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Evidence of Late Cretaceous/Cenozoic strike-slip faulting within the late Palaeozoic Holy Cross Mts. Fold Belt, Poland: Józefka releasing stepover

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ABSTRACT:

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The aim of this study was to reconstruct the location mechanism of a Triassic sandstone wedge within folded Palaeozoic rocks. A vertically oriented Buntsandstein succession (Lower Triassic) from Józefka Quarry (Holy Cross Mountains, central Poland), steeply wedged within folded Devonian carbonates, is recognised as an effect of normal faulting within a releasing stepover. The sandstone succession, corresponding to the Zagnańsk Formation in the local lithostratigraphic scheme, is represented by two complexes, interpreted as deposits of a sand-dominated alluvial plain (older complex), and coarse-grained sands and gravels of a braided river system (younger complex). The sandstone complex was primarily formed as the lowermost part of the several kilometres thick Mesozoic cover of the Holy Cross Mountains Fold Belt (HCFB), later eroded as a result of the Late Cretaceous/Paleogene uplift of the area. Tectonic analysis of the present-day position of the deformed sandstone succession shows that it is fault-bounded by a system of strike-slip and normal faults, which we interpret as a releasing stepover. Accordingly, the formation of the stepover in the central part of the late Palaeozoic HCFB is evidence of a significant role of strike-slip faulting within this tectonic unit during Late Cretaceous/Paleogene times. The faulting was probably triggered by reactivation of the terminal Palaeozoic strike-slip fault pattern along the western border of the Teisseyre–Tornquist Zone.

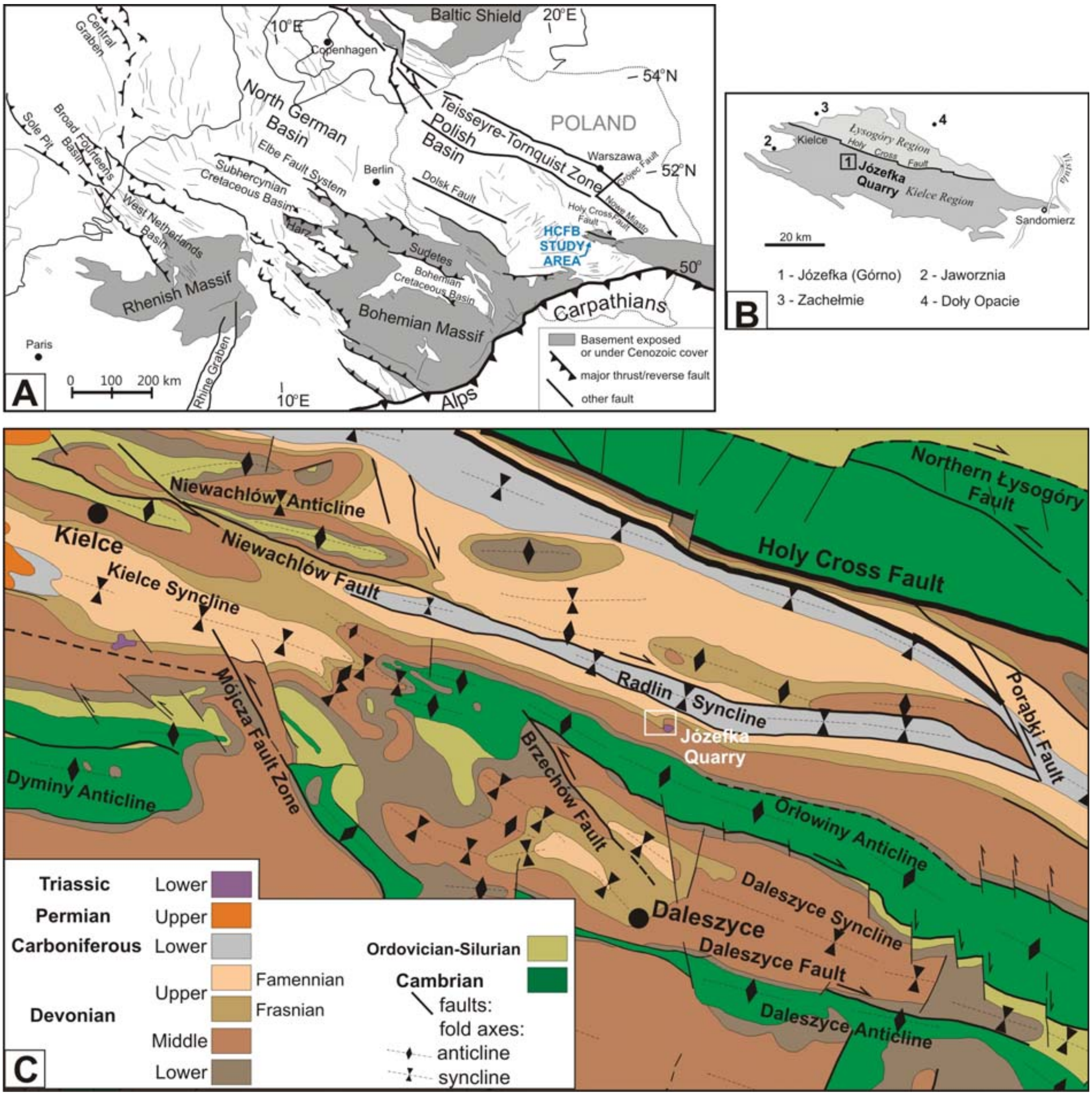
Key words: Strike-slip faulting; Releasing stepover; Holy Cross Mountains; Buntsandstein.

INTRODUCTION

A new finding of a Buntsandstein (Lower Triassic) succession, nearly vertically oriented and steeply wedged in a folded Devonian carbonate succession, was inspiration for the research presented in this paper. The aim of this paper is to reconstruct the tectonic process responsible for the location of a thick sandstone complex within the central part of the late Palaeozoic Holy Cross Mountains Fold Belt (HCFB) in central Poland, along the western border of the Teisseyre–Tornquist Zone (Text-fig. 1A, B).

Sedimentological and petrographic investigations of this complex, otherwise lacking palaeontological indicators, has enabled the recognition of its stratigraphic position by analogy to other Buntsandstein sections of the area. The discovery that the investigated sandstones are fault-bounded by dextral strike-slip faults and normal faults has allowed us to explain the relationships between these Lower Triassic rocks and the structures of the late Palaeozoic HCFB as an effect of normal faulting within a releasing stepover.

Releasing stepovers connected with normal faults are structures commonly recognised worldwide along

