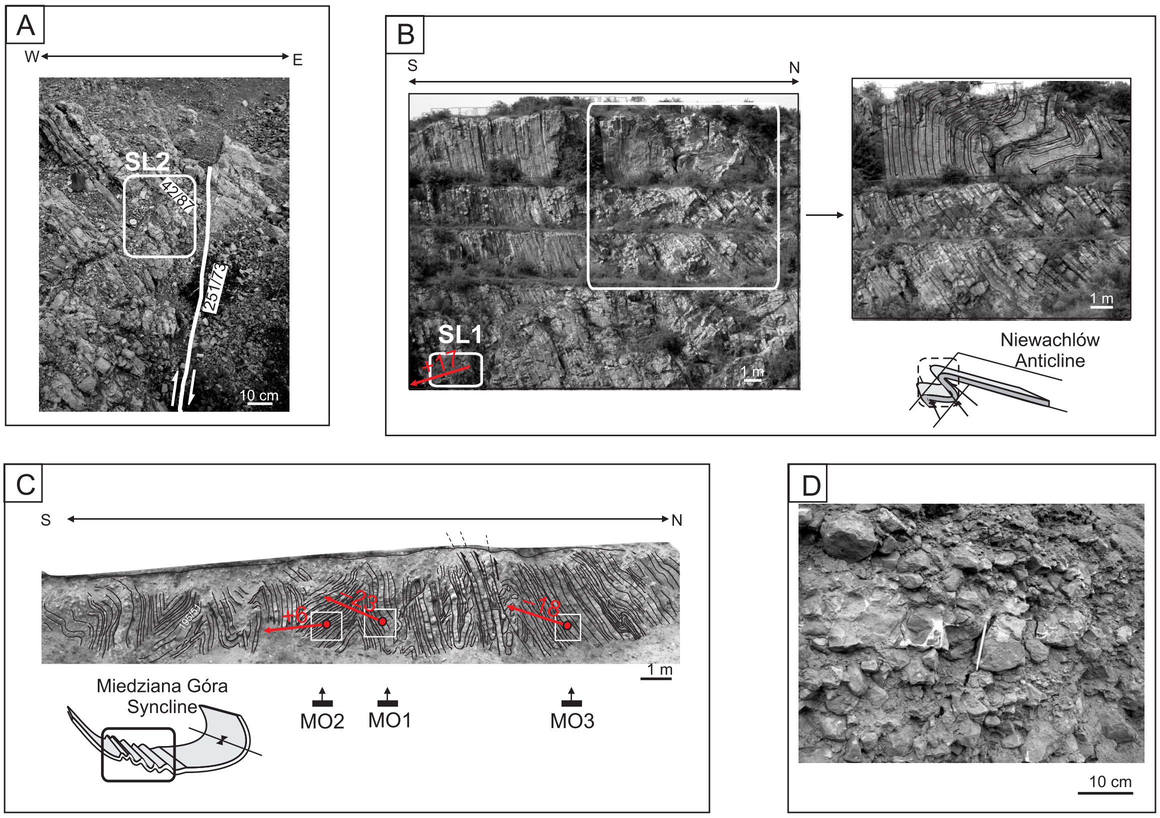

Fig. 4A–D – close-up views of selected tectonic structures

A – bird's-eye view of strike-slip fault studied with location of site SL2; **B**, **C** – second-order folds from Śluchowice and Mogiłki quarries with detailed location of sampling sites and values obtained of inclination, both photographs B and C are displayed as mirror images to correspond with the cross-section X–Y (Fig. 3); **D** – breccia from Laskowa Quarry

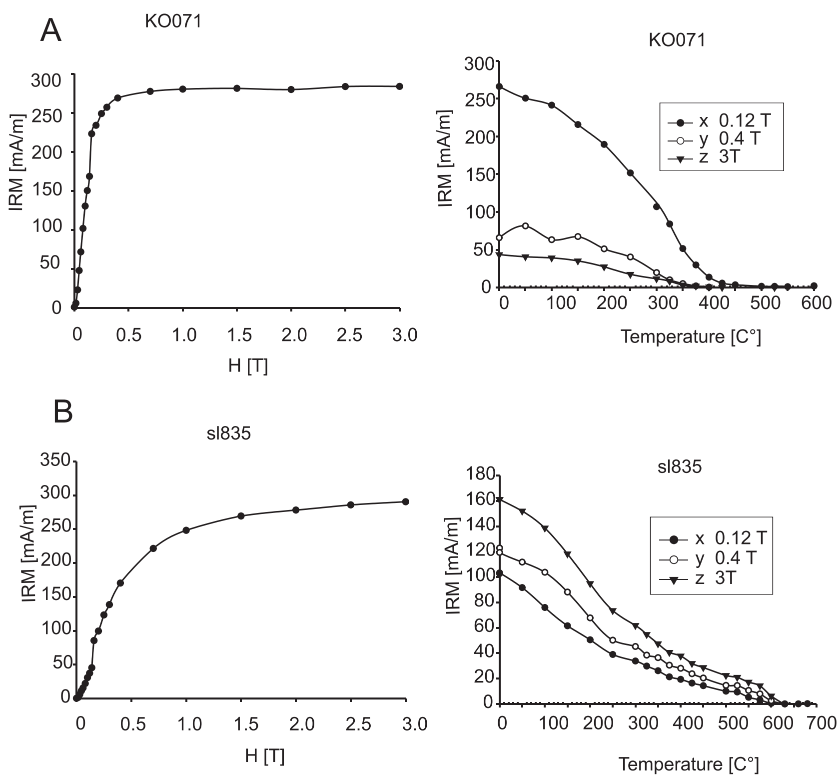

Fig. 5. Results of stepwise acquisition of IRM (left diagrams) along with thermal demagnetisation of a composite three axes IRM (Lowrie, 1990 – right diagrams) observed in the majority of samples studied (A – site KO1) and derived from reddish carbonates (B – site SL3)

