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

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.

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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; McWhinney et al., 1990; Stamatakis 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 (HCM – 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 Glazek, 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 compo-
GEOLOGICAL SETTING

The HCM represent an exposed fragment of the Trans-European Suture Zone (TESZ) that forms a transition between the Cambrian 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 Malopolska Block, that constitutes a tectonostratigraphic terrace 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; Szulczewski, 2008). The late Variscan compression terminated prior to late Permian times (Czarnocki, 1991), resulting in map-scale folds defining a fold belt comprised of the Kielce (=SHCM) and Lysogóry 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 Glazek, 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 (Gagol et al., 1976; Glazek 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 Lysogóry 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., Glazek and Kutek, 1970; Kowalczewski, 1971; Kutek and Glazek, 1972; Kowalski,
1975) and reactivation of faults has been suggested (e.g., Gągol et al., 1976; Gązęk et al., 1981).

Sampling sites were chosen along a transect cutting the western part of the SHCM from the area of Niewachłów 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 (Mogilki Quarry) and KO1 (Kostomloty Quarry) from the northern limb of the Niewachłów Anticline; site SL1 (Śluchowice Quarry) from the southern limb of the Niewachłów Anticline; DA1 (Dalnia Quarry) and JA1 (Jaworznia Quarry) from the northern limb of the Dyminy Anticline; SL1 (Śluchowice Quarry) from the southern limb of the Dyminy Anticline; ST1 (Stokówka Quarry) situated on the northern limb of the Chećiny 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 Chećiny 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 – Sultatskie Górki).

Additionally a number of sites were selected for studies of minor tectonic structures and of sedimentary breccia. In Mogilki 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 the map-scale Niewachłów 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-
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 kappabridge. 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,
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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
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 M03, 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., Chećiny Anticline west of Chećiny, 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).
SUMMARY OF PALAEOMAGNETIC RESULTS OBTAINED IN THIS STUDY

