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Results of shallow scientific drillings in the Upper Nysa Kłodzka Graben and the Zieleniec area, Sudetes

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Abstract A set of four new research boreholes, up to 200 m deep, were accomplished in the Nysa Kłodzka Graben and adjacent area, namely: Gniewoszów PIG-1, Międzygórze PIG-1, Krosnowice PIG-1 (plus Krosnowice PIG-1bis) and Zieleniec PIG-1. All boreholes were localized close to the important "frame dislocations" which determine the border between the graben filled with Upper Cretaceous sedimentary rocks and crystalline basement building the Orlica–Śnieżnik Dome. A purpose of the drillings was to confirm the presence of supposed thrusts or reverse faults, which was postulated for some of these dislocations in the past. Out of four boreholes, Upper Cretaceous rocks were encountered below metamorphic rocks only at one, Zieleniec PIG-1, in the strongly deformed footwall of the Zieleniec thrust. The deformed footwall and lack of fault-related folds in the region cast doubts on the thrust interpretation. In four other boreholes that drilled the footwalls of other supposedly reverse faults, Upper Cretaceous rocks invariably show signs of multiple tectonic deformation, which confirms multi-stage evolution of the Nysa Kłodzka Graben, first under extensional and then under compressional regime with duly changing kinematics.

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INTRODUCTION

Presently the Upper Nysa Kłodzka Graben (herein abbreviated to Nysa Graben, NG) is a large morphological depression filled with Upper Cretaceous, and to much lesser extent also Permian, sedimentary rocks, bordered by the older crystalline bedrock, with which they contact along the prominent fault lines – "frame dislocations" (Radwański 1962, 1975; Oberc 1972; Sawicki 1988; Don 1996; Don & Gotowała, 2008). Interpretations of tectonic origin of the NG developed and changed with time. The earliest concept of Cloos (1922) assumed that the graben originated due to gravitational collapse along the axial part of a basin. Later, the evolution of the NG was divided into two stages: (I) primary, syn-orogenic, sub-Hercynian gravitational downthrown (preceded by earlier doming of the metamorphic basement) and (II) secondary, Laramide and Tertiary compression (Don & Don, 1960; Don, 1996; Don & Wojewoda, 2005). All other explanations (Radwański, 1975; Cymerman, 1990; Wojewoda, 1997; Grygar & Jelinek, 2003) presented some variants of the basically two-stage model. Within the NG, in a number of outcrops (Dumicz, 1964; Frąckiewicz, 1965) and in underground prospecting drifts (i.e. in Młoty; Dziewański, 1984), sedimentary rocks were found to dip under metamorphic bedrock, which indicated tectonic shortening and reverse faulting during the final stages of the NG evolution. In order to shed more light on the significance of these observations a set of four research boreholes, up to 200 m deep, was completed by the Polish Geological Institute – National Research Institute between 2010 and 2011. Results of the drillings are presented in this paper and their bearing on the knowledge and understanding of tectonic evolution of the Nysa Graben and topography of its basement.

DESCRIPTIONS OF BOREHOLE LOGS

To investigate a supposedly reverse character of some "frame dislocations" of the NG four, fully cored boreholes were accomplished, namely: Gniewoszów PIG-1, Międzygórze PIG-1, Krosnowice PIG-1 (plus Krosnowice PIG-1bis) and Zieleniec PIG-1 (Fig. 1; Kozdrój *et al.*, 2011). Due to some technical difficulties it was decided to locate