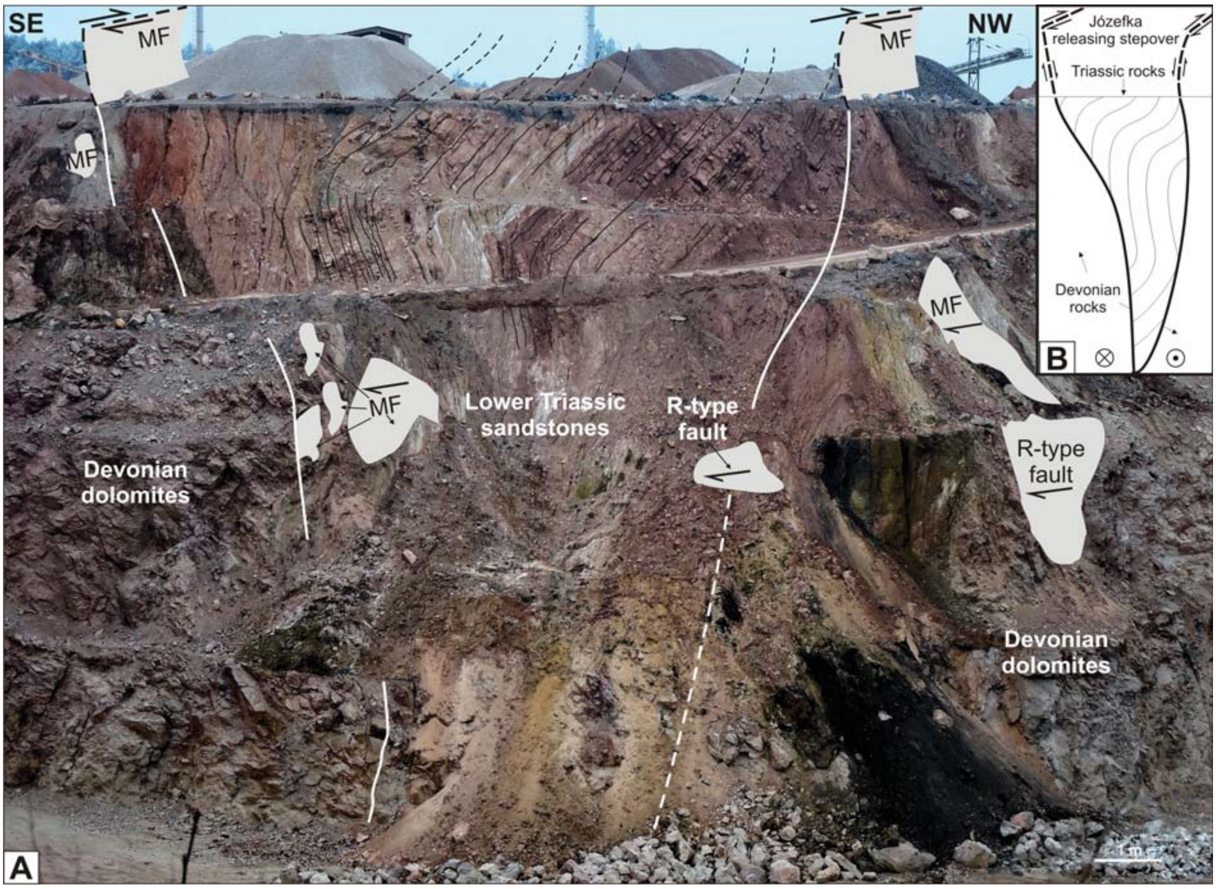


Text-fig. 1. Location of the investigated area. A – Position of the Holy Cross Mountains vs. epicontinental Mesozoic basins and the Teisseyre–Tornquist Zone (simplified after Kley and Voigt 2008, modified); B – Palaeozoic Holy Cross Mts. Fold Belt, subdivided into the Łysogóry and Kielce regions (grey), surrounded by a Mesozoic succession (white); numbers indicate position of quarries mentioned in the text; C – fragment of geological map of the Holy Cross Mts. (based on Czarnocki 1938; Filonowicz 1970; modified by Konon 2007)

the overstepping segments of parallel strike-slip faults (e.g., Crowell 1974; Reading 1980; Garfunkel 1981; Aydin and Nur 1982; Christie-Blick and Biddle 1985; Sylvester 1988; Woodcock and Schubert 1994; Dooley and McClay 1997; Wakabayashi *et al.* 2004; Wakabayashi 2007). The interaction of both strike-slip and normal faults allows for the formation of local transtensional areas between them. A characteristic feature of releasing stepovers is that the structures tend to subside vertically and that the formation of strike-slip basins is very rapid (e.g., Woodcock and Schubert 1994).

REGIONAL SETTING

Palaeozoic rocks forming the HCFB were folded and uplifted at the end of the Mississippian and eroded



Text-fig. 2. A – General view of the SW wall of Józefka Quarry with Devonian dolomites and a fault-bounded Buntsandstein succession, enlarged view in Text-fig. 5; B – simplified scheme of Józefka releasing stepover. MF – major fault

during the Pennsylvanian and Permian. Afterwards, they were completely covered by a several kilometres thick Mesozoic succession. The Late Cretaceous uplift of the region caused the nearly complete erosion of the Mesozoic complex (Kutek and Głazek 1972) and formed the present-day structure, where the HCFB, composed of Palaeozoic rocks, is visible in an erosional window (inlier) surrounded by rocks forming the Mesozoic margin and Miocene infilling of the Carpathian Foredeep (Text-fig. 1B).

The Triassic rocks, generally flat-lying in this region, unconformably overlie folded Palaeozoic rocks. The epi-Variscan unconformity is perfectly visible in the spectacular outcrops in Zachełmie (e.g., Kuleta and Zbroja 1995; Szulczewski 1995b; Waksmundzki 2012; Złonkiewicz and Becker 2015) and Doły Opacie (Jaroszewski 1976) quarries, situated in the western and eastern parts of the northern Mesozoic margin, as well as in Jaworznia Quarry (Głazek and Romanek 1976, 1978; Kuleta 1999) to the west of Kielce (Text-fig. 1B). Within the HCFB, the outcrops are not so impressive. They are concentrated in the south-western part of the Palaeozoic inlier, more or less related to the development of Permian to Triassic karst (Urban 2007, 2013) and infilling of palaeokarst forms or tectonic fissures (e.g., Głazek and Roniewicz 1976; Nawrocki 1987; Wierzbowski 1997). Small patches of flat-lying Triassic sandstones directly overlying the Palaeozoic bedrock are the only relics of the HCFB cover. Therefore, the occurrence of isolated, vertically oriented strongly deformed Triassic rocks within the central part of the HCFB, described in this report, is one of the crucial arguments in the discussion on the Mesozoic/Cenozoic evolution of the area.

The position of Józefka Hill in this context is exceptional. According to the earlier cartographic observations of Czarnocki (1938) and Filonowicz (1970), the top of this hill, generally composed of Devonian dolomites and limestones, was covered by a few metres of Buntsandstein sandstones. During the prospecting works for dolomite deposits (Żurak and Olszewska 1988; Żurak 2016) several outliers of such sandstones were documented there. All of them were completely destroyed during the exploitation in the quarry, which also removed the entire hill. However, at the same time, a nearly vertically oriented Buntsandstein succession has been revealed (Wysocka and Skompski 2016). It comprises an about 50 m thick succession of clays, mudstones, sandstone and conglomerates (Text-fig. 2). The perfectly exposed unit has allowed us to trace the changes of the sedimentary environment of the exceptionally long Buntsandstein interval, analogous to successions known only from boreholes located outside the Palaeozoic of the Holy Cross Mountains.

TECTONIC SETTING

The late Palaeozoic HCFB was formed by the end of the Mississippian as a result of NNE–SSW shortening (e.g., Czarnocki 1919, 1957; Tomczyk 1988; Stupnicka 1992; Mizerski 1995; Lamarche *et al.* 1999, 2002; Konon 2006). The fold belt consists of series of map-scale folds. Bedding-parallel shortening during the fold growth favoured buckle folding in the HCFB, which resulted in the formation of reverse faults striking parallel to the fold axes (Konon 2006). The process of folding terminated prior to the late Permian (e.g., Czarnocki 1938) and later these deformations were overprinted during uplift in Late Cretaceous/Palaeocene times (e.g., Jaroszewski 1972; Kutek and Głazek 1972; Kutek 2001). This second stage of deformation resulted in slight modification of the shapes of the earlier formed folds of the HCFB (Kutek and Głazek 1972; Lewandowski 1982, 1985; Szaniawski *et al.* 2011). During the late Palaeozoic, the folds of the HCFB were dissected by strike-slip faults (Mastella and Mizerski 2002; Konon 2007).