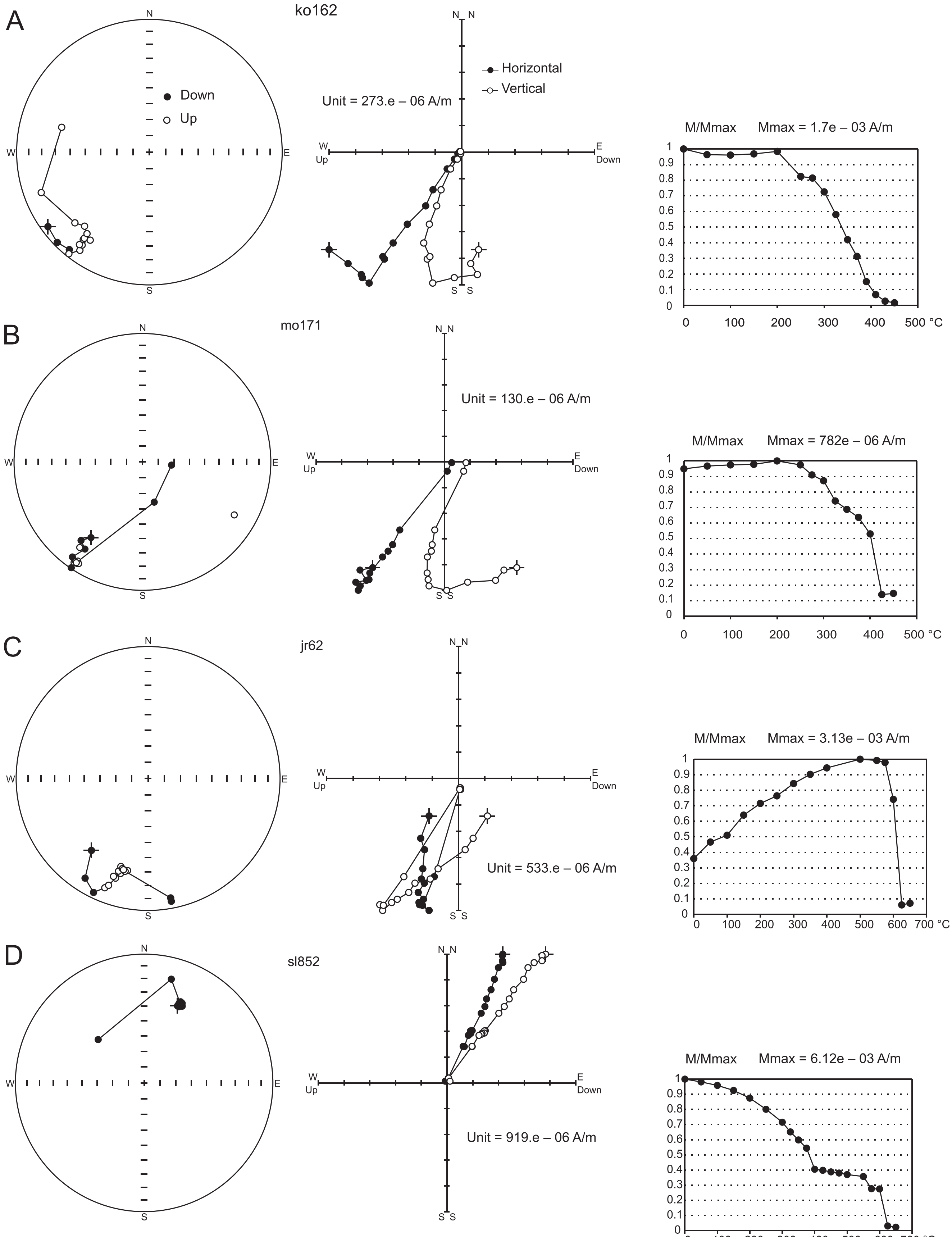

Fig. 6. Results of thermal demagnetisation of four representative specimens

A – site KO1; **B** – site MO3; **C** – site JA1; **D** – site SL3; left – stereographic projection of thermal demagnetisation path; middle – orthogonal projection of demagnetisation path (Zijderveld diagram); right – NRM intensity decay during thermal demagnetisation

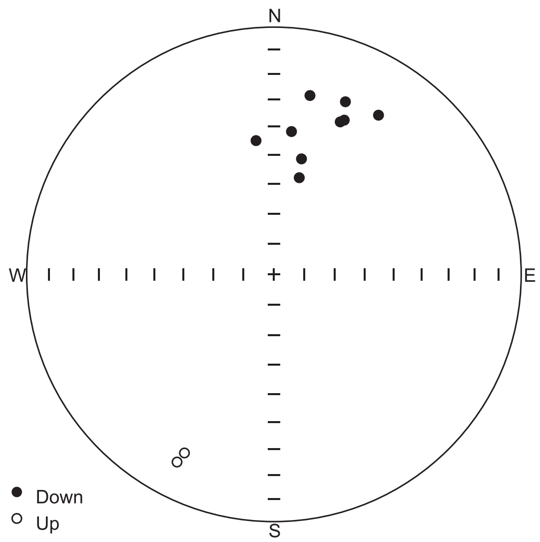

Fig. 7. Stereographic projection showing orientations of hematite-bearing component C' from specimens of site SL3

SW-directed declinations and shallow inclinations (before tectonic correction). The component A characterized by the same Tub was recognized also in breccia studied from Laskowa Quarry. In a small number of specimens from site MO3, besides the component A, traces of the another remanence component were observed. The component is characterized by slightly higher Tub than component A, and normal polarity that manifests itself by gradual migration of the magnetic vector towards the NE at temperatures above a demagnetisation step of 400°C (Fig. 6B). Unfortunately, this component was not possible to separate from component A due to partly overlapping unblocking temperatures, but its properties correspond to the B component after the terminology of Zwing (2003) and Szaniawski (2008).