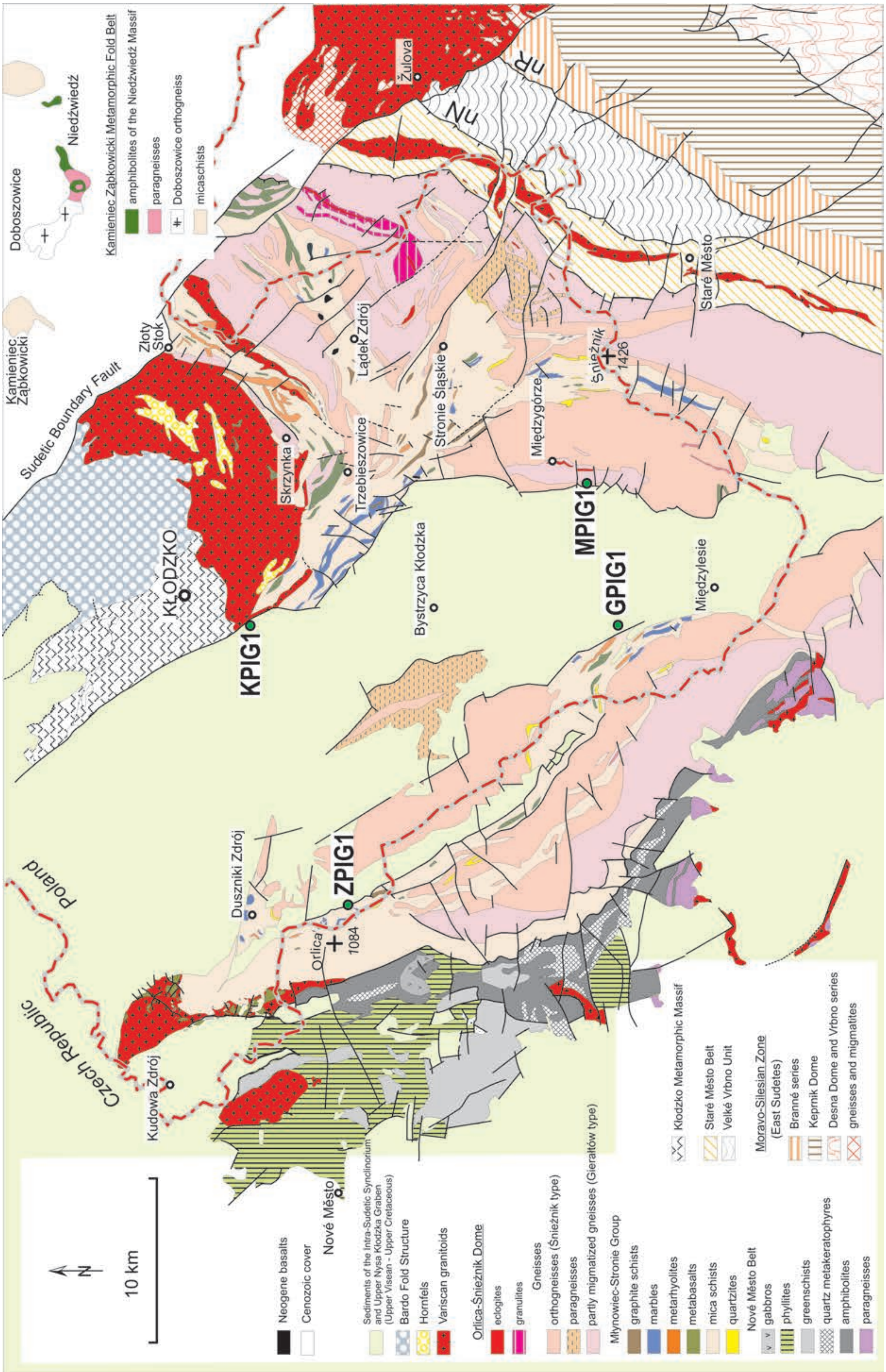


Fig. 1. Map of the Orlica–Śnieżnik Dome and the Upper Nysa Kłodzka Graben with location of the studied boreholes (after Żelaźniewicz, 2006). GPIG1 – borehole Gniewoszów PIG-1; MPIG1 – borehole Międzygórze PIG-1; KPIG1 – boreholes Krosnowice PIG-1 and Krosnowice PIG-1 bis; ZPIG1 – borehole Zieleniec PIG-1.

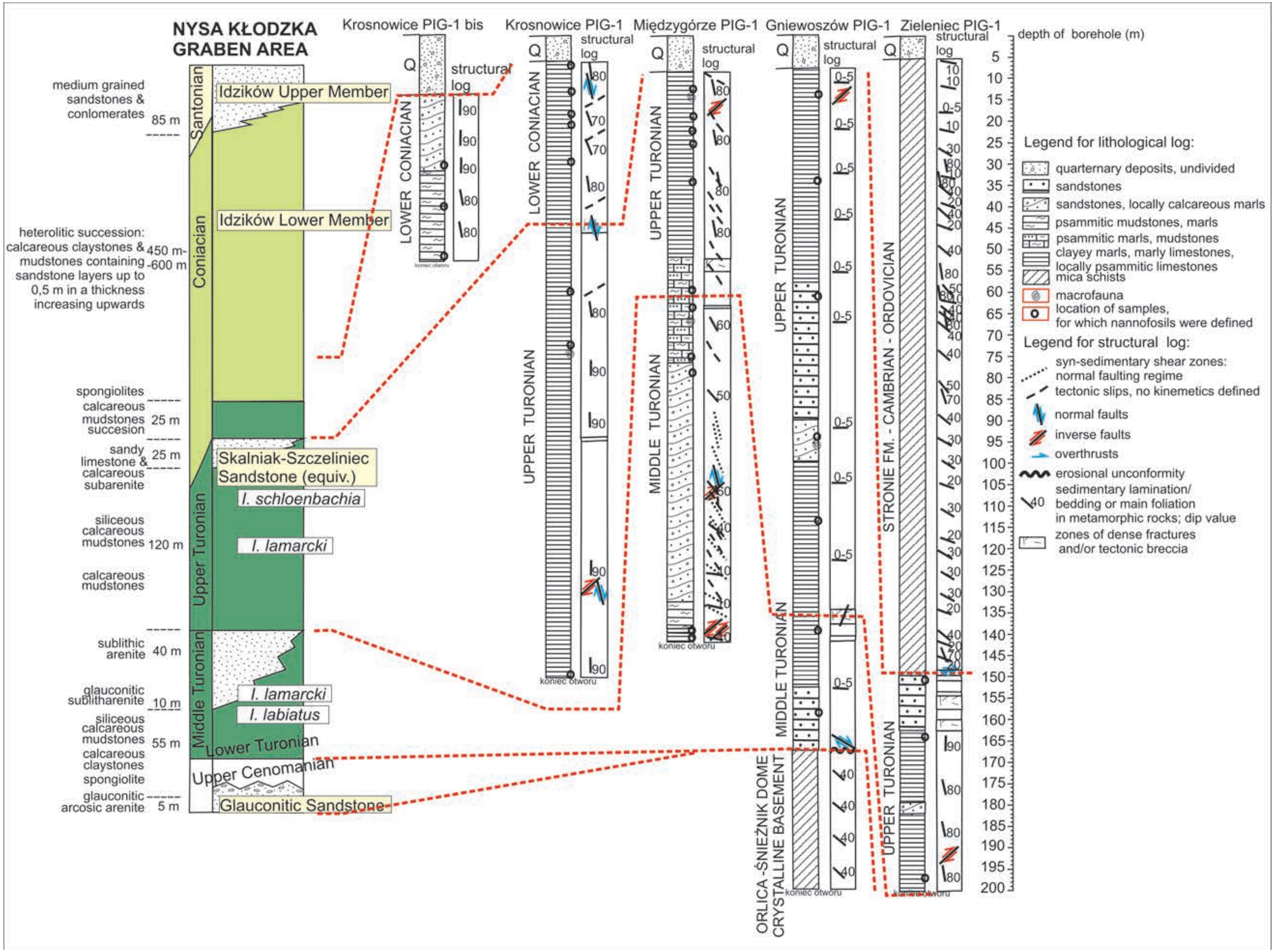


Fig. 2. Lithological and structural profiles of research boreholes in the Nysa Graben. Litho-stratigraphic scheme of NG (Don & Wojewoda, 2005) used for correlation of the drilled rocks.