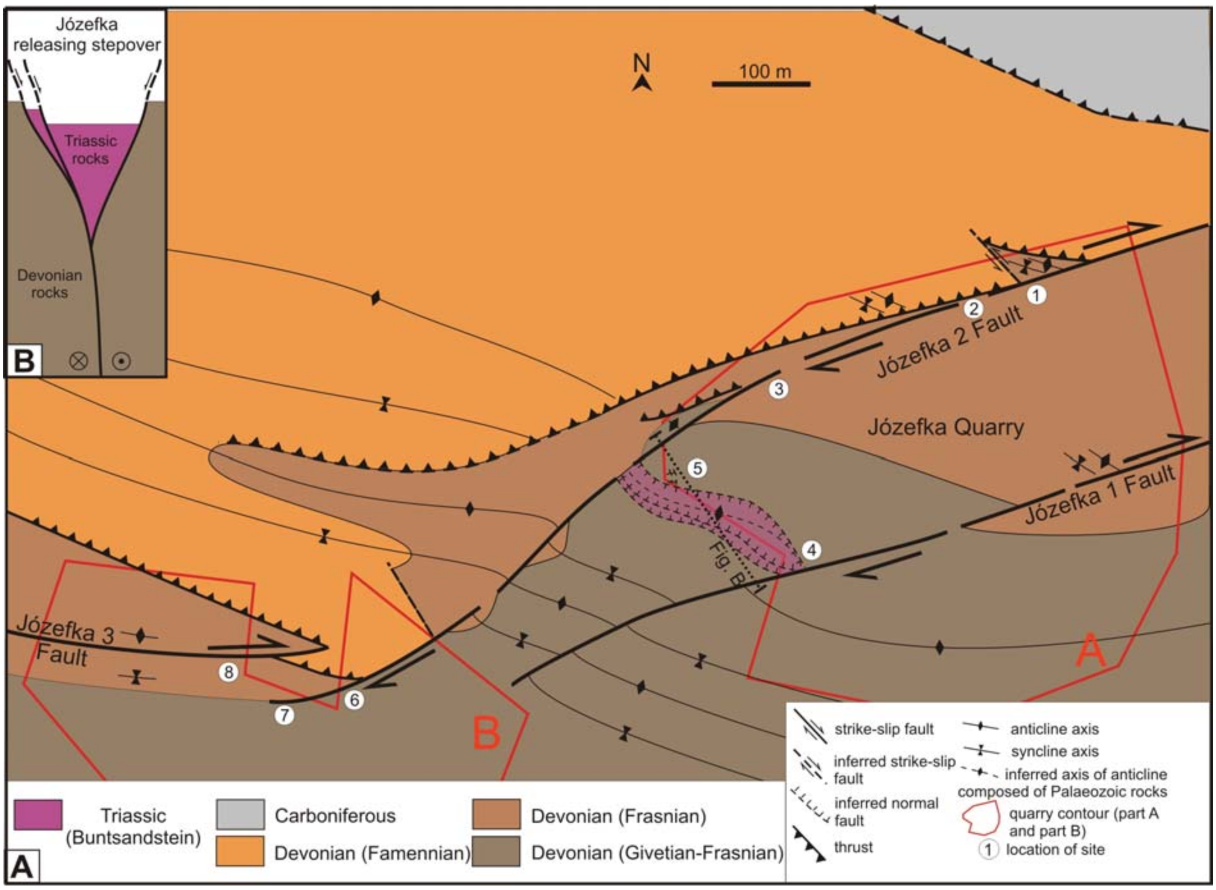
The location of the late Palaeozoic HCFB, with its Mesozoic cover in the transition zone between the Polish-North German Basin that is part of the Central European Basin System (e.g., Kutek and Głazek 1972; Ziegler 1982, 1990a, b; Dadlez *et al.* 1995; Dadlez 1997, 2003; Krzywiec 2000, 2002; Kutek 2001; Scheck *et al.* 2002; Mazur *et al.* 2005; Scheck and Lamarche 2005; Reicherter *et al.* 2008) and the northern Tethys shelf (Matyja 2009), defines the unique position of the region. Hence, the newly discovered releasing stepover is discussed in the context of reactivation of the late Palaeozoic strike-slip fault pattern during Mesozoic/Cenozoic times. It was a result of inversion tectonics along the northern Peri-Tethyan Platform during the Late Cretaceous.

The strike-slip fault pattern in the HCFB generally consists of WNW–ESE-striking longitudinal dextral faults (Text-fig. 1C) as e.g., the Holy Cross, Northern Łysogóry, Daleszyce, and Niewachlów faults, and a NW–SE to NNW–SSE-striking sinistral secondary strike-slip fault set, such as e.g., the Mójcza, Porąbki, and Brzechów faults (Konon 2007). Strike-slip faulting resulted from the transmission of horizontal stress during the collisional phases in the Variscan Orogen (Konon 2007).

The strike-slip fault network in the HCFB was later overprinted during the Turonian/Palaeocene strike-slip stage of deformation (e.g., Jaroszewski 1972; Konon and Mastella 2001; Mastella and Konon 2002; Konon 2007; Konon *et al.* 2016). The fault pattern that developed within the Permian−Mesozoic cover generally consists of major faults, with axes parallel to Mesozoic−Cenozoic folds and second-order transverse and oblique faults (Czarnocki 1938, 1948; Kutek and Głazek 1972; Stupnicka 1972; Konon and Mastella 2001; Mastella and Konon 2002; Konon *et al.* 2016**)**. Major faults prevail to the west and south of the HCFB. The fault sets comprise NW–SE and NNW–SSE-striking faults, as well as WNW–SSE-striking faults (Konon *et al.* 2016). The dextral strike-slip component of movement has already been recognised along major strike-slip faults that dissect the Permian−Mesozoic strata to the west and south of the Palaeozoic tectonic unit (Konon and Mastella 2001; Mastella and Konon 2002; Konon *et al.* 2016). The present-day interpretations suggest that the strike-slip faulting, active during the Late Cretaceous/Palaeocene times, has resulted from the transmission of horizontal stress from the zone of continent collision in the Pyrenees on European crust (Kley and Voigt 2008; Reicherter *et al.* 2008), considered earlier to be a result of deformation stages in the Alpine and Carpathian orogens or associated with the Late Cretaceous opening of the Atlantic (e.g., Ziegler 1987, 1990a, b; Golonka *et al.* 2000; Dadlez 2003; Mazur *et al.* 2005).

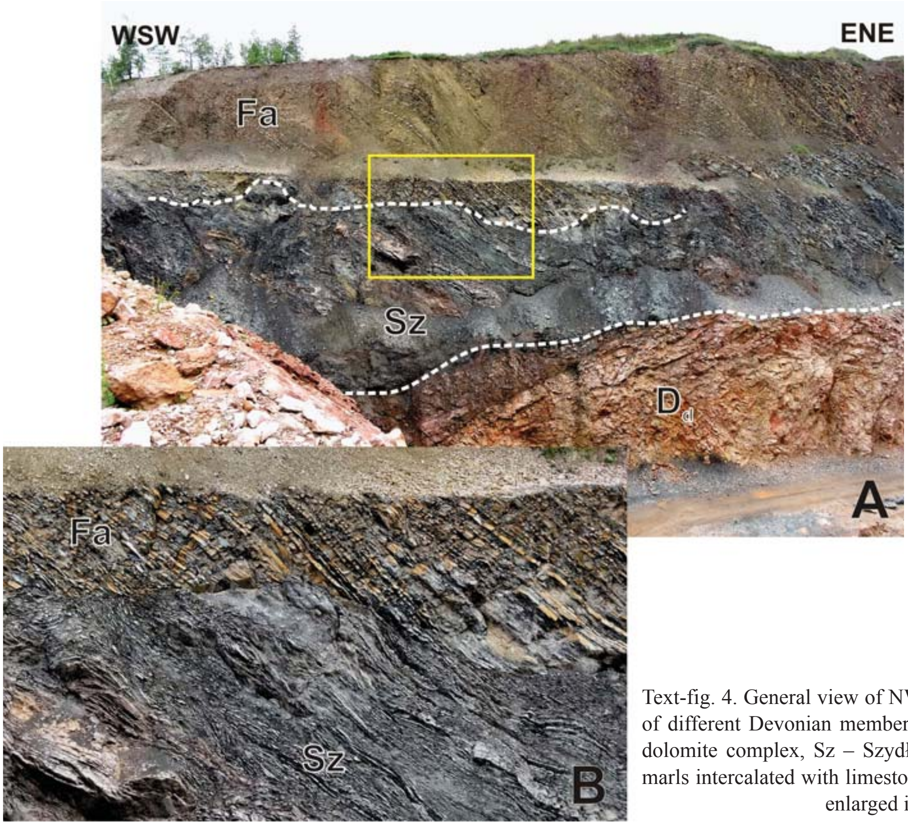
THE DEVONIAN SUCCESSION OF JÓZEFKA HILL

Józefka Hill is located south of Górno village (Text-fig. 1C) in the southern limb of the Radlin Syncline, one of the map-scale folds forming the