Different palaeomagnetic behaviour was observed in sites JA1, SZ1 and SL3, characterized by the presence of hematite. Samples from sites JA1 and SZ1 record a magnetisation component characterized by a maximum Tub of 620°C, SSW oriented declination and moderate negative inclination (Fig. 6C). These features match with the properties of the reversed polarity component C known from previous studies (Szaniawski, 1997; Zwing, 2003; Szaniawski, 2008). However, in site SL3, hematite-bearing rocks record a high Tub (maximally 620°C) component of mixed-polarity. Such a component is dominantly directed to the NNE with positive inclination but shows also SSW orientations and negative inclinations (Figs. 6D and 7). For the purpose of this paper, the hematite-bearing and mixed-polarity component from site SL3 was named the C' component (Table 1).

DISCUSSION

The majority of the sites analysed record the A component, otherwise known as the most common one in the western part of the SHCM (Zwing, 2003; Grabowski *et al*., 2006). In some of the rocks analysed the hematite-bearing C component were also recognized. Both components are well-known from previous studies, where a fold test performed within first-order, map-scale folds from the central part of the SHCM together with palaeolatitude dating that documented the post-folding nature of both the early Permian (A) and Permo/Triassic (C) overprints (Szaniawski, 2008). Component A was similarly dated by Grabowski *et al*. (2006) as 272–261 Ma as well as by Szaniawski (2008) as *ca*. 278 Ma (late early Permian). An acquisition of component A might have been synchronous with metasomatic alterations of Permian volcanics from the Kraków area (dated as 268.7 ±3.4 Ma – see Nawrocki *et al*., 2008), located *ca*. 100 km south of the SHCM. Palaeoinclinations of component C are concordant with Early Triassic (Lower to Middle Buntsandstein) palaeoinclinations from the HCM (Nawrocki *et al*., 2003), thus component C might be dated as *ca*. 250 Ma. However, according to Szaniawski (2008) the error of age estimation of component C is larger, being from *ca*. 270 to 230 Ma (late Permian to Middle Triassic). It is remarkable that late Variscan remagnetisations in the SHCM are, as a rule, younger than similar phenomena in the Moravo–Silesian Zone or Ardennes, where the last remagnetisation phase occurred around 290 Ma (Molina-Garza and Zijderveld, 1996; Márton *et al*., 2000; Szaniawski *et al*., 2003; Zegers *et al*., 2003; Grabowski *et al*., 2008).

TECTONIC ROTATIONS

Declination values and palaeopoles of the A component obtained in this study are rotated ~20° clockwise (Fig. 2) relative to both the early Permian segment of the apparent polar wander path (APWP) as well as relative to A-component directions derived from the central and eastern parts of the SHCM (Szaniawski, 2008). Our new results confirm that the observed clockwise rotation is limited to the westernmost parts of the SHCM (Lewandowski, 1981, 1999; Grabowski and Nawrocki, 1996, 2001; Zwing, 2003), being possibly related to local block rotation (as proposed by Zwing, 2003) and resulting probably from intense strike-slip faulting described by Konon (2007). Alternatively we propose that palaeomagnetic rotations might be linked with a bending of the original fold axes caused by a later tectonic compression acting at a low angle to them. The latter hypothesis is supported by an observation that the trend of some map-scale folds from the westernmost part of the SHCM is also deviated clockwise regarding the regional tectonic trend (e.g., Chęciny Anticline west of Chęciny, see Fig. 2).

The age of this hypothetical rotation can be estimated precisely since two sites studied (JA1 and SZ1) record the C component. This component is well-known from previous studies as originated from Permo-Triassic meteoric fluid migration (Szaniawski, 1997, 2008; Zwing, 2003). The directions obtained for the C component from the JA1 and SZ1 sites (Table 1) are similar to those reported from more internal parts of the SHCM (218/-38 after Zwing, 2003 and 220/-33 after Szaniawski, 2008).

Table 1

Summary of palaeomagnetic results obtained in this study

Site	Tectonic position	Dir/dip	Cm	D/I	k	$_{95}$	N/n
DA1	Dalnia Quarry – northern limb of Dyminy Anticline	12/30	A	216/4	71	11	4/8
JA1	Jaworznia Quarry – northern limb of Dyminy Anticline	43/35	C	207/-38	41	14	4/10
GZ1	Zamkowa Mt. – southern limb of Chęciny Anticline	193/71	–	–	–	–	–
GZ2	Zamkowa Mt. – southern limb of Chęciny Anticline	202/76	–	–	–	–	–
KO1	Kostomłoty Quarry – northern limb of the first-order Niewachlów Anticline, apart from second-order deformations	12/30	A	221/-15	119	4	12/17
MO1	Mogiłki Quarry – metre-scale fold (northern limb of anticline) situated within the northern limb of the first-order Niewachlów Anticline	19/76	A	233/-23	186	6	5/9
MO2	Mogiłki Quarry – metre-scale fold (southern limb of anticline) situated within the northern limb of the first-order Niewachlów Anticline	192/45	A	227/6	199	5	5/8
MO3	Mogiłki Quarry – northern limb of the first-order Niewachlów Anticline, apart from second-order deformations	22/54	A	231/-18	74	8	6/11
RZ1	Rzepka Quarry – southern limb of Rzepka Syncline, apart from second-order deformations	20/15	–	–	–	–	–
SG1	Sułtańskie Górki – southern limb of Rzepka Syncline, apart from second-order deformations	18/12	–	–	–	–	–
SS1	Sosnówka Hill – overturned southern limb of Chęciny Anticline, apart from second-order deformations	199/101	A	219/25	37	11	6/16
ST1	Stokówka Hill – northern limb of Chęciny Anticline, apart from second-order deformations	30/80	A	214/-18	41	11	6/12
SL1	Śluchowice Quarry – vertical, southern limb of the first-order Niewachlów Anticline, apart from second-order deformations	180/90	A	210/17	47	7	11/16
SL2	Śluchowice Quarry – layers dragged by strike-slip fault – situated within the southern, vertical limb of the first-order Niewachlów Anticline	42/87	A	250/-6	13	19	6/9
SL3	Śluchowice Quarry – red layers dragged by strike-slip fault – situated within the southern, vertical limb of the first-order Niewachlów Anticline	13/89	A C'	222/29 19/33	90 24	10 14	4/12 6/11
SZ1	Szewce Quarry – southern limb of Dyminy Anticline	203/23	C	213/-28	65	9	5/9