the boreholes, except for the Zieleniec PIG-1, not in the hanging walls of the supposed reverse faults, but in their footwalls and as close to these dislocations as possible.

Borehole Gniewoszów PIG-1

The purpose of the test borehole Gniewoszów PIG-1, located about 2 km to the east of the village of Gniewoszów, was to examine the N–S trending Jagodna fault interpreted by Dumicz (1964) as a reverse one. As locating the borehole in the hanging wall of the fault proved to be impossible, it was located in the footwall with an aim to drill trough Upper Cretaceous sedimentary rocks and reach a metamorphic basement.

In the profile of the Upper Cretaceous rocks, which starts at a depth of 7.9 m below ground level (m b.g.l.), four main parts can be distinguished: two with predominance of dark marls and two horizons built of lighter sandstones (Fig. 2).

The uppermost part of the log (7.9–66.25 m b.g.l; Fig. 3A, B) is dominated by massive, clayey marls passing into marly limestones, locally showing horizontally oriented, streaky lamination and bedding parallel cleavage (fissility). Below (66.25–68.05 m b.g.l.) dark or black-white, fine- to medium-grained sandstones, with poorly visible bedding occur, locally intensely bioturbated.

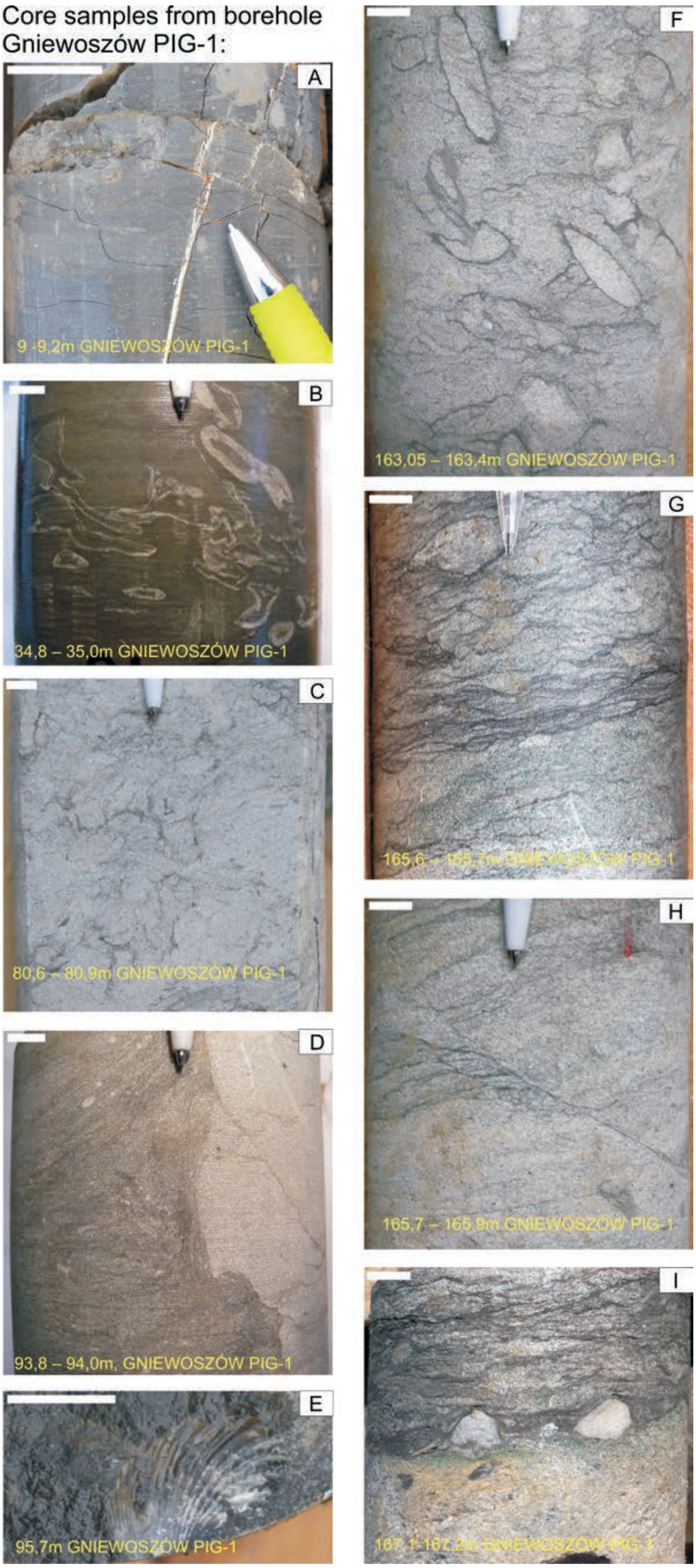


Fig. 3. Core samples from borehole Gniewoszów PIG-1. **A** – core section from a depth of 9.0–9.2 m: massive, dark grey marl without layering; note older cracks, healed with calcite veins and dipping at an angle of 80°, moved by younger cracks dipping 5–10° indicating the reverse regime of faulting; **B** – core section from a depth of 34.8–35.0 m: dark grey marl (marly limestone), massive, without layering, note white laminae as signs of bioturbations; **C** – core section from a depth of 80.6–80.9 m: sandstone (quartz arenite), medium-grained, with bedding completely disturbed by bioturbations; **D** – core section from a depth of 93.8–94.0 m: laminated marl and sandy limestone cross-cut by enclave of white, fine-grained sandstone (sandy dyke?); **E** – core section from a depth of 95.7 m: dark, calcareous sandstones with imprint of *Lima canalifera* (Middle Turonian); **F** – core section from a depth of 163.05–163.4 m: fine-grained sandstone with ellipsoid cross-sections of *Ophiomorpha* burrows (Middle Turonian); **G** – core section from a depth of 165.6–165.7 m: fine-grained, glauconite-bearing sandstone with wavy, low-angle lamination; **H** – core section from a depth of 165.7–165.8 m: fine-grained, glauconite-bearing sandstone with parallel, low-angle lamination cut by a 30° dipping shear band that shows the normal fault displacement; **I** – core section from a depth of 167.1–167.2 m: note a nonconformity (erosional) between the metamorphic basement (light mica schists) and dark Upper Cretaceous sandstones, decorated with basal quartz pebbles. Scale bar is 1 cm long in all photographs.

In the middle part (68.05–90.00 m b.g.l.), a horizon of light, less frequently dark, medium- to coarse-grained sandstones (quartz arenites) showing strong obliteration of bedding caused by synsedimentary movements and bioturbations (Fig. 3C) is observed. At the bottom of coarser sandstones (90.00–100.00 m b.g.l.) dark- or light-grey, fine-grained calcareous sandstones, passing into sandy marls and limestones or marly limestones occur. In these rocks an imprint of bivalve molluscs *Lima canalifera* (Fig. 3E) was found, which points to the Middle Turonian age (see Chrząstek, 2012, 2013). Below, from 100,00 to 152.80 m b.g.l. again appear dark-grey, clayey to sandy, marls, smoothly grading to marly limestones. Locally, from 134.50–138.00 and 140.80–141.70 m b.g.l., tectonic zones with strongly fractured and weathered marls are observed.

