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Strike-slip faulting in the Kielce Unit, Holy Cross Mountains, central Poland

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ABSTRACT:

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Strike-slip faults and associated tectonic structures have been investigated in the Holy Cross Mountains fold belt (HCM), which is located eastwards of the Variscan foreland basin. The strike-slip fault sets form a complex network, which developed during two faulting stages: in Late Palaeozoic (I) and Maastrichtian/Palaeocene (II) times.

The Late Palaeozoic fault pattern formed as a result of at least two strike-slip events: I-1 and I-2. During the first event (I-1), a N–S-striking dextral strike-slip fault set and a NNE–SSW to NE–SW-striking sinistral strike-slip fault set developed. During the next event (I-2), dextral strike slip occurred along the WNW–ESE-striking longitudinal master faults and formed a NW–SE to NNW–SSE-striking sinistral secondary strike-slip fault set. During this event, in zones north and south of the Holy Cross Fault, fault-bounded blocks developed which were rotated dextrally as a result of further displacements. The strike-slip fault network was overprinted during the Maastrichtian/Palaeocene second strike-slip stage (II).

Key words: Late Palaeozoic, Strike-slip faulting, Fault-bounded block domains, Holy Cross Mountains, Kielce Unit.

INTRODUCTION

The aim of this paper is to describe the geometry and developmental stages of the strike-slip fault network in the southern part of the Holy Cross Mountains fold belt (HCM) and to compare it with the fault network in the northern part of the HCM. In the HCM, in Late Carboniferous to Palaeocene times, strike-slip deformation occurred repeatedly (e.g. LAMARCHE & *al*. 1999), which brought about difficulties with identifying faults with a strike-slip component, especially when significant shortening took place across the fault zones during the folding. The strike-slip component occurred not only along the faults oblique or transverse to the fold axes but also along faults parallel to the axes.

Deformation associated with strike-slip faulting, particularly resulting from the Late Palaeozoic wrenching event, has been investigated in outcrops and quarries, generally within well-exposed Devonian rocks, as well as using geological maps, remote sensing techniques and analysis of Digital Elevation Model (DEM)-derived images.

Geological setting

The Holy Cross Mountains fold belt (HCM), made up of the Łysogóry (northern) and Kielce (southern) tectono-stratigraphic units (Czarnocki 1919, 1957a; Pożaryski 1978), are located within the Trans-European Suture Zone (Berthelsen 1993) (Text-figs 1 and 2). The boundary between the Kielce and Łysogóry units is formed by the at least 75 km long Holy Cross Fault (HCF). The HCF has been considered the border between the Małopolska block and the East European Craton (Pożaryski 1969, his fig. 1; Tomczyk 1988) or the boundary between the Małopolska and Łysogóry terranes (e.g. Pożaryski & *al*. 1992; Pożaryski & Tomczyk 1993; Unrug & *al.* 1999). Recent deep seismic sounding experiments (CELEBRATION 2000) confirm the suggestion of Brochwicz-Lewiński & *al.* (1983) that the Łysogóry and Kielce units, along with the rest of the Małopolska Block, have an identical crustal structure and are connected with the East European Craton (the Baltica palaeocontinent) (Malinowski & *al.* 2005). Some authors suggested that, apart from the shortening component, the HCF had a strike-slip component along the fault zone (e.g. Brochwicz-Lewiński & *al.* 1983; Pożaryski 1986; Tomczyk 1988; Pożaryski & *al*. 1992; Lewandowski 1993; Unrug & *al.* 1999; Lamarche & *al.* 2000, 2003), which was confirmed by the recognition of domino-style rotated blocks (Mastella & Mizerski 2002).

Rocks in the Kielce and Łysogóry units, ranging from the Cambrian to the Lower Carboniferous underwent folding (Czarnocki 1919, 1957a, b) during the Late Carboniferous (e.g. Czarnocki 1919, 1938, 1950, 1957a; Tomczyk 1988; Szulczewski 1995; Lamarche & *al*. 1999, 2002). These deformations were overprinted in Maastrichtian–Palaeocene times (e.g. Jaroszewski 1972; Kutek & Głazek 1972; Kutek 2001) and consequently the shapes of the earlier formed folds were modified (Kutek & Głazek 1972; Lewandowski 1982, 1985).

Methods

In analysis of the fault network, revised geological maps (Czarnocki 1938, 1961a-f; Filonowicz 1967, 1970, 1973, 1976; Hakenberg 1973), field observations, aerial photos, radar, satellite and DEM-derived images (e.g. Konon & Śmigielski 2006) have been applied. The DEM derivatives were made using the MICRODEM software series created by Peter Guth from the Department of Oceanography of the US Naval Academy.

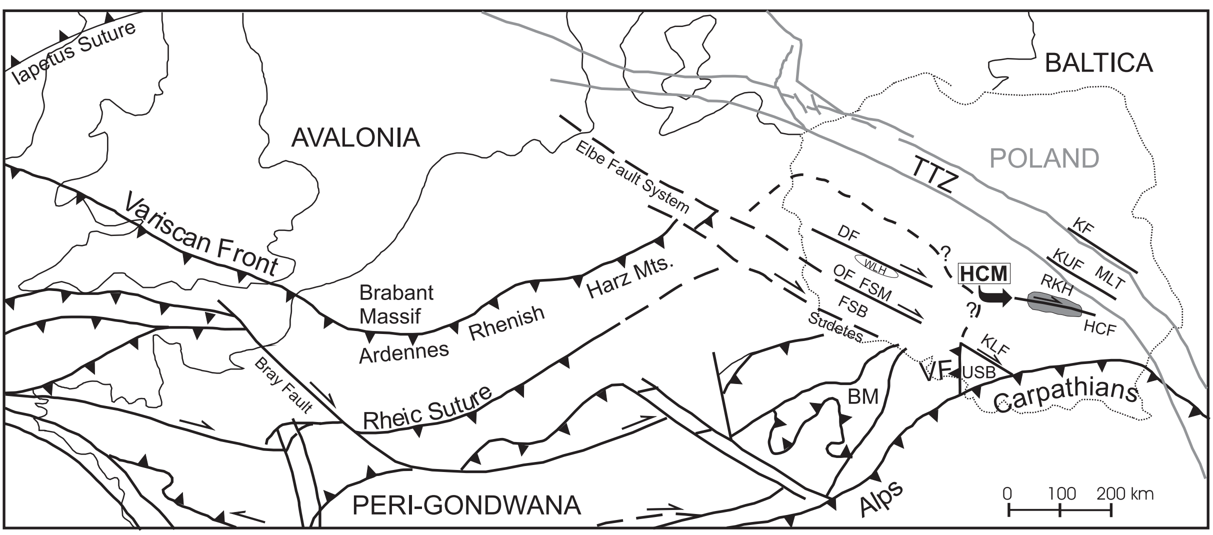

Fig. 1. Tectonic sketch-map of north-western and central Europe (simplified after Matte & *al.* 1990; Dadlez & *al.* 1994; Dadlez 2001; Mazur & *al.* 2006). BM – Bohemian Massif, DF – Dolsk Fault, FSB – Fore-Sudetic Block, FSM – Fore-Sudetic Monocline, HCF – Holy Cross Fault, HCM – Holy Cross Mountains, KF – Kock Fault, KLF – Kraków-Lubliniec Fault, KUF – Kazimierz-Ursynów Fault, MLT – Mazowsze-Lublin Trough, OF – Odra Fault, R-KH – Radom-Kraśnik High, USB – Upper Silesian Block, WLH – Wolsztyn-Leszno High

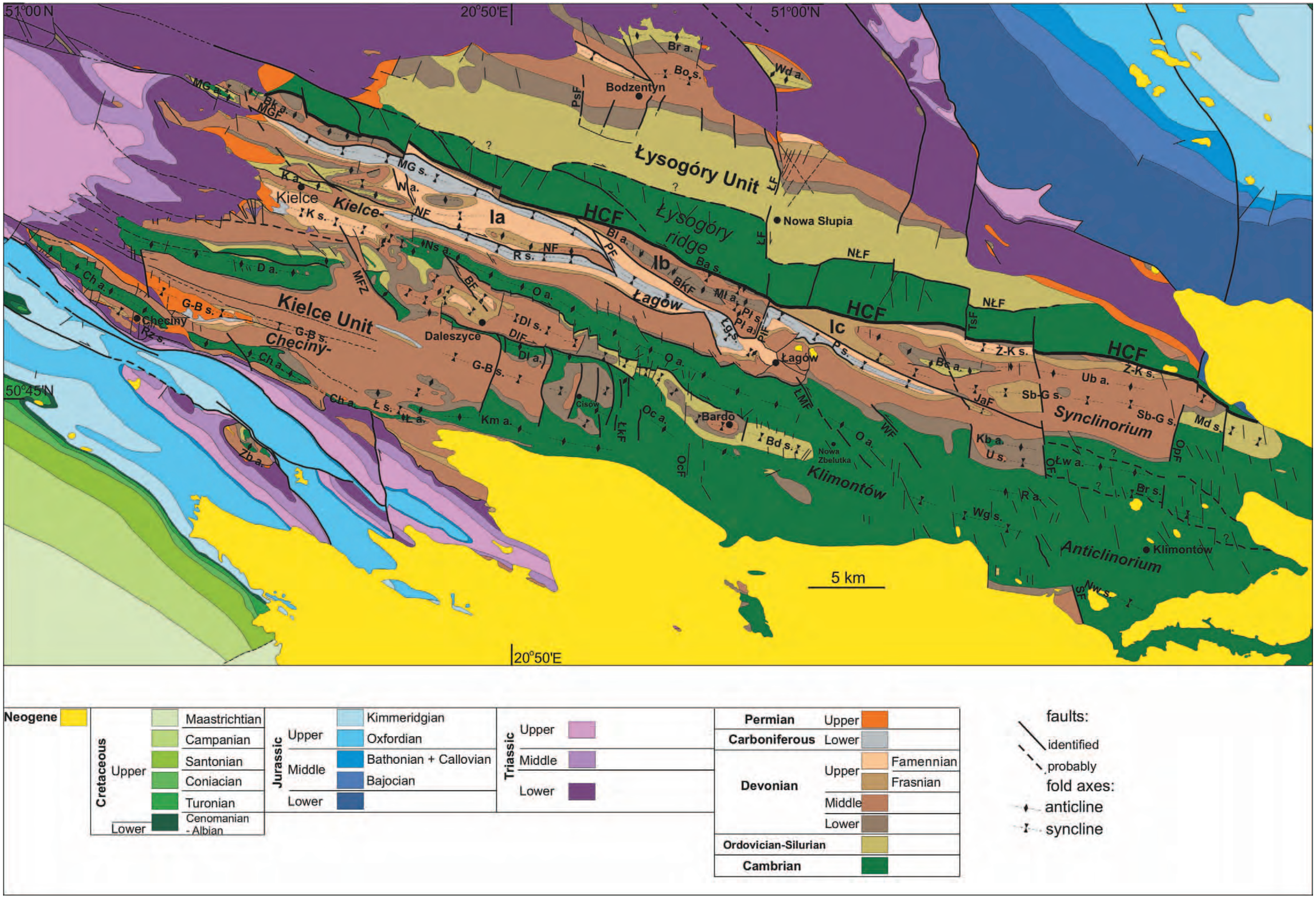

Fig. 2. Geological map of the Holy Cross Mountains (after Czarnocki 1938, 1961a-f; Filonowicz 1973a, modified). **Folds in the Kielce Unit**: Ba s. – Bartoszowiny Syncline, Bc s. – Baćkowice Anticline, Bd s. – Bardo Syncline, Bk a. – Bukowa Anticline, Bl a. – Bieliny Anticline, Br s. – Beradz Syncline, Ch a. – Chęciny Anticline, D a. – Dyminy Anticline, Dl a. – Daleszyce Anticline, Dl s. – Daleszyce Syncline, G-B s. – Gałęzice-Bolechowice Syncline, K a. – Kielce Anticline, K s. – Kielce Syncline, Kb a. – Kabza Anticline, Km a. – Komórki Anticline, Ł a. – Łabędziów Anticline, Ł s. – Łabędziów Syncline, Łg s. – Łagów Syncline, Łw a. – Łownica Anticline, Md s. – Międzygórz Syncline, MG s. – Miedziana Góra Syncline, Mł a. – Małacentów Anticline, N a. – Niewachlów Anticline, Ns a. – Niestachów Anticline, Nw s. – Nawodzice Syncline, O a. – Orłowiny Anticline, O a. – Orłowiny Anticline, O a. – Orłowiny Anticline, Oc a. Ociesęki Anticline, P s. – Piotrów Syncline, Pł a. – Płucki Anticline, Pł s. – Płucki Syncline, R a. – Radwan Anticline, R s. – Radlin Syncline, Rz s. – Rzepka Syncline, Sb-G s. – Sobiekurów-Grocholice Syncline, U s. – Ujazd Syncline, Ub a. – Ublinek Anticline, Wg s. – Wygiełzów Syncline, Zb a. – Zbrza Anticline, Ż-K s. – Żerniki-Karwów Syncline. **Folds in the Łysogóry Unit**: Bo – Bodzentyn Syncline, Br – Bronkowice Anticline, Wd – Wydryszów Anticline. **Main faults in the Holy Cross Mountains**: BF – Brzechów Fault, BKF – Bieliny Kapitulne Fault, DF – Daleszyce Fault, HCF – Holy Cross Fault, JaF – Janczyce Fault, ŁF – Łysogóry Fault, ŁkF – Łukawki Fault, ŁMF – Łagów-Michałów Fault, MFZ – Mójcza Fault Zone, MGF – Miedziana Góra Fault, NF – Niewachlów Fault, NŁF – Northern Łysogóry Fault, OF – Oziębłów Fault, OpF – Opatów Fault, PF – Porąbki Fault, PłF – Płucki Fault, SF – Samotnia Fault, WF – Wszachów Fault. For other explanations see text

Precise location of the fault zones has been enabled by analysis of fault scarps on slope and aspects maps (KONON & ŚMIGIELSKI 2006). Traces of the faults were identified mainly in places were they cut competent rocks.