Dir/dip – tectonic orientation of strata, Cm – symbol of the component, D/I – declination and inclination of site mean before tectonic correction, k,α_{95} – statistical parameters of site mean (sample level), N/n – number of samples/specimens used in calculations

This implies that the rotation discussed occurred between the acquisition times of the A and C components.

EVOLUTION OF FOLD STRUCTURES

Results from sampling sites situated along the western part of the SHCM are shown in Figure 3. The values of inclination for the A and C components are suitable for tracing modifications of fold geometry since both declinations are roughly perpendicular to the fold axes. Inclinations of the early Permian A component compared to the reference value of –15° (post-folding inclination from the central part of the SHCM, after Szaniawski, 2008) show significant reactivation of the southern limbs of the Niewachlów and Chęciny anticlines. In turn, the results from the northern limbs of these anticlines imply a lack of or only very small tilting after the acquisition of the A component. It is also worth noting that the documented modification of fold geometry concerns only the southern limbs of the folds studied (Fig. 8). Therefore, it is postulated that the classical fold test and calculation of the mean direction based on symmetrical unfolding of both limbs of a fold is pointless in this specific case. It is also suggested here that a selective reorientation of the A component can be attributed to local block tilting related to fold-parallel faults separating the northern and southern limbs of major anticlines (Fig. 3).

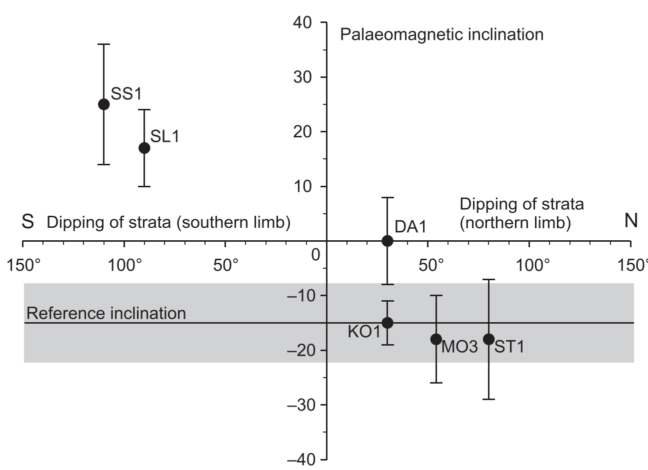

Fig. 8. Relationship of measured palaeomagnetic inclination of the A component (vertical axis) to the dip of the strata (horizontal axis)

Site mean values are shown with their α_{95} error; grey bar illustrates reference inclination with its α_{95} limit of error after Szaniawski (2008)

Results from rocks recording the C component have a special importance since they potentially clarify whether the observed shape modification of folds originated in late Variscan or Maastrichtian-Palaeocene time. Unfortunately, in this study the C component was determined only in two sites from the Dyminy Anticline (JA1 and SZ1) where there are no results for the A component (Fig. 3). Inclination values of the C component in both sites are slightly different and may have fitted the model of tectonic overprinting that occurred later than the acquisition of component C (Permo/Triassic). However since the values of α_{95} error are quite large, it is not certain whether the directions of component C for both JA1 and SZ1 sites (Table 1) are really statistically different.

Further conclusion could be reached from the analysis of small-scale tectonic structures. The results of fold tests performed at the Śluchowice (Zwing, 2003) and Kostomłoty (Lewandowski, 1981) quarries imply that metre-scale second-order folds formed before the acquisition of the A component. On the other hand, previous data (Grabowski and Nawrocki, 2001) and the results of the present study (Fig. 4C) show that the geometry of metre-scale chevron folds in the nearby Mogiłki Quarry was significantly rebuilt after the remagnetisation phase A. It is worth noting that the palaeoinclinations of component A from site MO3 from Mogiłki Quarry, situated within uniformly dipping strata of the northern limb of the large Niewachlów Anticline, differ neither from those from Kostomłoty nor from the reference palaeoinclination (Figs. 3 and 4C). This implies that, although the northern limb of the first-order Niewachlów Anticline in Mogilki, as a whole, had not been tilted after the acquisition of the A component, the second-order folds from Mogiłki Quarry situated within this limb, were subjected to reactivation which postdated the component A.

The entire dataset reveals that the main profile of the Niewachlów Anticline together with minor folds from Śluchowice and Kostomłoty were formed before the acquisition of the A component, whereas after this event the southern limb of the Niewachlów Anticline was additionally tilted and metre-scale folds from Mogiłki were moderately modified. The latter phenomenon is most possibly related to the locally intense dextral strike-slip faulting in the area of Mogiłki Quarry (Konon, 2006).

RELATIVE AGE OF THE DEXTRAL STRIKE-SLIP FAULTING EVENT

New and important outcomes follow also from study of strike-slip faults from Śluchowice Quarry. Both faults studied represent a post-folding dextral strike-slip faulting event described by Konon (2007). In sites SL2 and SL3, both located in zones of fault drag, the directions of the A component differ from the results obtained in other parts of the quarry (site SL1). The magnitude of this deviation is proportional to the intensity of fault drag of the sedimentary layers, being thus the most distinctive in site SL2 (Table 1 and Fig. 4A). This shows that the activity of faults postdated the acquisition of the A component.