In the lower part of the borehole (152.80–167.10 m b.g.l.), a second level of medium– to coarse-grained sandstones (quartz wackes and arenites) with glauconite was encountered. This also shows strongly disrupted bedding due to ubiquitous bioturbations (Fig. 3F, G). The bottom parts of the horizon is enriched with glauconite which underlies surfaces of regular, almost horizontal (3–5°) bedding (Fig. 3H).

A contact between the Upper Cretaceous sandstones and metamorphic basement, occurring at a depth of 167.10 m b.g.l., has a character of a distinct erosional nonconformity (Fig. 3I). The basement (167.10 to 200.00 m b.g.l.) is composed of dark, quartz-biotite schist of the Stronie Formation, with foliation dipping at an angle of 45°.

Besides dominant foraminifera, also were identified: elements of skeleton and idles of sponges, fragments of bivalves, stems of crinoids as well as coccolites and calcareous cysts of dinoflagellata. The forams allow to assign rocks occurring in Gniewoszów PIG-1 borehole to the Middle Turonian age (assemblage *Dicarinella sudetica*) and Upper Turonian (assemblage *Archeoglobigeryna cretacea* and *Dicarinella covcavata*) and (Kozdrój *et al.*, 2011). Based on forams, the border between M/U Turonian may be located in a tectonic zone at a depth of about 134.50–138.00 m. b.g.l., however, the presence of *Lima canalifera (?)* suggests its higher position. The Middle Turonian sandstones lie directly on the crystalline basement, which indicates the lack of Lower Turonian and Cenomanian rocks at this location.

The examined sequence of Upper Cretaceous rocks in Gniewoszów PIG-1 borehole corresponds well with regional lithostratigraphic scheme for the Nysa Graben (Don & Wojewoda, 2005) (Fig. 2). The lower horizon of sandstones of Middle Turonian age may be correlated with "glauconitic sandstones", passing upward into "quartz-feldspar sandstones" of the NG and with the Radków sandstones, recognized in the Góry Stołowe (Table Mts.) in the Intra-Sudetic Synclinorium. Marls occurring above the lower horizon of sandstones represent partly Middle and Upper Turonian. Thus the higher level of sandstones (quartz arenites) may also be considered as Upper Turonian in age and as an equivalent of "sandy limestone and calcareous arenite" of the NG or "Skalniak–Szczeliniec sandstones" from the Góry Stołowe Mts. The assemblages of foraminifera indicate that marls above this sandstones are also of Late Turonian age.

The Upper Cretaceous rocks from the Gniewoszów PIG-1 borehole are weakly tectonised and weathered. Locally visible sedimentary bedding planes dip at an angle of few degrees (Fig. 2). Besides rare fractures only some low-angle reverse and normal faults are observed in the studied cores (Fig. 3). No evidence of fault-related bending of the bedding planes was observed. The Jagodna "frame" fault appears to be a normal not a reverse fault.

Borehole Międzygórze PIG-1

Borehole Międzygórze PIG-1 was drilled to examine the presence of N–S trending reverse fault, recognized earlier in the vicinity of Nowa Wieś and referred to as the Międzygórze thrust (Fig. 1; Frąckiewicz, 1965). The borehole was planned to start in metamorphic rocks of the eastern hanging wall. However, the drilling immediately entered Upper Cretaceous sedimentary rocks. To relocate the borehole higher up in the valley was impossible due to steep slopes.