The strike-slip component on the faults was recognized during field studies from analysis of slickensides, drag of beds along faults and e.g. asymmetrical folding in the fault sides observed in the field (e.g. KONON 2006b). On geological maps, radar and DEM-derived images, this component was initially interpreted from the strike separations and the drag of beds along faults, as well as on the basis of structures associated with strike-slip faults, e.g extensional normal faulting at the termination of faults, splay of faults, blocks rotated in domino style, stepovers, contractional folds which developed as a result of compensation of the displacements along the faults, and minor faults associated with the movement along the major faults. This component was also interpreted from the offsets of fold axes along transverse and oblique faults without significant change of widths of their hinge zones (KONON & ŚMIGIELSKI 2006; KONON 2006a, b). The observation of discontinuities between parallel faults and recognition of the sense of overlapping also proved helpful.

During the collection of data for fault-slip analysis, two fault sets with sinistral and dextral strike-slip occurring at outcrop in the same beds, with the sets enclosing acute dihedral angles generally below 75°, were interpreted as conjugate mesofault sets. Furthermore, in analysis of fault-slip data obtained from slickensides, approximated attitudes of the shortening axes were calculated with the selected Θ angle (30°) for each fault plane (TURNER 1953), using TectonicsFP software by REITER & ACS (1996-2000).

Determination of the age of the faults was based mainly on their cross-cutting relationships, relationships to the folds, attitudes of their fault planes, palaeomagnetic data, structures which developed as a result of displacement along the faults, mineralization developed during faulting and differences between the structure of the zones occurring in the Kielce and Łysogóry units, located close to the Holy Cross Fault, and the structural pattern observed in the overlying Upper Permian to Mesozoic strata around the terminations of the major faults.

STRIKE-SLIP FAULTS IN PALAEOZOIC STRATA

In the HCM, the complex fault network comprises numerous longitudinal faults parallel to the fold axes, as well as transverse and oblique faults, striking at high or low angles to the fold axes respectively (CZARNOCKI 1919, 1924, 1938, 1950, 1956, 1957a, b, 1958, 1961a-f; SAMSONOWICZ 1922, 1934) (Text-figs 2 and 3). These faults dissect series of map-scale folds, developed in Lower Cambrian to Lower Carboniferous sedimentary rocks (e.g. CZARNOCKI 1938).

In the Kielce Unit, the fault network consists mainly of approximately WNW–ESE-striking longitudinal faults, transverse and oblique N–S, NNW–SSE and NNE–SSW to NE–SW-striking faults (Text-fig. 3, Kielce Unit). For comparison, in the zone between the Holy Cross Fault and Northern Łysogóry Fault (HCF-NŁF Zone), directly to the north of the Kielce Unit, occur similar WNW–ESE, NW–SE, N–S and NNE–SSW to NE–SW-striking fault sets – (Text-fig. 3, Łysogóry Unit – part A). In part of the Łysogóry Unit, northwards of the Northern Łysogóry Fault, occur NW–SE, approximately N–S and NNE–SSW-striking transverse and oblique faults (Text-fig. 3, Łysogóry Unit – part B).

Longitudinal faults

In the Kielce Unit, the longitudinal WNW–ESE-striking fault traces, parallel to the fold axes, are up to 30 km long (Text-fig. 2). These map-scale faults dissect the short limbs of asymmetric map-scale folds as well as both limbs of map-scale symmetric folds (e.g. CZARNOCKI 1956, pl. 12; BEDNARCZYK & *al.* 1970; MIZERSKI 1995, fig. 17; KONON 2006a, b). During folding, a reverse sense of the dip-slip component predominated on the longitudinal faults (e.g. CZARNOCKI 1957b; KOWALCZEWSKI & RUBINOWSKI 1962; FILONOWICZ 1970, 1973), which is confirmed by earlier field observations of the author (KONON 2006a, b). On the surfaces of the steeply-dipping beds, in addition to the older dip-slip component resulting from the flexural slip mechanism (Text-fig. 4, area 1), evidence for a younger strike-slip component can also be seen (e.g. Text-fig. 4, area 2). Magnitudes of displacements along these faults, associated with the strike-slip faulting event, are difficult to estimate due to a

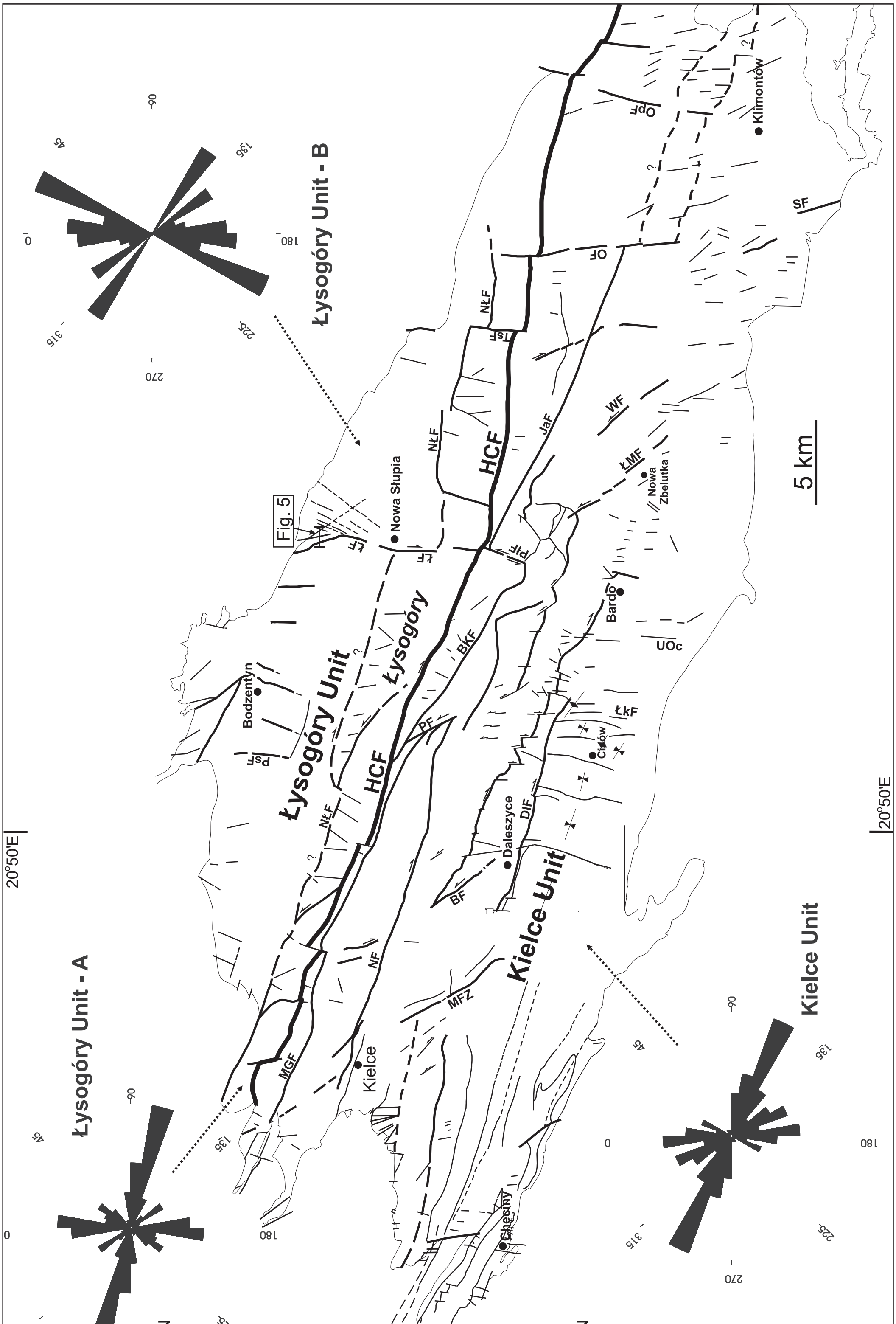

Fig. 3. Fault pattern in the Holy Cross Mountains. Rose diagrams of the fault traces in the Kielce and Łysogóry units. For other explanations see text and Text-fig. 2

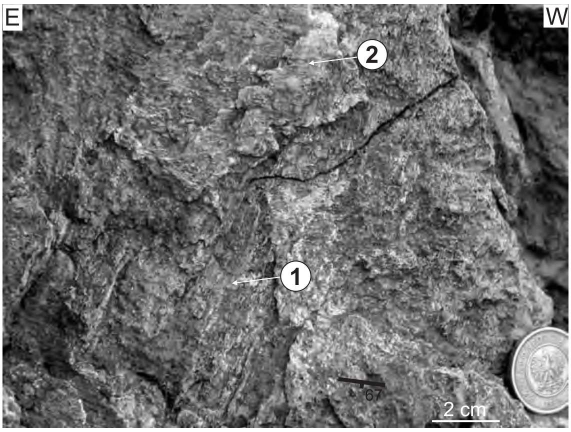

Fig. 4. Surface of bed with slickenside lineations – parallel (1) and subperpendicular to the dip (2) in the Mogiłki Quarry. The bedding plane orientation and dip value are indicated

lack of data on offsets of characteristic geological structures.

Transverse and oblique faults

The transverse and oblique faults have significantly shorter traces than the longitudinal faults – up to a few kilometres long (Text-figs 2 and 3). In the Kielce Unit, NNW–SSE and N–S-striking fault sets prevail (Text-fig. 3 – Kielce Unit). The NNE–SSE fault set is weakly developed. In the Łysogóry Unit, approximately N–S-striking faults are common e.g. the Łysogóry Fault, Psary Fault, as are also NNE–SSW-striking faults, such as the fault dissecting the Devonian and Silurian strata near Bodzentyn (Text-figs 2 and 3 – Łysogóry Unit – part B) (CZARNOCKI 1956, tab. 2).

The strike-slip component, as well as the extension or shortening component, also occurred across the transverse and oblique fault zones in both the Kielce and Łysogóry units (e.g. CZARNOCKI 1950, 1956; JAROSZEWSKI 1973, 1980; JUREWICZ & MIZERSKI 1991; MIZERSKI 1991; MIZERSKI & ORŁOWSKI 1993). For example, across the Łysogóry Fault, which is one of the major faults in the Łysogóry Unit, both extension as well as strike-slip occurred (Text-fig. 5). Displacements on transverse and oblique faults range from over ten metres to about 3 km, as in the case of the Łysogóry Fault (CZARNOCKI 1950, 1957b), and faults dissecting the central part of the Niewachlów Anticline (Text-fig. 2) formed during the post-folding stage of deformation (KONON & ŚMIGIELSKI 2006).