Further conclusions follow from the analysis of site SL3, where part of dragged rock layers are distinguished by a reddish colour. Such a characteristic reddening of carbonates has been described before (Szaniawski, 1997; Zwing, 2003; Szaniawski, 2008) as a result of hematite pigment mineralisation during the Permo-Triassic remagnetisation episode C. Field observations revealed that the red pigmentation postdated the fault studied, and implied that the fault constituted the path for mineralisation fluids. Reddish colour carbonates record the C' component characterized by the same Tub spectra as the C component. Furthermore, the orientation of the mixed polarity C' component corresponds with the orientation of the C component within α_{95} limits of error (*cf.* Szaniawski, 2008). Therefore, it is suggested here that the C' component was recorded after the deformation and originated from the same Permo-Triassic remagnetisation process as the C component.

Our observations suggest that the faults studied were active between the acquisition of components A (early Permian) and C (Permian/Triassic). It follows, too, that partial tilting of the southern limb of the Niewachlów Anticline (described in chapter "Evolution of fold structures" as postdating component A) occurred most likely before the remagnetisation event C/C' (Permian/Triassic).

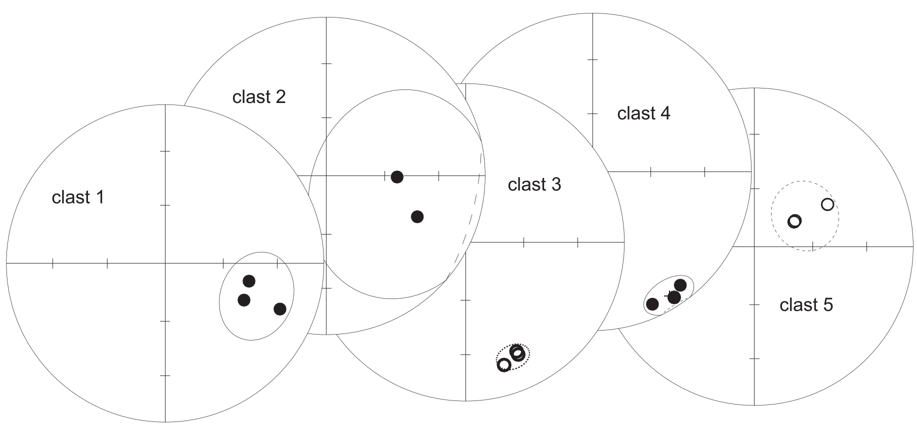

Fig. 9. Stereographic projection showing directions of the A component derived from individual clasts of Laskowa breccia

RELATIVE AGE OF BRECCIA FROM LASKOWA QUARRY

The directions of the A component in the breccia show good clustering within separate clasts but differ between individual clasts of the breccia (Fig. 9). These directions differ also from those reported from *in situ* rocks (Grabowski and Nawrocki, 1996) and, hence, the formation of the breccia is inferred to have postdated the acquisition of the A component. These results correspond with previous data documenting that the age of another breccia from Wietrznia Quarry is also younger then the A component (Szaniawski and Lewandowski, 2009). The results of palaeomagnetic dating of both breccias are in line with interpretations assuming a Permian age for intense erosion and karstification that followed the main stages of late Carboniferous deformation and uplift (e.g., Szulczewski, 1995; Urban and Rzonca, 2009).

CONCLUSIONS

The results presented together with the outcomes of previous studies enable us to formulate important conclusions concerning the age of a number of tectonic events in relation to well-dated remagnetisation phases in the SHCM.

1. The new data confirm previous reports of ~20^{o} clockwise rotated early Permian palaeomagnetic declinations from the westernmost part of the SHCM, most probably due to late Variscan tectonism.

2. The palaeomagnetic analysis of map-scale folds at the westernmost transect of the SHCM implies a post-early Permian tilting of their southern limbs. The post-early Permian fold shape modifications were found also in a minor fold at Mogiłki, however, most other meso-folds did not change their geometry after the early Permian remagnetisation.

3. Palaeomagnetic results show that the dextral N–S trending strike-slip faults, common in the western SHCM, were active after the early Permian and most probably prior to the Maastrichtian-Paleocene overprint

4. Sedimentary breccia from Laskowa Quarry, resting unconformably on top of tilted Devonian rocks, is of post-early Permian age.

Our results supplement current knowledge about the local structural evolution of the SHCM. In late Paleozoic time, the area studied was situated in the foreland of the main Variscan orogenic belt, so the Variscan deformations in the HCM can be defined as of intraplate-type. However, the deformations of the upper Paleozoic rocks were relatively intense, which makes probable a hypothesis of partial reactivation of some more ancient structures in the basement (e.g., faults developed during amalgamation of the Małopolska Block with the EEC in the Cambrian). Late Paleozoic deformation of the SHCM comprised several tectonic episodes and during their latest stages some of the folds became modified and dextral strike-slip faulting was active.

Acknowledgements. This work was financially supported by a research grant of the Polish Ministry of Science and Higher Education (N307037 31/2527, project no. 51.2401.0608.31.0 of the Polish Geological Institute – National Research Institute) and project of the Grant Agency of the Czech Republic (Grant No.GACR P210-10-2351). We are grateful to M. Narkiewicz for field guidance to the breccia outcrop in the Laskowa Quarry. W. Zuchiewicz and anonymous reviewer are thanked for careful and constructive reviews, H. Norberciak is thanked for technical assistance.

REFERENCES

BEŁKA Z., AHRENDT H., FRANKE W. and WEMMER K. (2000) – The Baltica-Gondwana suture in central Europe: evidence from K-Ar ages of detrital muscovites and biogeographical data. In: Orogenic Processes: Quantification and Modelling in the Variscan Belt of Central Europe (eds. W. Franke, V. Haak, O. Oncken and D. Tanner). Geol. Soc., London, Spec. Publ., **179**: 87–102.