In the log of Międzygórze PIG-1 borehole (Fig. 2), which reached a depth of 142.00 m b.g.l., three different parts can be distinguished. The upper one is dominated by grey marls: clayey marls passing to marly or sandy limestones (8.50–52.40 m b.g.l., (Fig. 3A), locally with light sandstones forming ellipsoidal enclaves and below (52.40–76.40 m b.g.l.) sandy marls and marly-sandy limestones passing into fine-grained calcareous sandstones of streaky, irregular lamination. In the central part (76.40–132.75 m b.g.l.) light, calcareous sandstones with no visible bedding prevail. They pass downwards into fine- to medium-grained subarcosic arenites (Fig. 3B, C). Locally observed (103.00–104.00 m b.g.l.) lobed shapes of deformed, sandy laminae which occur sometimes as isolated "meshes" resemble fabric of a sedimentary breccia.

In the lower part of Międzygórze PIG-1 borehole slaty claystones and calcareous marls (132.75–139.00 m b.g.l.), passing downwards (139.00–142.00 m b.g.l) into marls and marly limestones (Fig. 4D, E) occur.

Within the samples taken from Międzygórze PIG-1 borehole, besides foraminifera assemblages, also were identified: elements of skeleton and idles of sponges, fragments of molluscs, bryozoans, ostracods and crinoids (Kozdrój *et al.*, 2011). The representative group of foraminifera allows to assign the drilled sedimentary rocks to the Upper Turonian (assemblage of *Archeoglobigeryna cretacea* and *Dicarinella covcavata*) and Middle Turonian (assemblage of *Dicarinella sudetica*). The border between Upper and Middle Turonian was quite strictly defined at the depth of 59.00 to 63.00 m b.g.l.. The examined sequence of the Upper Createceaous rocks found in Międzygórze PIG-1 borehole corresponds well with the NG stratigraphic scheme of Don & Wojewoda (2005) (Fig. 2). A characteristic marker horizon is the level of sandstone (76.40–132.75 m b.g.l.), which belong to the Middle Turonian. Hence, it may be recognized as comparable with "quartz-feldspar sandstones".

All the rock varieties from Międzygórze PIG-1 borehole display poorly developed sedimentary bedding (streaky fabric), often obliterated by syndepositional processes and bioturbations, which affected nearly unconsolidated sediments. In many sandstone beds, continuous lami-