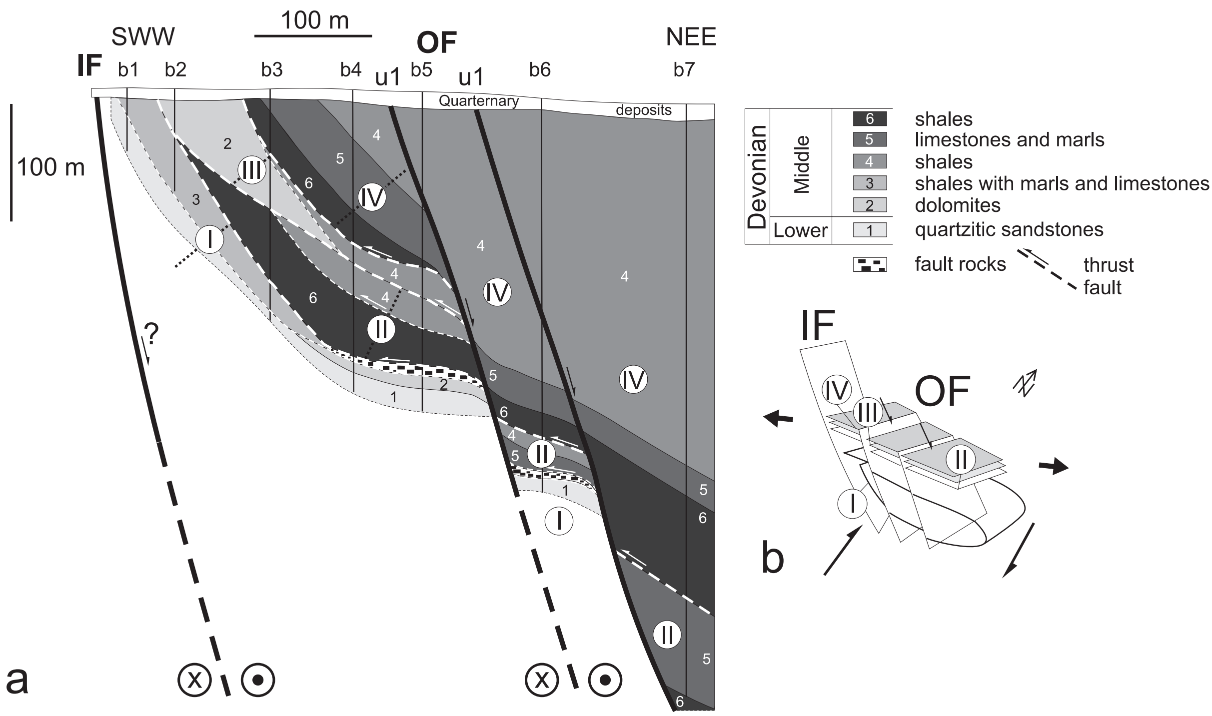

Fig. 5. a – Cross-section across the Łysogóry Fault zone (after CZARNOCKI 1956, modified). IF – inner fault, OF – outer fault. b – Extensional event in the Łysogóry Fault zone. Scheme of development of deformation in the fault zone. For location see Text-fig. 3. For other explanations see text

Structures associated with strike-slip faults

The strain partitioning of all slip components on longitudinal, transverse and oblique fault sets was not an easy task. Identifying the strike-slip component was often only possible on the basis of the identification of structures associated with the strike-slip displacement. Diagnostic features that can be used to recognize horizontal shear are: an *en échelon* arrangement of faults or folds in the fault zone in map view (e.g. HARDING 1973; WILCOX & *al.* 1973), imbricate fans of minor faults as horsetail splays at terminations of major faults (e.g. WOODCOCK & FISHER 1986; SYLVESTER 1988; WOODCOCK & RICKARDS 2003), strike-slip duplexes forming at bends or stepovers along the major fault (WOODCOCK & FISHER 1986; WOODCOCK & SCHUBERT 1994) and blocks rotated in domino style according to the 'bookshelf' mechanism (e.g. MANDL 1987). These structures, associated with strike-slip faulting, were recognized in both the Kielce and Łysogóry units (Text-figs 6-12).

Contractional folds

In the southern part of the HCM, symmetric and asymmetric mesofolds, with small wavelengths in the range of 0.7-9 m, commonly occur on limbs of map-scale folds. Some of them are located near the southern terminations of approximately N–S-striking faults (CZARNOCKI 1938, 1956, pl. 22; KONON 2006a, b). Examples of such mesofolds occur on the southern limb of the Gałęzice-Bolechowice Syncline, and on the southern limb of the Miedziana Góra Syncline (Text-fig. 6) (KONON 2006a, b). In both cases, strongly folded beds on the

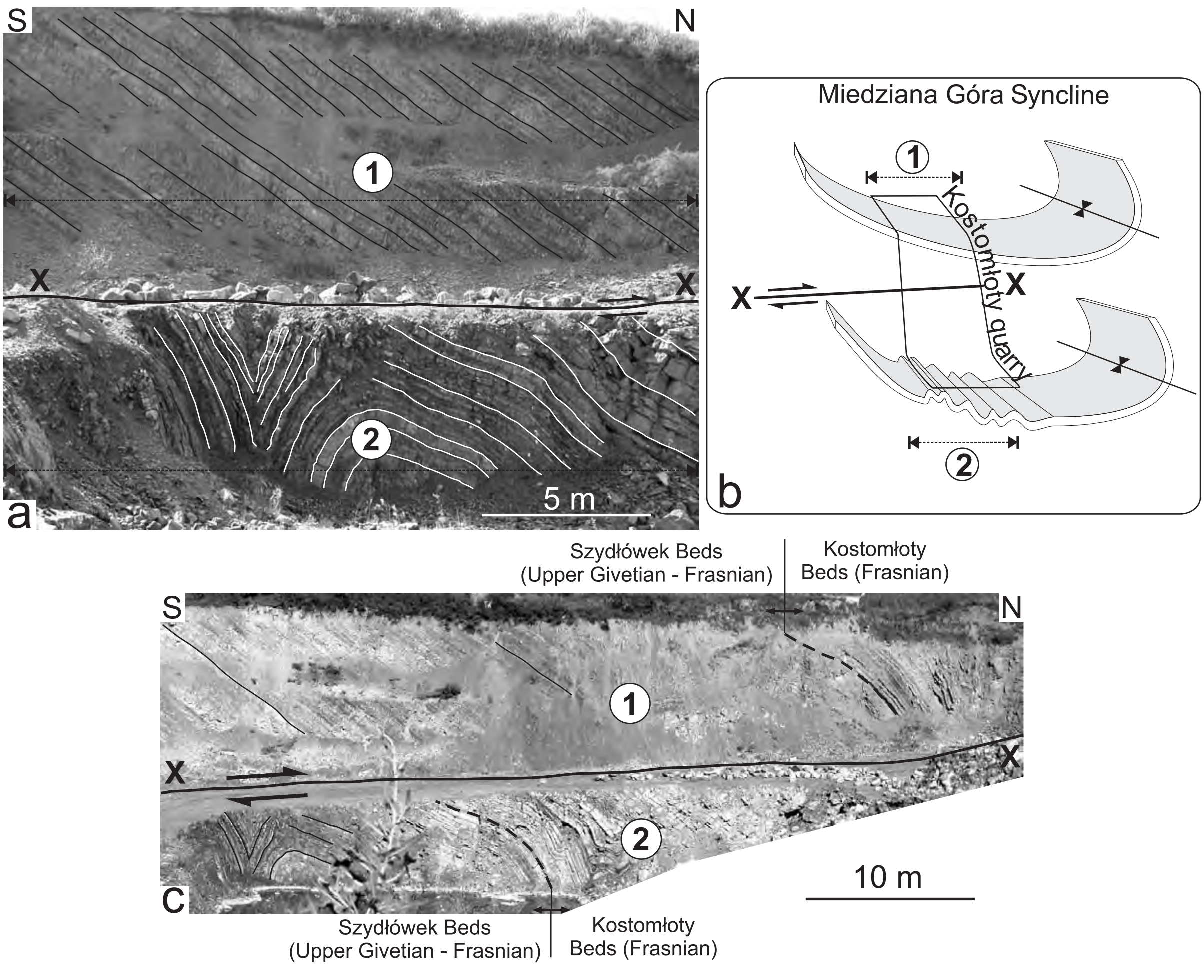

Fig. 6. a – Compensation of strike-slip movement along the dextral strike-slip fault, dissecting the southern limb of the Miedziana Góra Syncline (Kostomłoty Quarry). b – Scheme of fold development resulting from the activity of the strike-slip component along the fault. c – The strike-slip separation along the fault plane. Lithostratigraphic units after M. SZULCZEWSKI (personal communication, 2005)

eastern side of the fault contrast with less intensively folded beds on the western side. Displacements along the faults were small. For example, the strike separation calculated for the fault dissecting the southern limb of the Miedziana Góra Syncline was about 25 m. Asymmetry of folding in the fault blocks indicates that the folds developed as a result of compensation of displacement along these faults and that the faults were active as dextral strike-slip faults (KONON 2006b, fig. 7b).

Palaeomagnetic investigations suggest that the folds as well as the strike-slip faults formed in Late Carboniferous time (LEWANDOWSKI 1981, 1985; GRABOWSKI & NAWROCKI 1996 – KS1 component of magnetization – Namurian/Westphalian boundary).

Extensional imbricate fan of faults

In the eastern part of the Gałęzice-Bolechowice Syncline, near Daleszyce, at least three half-graben type tectonic blocks occur at the south-eastern tip of the Daleszyce Fault (Text-figs 2 and 7). The blocks are bounded by N–S-striking, west-dipping normal faults. These faults strike about 60° at the Daleszyce Fault. Normal faulting at the termination of the Daleszyce Fault suggests that, during the formation of the characteristic tilted blocks, the dextral strike-slip component prevailed along the fault after the folding (Text-fig. 7b).

Horsetail splay

The major transverse fault in the Łysogóry Unit is the approximately N–S-striking Łysogóry Fault, which is at least 11 km long (Text-figs 2 and 5). This steeply dipping fault dissects strata of Cambrian through Devonian age (CZARNOCKI 1950, 1957b). Both dextral strike-slip as well as dip-slip occurred along the fault (Text-fig. 5b) (CZARNOCKI 1950; JAROSZEWSKI 1973, fig. 7; 1980, fig. 227), although the sole occurrence of the dip-slip component with a normal sense, was also suggested (MIZERSKI 1982).

A series of secondary faults at the north-eastern tip of the master fault (CZARNOCKI 1950, fig. 29; 1956, tab. 11, 1957, tab. 1) probably developed as a splay of faults during dextral shear (KONON & ŚMIGIELSKI 2006). In one of these opened faults/fractures (JAROSZEWSKI 1973) a hydrothermal iron ore body was formed, which, according to the observations of SAMSONOWICZ and CZARNOCKI, does not cut the Upper Permian conglomerates (CZARNOCKI 1950).

Stepping and stepovers

An *en échelon* arrangement of fault segments is common in strike-slip fault zones (e.g. SEGALL & POLLARD 1980; WOODCOCK & SCHUBERT 1994; WOODCOCK & RICKARDS 2003), but also occurs in dip-slip fault zones (e.g. WALSH & *al.* 1999; ACOCELLA & *al.* 2000). Additional structures that are diagnostic of horizontal shear, such as horizontal lineations on slickensides, have therefore been used in the interpretations of the fault zones.

Common stepping of *en échelon* segments was observed in fault zones in the HCM (e.g. Text-figs 2, 3, 8). The segments are in the range of a few

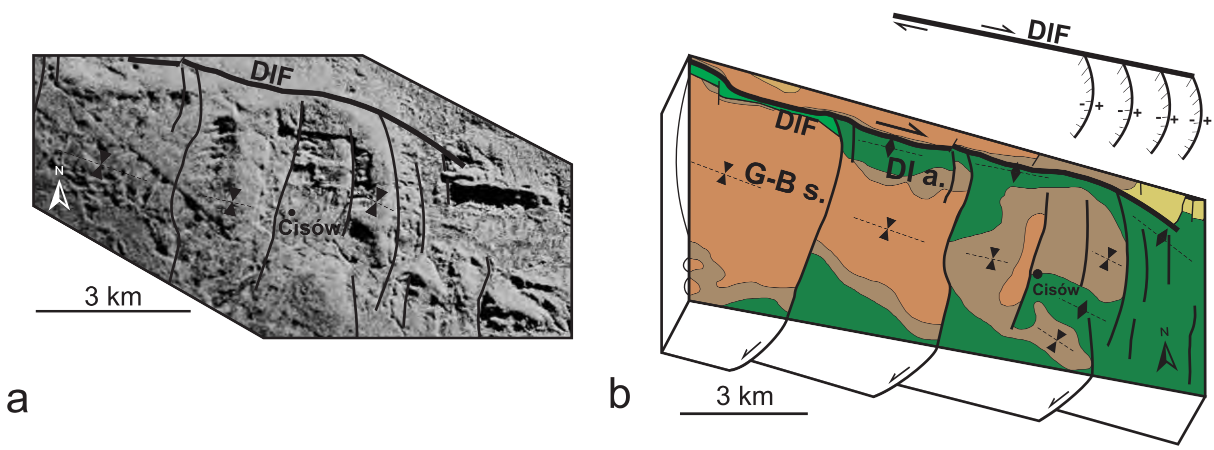

Fig. 7. Extensional imbricate fan of faults at the tip of the Daleszyce Fault (DIF). a – Radar image with marked fault traces. b – Tectonic block-diagram showing the development of tilted blocks in the extension zone during the dextral strike-slip displacement along the Daleszyce Fault; G-B s. Gałęzice-Bolechowice Syncline. For other explanations see text and Text-fig. 2