<table>
<thead>
<tr>
<th>Site</th>
<th>Tectonic position</th>
<th>Dir/dip</th>
<th>Cm</th>
<th>D/I</th>
<th>k</th>
<th>α5%</th>
<th>N/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>DA1</td>
<td>Dalnia Quarry – northern limb of Dyminy Anticline</td>
<td>12/30</td>
<td>A</td>
<td>216/4</td>
<td>71</td>
<td>11</td>
<td>4/8</td>
</tr>
<tr>
<td>JA1</td>
<td>Jawornia Quarry – northern limb of Dyminy Anticline</td>
<td>43/35</td>
<td>C</td>
<td>207/-38</td>
<td>41</td>
<td>14</td>
<td>4/10</td>
</tr>
<tr>
<td>GZ1</td>
<td>Zamkowa Mt. – southern limb of Chęciny Anticline</td>
<td>193/71</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>GZ2</td>
<td>Zamkowa Mt. – southern limb of Chęciny Anticline</td>
<td>202/76</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>KO1</td>
<td>Kostomloty Quarry – northern limb of the first-order Niewachłów Anticline, apart from second-order deformations</td>
<td>12/30</td>
<td>A</td>
<td>221/-15</td>
<td>119</td>
<td>4</td>
<td>12/17</td>
</tr>
<tr>
<td>MO1</td>
<td>Mogilki Quarry – metre-scale fold (northern limb of anticline) situated within the northern limb of the first-order Niewachłów Anticline</td>
<td>19/76</td>
<td>A</td>
<td>233/-23</td>
<td>186</td>
<td>6</td>
<td>5/9</td>
</tr>
<tr>
<td>MO2</td>
<td>Mogilki Quarry – metre-scale fold (southern limb of anticline) situated within the northern limb of the first-order Niewachłów Anticline</td>
<td>192/45</td>
<td>A</td>
<td>227/6</td>
<td>199</td>
<td>5</td>
<td>5/8</td>
</tr>
<tr>
<td>MO3</td>
<td>Mogilki Quarry – northern limb of the first-order Niewachłów Anticline, apart from second-order deformations</td>
<td>22/54</td>
<td>A</td>
<td>231/-18</td>
<td>74</td>
<td>8</td>
<td>6/11</td>
</tr>
<tr>
<td>RZ1</td>
<td>Rzepka Quarry – southern limb of Rzepka Syncline, apart from second-order deformations</td>
<td>20/15</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SG1</td>
<td>Sultańskie Górki – southern limb of Rzepka Syncline, apart from second-order deformations</td>
<td>18/12</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SS1</td>
<td>Sosnowka Hill – overturned southern limb of Chęciny Anticline, apart from second-order deformations</td>
<td>199/101</td>
<td>A</td>
<td>219/25</td>
<td>37</td>
<td>11</td>
<td>6/16</td>
</tr>
<tr>
<td>ST1</td>
<td>Stokówka Hill – northern limb of Chęciny Anticline, apart from second-order deformations</td>
<td>30/80</td>
<td>A</td>
<td>214/-18</td>
<td>41</td>
<td>11</td>
<td>6/12</td>
</tr>
<tr>
<td>SL1</td>
<td>Słuchowice Quarry – vertical, southern limb of the first-order Niewachłów Anticline, apart from second-order deformations</td>
<td>180/90</td>
<td>A</td>
<td>210/17</td>
<td>47</td>
<td>7</td>
<td>11/6</td>
</tr>
<tr>
<td>SL2</td>
<td>Słuchowice Quarry – layers dragged by strike-slip fault – situated within the southern, vertical limb of the first-order Niewachłów Anticline</td>
<td>42/87</td>
<td>A</td>
<td>250/-6</td>
<td>13</td>
<td>19</td>
<td>6/9</td>
</tr>
<tr>
<td>SL3</td>
<td>Słuchowice Quarry – red layers dragged by strike-slip fault – situated within the southern, vertical limb of the first-order Niewachłów Anticline</td>
<td>13/89</td>
<td>A</td>
<td>222/29</td>
<td>C’</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>SZ1</td>
<td>Szewce Quarry – southern limb of Dyminy Anticline</td>
<td>203/23</td>
<td>C</td>
<td>213/-28</td>
<td>65</td>
<td>9</td>
<td>5/9</td>
</tr>
</tbody>
</table>

Dir/dip – tectonic orientation of strata, Cm – symbol of the component, D/I – declination and inclination of site mean before tectonic correction, k, α5% – 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 Niewachłów 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).
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 Dymyń 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 overprint that occurred later than the acquisition of component C (Permian/Triassic). However since the values of $\alpha_{95}$ 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 Słuchowice (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 Mogilki Quarry was significantly rebuilt after the remagnetisation phase A. It is worth noting that the palaeoinclinations of component A from site MO3 from Mogilki Quarry, situated within uniformly dipping strata of the northern limb of the large Niewachłow 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 Niewachłow Anticline in Mogilki, as a whole, had not been tilted after the acquisition of the A component, the second-order folds from Mogilki Quarry situated within this limb, were subjected to reactivation which postdated the component A.

The entire dataset reveals that the main profile of the Niewachłow Anticline together with minor folds from Słuchowice and Kostomłoty were formed before the acquisition of the A component, whereas after this event the southern limb of the Niewachłow Anticline was additionally tilted and metre-scale folds from Mogilki were moderately modified. The latter phenomenon is most possibly related to the locally intense dextral strike-slip faulting in the area of Mogilki 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 Słuchowice 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 red-dish colour. Such a characteristic reddening of carbonates has been described before (Szaniawski, 1997; Zwing, 2003; Szaniawski, 2008) as a result of haematite 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 Tuba spectra as the C component. Furthermore, the orientation of the mixed polarity C’ component corresponds with the orientation of the C component within $\alpha_{95}$ 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 Permain) and C (Permian/Triassic). It follows, too, that partial tilting of the southern limb of the Niewachłow 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](image-url)
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 \textit{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 than 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 $\approx 20^\circ$ 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 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 Mogilki, 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 Palaeozoic 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 Palaeozoic 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 Malopolska Block with the EEC in the Cambrian). Late Palaeozoic 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.

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