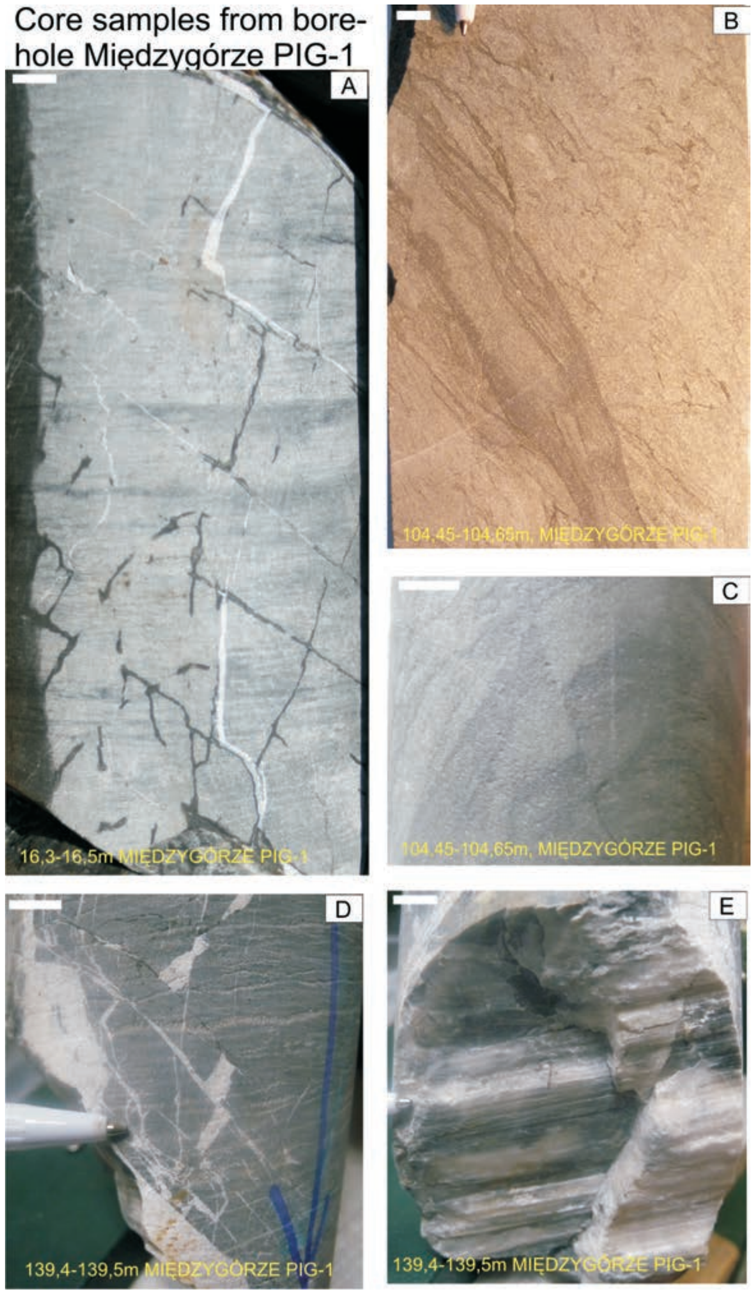


Fig. 4. Core samples from borehole Międzygórze PIG-. **A** – core section from a depth of 16.3–16.5 m: grey, massive marl with poorly visible, vertically disposed layering; note older cracks, healed with calcite veins that dip at an angle of 80°, moved by younger cracks dipping 25–30°, which indicates the reverse regime of faulting; **B** – core section from a depth of 104.45–104.65 m: light-grey, fine-grained and bioturbated sandstone cut by steeper (and oblique against layering) dark shear-band filled with muddy material; **C** – another view of the same situation: laminated bright and dark fine-grained sandstone, note small normal –fault younger than the shear band; **D** – core section from a depth of 139.4–139.5 m: grey marl with parallel sub-horizontal bedding, note fragments of older, steep calcite vein displaced by a set of reverse faults (dip at 45°) also healed with calcite; **E** – another view of the same situation as in D: slickensides on a tectonic mirror documents mixed, reverse and strike-slip character of faulting. Scale bar is 1 cm long in all photographs.

nation was torn out due to activity of benthic organism (ichnofossils) or by semi-fluidal clastic debris induced by seismic tremors (seismites). The latter transferred the laminated light sandstones and darker siltstones into sedimentary breccias being a mixture of isolated, sandy or silty enclaves.

Within the first two sections of the Międzygórze PIG-1 borehole, the streaky fabric is arranged steeply or vertically, while in the bottom of the middle section and in the lower section, the dip of these surfaces gradually decreases up to 10–15° (Fig. 2). Such attitude documents a fold (flexure) related to development of the Międzygórze fault. Locally, streaky or regular, parallel lamination is cut at a low angle, by dark surfaces of shear band that pass into more dense cleavage (Fig. 4B). Most of these post-lithification, deformational features occur at a depth 92.00–132.00 m b.g.l. (Fig. 2). Like sedimentary bedding, the shear zones are much steeper in the upper part of the borehole than in the lower part. Therefore, it seems reasonable that shear zones were originally more flat and then, together with bedding planes, were steepened owing to the movement on the Międzygórze fault.

A careful examination of the synsedimentary shear zones allow to notice broken fragments of sandy beds consistent with kinematics of normal faulting. Such kinematics may indicate their connection with the subsidence of an old marine basin still during accumulation of sediments or with the initial phases of basin inversion, when movements of the basement block disrupted stability and continuity of the overlying Upper Cretaceous rocks.

Younger than the shear zones are numerous, brittle fractures and faults, often healed with calcite veins. These features usually show a conjugate arrangement and dip at angles of 40 to 70°. The geometry of fractures, fault planes and orientation of slickensides on them point to normal, reverse and strike-slip regimes of tectonic transport (Fig. 4A, D, E). Steep or vertical attitude of bedding along with slickensides on the fault planes clearly document a flexure connected with the Międzygórze fault but do not prove its reverse nature. Hence the existence of the "Międzygórze thrust" of Frąckiewicz (1965) could not be confirmed.

Boreholes Krosnowice PIG-1 and Krosnowice PIG-1bis

Two boreholes, namely: Krosnowice PIG-1 and Krosnowice PIG-1bis, were located in the valley of the Nysa Kłodzka River, to the south of the so called Krosnowice thrust (Fig. 1) along which metamorphic rocks and granites were transported over Permian and Mesozoic sedimentary rocks. The overthrust defines the northeastern border of the NG (Grocholska & Grocholski, 1958; Oberc, 1972; Radwański, 1975). More detailed description is given by Cwojdziński (1979) and Wojewoda & Burliga

(2008). The hanging wall of the Krosnowice thrust is built of amphibolites and granitoides of the Kłodzko–Złoty Stok pluton. The footwall is composed of steeply dipping, locally overturned, Permian and Upper Cretaceous sedimentary rocks.

Quarternary alluvial deposits mask a fault line of the Krosnowice thrust, which caused a failure of Krosnowice PIG-1bis drilling that encountered Cretaceous rocks immediately below the alluvium. For this reason borehole Krosnowice PIG-1 was shifted few tens of meters to the north in order to reach the hanging wall of the thrust. Unfortunately, in the second drilling also only Cretaceous sedimentary rocks were found, thus the Krosnowice thrust remained unproved.

Within the Krosnowice PIG-1bis borehole, below Quaternary sediments that reach the maximum depth of 14.00 m b.g.l., Upper Cretaceous rocks (Fig. 2) occur down to 53.00 m b.g.l. In the range of 14.00–32.00 m b.g.l., the dark-grey, fine-grained marly and calcareous sandstones occur, locally with thin, dismembered inlayers of white, medium- grained sandstones (Fig. 5A, B). Irregular shape of these bright sandy bodies indicate their syn-sedimentary, pre-lithification origin (storm waving, seismic movements, bioturbations), which bursted their original spatial continuity. In the range of 32.00–53.00 m b.g.l. the dark-grey, sandy mudstones and calcareous sandstones were found, passing gradually into marls devoid of any bedding. Locally the marls contain isolated relics of white, sandy laminas. Vertical orientation of these elongated sandy intercalations give evidence of strong tectonic deformation.