BEŁKA Z., VALVERDE-VAQUERO P., DORR W., AHRENDT H., WEMMER K., FRANKE W. and SCHAFFER J. (2002) – Accretion of first Gondwana-derived terranes at the margin of Baltica. In: Palaeozoic Amalgamation of Central Europe (eds. J. A. Winchester, T. C. Pharaoh and J. Verniers). Geol. Soc., London, Spec. Publ., **201**: 19–36.

CEDERQUIST D. P., van der VOO R. and van der PLUIJM B. A. (2006) – Syn-folding remagnetization of Cambro-Ordovician carbonates from the Pennsylvania Salient postdates oroclinal rotation. Tectonophysics, **422**: 41–54.

CHADIMA M. and HROUDA F. (2006) – Remasoft 3.0 a user-friendly palaeomagnetic data browser and analyzer. Travaux Géophys., **27**: 20–21.

CZARNOCKI J. (1919) – Stratygrafia i tektonika Gór Świętokrzyskich. Stratygrafia i tektonika staropaleozoicznych utworów Gór Świętokrzyskich (Kambr, sylur i dewon dolny). Pr. Tow. Nauk. Warszawskiego, **28**.

CZARNOCKI J. (1938) – Ogólna mapa geologiczna Polski 1:000 000. Arkusz 4, Kielce. Państw. Inst. Geol., Warszawa.

CZARNOCKI J. (1957) – Tectonics of the Święty Krzyż Mountains. Stratigraphy and tectonics of the Święty Krzyż Mountains (in Polish with English summary). Pr. Inst. Geol., **18**.

DADLEZ R., KOWALCZEWSKI Z. and ZNOSKO J. (1994) – Some key problems of the pre-Permian tectonics of Poland. Geol. Quart., **38** (2): 169–190.

ENKIN R. J., OSADETZ K. G., BEKER J. and KISILEVSKY G. (2000) – Orogenic remagnetizations in the Front Ranges and Inner Foothills of the southern Canadian Cordillera: chemical harbinger and thermal handmaiden of Cordilleran deformations. Geol. Soc. Am., Bull., **112** (6): 929–942.

FILONOWICZ P. (1973) – Szczegółowa mapa geologiczna Polski w skali 1:50 000 wraz z objaśnieniami. Arkusz Kielce. Wyd. Geol., Warszawa.

GĄGOL J., GŁAZEK J., JURKIEWICZ H., KOWALSKI W. and ROMANEK A. (1976) – Tektonika, wykształcenie i surowce mineralne starszego mezozoiku oraz jego stosunek do podłoża waryscyjskiego. In: Przewodnik 48 Zjazdu Pol. Tow. Geol. (ed. W. Pożaryski): 228–254.

GŁAZEK J., KARWOWSKI Ł., RACKI G. and WRZOŁEK T. (1981) – The early Devonian continental/marine succession at Chęciny in the Holy Cross Mts, and its palaeogeographic and tectonic significance. Acta Geol. Pol., **31** (3–4): 233–250.

GRABOWSKI J., BÁBEK O., NAWROCKI J. and TOMEK Č. (2008) – New palaeomagnetic data from the Palaeozoic carbonates of the Moravo–Silesian Zone (Czech Republic): evidence for a timing and origin of the late Variscan remagnetizations. Geol. Quart., **52** (4): 321–334.

GRABOWSKI J., MICHALÍK J., SZANIAWSKI R. and GROTEK I. (2009) – Synthrusting remagnetization of the Krížna nappe: high resolution palaeo- and rock magnetic study in the Strážovce section, Strážovské vrchy Mts, Central West Carpathians (Slovakia). Acta Geol. Pol., **59** (2): 137–155.

GRABOWSKI J., NARKIEWICZ M. and SOBIEŃ K. (2006) – Thermal controls on the remagnetization of Devonian carbonate rocks in the Kielce region (Holly Cross Mts.) (in Polish with English summary). Prz. Geol., **54** (10): 895–905.

GRABOWSKI J. and NAWROCKI J. (1996) – Multiple remagnetizations in the Devonian carbonates in the northwestern part of the Kielce region (Holy Cross Mts., southern part). Geol. Quart., **40** (1): 47–64.

GRABOWSKI J. and NAWROCKI J. (2001) – Palaeomagnetism of some Devonian carbonates from the Holy Cross Mts. (Central Poland): large pre-Permian rotations or strain modified palaeomagnetic directions? Geol. Quart., **45** (2): 165–178.

GRAHAM J. W. (1949) – The stability and significance of magnetism in sedimentary rocks. J. Geoph. Res., **54**: 131–167.

HAKENBERG M. (1973) – Szczegółowa mapa geologiczna Polski w skali 1: 50 000 wraz z objaśnieniami. Arkusz Chęciny. Wyd. Geol., Warszawa.

JAROSZEWSKI W. (1972) – Mesoscopic structural criteria of tectonics of non-orogenic areas: an example from trhe north-eastern Mesozoic margin of the Świętokrzyskie Mountains (in Polish with English summary). Stud. Geol. Pol., **38**.

JAWOROWSKI K. (2002) – Geotectonic significance of Carboniferous deposits NW of the Holy Cross Mts. (central Poland). Geol. Quart., **46** (3): 267–280.

KIRSCHVINK J. L. (1980) – The least square line and plane and the analysis of palaeomagnetic data. Geoph. J. Royal Astronom. Soc., **62**: 699–718.

KONON A. (2006) – Buckle folding in the Kielce Unit, Holy Cross Mountains, central Poland. Acta Geol. Pol., **56** (4): 375–405.

KONON A. (2007) – Strike-slip faulting in the Kielce Unit, Holy Cross Mountains, central Poland. Acta Geol. Pol., **57** (4): 415–441.

KONON A. (2008) – Tectonic subdivision of Poland: Holy Cross Mountains and adjacent areas (in Polish with English summary). Prz. Geol., **56** (10): 921–926.