Text-fig. 3. A – Geological map of the part of the southern limb of the Radlin syncline (based on Filonowicz 1970, modified). B – Sketch of the subsided area within the releasing stepover

HCFB. This syncline is composed of Devonian strata in the limbs and lower Carboniferous rocks (Culm facies) in the hinge zone. The Radlin Syncline forms a typical m-fold comprising two second-order synclines with a smaller subsidiary anticline in the hinge zone bordered by faults striking parallel to the fold axes (Czarnocki 1948; Żakowa and Pawłowska 1961). An even more complex tectonic pattern is visible within a large quarry, located in the central part of the hill and composed of 2 exposures (A and B in Text-fig. 3). Generally, Middle and Upper Devonian dolomites and limestones are exposed in the quarry and sub-divided into 5 complexes (in a stratigraphic order): Givetian dolomites with an uppermost fossiliferous set corresponding to the *Stringocephalus* Beds; Givetian marly-limestone units of the Laskowa (Góra) Beds; Givetian to Frasnian black bituminous limestones of the Szydłówek Beds; Frasnian Kostomłoty Beds dominated by platform slope detritic limestones, and finally a thick succession of Famennian basinal limestones regularly intercalated with marly shales (see Małkowski 1981; Vierek 2008, 2014; Baliński *et al.* 2016; Zawadzka 2016; for general characteristics of the Devonian in the Holy Cross Mountains see Szulczewski 1971, 1995a and Racki 1993). The units presented above are recognised in the eastern wall of quarry A in a normal succession, but the contacts between them are usually of a tectonic nature. The numerous overthrusts with NW-dipping surfaces have modified this succession in the north-western wall (Text-fig. 4). On the lowermost level of the quarry, the dolomites contact with the Szydłówek Beds, which abound in lens-shaped mass occurrences of brachiopods (Skompski *et al.* 2018). The stratigraphically younger units (Upper Frasnian to Famennian) appear on the higher levels of the quarry (Text-fig. 4). They are composed of marls intercalated with micritic limestones (diverse thickness relationships of both lithotypes) and pelagic nodular limestones.



Text-fig. 4. General view of NW wall of Józefka Quarry. Contacts of different Devonian members overthrust in SE direction; Dd – dolomite complex, Sz – Szydłówek Formation, Fa – Famennian marls intercalated with limestones; yellow rectangle indicates part enlarged in Text-fig. 4B

BUNTSANDSTEIN SUCCESSION

The south-eastern wall of quarry A is generally composed of dolomites, although a red-coloured complex of terrigenous rocks, dominated by sandstones and conglomerates (Text-figs 5 and 6), typical of the Lower Triassic Buntsandstein facies, appears in its middle part. Their orientation is nearly vertical (Text-figs 2 and 5A), with strikes varying from 60º to 80º, contrasting with the general strike of Devonian rocks, varying from 100º to 140º, and a general dip angle of 45º to 60º NW. The sandstone complex occurs on the higher levels of quarry A and is absent on the bottom level of quarries A and B.

Petrographic and sedimentological interpretation

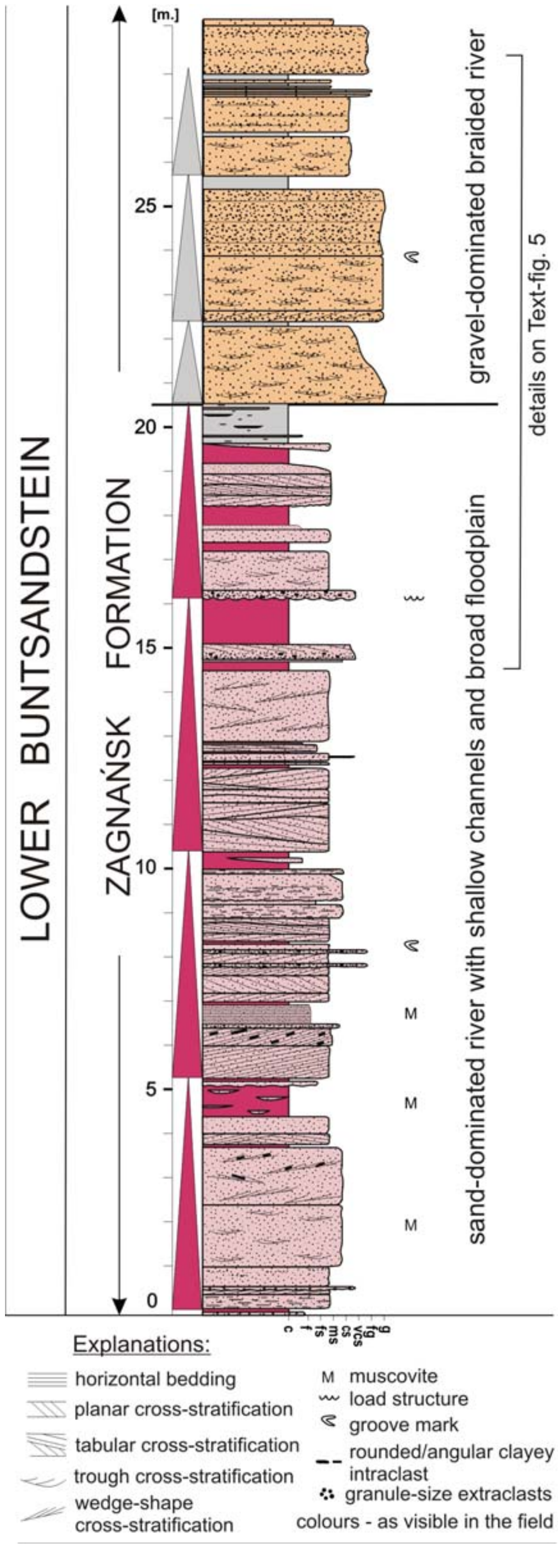
The investigated section of the Buntsandstein is characterised by a bi-partite clastic succession (Text-fig. 6), a sand-dominated lower complex and a gravel-dominated upper complex.

The red, planar cross-stratified sandstones with clayey interbeds are the most typical rocks of the lower part. Sandstones are poorly- to well-sorted, medium- to coarse-grained, occasionally with gravel-sized clasts. Sandstone units are represented by centimetre- to decimetre-thick sets building metre-thick cosets that are organised in four, normal graded sedimentary cycles (Text-figs 5A and 6) starting with a prominent erosional surface. The relatively thick reddish siltstones and claystones capping the fining-upward sequences indicate deposition during the lowest velocity flow. Based on XRD analysis, all clayey deposits are characterised by the occurrence of quartz, muscovite, kaolinite, dolomite and illite with additional hematite. Occasionally, muddy intraclasts are dispersed within these fine-grained deposits.