In Krosnowice PIG-1 borehole, from 6.00 to 150.70 m only Upper Cretaceous rocks (Fig. 2) occur. These are predominantly dark-grey marls, microscopically identified as marly limestones, limestones, and sandy limestones gradually passing into each other (Fig. 6). The majority of them are unweathered, massive, and unbedded. Very few bioturbations and macrofossils were also noticed. Rare ore mineralization features appear as tiny veins or concretions 2–3 cm in diameter. Poor lamination occurs rather seldom, but wherever present it dips steeply or vertically, pointing to deformation most probably related to the Krosnowice thrust. Fractures and network of calcite veins are more frequent. In a depth range of 94.00–95.45 m b.g.l. a zone of tectonic breccias occurs.

In samples taken from Krosnowice PIG-1bis and Krosnowice PIG-1 boreholes foraminifera assemblages were found along with other microfossils: elements of sponges, some fragments of mollusca, bryozoans, and crinoids, coccolites and calcareous cysts of dinoflagellata (Kozdrój *et al.*, 2011). The representative group of foraminifera allows to classify all rocks from Krosnowice PIG-1bis borehole and the upper part of Krosnowice PIG-1 borehole as the Lower Coniacian (assemblage *Gaudryina sudetica*) age, and assign the lower part of Krosnowice PIG-1 borehole to the Upper Turonian (assemblage *Archeoglobigeryna cretacea* and *Dicarinella covcavata*). The border between the Turonian and Coniacian has not been precisely defined. Most probably it coincides with the zone of strongly fractured rocks at a depth of 44.40–46.30 m b.g.l. Comparing the obtained biostratigraphic data with the tectonic scheme of Don & Wojewoda (2005), one may correlate the lower part of marls from borehole Krosnowice PIG-1 with the succession of calcareous mudstones of the uppermost Turonian, while the upper part of marls in Krosnowice PIG-1 borehole and the entire profile of sandstones and mudstones in Krosnowice PIG-1bis with a heterolithic succession of the Idzików member composed in turn of calcareoaus claystones and mudstones with inlayers of sandstones.

Fig. 5. Core samples from borehole Krosnowice PIG-1bis. **A** – core section from a depth of 17.6–18.0 m: dark mudstone and white, medium-grained sandstone showing nearly vertical, irregular bedding planes; **B** – core section from a depth of 30.3–30.4 m: dark, fine-grained sandstone with visible sub-vertically disposed sedimentary lamination. Scale bar is 1 cm long in all photographs.