KONON A. (2009) – Discussion on: strike-slip faulting in the Kielce Unit, Holy Cross Mountains, central Poland. Reply on Świdrowska and Lamarche. Acta Geol. Pol., **59** (1): 123–135.

KOWALCZEWSKI Z. (1971) – Główne rysy tektoniki Gór Świętokrzyskich. Przew. 43 Zjazdu Pol. Tow. Geol.: 10–19.

KOWALSKI W. R. (1975) – Tectonics of the western end of Chęciny anticline and surrounding structures of Mesozoic margins of the Holy Cross Mts. Rocz. Pol. Tow. Geol., **45**: 45–61.

KRZEMIŃSKI L. (1999) – Anorogenic Carboniferous sandstones from the northwestern border of the Holy Cross Mountains, Central Poland (in Polish with English summary). Prz. Geol., **47** (11): 978–986.

KRZYWIEC P. (2009) – Devonian-Cretaceous repeated subsidence and uplift along the Teisseyre-Tornquist zone in SE Poland – insight from seismic data interpretation. Tectonophysics, **475** (4): 142–159.

KUTEK J. (2001) – The Polish Permo-Mesozoic Rift Basin. In: Peri-Tethyan Rift/Wrench Basins and Passive Margins (eds. P. A. Ziegler, W. Cavazza, A. H. P. Robertson and S. Crasquin-Soleau). Peri-Tethys Mem., 6, Mém. Mus. Nat. Histoire Naturelle, **186**: 213–236. Paris.

KUTEK J. and GŁAZEK J. (1972) – The Holy Cross area, Central Poland, in the Alpine cycle. Acta Geol. Pol., **22**: 603–653.

LAMARCHE J., BERGERAT F., LEWANDOWSKI M., MANSY J. L., ŚWIDROWSKA J. and WIECZOREK J. (2002) – Variscan to Alpine heterogenous palaeo-stress field above a major Palaeozoic suture in the Carpathian foreland (southeastern Poland). Tectonophysics, **357**: 55–80.

LAMARCHE J., LEWANDOWSKI M., MANSY J. L. and SZULCZEWSKI M. (2003) – Partitioning pre-, syn- and post-Variscan deformation in the Holy Cross Mountains, eastern Variscan foreland. In: Tracing Tectonic Deformation Using the Sedimentary Record (eds. T. McCann and A. Saintot). Geol. Soc., London, Spec. Publ., **208**: 159–184.

LAMARCHE J., MANSY J. L., BERGERAT F., AVERBUCH O., HAKENBERG M., LEWANDOWSKI M., STUPNICKA E., ŚWIDROWSKA J., WAJSPRYCH B. and WIECZOREK J. (1999) – Variscan tectonics in the Holy Cross Mountains (Poland) and the role of structural inheritance during Alpine tectonics. Tectonophysics, **313**: 171–186.

LEWANDOWSKI M. (1981) – Post-folding characteristic remanent magnetization of the Upper Devonian Kostomłoty Beds in the Holy Cross Mts. Acta Geol Pol., **31** (3–4): 265–272.

LEWANDOWSKI M. (1985) – On tectonics of the Holy Cross Mts in the light of palaeomagnetic studies. Publ. Inst. Geoph. Pol. Acad. Sc., **A-16** (175): 131–150.

LEWANDOWSKI M. (1999) – Palaeomagnetic study of fracture fills in the Holy Cross Mountains of Central Poland and its application in dating tectonic processes. Geoph. J. Internat., **317**: 783–792.

LOWRIE W. (1990) – Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. Geoph. Res. Lett., **17**: 159–162.

MÁRTON E., MANSY J.-L., AVERBUCH O. and CSONTOS L. (2000) – The Variscan belt of Northern France–Southern Belgium: geodynamic implications of new paleomagnetic data. Tectonophysics, **324**: 57–80.

MASTELLA L. and MIZERSKI W. (2002) – Geological setting of the Łysogóry Unit (Holy Cross Mountains, Central Poland) based on analysis of the radar images (in Polish with English summary). Prz. Geol., **50** (9): 767–772.

MAZUR S., ALEKSANDROWSKI P., KRYZA R. and OBERC-DZIEDZIC T. (2006) – The Variscan Orogen in Poland. Geol. Quart., **50** (1): 89–118.

McCABE C. and ELMORE R.D. (1989) – The occurrence and origin of late Paleozoic remagnetization in the sedimentary rocks of North Am. Rev. Geoph., **27**: 471–494.

McWHINNIE S. T., van der PLUIJM B. A. and van der VOO R. (1990) – Remagnetizations and thrusting in the Idaho–Wyoming Overthrust Belt. J. Geoph. Res., **95** (B4): 4551–4559.

MIZERSKI W. (1995) – Geotectonic evolution of the Holy Cross Mts in Central Europe. Biul. Państw. Inst. Geol., **372**.

MOLINA-GARZA R. S. and ZIJDERVELD J. D. A. (1996) – Paleomagnetism of Paleozoic strata, Brabant and Ardennes Massifs, Belgium: implications of prefolding and postfolding Late Carboniferous secondary magnetizations for the European apparent polar wander. J. Geoph. Res., **101** (B7): 15 799–15 818.

NAWROCKI J. (2000) – Late Silurian paleomagnetic pole from the Holy Cross Mountains: constraints for the post-Caledonian tectonic activity of the Trans-European Suture Zone. Earth Planet. Sc. Lett., **179** (2): 325–334.

NAWROCKI J., DUNLAP J., PÉCSKAY Z., KRZEMIŃSKI L., ŻYLIŃSKA A., FANNING M., KOZŁOWSKI K., SALWA S., SZCZEPANIK Z. and TRELA W. (2007) – Late Neoproterozoic to Early Palaeozoic palaeogeography of the Holy Cross Mountains (Central Europe): an integrated approach. J. Geol. Soc., **164** (2): 405–423.