The upper part of the Buntsandstein succession is predominantly composed of sand- and clast-supported, poorly to well-sorted, sub-rounded to well-rounded granule to pebbly conglomerates (Text-figs 5B and 6), and poorly sorted pebbly sandstones. The bed thickness is up to several centimetres, moreover, the beds are highly amalgamated and characterised by low angle trough cross-stratification (Text-fig. 5B). Results of sieve analysis of the coarse-grained deposits show that the deposits can be classified as coarse and very coarse sand (Mz

Text-fig. 5. Buntsandstein succession on the SW wall of Józefka Quarry. A – lower (a) and upper (b) parts of the bi-partite clastic fluvial succession; fining upward cyclothems are indicated; B – trough cross-stratified coarse-grained sands and gravels within the upper part of succession; C – normal-graded cycles within the lower part of the succession, note abundant intraclasts in the upper part of the cycle (white arrow) as well as extraclasts in the coarse-grained lower part of the cycles (black arrow); D – normal-graded subcycles within the lower part of the succession

from 0.12 to −0.1); the standard deviation values (1.89–2.01) indicate very poor and poor sorting of the deposits. Sieve analysis indicates that the content of gravel- and sand-size classes is c. 40% and 60%, respectively. Silt- and clay-sized classes comprise less than 2%. Taking into account the percentage data, the studied coarse-grained deposits can be classified as sandy gravels. Petrographic analysis of thin sections of the studied deposits allowed the distinguishing of several lithological types of the gravel-sized clasts, dominated by chert fragments (Text-fig. 7A, C). They are usually composed of subrounded and subangular microquartz. Remnants of siliceous microfossils, such as radiolaria and sponge spicules, were noted in a few grains only. The second dominant lithological type includes quartzite lithoclasts, composed of metamorphically deformed, subangular, subrounded and rarely rounded quartz grains (Text-fig. 7B). The next group is represented by granitoid rock fragments, which are subrounded and subangular and made up of quartz, and rarely feldspar and muscovite crystals. Sedimentary rock fragments are represented by subrounded and subangular siltstones (Text-fig. 7C) and sandstones (Text-fig. 7D). Siltstones are composed of quartz grains, but mica flakes also were noted. Quartzose cement was noted in the arenites, with a minor addition of micas and heavy minerals. The next lithological type is represented by quartzitic sandstones, in which, due to diagenetic processes such as compaction, dissolution and recrystallization of the primary matrix, the boundaries between the grains cannot be identified (Text-fig. 7E). The clasts are better rounded than the other lithological types observed in the studied deposits. Gravel-sized single quartz grains, sporadically noted during the analysis, are represented by subrounded or subangular polycrystalline grains (Text-fig. 7F). Moreover, gneisses and schists were rarely noted, as similarly were volcanic rock fragments (Text-fig. 7G).



Text-fig. 6. Lithological column of the investigated Buntsandstein complex; grain fraction is indicated as: c – clay, f – silt, fs – fine sand, ms – medium sand, cs – coarse sand, vcs – very coarse sand, fg – fine gravel, g – gravel. Triangles on the left side of the column indicate fining-upward cyclothems.

The matrix of the studied deposits is composed of grains representing sandy grain-size classes. Because quartz predominates and other components such as lithoclasts, micas and heavy minerals are rarely present, the matrix is mineralogically mature. It is cemented by autogenic quartz developed mostly as overgrowths around the grains. Concavo-convex and sutured contacts between the matrix grains point to advanced diagenetic processes such as compaction and pressure dissolution.

The alternation of fine-grained facies with coarse sediment admixtures within the lower complex indicates deposition from bedload transport in sand-dominated fluvial channels, carrying dune-scale sinuous- and straight-crested barforms covered with ripples, in continuous, highly variable sediment discharge. The red colour of the siltstones and claystones from the topmost part of normal graded cyclothems may suggest oxidizing conditions during or after deposition. Generally, all features of the rocks included to the lower complex point to deposition in hot, oxidizing conditions in a sand-dominated river system, probably characterised by a river plain with rather shallow channels and a broad floodplain (Text-fig. 6).

The results of the analysis of the upper complex indicate that the deposits were transported in a high-energy sedimentary environment and/or point to relatively short transport. The textural, structural and petrographic features indicate deposition from bedload transport in the form of barforms with different fluid flow and sediment discharge that is characteristic of gravel-dominated fluvial channels typical of braided rivers.

Lithostratigraphy

No micropalaeontologic indexes have been found in the investigated sandstone succession. Therefore, the only possibility of estimating the stratigraphic position of the complex is by lithostratigraphic analogy and correlation with sedimentary events, known from better recognised successions.

At the end of the Permian and the beginning of the Triassic, the landscape of the Variscan Holy Cross

Text-fig. 7. Lithological types of the gravel-sized clasts and matrix of the coarse-grained deposits from the Buntsandstein succession in Józefka Quarry. A – chert (cht) surrounded by quartzose matrix; B – quartzite (qtz); C – siltstone (Z) and chert (ch) stick in matrix; D – sandstone (S); E – quartzitic sandstone (qtzS) surrounded by poorly sorted matrix; F – monocrystalline quartz grain (Q) encompassing by poorly sorted matrix; G – volcanic rock fragment (vc); H – poorly sorted matrix cemented by autogenic quartz and composed of quartz grains and a few lithoclasts

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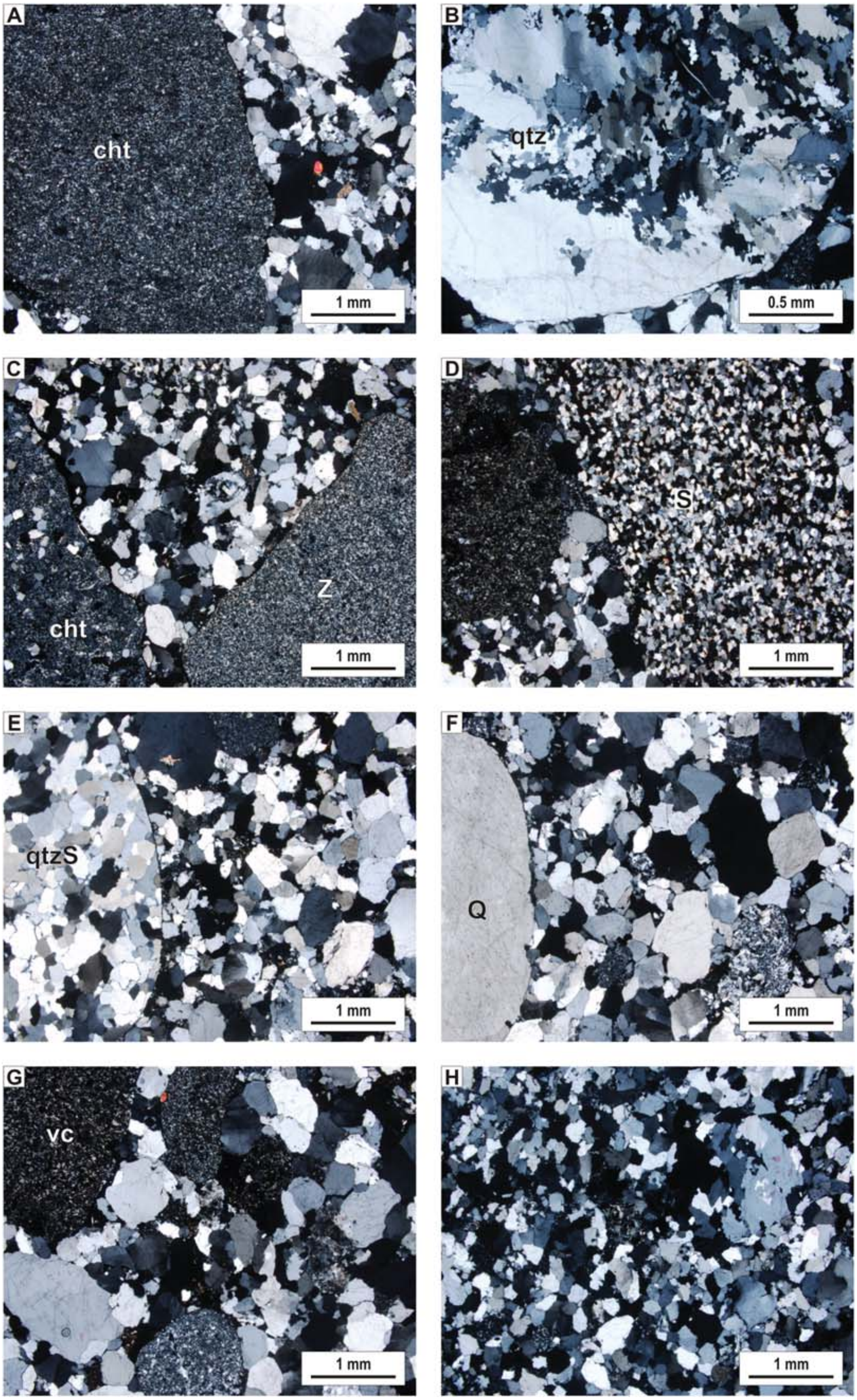
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Mts. was typical of a peneplained upland, with low ranges of hills corresponding to the axial parts of anticlines and valleys formed in the axial parts of synclines. The location of the western mouths of the valleys is well indicated by the distribution of earlier Zechstein sediments, which were deposited in narrow bays that were open westwards (Bełka 1991; Kuleta and Zbroja 2006). Terrigenous clastic material of the Buntsandstein facies, transported from the south and south-east (Senkowiczowa and Ślączka 1962), was initially deposited in localised karstic depressions or tectonic traps, and finally infilled also the valleys. During erosion after the uplift of the area at the end of the Cretaceous, these sediments had the greatest chance of being preserved. This explains why all relics of the Buntsandstein cover in the central part of the Holy Cross Mts., trustworthily presented by Czarnocki (1938), i.e., the Wietrznia Quarry, a small patch of sandstones in the Zagórze district of Kielce, and occurrences to the south of Radlin village and Józefka Hill, are located in the axis of a palaeovalley, running from Szczukowice village in the west to Górno village in the east. It is obvious that the search for lithostratigraphic analogies of the Józefka succession should concentrate on the borehole sections west of Kielce, where the Buntsandstein succession is more complete. According to the data presented by Kuleta and Zbroja (2006), the region of Szczukowice, the western suburb of Kielce, penetrated by several boreholes, is the best analogue to the Józefka succession. The lower Buntsandstein succession in this area is unusually thin and composed practically of 2 units: the Szczukowice and the Zagnańsk formations (Kuleta and Zbroja 2006, fig. 7: Szczukowice IG-2 borehole).