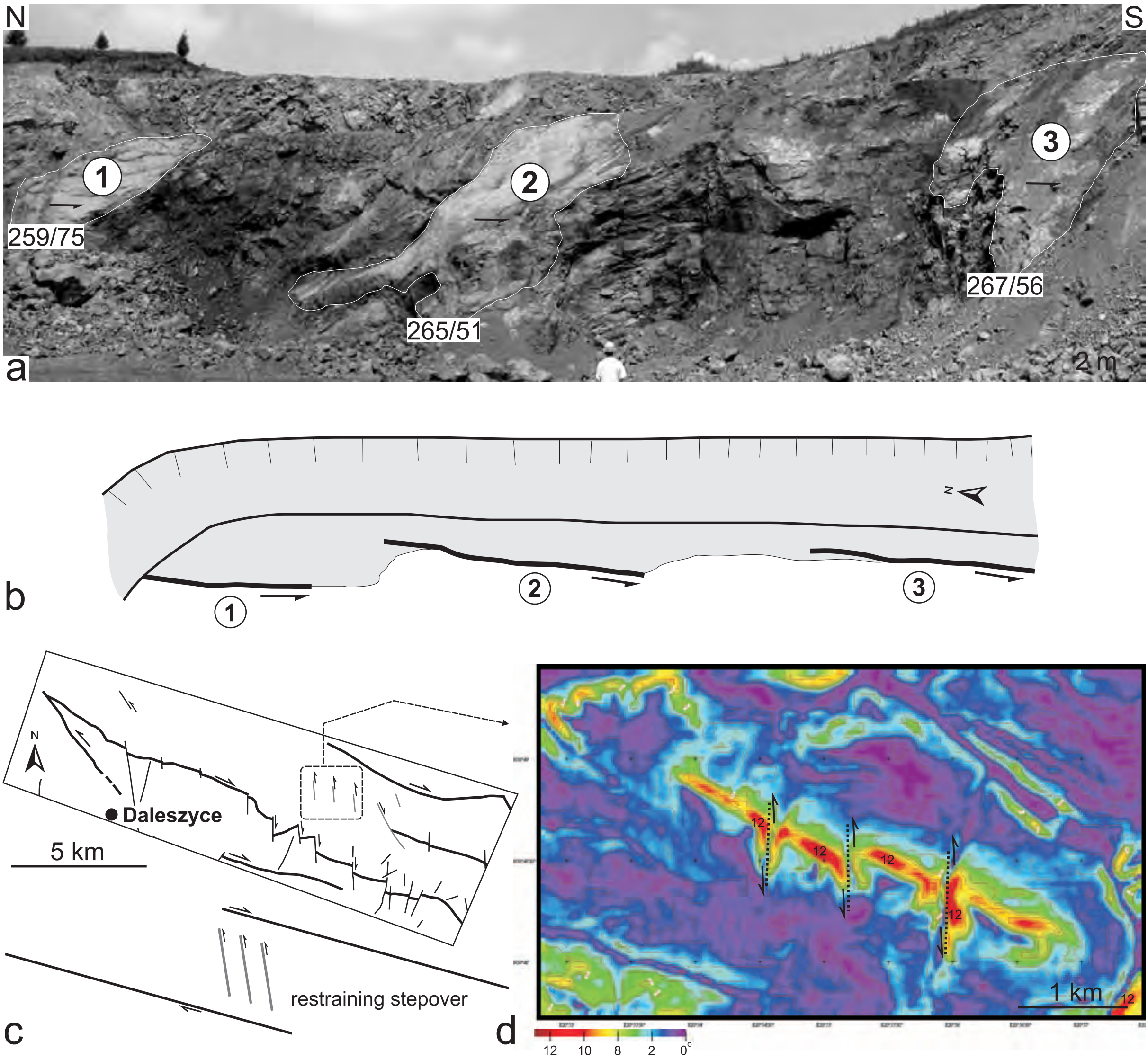

Fig. 8. a – Left-stepping in the sinistral strike-slip fault zone in the Piskrzyn Quarry. 1-2-3 slickensides with horizontal slickenside lineation. b – Sketch-map of the location of left-stepping of the fault segments in the Piskrzyn Quarry. c – Dextral restraining stepover near Daleszyce. d – Slope map (values of slopes presented in degrees) made with the application of the MICRODEM software series. For location see Text-figs 2, 11-13

metres to about 2 km. In map-scale fault zones, both right- and left-stepping was observed. Right-stepping was recognized e.g. in the fault zone which cuts the central part of the Baćkowice Anticline (Text-figs 2 and 3). An offset of the Baćkowice Anticline axis along the transverse fault without significant change of the hinge zone width presumably resulted from the strike-slip displacement. The Łagów-Michałów Fault zone displays probable left-stepping (Text-fig. 2 – ŁMF). At the NW tip of the fault, the drag of beds along the fault zone suggests horizontal shear.

Apart from these map-scale examples, left-stepping was also determined in the mesofault zone e.g. in the Piskrzyn Quarry (e.g. Text-figs 8a, b). Horizontal lineation on the slickensides displays a sinistral slip.

In strike-slip zones, additional structures were formed between the stepping segments of the faults. Eastwards of Daleszyce, between the two WNW–ESE-striking, left-stepping fault segments, four blocks segmented by three smaller N–S-striking sinistral strike-slip faults developed (Text-figs 8c, d). The sense of displacements along these

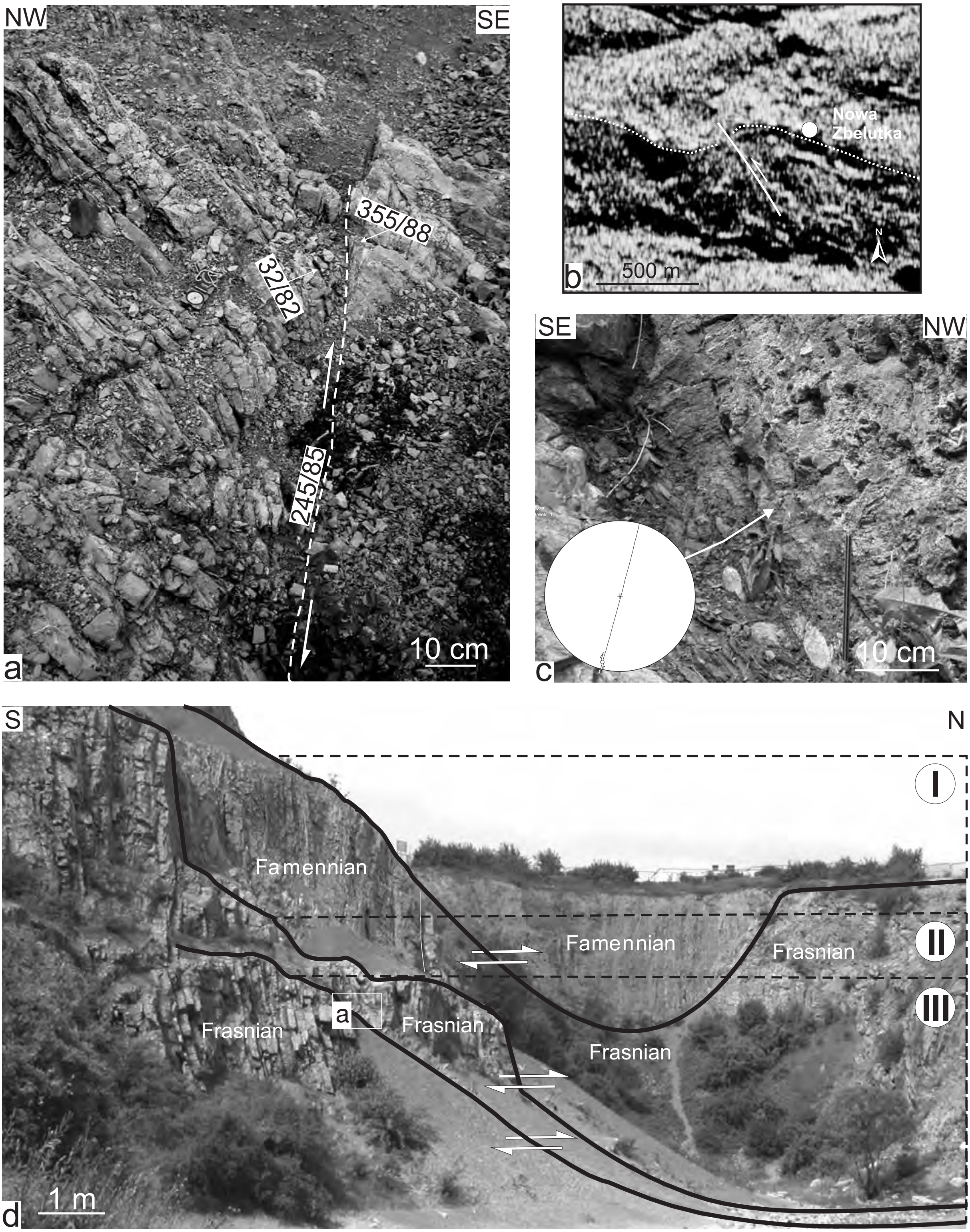

Fig. 9. a – Drag of beds along the dextral strike-slip fault in the Śluchowice Quarry. b – Radar image showing the map-scale drag of beds along the sinistral strike-slip fault near Nowa Zbelutka. c – Slickenside of the dextral strike-slip fault in the Śluchowice Quarry. d – Examples of three dextral strike-slip faults (I-III) in the Śluchowice Quarry. For location see Text-figs 2, 11-13

blocks and left-stepping of the major fault segments suggest that this part of the major fault zone can be interpreted as a dextral restraining stepover.

Drag of beds

In some fault zones in the HCM, vertical drag folds were formed in the generally steeply-dipping beds (e.g. Text-figs 9a, b). Map-scale drag of beds was observed e.g. near Nowa Zbelutka, where fault slip caused the curving of Cambrian shales and thin-bedded sandstones in both blocks of a NNW–SSE-striking fault (Text-fig. 9b). The strike separation along this fault was over ten metres. The drag of beds suggests the occurrence of a sinistral strike-slip component along the fault (Text-fig. 9b). A similar, but in meso-scale, deformation of beds was observed e.g. in the Śluchowice Quarry (Text-fig. 9a). Along at least three sub-vertical faults dissecting the Upper Devonian rocks, with strikes from NNW–SSE to N–S, drag folds were formed in the thin-bedded limestones (Text-figs 9a, c, d, I-III faults). The strike separations along the major faults range from a few to over ten metres (Text-fig. 9d). The drag of beds and horizontal lineations on slickensides of secondary faults imply that dextral displacement occurred along the major faults.

Minor strike-slip faults

Multilayer folds in the Kielce Unit display mesofaults which can cut over ten metres of strata (Text-figs 10-12). On these generally vertical faults, the directions and senses of slip point to the prevalence of the strike-slip component. Generally, the faults strike obliquely to the fold axes (Text-figs 11 and 12) and form conjugate fault sets (e.g. Text-fig. 10d).

The development of post-fold mesofaults was not associated directly with progressive modifications of the shape of map-scale folds (KONON 2006b). The mesofaults comprise mainly N–S to NE–SW-striking dextral and W–E-striking sinistral conjugate strike-slip fault sets (Text-figs 11 – diagrams 2b, 5b, 6, 8a, 8c, 9, 10 and 12 – diagrams 14, 15a, 17, 18a, 19a, 21, 24b), as well as W–E to WNW–ESE-striking dextral and NW–SE to N–S-striking sinistral strike-slip conjugate fault sets (Text-figs 11 – diagrams 1, 2a, 3, 5a, 7, 8b, 8c, 11, 12, 13 and 12 – diagrams 15b, 16, 18b, 20, 22, 23, 24a, 25, 27). WNW–ESE-striking sinistral and NE–SW-striking dextral conjugate strike-slip faults also occur rarely (Text-fig. 12 – diagrams 19b and 26), as do conjugate sets of NW–SE to NNW–SSE dextral and NNE–SSW sinistral strike-slip faults (Text-fig. 11 – diagram 4).

The attitudes of the measured fault sets in the Devonian rocks are similar to those occurring in the overlying Permian–Triassic rocks (Text-figs 11 and 12). Conjugate fault sets often occur in the outcrops and allow calculation of the different approximated attitudes of the shortening axes (Text-fig. 13). Two main directions of shortening prevail – an approximately NW–SE direction and a NE–SW direction (Text-figs 13d, e). Most of the mesofaults were observed near larger faults (Text-figs 13a-c).

Rotated blocks

To the north and south of the HCF there are two zones, up to 5 km wide, composed of fault-bounded block domains rotated around their vertical axes (Text-figs 2, 14 and 15).

To the south of the HCF, in the northern part of the Kielce Unit, is located a distinct zone consisting of fault-bounded block domains – Ia-Ib-Ic (Text-figs 2 and 14a) (KONON 2006a, b). In this zone at least three blocks developed, the Niewachlów (Ia), Małacentów (Ib) and Baćkowice blocks (Ic) (Text-fig. 14a). These blocks are a few to over ten kilometres long. The zone is bordered in the north by the HCF and in the south by WNW–ESE-striking longitudinal faults (CZARNOCKI 1938, 1957a, b, 1961a-f): Niewachlów (NF) (CZARNOCKI 1957a), Bieliny Kapitulne (BkF) and Janczyce faults (JaF) (Text-figs 2 and 14a) (KONON 2006a, b). To the east, the Niewachlów block (Ia) is bordered by the Porąbki Fault (PF), and the Małacentów block (Ib) by the Płucki Fault (PłF) (Text-figs 2 and 14a). First-order folds within the blocks are a few to over ten kilometres long (Text-fig. 2). The axes of the folds are distinctly offset about 2-4 km along the Porąbki (PF) and Płucki faults (PłF) (Text-fig. 2). Rotated axes of folds occurring in the blocks suggest clockwise rotation of the blocks Ia–c (Text-fig. 14).