NAWROCKI J., FANNING M., LEWANDOWSKA A., POLECHOŃSKA O. and WERNER T. (2008) – Palaeomagnetism and the age of the Cracow volcanic rocks (S Poland). Geoph. J. Internat., **174** (2): 475–488.

NAWROCKI J., KULETA M. and ZBROJA S. (2003) – Buntsandstein magnetostratigraphy from the northern part of the Holy Cross Mountains. Geol. Quart., **47** (3): 253–260.

POŻARYSKI W., GROCHOLSKI A., TOMCZYK H., KARNKOWSKI P. and MORYC W. (1992) – Tectonic maps of Poland during the Variscan time (in Polish with English summary). Prz. Geol., **40** : 643–651.

PUEYO E. L., MAURITSCH H. J., GAWLICK H.-J., SCHOLGER R. and FRISCH W. (2007) – New evidence for block and thrust sheet rotations in the central northern Calcareous Alps deduced from two pervasive remagnetization events. Tectonics, **26**: ID TC5011.

RACKI G. (1992) – Evolution of the bank to reef complex in the Devonian of the Holy Cross Mountains. Acta Palaeont. Pol., **37** (2–4): 87–182.

RACKI G. and NARKIEWICZ M. (2000) – Tectonic versus eustatic controls of sedimentary development of the Devonian in the Holy Cross

Mts., Central Poland (in Polish with English summary). Prz. Geol., **48** (1): 65–76.

SAMSONOWICZ J. (1934) – Explication de la feuille Opatów. Carte 404 Géologique Générale de la Pologne au 100 000. Varsovie.

SANDBERG S. A. and BUTLER R. F. (1985) – Paleomagnetic fold test evidence for Laramide age of monoclinal folding, Salt River Canyon, Arizona. Earth Planet. Sc. Lett., **73**: 140–146.

STAMATAKOS J., HIRT A. M. and LOWRIE W. (1996) – The age and timing of folding in the Central Appalachians from paleomagnetic results. Geol. Soc. Am. Bull., **108**: 815–829.

STEWART S. (1995) – Paleomagnetic analysis of fold kinematics and implications for geological models of the Cantabrian/Asturian arc, north Spain. J. Geoph. Res., **100** (B10): 20079–20094.

SZANIAWSKI R. (1997) – Paleomagnetyzm a diageneza dolomitów dewońskich z regionu kieleckiego Gór Świętokrzyskich. MSc Thesis. Faculty of Geology, University of Warsaw.

SZANIAWSKI R. (2008) – Late Paleozoic geodynamics of the Małopolska Massif in the light of new paleomagnetic data for the southern Holy Cross Mountains. Acta Geol. Pol., **58** (1): 1–12.

SZANIAWSKI R. and LEWANDOWSKI M. (2009) – Palaeomagnetic age constraints indicate post-Variscan origin of massive breccia in Wietrznia Quarry (Holy Cross Mountains, Central Poland). Geol. Quart., **53** (3): 357–362.

SZANIAWSKI R., LEWANDOWSKI M., MANSY J.-L., AVERBUCH O. and LACQUEMENT F. (2003) – Syn-folding remagnetization events in the French-Belgium Variscan thrust front as markers of the fold-and-thrust belt kinematics. Bull. Soc. Geol. France. **174** (5): 511–523.

SZULCZEWSKI M. (1971) – Upper Devonian conodonts, stratigraphy and facial development in the Holy Cross Mts. Acta Geol. Pol., **21** (1): 1–128.

SZULCZEWSKI M. (1989) – Światowe i regionalne zdarzenia w zapisie stratygraficznym pogranicza franu z famenem Gór Świętokrzyskich (in Polish with English summary). Prz. Geol., **37** (11): 551–557.

SZULCZEWSKI M. (1990) – Światowe i regionalne zdarzenia w zapisie stratygraficznym pogranicza franu i famenu Gór Świętokrzyskich – odpowiedź (in Polish with English summary). Prz. Geol., **38** (7–8): 330–334.

SZULCZEWSKI M. (1995) – Depositional evolution of the Holy Cross Mts. (Poland) in the Devonian and Carboniferous – a review. Geol. Quart., **39** (4): 471–488.

SZULCZEWSKI M., BEŁKA Z. and SKOMPSKI S. (1996) – The drowning of a carbonate platform: an example from the Devonian-Carboniferous of the southwestern Holy Cross Mountains, Poland. Sediment. Geol., **106** (1–2): 21–49.

ŚWIDROWSKA J. and LAMARCHE J. (2009) – Discussion on: Strike-slip faulting in the Kielce Unit, Holy Cross Mountains, central Poland by A. Konon. Acta Geol. Pol., **59** (1): 123–135.

TOMCZYK H. (1988) – Region łysogórski a platforma wschodnioeuropejska w cyklu kaledońsko-waryscyjskim (in Polish with English summary). Prz. Geol., **36** (1): 9–17.

URBAN J. and RZONCA B. (2009) – Karst systems analyzed using borehole logs – Devonian carbonates of the Swietokrzyskie (Holy Cross) Mountains, central Poland. Geomorphology, **112**: 27–47.

WINCHESTER J., PHARAOH C. and VERNIERS J . (2002) – Paleozoic amalgamation of Central Europe: new results from recent geological and geophysical investigations. Tectonophysics, **360**: 5–21.

ZEGERS T. E., DEKKERS M. J. and BAILLY S. (2003) – Late Carboniferous to Permian remagnetization of Devonian limestones in the Ardennes: role of temperature, fluids, and deformation. J. Geoph. Res., **108** (B7): EPM 5 1–5 19.

ZWING A. (2003) – Causes and mechanisms of remagnetisation Palaeozoic sedimentary rocks: a multidisciplinary approach. PhD thesis, LMU Munchen, http://edoc.ub.uni-muenchen.de/archive/00001578/