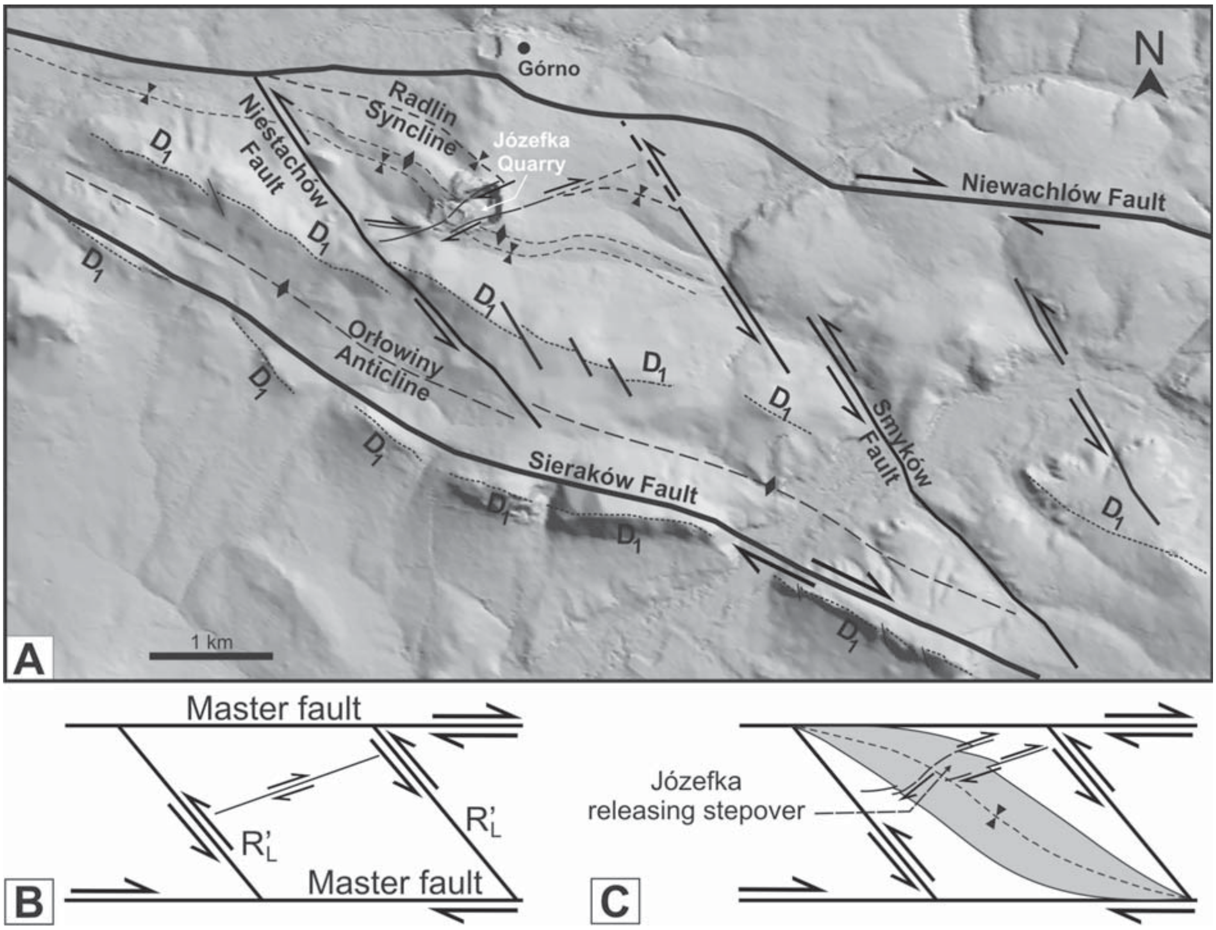
The Buntsandstein succession investigated here most probably corresponds to the Zagnańsk Formation. This comparison is confirmed by the general lithology and sedimentary features, indicating transition from a sand-dominated river plain with shallow channels to a coarse-grained sandy-gravel braided river system. This similarity is also emphasised by the specific petrographic content of the Zagnańsk sandstones, which are characterised by numerous grains of volcanic rocks and micas, a feature that is also typical of the Józefka succession. According to Kuleta and Zbroja (2006), the Zagnańsk Formation represents a regressive unit in comparison to the lower Szczukowice Formation. The suggested lowering of the erosional base could cause a more dynamic environment of erosion and transportation of coarser clastic material, and in consequence the appearance of numerous gravel intercalations. The succession of both parts of the investigated section confirms this model.

JÓZEFKA RELEASING STEPOVER

The Józefka stepover forms a right-stepping stepover zone, comprising at least three segments of the generally WSW–ENE-trending major strike-slip faults termed as Józefka: 1, 2 and 3, and connected with NW–SE-striking second-order normal faults (Text-figs 1C and 8). The major strike-slip faults connect with the Niestachów and Smyków faults and dissect the axis of the Radlin Syncline and the axes of smaller, second-order folds belonging to the southern limb of the syncline (Text-figs 1 and 8). The offset of the fold axes is c. 100 m. The strike-slip and normal components of movement across the major faults are confirmed based on field observations of slickensides on the major and subsidiary faults, as well as bed drag (Text-figs 9–11). The senses of movement along the major and subsidiary R and R_1 type strike-slip fault planes indicate that the faults represent dextral strike-slip faults. The subsidiary faults R are consistent with Riedel shears (Riedel 1929). The R_1 type faults formed at the dolomite/limestone contact. The faults are also consistent with Riedel shears but their relation to the major fault planes suggests that the changes of their strikes resulted probably from the refraction of the fault traces during propagation of the faults through dolomites and limestones of strongly differing competency.