A similar zone of fault-bounded blocks occurs north of the HCF in the Łysogóry Unit (MASTELLA & MIZERSKI 2002) (Text-figs 2 and 14a, b). The zone is bordered to the north by the Northern Łysogóry Fault, which is recognized only in the eastern part (KOWALCZEWSKI *& al.* 1976; KOWALCZEWSKI 2004), but probably also continues westwards

(MASTELLA & MIZERSKI 2002). The zone comprises, from west to east, the Krzemianka, Wiśniówka, Radostowa, Łysogóry, Truskolaska and Gołoszyce blocks (MASTELLA & MIZERSKI 2002) (Text-figs 2 and 14a, b). In the Radostowa block occur four smaller blocks rotated clockwise around the vertical axis (Text-fig. 15c) (FILONOWICZ 1970; MASTELLA & MIZERSKI 2002). The blocks are rotated, together with the Cambrian beds, in a domino style according to the 'bookshelf' mechanism of MANDL (1987), which suggests that a dextral strike-slip component also occurred along the master Holy Cross Fault

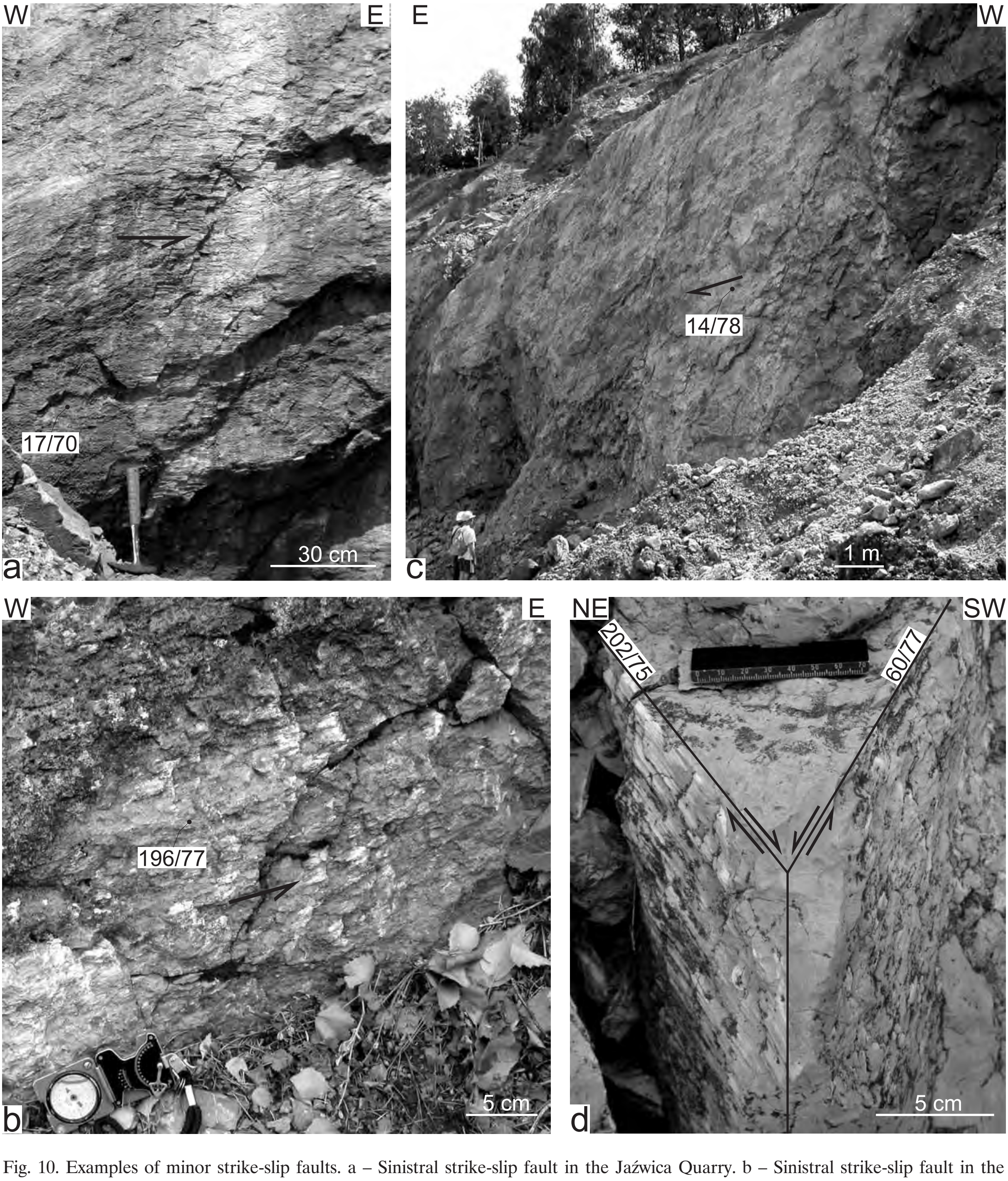

Fig. 10. Examples of minor strike-slip faults. a – Sinistral strike-slip fault in the Jaźwica Quarry. b – Sinistral strike-slip fault in the Zamkowa Quarry. c –Dextral strike-slip fault in the Szczukowskie Górki Quarry. d – Conjugate dextral and sinistral strike-slip fault sets in the Wietrznia Quarry. For location see Text-figs 2, 11-13

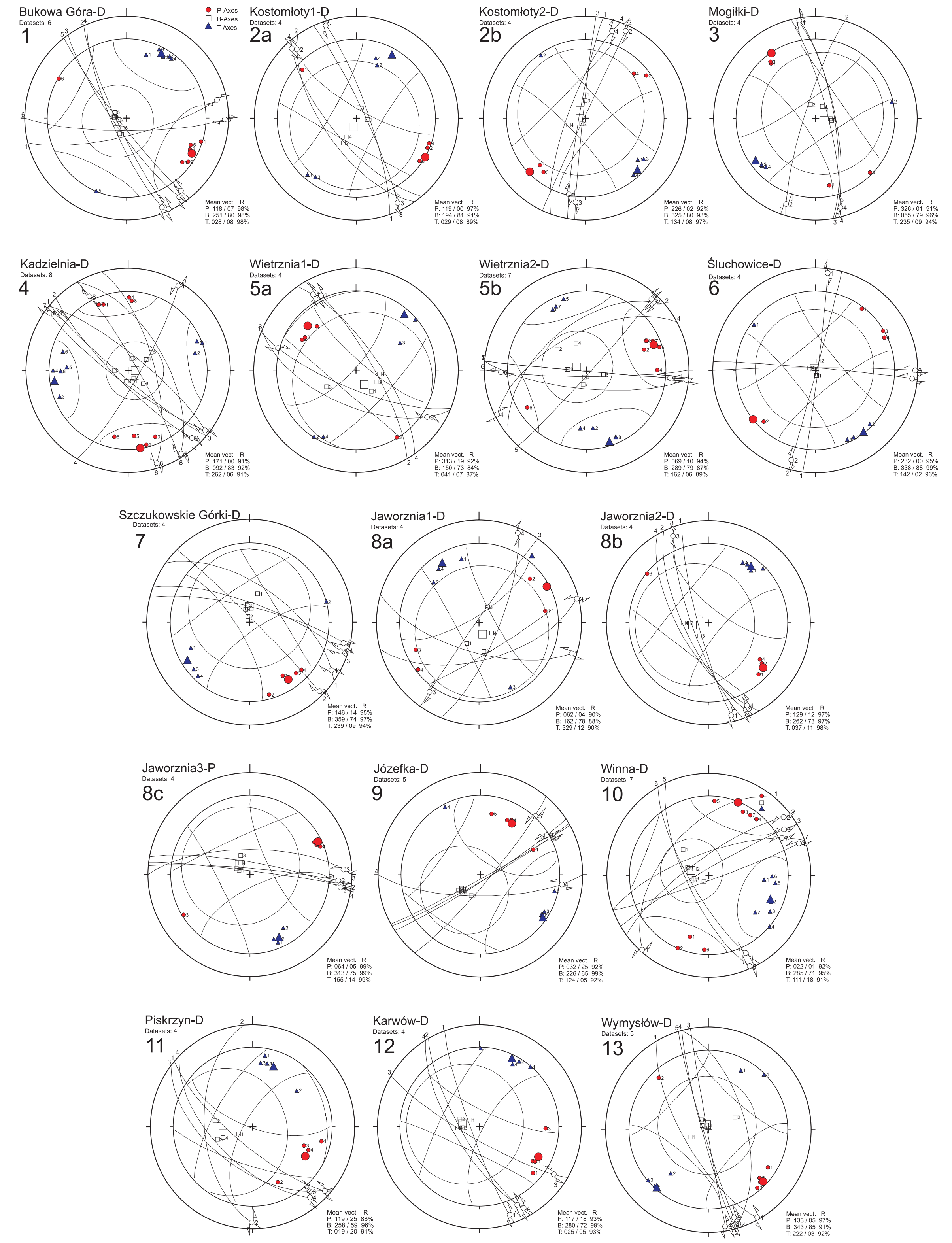

Fig. 11. Diagrams of selected minor strike-slip faults with attitudes of the axes of shortening (P) and extension (T) from the northern part of the Kielce Unit (Kielce-Łagów Synclinorium) and one diagram from the Łysogóry Unit. On diagrams are marked the mean vectors with cones of confidence for P-T axes. D – fault sets measured in Devonian strata, P – fault sets measured in Permian-Triassic strata. For location see Text-figs 2 and 13

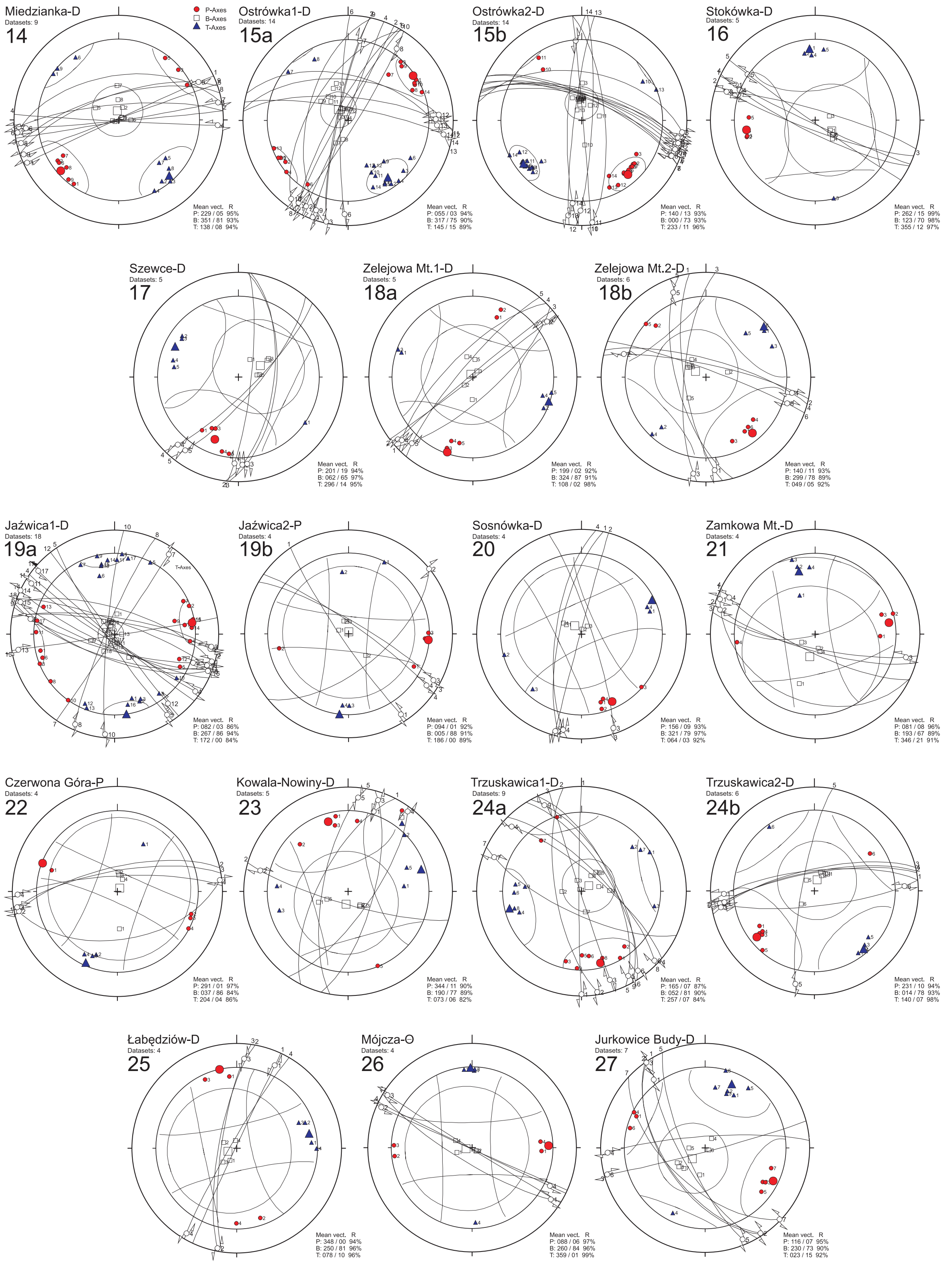

Fig. 12. Diagrams of selected minor strike-slip faults with attitudes of axes of shortening (P) and extension (T) from the southern part of the Kielce Unit (Chęciny-Klimontów Anticlinorium). On diagrams are marked the mean vectors with cones of confidence for P-T axes. Θ – fault sets measured in Ordovician strata, D – fault sets measured in Devonian strata, P – fault sets measured in Permian–Triassic strata. For location see Text-figs 2 and 13