The stepover is a small structure, c. 210 m wide and c. 550 m long, which points to a length-to-width ratio of 2.6. All of the major fault planes have a non-planar geometry and dissect Palaeozoic rocks (Text-fig. 1). Part of the major strike-slip fault system formed along reactivated sub-vertically dipping thrust planes (Text-figs 1 and 10).

Lower Triassic sandstones representing the Buntsandstein facies are nearly vertically wedged within the central part of the stepover, between the segments of the Józefka 1 and Józefka 2 major dextral strike-slip faults (Text-fig. 2). The position of the sandstone complex, fault-bounded by dextral strike-slip faults and normal faults in relation to the Palaeozoic rocks cut by the faults, suggests that the tectonic structure formed as a releasing stepover. The system of Józefka faults forming the stepping zone developed between two oblique faults, the Niestachów and Smyków faults, which in turn connect with the major Niewachlów and Sieraków faults striking parallel to the fold axes (Text-figs 1 and 8).



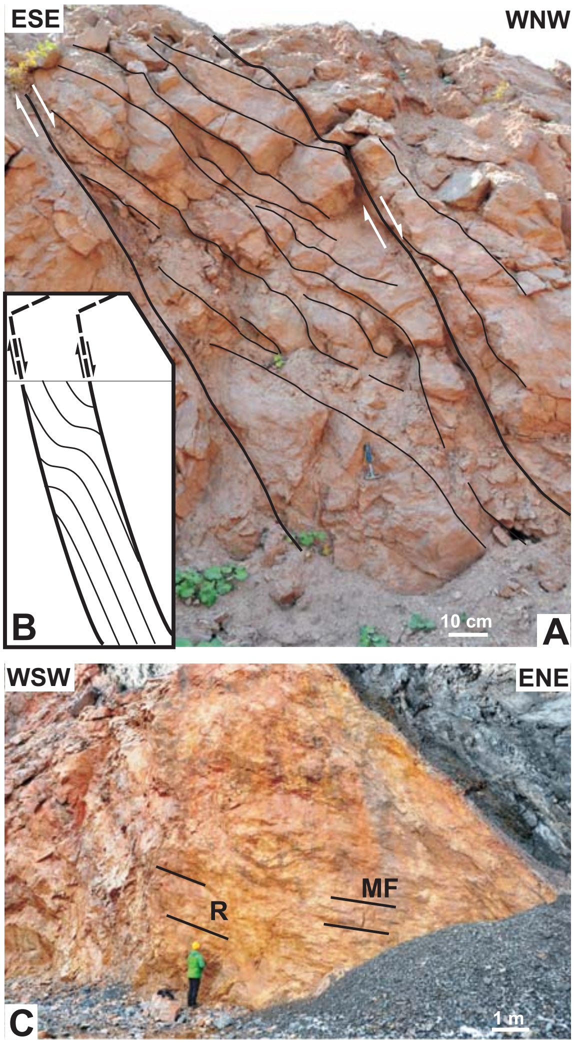
Text-fig. 8. A – Simplified tectonic map of the Józefka releasing stepover area marked on a shaded-relief Shuttle Radar Topography Mission (SRTM) image (based on Czarnocki 1938; Filonowicz 1970; Konon 2007; modified). B – Tectonic sketch displaying the fault pattern consistent with analogue model experiments of Schreurs (2003). C – Tectonic sketch displaying formation of the Józefka releasing stepover

DISCUSSION

The fault pattern in the central part of the late Palaeozoic HCFB, consisting of WNW–ESE-trending master faults and NW–SE- to NNW–SSE-trending second-order faults, was recognised by Konon (2007) as very similar to that developed during the analogue model experiments of Schreurs (2003). In these experiments, both brittle and viscous materials were used, which allowed for the investigation of faulting in rheologically strongly contrasting materials. The strongly contrasting unmetamorphosed sedimentary rock sequences comprising alternating competent (dolomites, limestones, sandstones, quartzitic sandstones) and incompetent (shales, thin-bedded limestones) beds in the HCFB probably favoured the formation of the characteristic strike-slip fault pattern (Konon 2007). Using these analogies, according to Schreurs' terminology, the Niewachlów and Sieraków faults represent master dextral strike-slip faults, and the oblique Niestachów and Smyków sinistral strike-slip faults are consistent with faults termed as R'_L (Text-fig. 8).

Between the master Niewachlów dextral strike-slip fault and the antithetic second-order Niestachów sinistral fault, a synthetic dextral strike-slip fault, consistent with the RL type fault of the Schreurs' model, could have developed (Schreurs 2003, fig. 11). The Józefka releasing stepover formed within the stepping zone of the R_L type fault.

According to the Schreurs' model, the R_L type fault developed as a result of counter-clockwise rotation of the direction of local maximum compressional stress S1 between master parallel faults. This



Text-fig. 9. Examples of normal and strike-slip faults. A – Normal fault sets from the zone bordering the subsided area within the releasing stepover (site No. 5). See characteristic dragging of the beds between two sets of normal faults. B – sketch displaying dragging of the beds. C – Slickensides of the main dextral strike-slip Józefka 2 fault (MF) and subsidiary R type faults (site No. 3). See text for explanations. For location see Text-fig. 3A

means that the orientation of the far-field maximum horizontal compressional stress SHmax may differ in orientation from the local stress S_1.

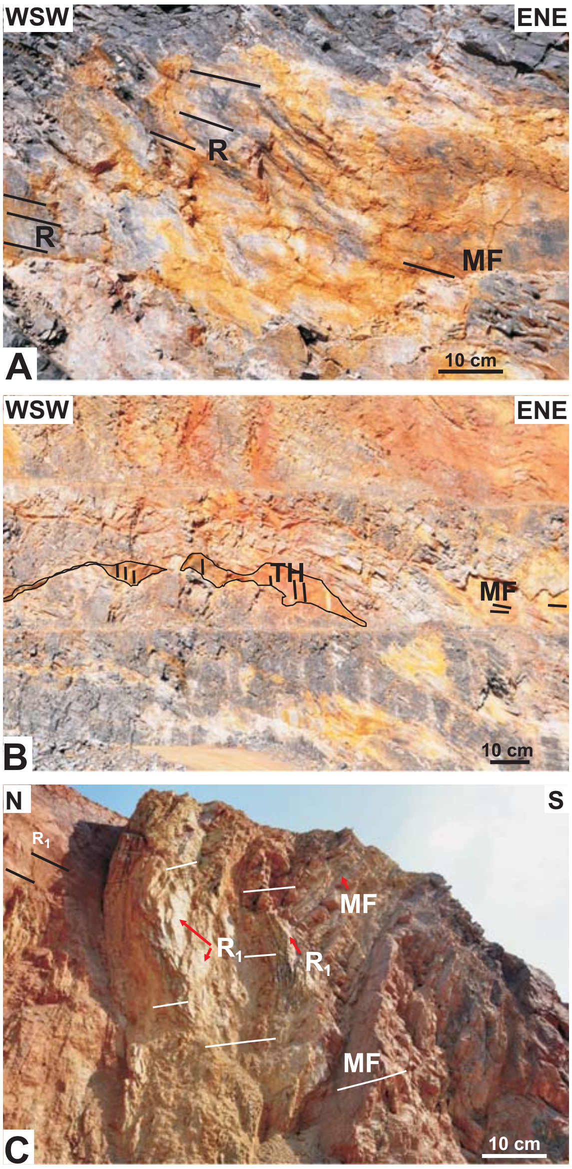
An important and controversial problem is determination of the time when the Józefka stepover was formed. A common feature of the subsided areas between the overlapping segments of the faults is filling by sediments during active transtension (Reading 1980; Sylvester 1988, p. 1683; Woodcock and Schubert 1994). A diagnostic feature of the sedimentary facies forming within fault-bounded, rapidly subsiding grabens is their limited lateral extent and deposition of locally derived conglomerates and breccias (e.g., Reading 1980). The initial sediments represent lacustrine environment and the lakes are bordered by alluvial fans; they can link with rivers at both ends. A typical fill pattern comprises deep water deposits which pass to shallow water deposits. The formation mechanisms of the strike-slip basins favour lateral migration of the facies filling the subsided areas (Reading 1980).