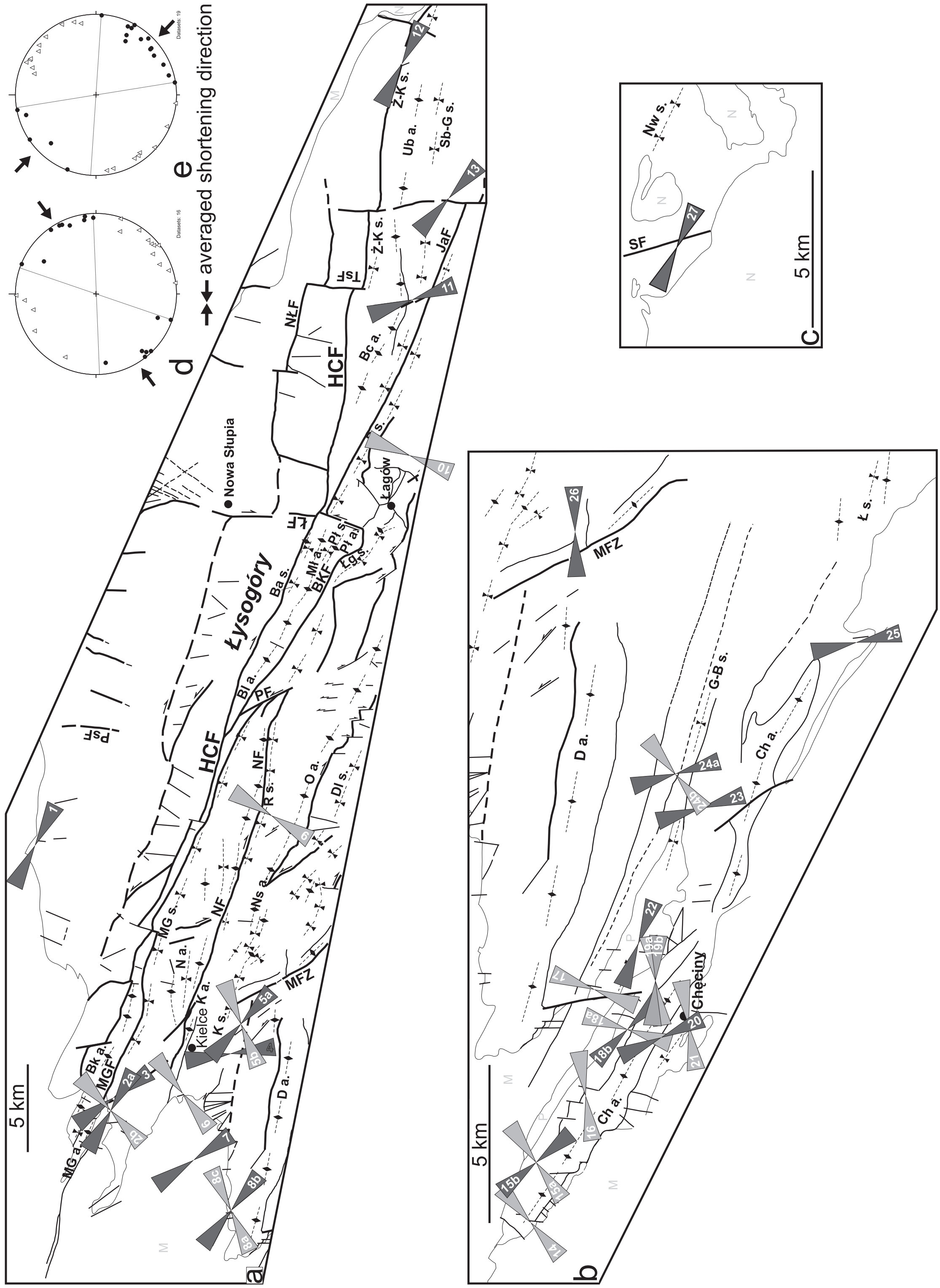

Fig. 13. Approximated axes of shortening directions for the minor strike-slip fault sets. a – Shortening directions from the northern part of the Kielce Unit. b – Shortening directions from the south-western part of the Kielce Unit. c – Shortening directions from the south-eastern part of the Kielce Unit. d – NNE–SSW to ENE–WSW shortening directions (dots) and N–S to WNW–ESE extension directions (triangles) deduced from fault-slip data. e – WNW–ESE to NNW–SSE shortening directions (dots) and NNE–SSW to ENE–WSW extension directions (triangles) deduced from fault-slip data. For other explanations see text and Text-fig. 2

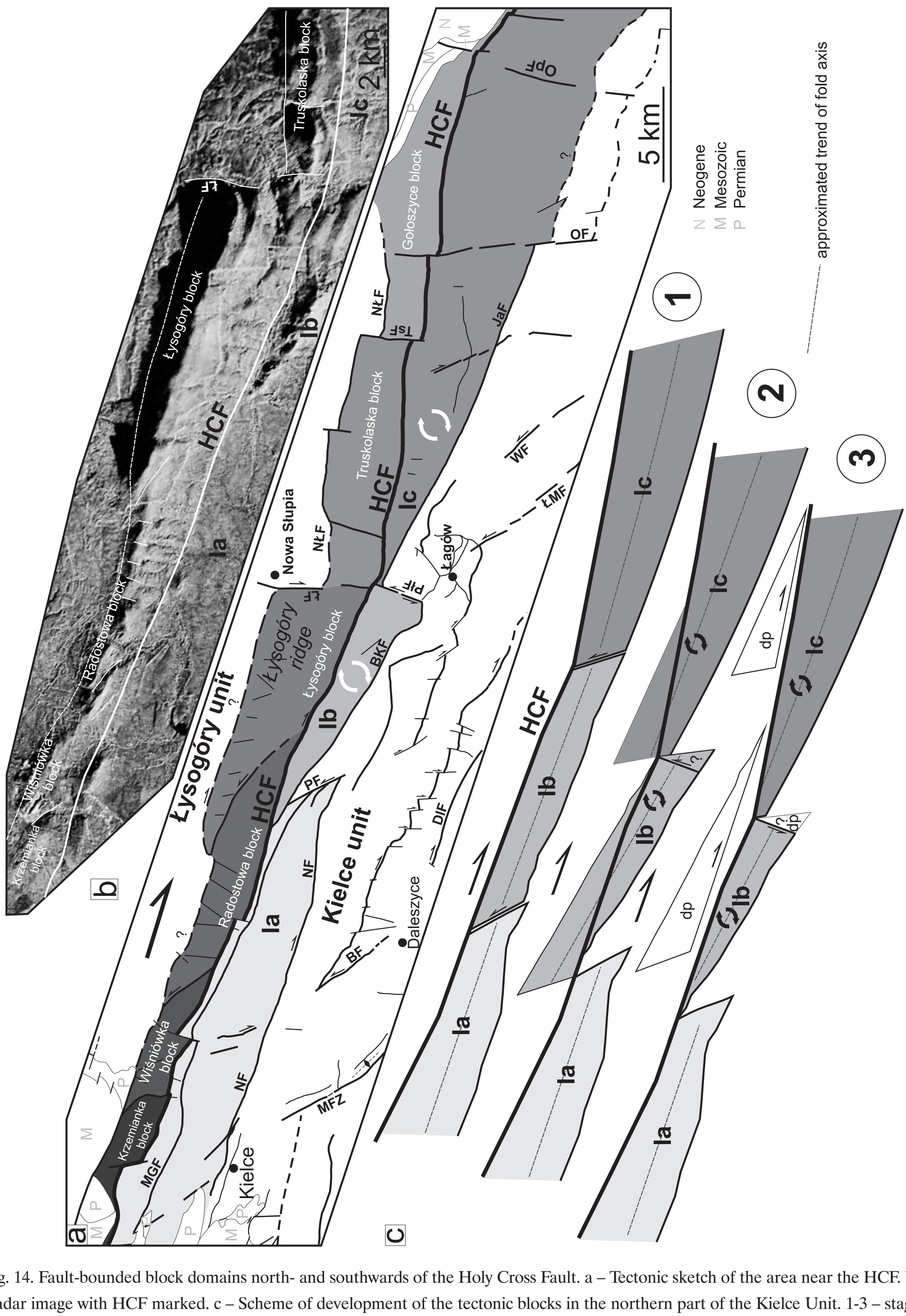

Fig. 14. Fault-bounded block domains north- and southwards of the Holy Cross Fault. a – Tectonic sketch of the area near the HCF. b – Radar image with HCF marked. c – Scheme of development of the tectonic blocks in the northern part of the Kielce Unit. 1-3 – stages of formation of rotated blocks, dp – disintegrated part of the block during strike-slip movement along the HCF

(MASTELLA & MIZERSKI 2002). Strike separations along the NW–SE striking faults between the Wiśniówka and Radostowa blocks, and the Łysogóry and Radostowa blocks suggest that a sinistral strike-slip component could have occurred along these second-order faults during dextral strike-slip displacement along the master HCF (Text-figs 3 – Łysogóry Unit part A, 14 and 15a, b).

STRIKE-SLIP FAULTS IN PERMIAN–MESOZOIC STRATA

First and second-order strike-slip faults also formed in the Permian–Mesozoic strata that overlie the Lower Cambrian to Lower Carboniferous rocks of the Kielce Unit. The faults occurring south of the HCM developed in Maastrichtian/Palaeocene times (KONON & MASTELLA 2001; MASTELLA & KONON 2002), as did the strike-slip faults that dissect the Mesozoic strata north of the HCM (JAROSZEWSKI 1972).

In the vicinity of the HCM, south of the Kielce Unit, the fault network comprises several WNW–ESE-striking longitudinal faults, as well as oblique N–S-striking faults (CZARNOCKI 1938, 1961a-f) (Text-fig. 2). Part of the longitudinal major faults show dextral strike-slip (KONON & MASTELLA 2001; MASTELLA & KONON 2002). The minor fault system comprises NNW–SSE to N–S-striking dextral and NE–SW-striking sinistral strike-slip conjugate fault sets (KONON & MASTELLA 2001; MASTELLA & KONON 2002).

TIMING OF STRIKE-SLIP FAULTING

The structures associated with strike-slip faulting, attitudes of fault planes, mineralization and palaeomagnetic data all indicate that two strike-slip faulting events (**I-1** and **I-2**) probably occurred during the Late Palaeozoic. The N–S-striking dextral strike-slip faults such as the Łysogóry Fault, Psary Fault and the fault dissecting the Niewachlów Anticline, as well as an approximately NE–SW-striking sinistral set, were probably active during the **I-1** event. The hydrothermal iron ore body which developed in the horsetail splay of the Łysogóry Fault before the Late Permian (CZARNOCKI 1950), as well as the similarity of the

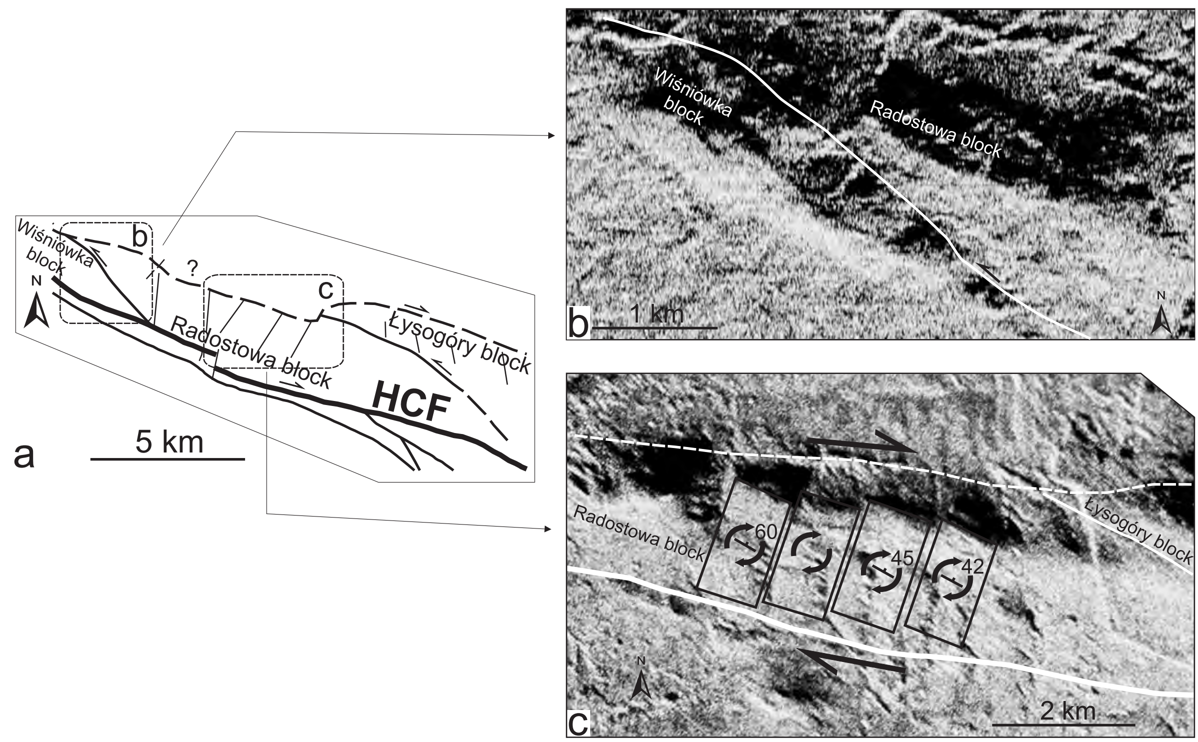

Fig. 15. Examples of rotated blocks in the Holy Cross Fault – Northern Łysogóry Fault zone. a – Location sketch-map. b – Radar image with marked fault between the Radostowa and Wiśniówka blocks. c – Rotated small blocks in the Radostowa block (bedding plane orientations with dip values after FILONOWICZ 1970)

shortening directions – approximately NNE–SSW, which resulted in the development of the fault sets and folds during the Late Palaeozoic in the HCM (e.g. CZARNOCKI 1938, 1950, 1957a, b, 1961a-f) suggest that the faults formed during a late phase of folding or even in the post-fold phase.

A Late Palaeozoic time of development of the Łysogóry Fault is additionally confirmed by the occurrence of horsetail splays at the north-eastern tip of the fault, where these faults do not dissect the Triassic rocks (Text-fig. 2). Such structures are usually restricted to the tips of strike-slip faults (e.g. WOODCOCK & FISCHER 1986; WOODCOCK & SCHUBERT 1994; KIM & *al.* 2004). This suggests that the first-order fault formed in this part of the Łysogóry Unit and that its continuation into the Permian-Mesozoic rocks could only have been a result of a later faulting event. During the same faulting event (**I-1**) developed similarly striking dextral faults such as those observed in the Kostomłoty and Śluchowice quarries and testified by palaeomagnetic data (LEWANDOWSKI 1981, 1985; GRABOWSKI & NAWROCKI 1996) (Text-figs 6 and 9).

The faults that were probably active during the next phase of strike-slip faulting (**I-2**) were the WNW–ESE-striking dextral strike-slip faults and the NW–SE to NNW-SSE-striking sinistral faults which developed as a result of a probable NW–SE shortening direction that differed from the shortening direction prevailing during the main phase of Late Palaeozoic folding in the HCM. Strike-slip fault activity during the **I-2** event is suggested by the occurrence of the complex structure of zones north and south of the HCF, consisting of tectonic blocks in the Holy Cross Mountains fold belt, and a simplified structural pattern observed in the overlying Upper Permian to Mesozoic strata around both tips of the HCF (Text-figs 2, 14 and 15). Additionally, the lack of significant displacement of Cambrian strata along the Łysogóry Fault in the southern part of the Łysogóry Unit (CZARNOCKI 1956, fig. 19, 1957b) indicates that the displacement which occurred along the HCF was younger than that which occurred along the Łysogóry Fault, which suggests that the occurrence of the I-2 event was after the I-1 event.

The second significant stage of strike-slip faulting took place in Maastrichtian/Palaeocene times (KONON & MASTELLA 2001; MASTELLA & KONON 2002).

DISCUSSION

Fault pattern

The HCM fold belt was formed after the Viséan (e.g. CZARNOCKI 1919, 1957a; TOMCZYK 1988; SZULCZEWSKI 1995; LAMARCHE & *al*. 1999, 2002) by buckle folding of the sedimentary rock complex (KONON 2006a, b). The process of fold growth terminated prior to the Late Permian (e.g. CZARNOCKI 1938). During the folding map-scale thrust faults developed (KONON 2006a, b). The first faults with a predominant strike-slip component probably developed later, in the next phase of folding or already in the post-fold stage of deformation. The problem of precise estimation of strike-slip timing and strain partitioning on the individual faults results from the fact that in the HCM at least two significant strike-slip faulting stages took place – (**I**) in the Late Palaeozoic (BROCHWICZ-LEWIŃSKI & *al.* 1983; TOMCZYK 1988; POŻARYSKI & *al*. 1992; UNRUG & *al.* 1999; LAMARCHE & *al.* 2000, 2003; MASTELLA & MIZERSKI 2002) and (**II**) in Maastrichtian/Palaeocene times (JAROSZEWSKI 1972; KONON & MASTELLA 2001; MASTELLA & KONON 2002). The similar shortening directions – NNE–SSW during the Late Carboniferous and generally NE–SW during the Maastrichtian/Palaeocene folding events (e.g. CZARNOCKI 1938, 1950, 1957a, b, 1961a-f) cause an additional problem with the interpretation of the timing of the faults. It means that in the later phase of folding and also during younger strike-slip faulting stage (II) new faults developed; moreover, some of the older faults were reactivated in the strike-slip mode.

Structures associated with strike-slip faulting suggest that dextral strike-slip occurred along the WNW–ESE and approximately N–S-striking fault sets, and that sinistral strike-slip occurred along the NNW–SSE to NW–SE or NNE–SSW to NE–SW-striking fault sets.

Late Palaeozoic strike-slip faulting event (I-1)

During the first strike-slip faulting event (**I-1**) in the Late Palaeozoic, a N–S-striking dextral strike-slip fault set and a NNE–SSW to NE–SW-striking sinistral strike-slip fault set probably developed, resulting from an approximately NNE–SSW shortening direction. The faults form a conjugate pair of fault sets. The fault traces refract strongly during propagation through rocks with significant differerences in competence as e.g. in the Bodzentyn Syncline, at the border between competent Emsian sandstones and incompetent Silurian shales (Text-fig. 2). The acute dihedral angle between the sets is underestimated, because the observations can be made only within competent strata. Thus, the fault sets probably enclose the acute dihedral angle (2Θ) of over 30°.

During the strike-slip faulting event, some of the mesofault sets probably formed (Text-figs 11 and 12) in addition to the major faults such as the Łysogóry Fault and the minor faults noted in the Kostomłoty and Śluchowice quarries. Across these faults, as e.g. the Łysogóry Fault, an extension component probably occurred in addition to the strike-slip component, this being suggested by the presence of a hydrothermal iron ore body (CZARNOCKI 1950) in the horsetail splay of the fault and normal faulting recognized in boreholes drilled across the fault zone (Text-fig. 5).

From mesofault sets could develop the N–S to NE–SW-striking dextral strike-slip fault set and the W–E-striking sinistral strike-slip fault set, similar to those described by LAMARCHE & *al.* (1999) (Text-figs 11 – diagrams 2b, 5b, 6, 8a, 8c, 9, 10 and 12 – diagrams 14, 15a, 17, 18a, 19a, 21, 24b), resulting from an approximately NE–SW shortening direction (Text-fig. 13d). These secondary fault sets could probably form locally as conjugate Riedel shears (R-R'), accompanying a first-order N–S striking dextral strike-slip fault set, similar to that described by KUHN & REUTHER (1999) in Cordillera de Domeyko in northern Chile.

During this event, the axis of maximum shortening was sub-perpendicular to longitudinal faults such as the HCF, resulting in the prevalence of the shortening component across the fault zones. Some authors (e.g. BROCHWICZ-LEWIŃSKI & *al.* 1983; TOMCZYK 1988; POŻARYSKI & *al.* 1992; UNRUG & *al.* 1999; LAMARCHE & *al.* 2000, 2003) suggested the occurrence of a significant strike-slip component along the HCF, which was confirmed by the recognition of domino-style rotated blocks in the Radostowa block (MASTELLA & MIZERSKI 2002).

Based on the present-day fold pattern, it is difficult to determine the beginning of the appearance of the strike-slip component along the HCF and other longitudinal faults. This complex fault pattern was undoubtedly overprinted, and new faults developed, during later deformational events – e.g. in Maastrichtian/Palaeocene times. Additionally, according to e.g. JAMISON (1991), in transpressive zones the folds can rotate with respect to master fault zones. The acute angles between the fold axes and the HCF are very low (Text-fig. 2). If oblique shortening was responsible for the formation of folds in both units of the HCM fold belt, this suggests the domination of pure shear over the strike-slip component (after JAMISON 1991).

Late Palaeozoic strike-slip faulting event (I-2)

During the next strike-slip faulting event (**I-2**), a dextral strike-slip component probably occurred along the WNW–ESE-striking longitudinal faults and formed the NW–SE to NNW–SSE-striking sinistral strike-slip fault set.

During the faulting event, zones consisting of rotated tectonic blocks developed in the Holy Cross Mountains fold belt to the north and south of the HCF (Text-figs 2, 14 and 15). The blocks in the zone south of the HCF (Ia–c) are bounded by WNW–ESE-striking longitudinal faults as well as by a generally NW–SE to NNW–SSE-striking sinistral strike-slip fault set (Text-figs 2, 3 and 14). The small blocks rotated dextrally in a domino style in the Radostowa block north of the HCF (FILONOWICZ 1970; MASTELLA & MIZERSKI 2002) and the similarly rotated blocks Ia–c in the zone south of the HCF suggest that a dextral strike-slip component occurred along this fault (Text-figs 2, 14 and 15). Apart from the tectonic blocks in the zones to the north and south of the HCF, structures recognized along the remaining longitudinal faults, such as a restraining stepover near Daleszyce or an extensional imbricate fan of the Daleszyce Fault, also suggest that a dextral sense of movement predominated during the strike-slip faulting event along these and other similar faults (Text-figs 7 and 8c, d).

The Krzemianka, Wiśniówka, Radostowa, Łysogóry, Truskolaska and Gołoszyce blocks (MASTELLA & MIZERSKI 2002) probably also developed as a result of dextral strike-slip movement. Theoretically, offsets along the NW–SE-striking faults suggest that the blocks could have been formed initially as contractional strike-slip duplexes resulting from sinistral strike-slip movement; however, the dextrally-rotated small blocks in the Radostowa block and structures associated with the movement along other longitudinal faults rather contradict this view (Text-figs 2, 7, 8c, d, 14, 15c).

Apart from the NW–SE and NNW–SSE-striking faults bounding the blocks in the Kielce Unit, similar NNW–SSE-striking faults also occur, including the Brzechów Fault, the Łagów-Michałów Fault, the Wszachów Fault and a series of faults at the eastern end of the Dyminy Anticline (TOMCZYK 1974) (Text-figs 2 and 3). Common stepping, e.g. left-stepping in the Łagów–Michałów Fault zone, and map-scale drag of beds observed e.g. near Nowa Zbelutka, suggest that a sinistral strike-slip component occurred along these faults. Probably, part of the strike-slip mesofaults, the NNW–SSE to N–S-striking sinistral strike-slip fault set and the W–E to WNW–ESE-striking dextral strike-slip faults set developed as a result of displacements along these faults (Text-figs 11 – diagrams 1, 2a, 3, 5a, 7, 8b, 8c, 11, 12, 13 and 12 – diagrams 15b, 16, 18b, 20, 22, 23, 24a, 25, 27), which resulted from an approximately NW–SE shortening direction (Text-fig. 13e).

The fault network consisting of longitudinal WNW–ESE-striking dextral strike-slip faults and NW–SE to NNW–SSE-striking sinistral faults is very similar to that developed during the analogue model experiments of SCHREURS (2003). In the experiments, both brittle and viscous materials were applied, allowing the investigation of faulting in such rheologically strongly contrasting materials. The unmetamorphosed sedimentary rock sequences comprising alternating competent and incompetent beds in the HCM probably favoured the development of such a characteristic fault network. Results of the experiments suggest that the master dextral strike-slip faults and the sinistral strike-slip faults, striking at 40-50° to these faults, were not conjugate sets but were active coevally (SCHREURS 2003).

Younger strike-slip faulting probably formed as a result of regional approximately NW–SE shortening. During this stage pure shear decreased significantly and the strike-slip component began to dominate. This suggests that the fault sets can be interpreted as having been formed through dextral transtension. Such conditions probably allowed the gradual clockwise rotation of the blocks (Niewachlów block – Ia, Małacentów block – Ib and Baćkowice block – Ic) between the major faults – the Holy Cross Fault and probably the Daleszyce Fault, in the northern part of the Kielce-Łagów Synclinorum in the Kielce Unit (Text-figs 2 and 14c). During the dextral strike-slip movement the north-western parts of the tectonic blocks (Ia–c) were progressively rotated and gradually disintegrated (Text-fig. 14c, stages 1→2→3).

During this phase, the flower structure in the HCF zone suggested by LAMARCHE & *al.* (2003) could have developed but this has not yet been confirmed. Palaeomagnetic data (GRABOWSKI & NAWROCKI 2001) suggest that rotations of blocks around the vertical axis could also have occurred in many parts of the HCM.

Differences between the strike-slip fault network are observed to the north and south of the Northern Łysogóry Fault. Nevertheless, the zone of main horizontal shear was southwards of the HCF, which is the major fault in the HCM fold belt, separating the Kielce and Łysogóry units. According to the geophysical investigations of MALINOWSKI & *al.* (2005) it can be interpreted as a regionally significant intra-plate strike-slip fault *sensu* WOODCOCK & SCHUBERT (1994).

The strike-slip fault network was reactivated during the second major faulting stage (**II**) in the Maastrichtian/Palaeocene, but the strike-slip faulting activity at that time was weaker than during the Late Palaeozoic faulting events (KONON & MASTELLA 2001; MASTELLA & KONON 2002).