The depositional environment of the Buntsandstein succession investigated in Józefka, consisting of a sand-dominated alluvial plain as well as coarse-grained sands and gravels of a braided river system is interpreted as continental, but it is widely divergent with features presented above.

The sub-vertically inclined Buntsandstein strata in the Józefka Quarry are strongly deformed and fault-bounded by dextral strike-slip faults and normal faults, whereas the Triassic rocks in the vicinity of Józefka Hill are generally flat-lying on folded Palaeozoic rocks (Text-fig. 2). The steep inclination of beds is consistent with sedimentation in a strike-slip basin, but any evidence for fault activity during the deposition of Triassic sandstones is lacking. There are no small-scale structures pointing to down-basin extension and the palaeo-sedimentary slopes are consistent with syn-sedimentary fault scarps within this sandstone succession. The lack of small-scale structures, locally derived conglomerates and breccias, as well as the small thickness of the Triassic succession confirm that there is no evidence of sandstone deposition as a result of rapid formation of a strike-slip basin. The recognition within the sandstones of advanced diagenetic features such as compaction and pressure dissolution as well as well the preserved sedimentary structures suggest that the subsidence of the Triassic rocks within the fault-bounded area was much later than the formation of the sediments themselves.

The deformation of the Lower Triassic rocks in the Józefka releasing stepover resulted from a fault-associated drag along both major strike-slip faults and normal faults (Text-fig. 8). The drag along major dextral strike-slip fault planes resulted from the occurrence of both strike-slip and normal components. The normal component on the fault planes prevailed within a shallow damage zone allowing for the formation of the subsided area within a releasing stepover (Text-fig. 8).

Based on all these observations, we suggest that the timing of formation of the Józefka releas-



Text-fig. 10. A-C – Examples of slickensides of dextral strike-slip faults and thrusts. A – Slickensides of the main dextral strike-slip Józefka 2 fault (MF) and subsidiary R type faults (site No. 1); B – Slickensides of the main dextral strike-slip Józefka 2 fault (MF) and thrust (TH) (site No. 2); C – Slickensides of the main dextral strike-slip Józefka 2 fault (MF) and subsidiary R_1 type faults (site No. 8). See text for explanations. For location see Text-fig. 3A

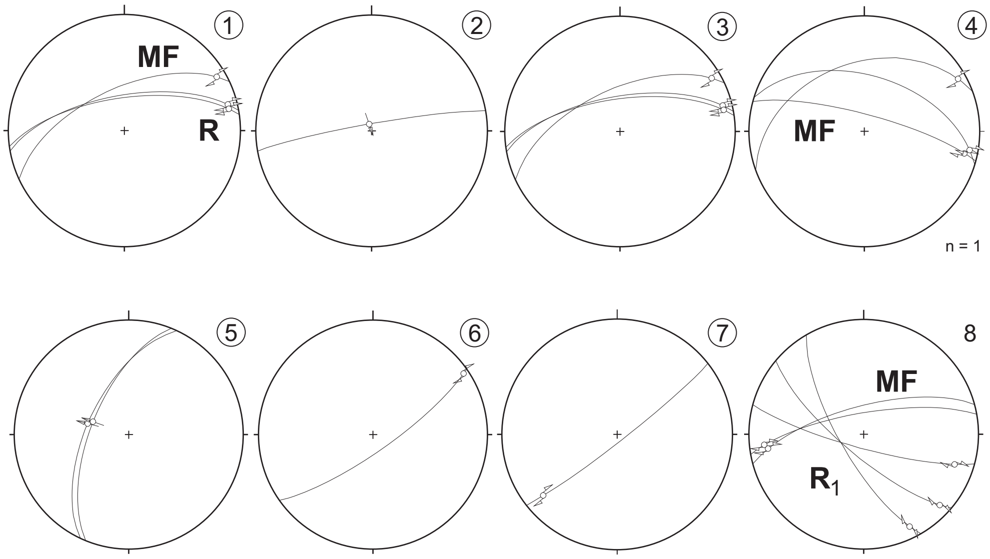
ing stepover may have been significantly later than the Early Triassic deposition of the Buntsandstein sandstones. According to the data available, there were no significant folding or strike-slip faulting stages of deformation between the Triassic and Late Cretaceous in the area of the Holy Cross Mts. Thus, we interpret that the strike-slip faulting was related to the Late Cretaceous/Paleocene dextral strike-slip faulting stage, recognised to the west of the HCFB along NW–SE- and NNW–SSE-striking faults, and south of the HCFB along WNW–SSE-striking faults (Konon and Mastella 2001; Mastella and Konon 2002; Konon *et al.* 2016).

The single occurrence of a deformed Buntsandstein succession within the subsided area of the releasing stepover suggests that the Józefka stepover is a rare, small, and single structure. However, the presence of the stepover in the central part of the late Palaeozoic HCFB provides evidence for a significant role for strike-slip faulting during the Late Cretaceous/Paleocene. This indicates that the strike-slip fault pattern dissecting the HCFB that formed during the late Palaeozoic (Konon 2007; Szaniawski *et al.* 2011) was only slightly overprinted during the Late Cretaceous/Paleocene strike-slip stage, as proven by previous observations (e.g., Jaroszewski 1972; Konon and Mastella 2001; Mastella and Konon 2002; Konon *et al.* 2016). Importantly, identification of the stepover was possible only due to the presence of a sandstone complex. In the opposite case – in the absence of the sandstone infill – the kinematic reconstruction would evidently be more difficult. Therefore, it cannot be excluded that strike-slip faults active during the Late Cretaceous/Palaeocene time are more numerous within the Palaeozoic inlier of the Holy Cross Mts.

CONCLUSIONS

1. Sedimentological and petrographic investigations of the sandstone complex, vertically wedged within the Devonian succession of Józefka Quarry in the central part of the Palaeozoic HCFB, point to its similarity to a typical Buntsandstein succession. The relatively thick complex represents fluvial facies characteristic of the Zagnańsk Formation in the local lithostratigraphic scheme.

2. The sandstone complex is considered a remnant of a several kilometres thick succession, which covered the Palaeozoic rocks during Mesozoic subsidence of the Polish Basin. The finding of a several tens of metres thick succession in the central part of the Palaeozoic inlier confirms that the entire Palaeozoic was covered by younger strata. The Mesozoic cover, presently known only from the margins of the Palaeozoic inlier, must have been nearly completely eroded as an effect of Late Cretaceous/Paleogene inversion tectonics.



Text-fig. 11. Diagrams displaying selected dip-slip and strike-slip fault planes in the study area. MF – main fault, R, R_1 – slickensides of second-order minor faults. See text for explanations. For location see Text-fig. 3A

3. The investigated Buntsandstein complex is preserved due to its location within the subsided area of the releasing stepover. The stepover was formed during Late Cretaceous/Paleogene strike-slip faulting. Most probably, the post-Mesozoic strike-slip fault associated structure formed during reactivation of the late Palaeozoic strike-slip pattern, developed along the western border of the Teisseyre–Tornquist Zone.

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