Reactivation of the strike-slip faults could, for example, have resulted in the development of the secondary NNW-vergent mesofolds (II) that occur in the southern limb of the Gałęzice-Bolechowice Syncline. The fold axes of these mesofolds differ from those which occur lower and are generally SSW-vergent mesofolds (I); the latter folds (I) have a similar trend to that of the map-scale-folds (KONON 2006b, fig. 8), but only detailed palaeomagnetic studies could allow recognition of the timing of the development of the folds.

HCM during the Late Palaeozoic wrenching event in the European Variscides

The HCM fold belt is located eastwards of the Variscan Orogen thrust front (e.g. POŻARYSKI & *al.* 1992; DADLEZ & *al.* 1994; MIZERSKI 1995; SZULCZEWSKI 1995; KRZEMIŃSKI 1999; JAWOROWSKI 2002; MAZUR & *al.* 2006). Precise estimation of the present-day distance from the Holy Cross Mountains to the Variscan thrust front is problematic. According to the modern structural concept, the main front of the orogenic belt is the complex zone of deformation (e.g. VANN & *al*. 1986). In the simplest case, the tip line of the external fold-and-thrust belt of the Variscan Orogen should be defined as the tip line where the basal detachment is present, crops out on the present-day surface, or in the case of a blind thrust, where displacement at the basal detachment becomes zero (for discussion see BRESSER & WALTER 1999 and citations therein). According to this definition, a typical case occurs e.g. in northern France and southern Belgium, where the crustal-scale Ardennes Basal Thrust, along which the Ardennes fold-and-thrust belt is overthrust onto the Namurian–Westphalian coal-bearing foreland basin, represents the northern thrust front of the western European Variscan orogenic belt (e.g. MANSY & *al.* 1999; LACQUEMENT & *al.* 2005).

In western and central Poland it is difficult to trace the tectonic front because the external fold-and-thrust belt is buried deeply beneath the Permian-Mesozoic rocks and can be identified only on the basis of source area analysis (for discussion see SKOMPSKI 1995, 2006 and citations therein). These analyses suggest that the HCM fold belt probably lies presently about 100 km eastwards of the front of the main Variscan deformations (Text-fig. 1).

The HCM fold belt formed during the Late Palaeozoic as a result of NNE–SSW shortening (e.g. CZARNOCKI 1919, 1938, 1950, 1957a, b; TOMCZYK 1988; STUPNICKA 1992; MIZERSKI 1995; LAMARCHE & *al*. 1999, 2002).

The **I-1** faulting event, probably corresponding to the 'pre-intrusive stage' recognized at the NE boundary of the Upper Silesian Block, is related to strike-slip movements (ŻABA 1994, 1995, 1996, 1999) along the Kraków–Lubliniec Fault zone, mapped in detail by BUŁA (1994) and BUŁA & *al.* (2002) (Text-fig. 16a). During this stage of defor-

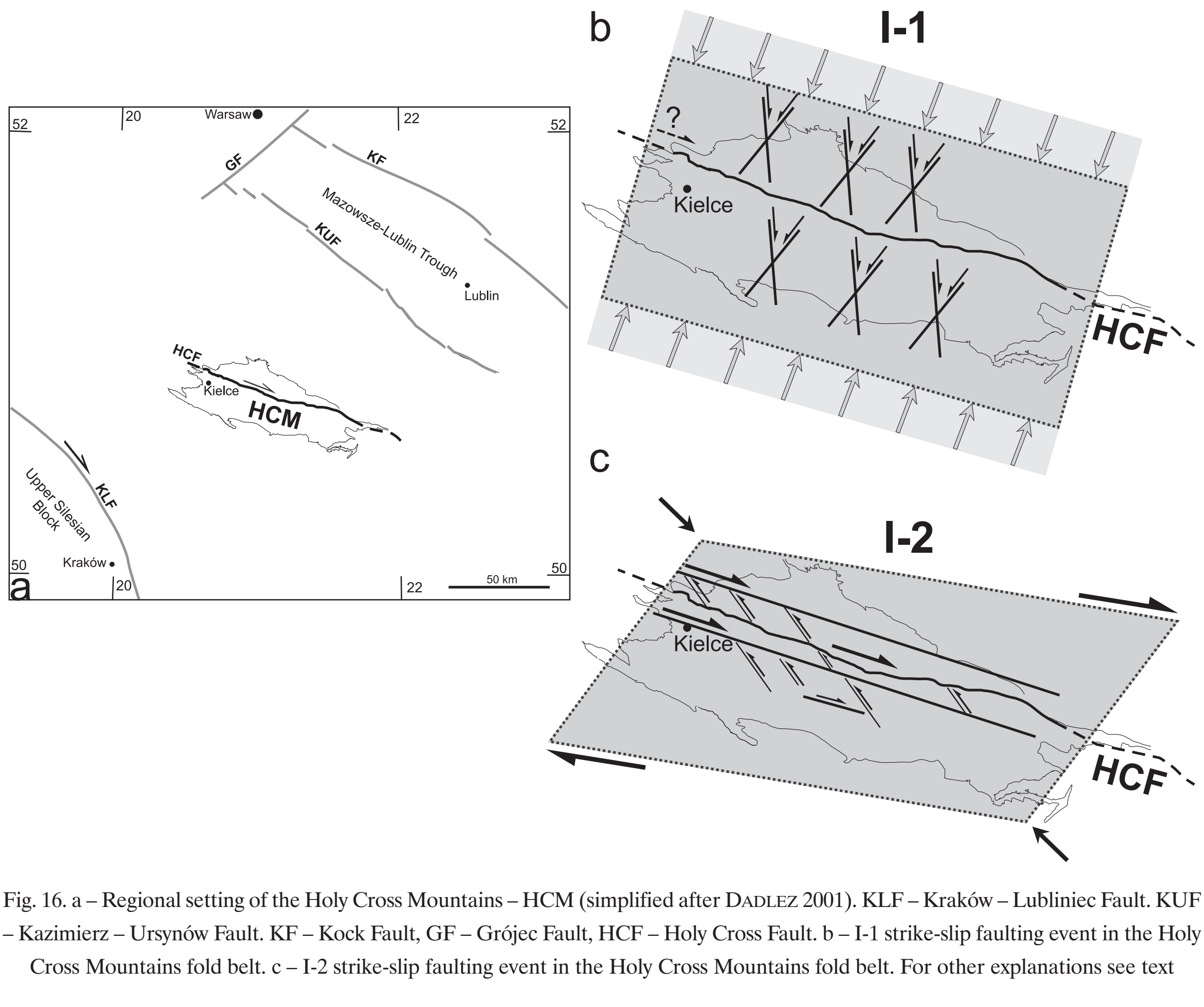

Fig. 16. a – Regional setting of the Holy Cross Mountains – HCM (simplified after DADLEZ 2001). KLF – Kraków – Lubliniec Fault. KUF – Kazimierz – Ursynów Fault. KF – Kock Fault, GF – Grójec Fault, HCF – Holy Cross Fault. b – I-1 strike-slip faulting event in the Holy Cross Mountains fold belt. c – I-2 strike-slip faulting event in the Holy Cross Mountains fold belt. For other explanations see text

mation (probably after Namurian A), folds and thrusts formed as a result of NNE–SSW shortening in a dextrally transpressive stress field (ŻABA 1996, 1999).

A similar NE–SW direction of shortening somewhat earlier, in the Late Tournaisian, probably also resulted in the formation of large-scale overturned folds in the Fore-Sudetic Monocline, involving the Variscan foreland basement (ŻELAŹNIEWICZ & *al.* 2003). During a further folding event, probably during the Late Namurian – Early Westphalian, the Upper Visean – Namurian A flysch succession was also folded (ŻELAŹNIEWICZ & *al.* 2003). North-eastwards of the Holy Cross Mountains, during the same event, folds resulting from NNE–SSW to NE–SW shortening formed (e.g. ANTONOWICZ & *al.* 2003; KRZYWIEC 2007, NARKIEWICZ & *al.* 2007).

Similar directions of shortening, recognized in the: Fore-Sudetic Monocline, NE part of the Upper Silesian Block, north-eastwards of the Radom-Kraśnik High and the HCM fold belt, suggest that this could have been a regional shortening direction (approximately NNE–SSW) at this time in the eastern termination of the European Variscides and its foreland.

The change of the regional shortening direction to approximately NW–SE in the eastern foreland area of the European Variscides, probably during the **I-2** faulting event, resulted in the domination of the strike-slip component along the NW–SE to NNW–SSE and WNW–ESE-striking faults and a significant decrease in the pure shear component across the longitudinal faults (Text-fig. 16). The **I-2** faulting event in the HCM fold belt probably corresponds to the 'syn-intrusive stage' (after Westphalian B), recognized by ŻABA (1996, 1999) at the NE boundary of the Upper Silesian Block. During this stage, as a result of NNW–SSE to NW–SE shortening, dextral transtension prevailed in the Kraków–Lubliniec Fault zone (ŻABA 1996, 1999) (Text-fig. 16a). The Kraków–Lubliniec Fault zone was a long-lived fault zone active until the Permian (BUŁA 1994; ŻABA 1996, 1999; BUŁA & ŻABA 2005).

During the Carboniferous, strike-slip activity probably also occurred in the Mazowsze-Lublin Trough (e.g. ŻELICHOWSKI 1972, 1983; NARKIEWICZ & *al*. 1998a, b; ŻYWIECKI & POPRAWA 2002; KRZYWIEC & NARKIEWICZ 2003; NARKIEWICZ 2003) (Text-fig. 16a) and in the Sudetes (ALEKSANDROWSKI 1990, 1995; MATTE & *al.* 1990; ALEKSANDROWSKI & *al.* 1997; ŻELAŹNIEWICZ 1997; ALEKSANDROWSKI & MAZUR 2002), and probably also in their foreland area (ŻELAŹNIEWICZ & CWOJDZIŃSKI 1994; MAZUR & *al.* 2006).

In Late Carboniferous and Permian times a number of major Variscan faults formed or became reactivated as dextral strike-slip faults (e.g. ARTHAUD & MATTE 1977; ZIEGLER 1989). For example, dextral strike-slip displacement occurred during Late Carboniferous–Early Permian time along faults in the strike-slip zone of the Elbe Fault System (e.g. ZIEGLER 1989, fig. 3; MATTERN 1996; FRANKE 1999) (Text-fig. 1). As in the Kraków-Lubliniec Fault zone, transtension occurred during the deformation in the Elbe Fault Zone (e.g. ONCKEN 1997). The fault zone acted also during the formation of the Permian Basins (e.g. SCHECK & *al.* 2002) and the Late Cretaceous/Palaeogene tectonic inversion (e.g. VOLKER 2003). Westwards of the Elbe Fault System, the Bray Fault, one of the major Variscan dextral strike-slip faults, was already active (from Namurian A) (MATTE & *al.* 1986), as well as a number of other strike-slip faults (e.g. ARTHAUD & MATTE 1977; HOLDSWORTH 1989; WARR 2002; SIMANCAS & *al*. 2005). Likewise, the strike-slip fault zones were active in north-western England, in the far foreland of the Variscan Orogen, about 300 km northwards of the front of strong Variscan folding (WOODCOCK & RICKARDS 2003).

CONCLUSIONS

- Based on detailed structural analysis, analysis of revised geological maps, aerial photo, radar, satellite and DEM-derived images in the Kielce Unit, and for comparison also in the Łysogóry Unit, a strike-slip fault network was recognized in the Holy Cross Mountains fold belt (HCM). The analysis enabled the identification in the study area of previously undescribed minor and map-scale tectonic structures associated with strike-slip faults, such as extensional normal faulting, contractional folds and horsetail splay at the terminations of faults, minor strike-slip faults, blocks rotated in domino style, right- and left-stepping, dextral restraining stepovers and drag of beds.
- The methods applied showed that the fault pattern during the Late Palaeozoic formed as a result of at least two strike-slip faulting events (I-1 and I-2).

- During the first strike-slip event (**I-1**), in the late phase of folding or already in the post-fold phase, a N–S-striking dextral strike-slip fault set and an approximately NNE–SSW to NE–SW-striking sinistral fault set developed (Text-fig. 16b). The shortening direction during the development of the fault sets was NNE–SSW, similar to that obtaining during folding after the Viséan.
- During the second strike-slip faulting event (**I-2**), the dextral strike-slip component occurred along the WNW–ESE-striking longitudinal faults and the sinistral strike-slip component along the NW–SE to NNW–SSE-striking fault set. The shortening direction rotated counter-clockwise to an approximately NW–SE direction. Across the WNW–ESE-striking longitudinal faults, which formed during folding, the pure shear component decreased significantly and the dextral strike-slip component began to dominate along the master faults. These fault zones accommodated most of the strike-slip displacement. Between the dominating master faults, as in the model of SCHREURS (2003), secondary sinistral strike-slip faults were formed (Text-fig. 16c).
- The strike-slip fault network in the HCM formed during the Late Palaeozoic was slightly overprinted during the Maastrichtian/Palaeocene second strike-slip stage (e.g. JAROSZEWSKI 1972; KONON & MASTELLA 2001; MASTELLA & KONON 2002).

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