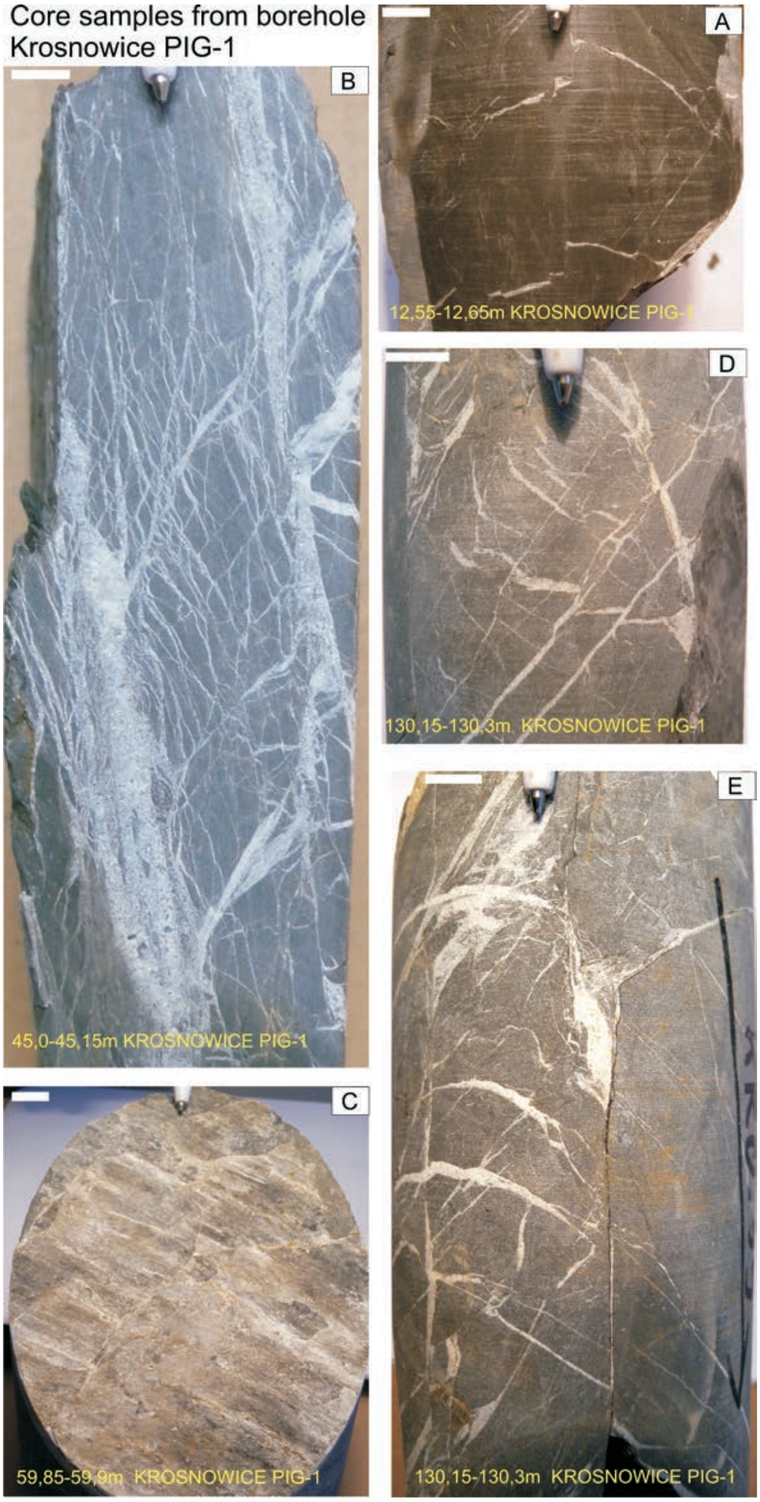


Fig. 6. Core samples from borehole Krosnowice PIG-1. **A** – core section from a depth of 12.55–12.65 m: dark grey marl cut by normal fault with ~1 cm displacement; **B** – core section from a depth of 45.0–45.15m: strongly tectonized dark grey marl; dense network of fractures sealed with calcite, note possibly reverse faulting on the steep veins; **C** – core section from a depth of 59.85–59.9 m: a reverse fault surface dipping at an angle of ~30° with slickensides; **D** – core section from a depth of 130.15–130.3 m: dark grey marl cut by a network of fractures sealed with calcite, note small reverse faults and displacements along fractures dipping at an angle of 45°; **E** – another view of the same sample as shown on D; note normal fault cutting the central part of the core. Scale bar is 1 cm long in all photographs.

Sandstones and mudstones of the Krosnowice PIG-1bis borehole, located a bit further away from the thrust line than borehole Krosnowice PIG-1, are tectonically less deformed and cut by seldom, vertical fractures filled with calcite veinlets. The rocks of Krosnowice PIG-1 borehole, located closer to the thrust line, show much denser network of brittle, complementary fractures and faults often healed with calcite veins. The dip of fracture planes is usually around 25–50°. Geometric layout of these veins and fault planes with slickensides indicate mass transfer that operated first in the reverse and then in the normal fault regime (Fig. 6).

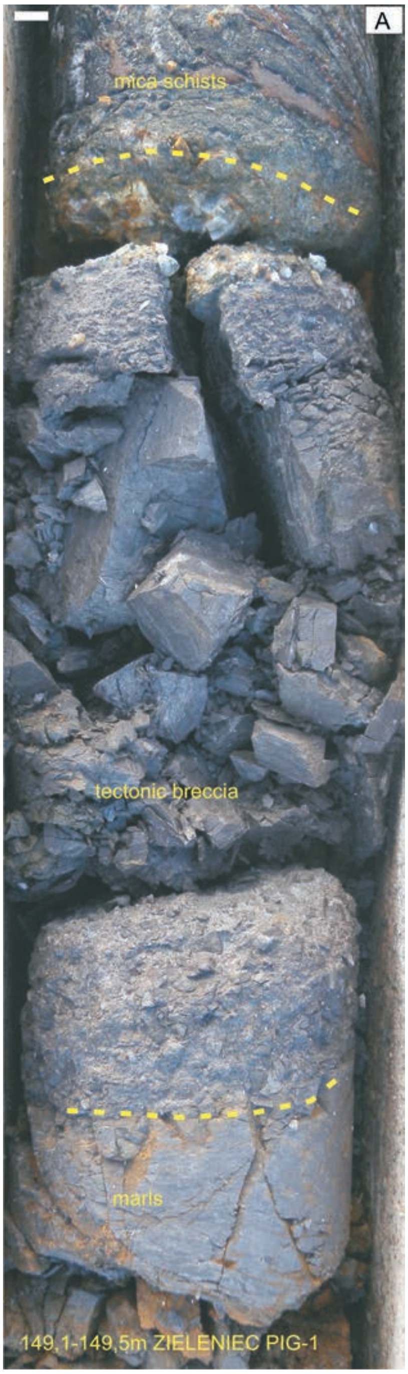
Tectonic steepening of rock bedding found for both boreholes as well as for other outcrops in the neighborhood can certainly be related to movement on the fault and formation of a large flexure. This process may be presumably linked with an uplift and thrusting of the crystalline basement observed on the eastern slopes of the Czerwoniak Hill (Wojewoda & Burliga, 2008). A zone of the flexural steepening is considerably thick and comprises Permian as well as the whole section of Upper Cretaceous rocks.

Borehole Zieleniec PIG-1

Zieleniec PIG-1 borehole was located in the Orlickie Mts., west of the Nysa Graben (Fig. 1). Its purpose was to confirm the presence of Zieleniec overthrust (Cymerman, 1990, 1992). The borehole, as expected, drilled metamorphic rocks (5.30 to 149.30 m b.g.l.) and entered Cretaceous sedimentary rocks (149.60–200.0 m b.g.l.; Fig. 2). The crystalline rocks are dark two-mica schists, locally with interlayers of brighter, massive quartz-mica schists or black graphite–mica schists. Zones of more intense tectonic deformations are associated with irregular veins and enclaves of white quartz.

In the vertical profile, the crystalline rocks are separated from the underlying Upper Cretaceous marls by about a ~30 cm thick zone of tectonic breccia, filled with mingled debris of mica schists and Cretaceous rocks suspended in a blue tectonic clay (Fig. 7A). In the breccia, however, any kinematic indicators of tectonic transport are lacking. Horizontal orientation of the mica schist/marl interface and of the breccia zone is not typical for brittle reverse fault or thrust.

Upper Cretaceous rocks, within a depth range of 149.60 to 179.40 m b.g.l., are represented by fine-grained sandstones and mudstones with transitions to marls. Below, towards the bottom, at a depth of 200.00 m b.g.l., rusty in colour, strongly weathered clayey and sandy marls predominate. A layer of weakly compacted, dark-grey, fine-grained sandstones, gradually passing into black



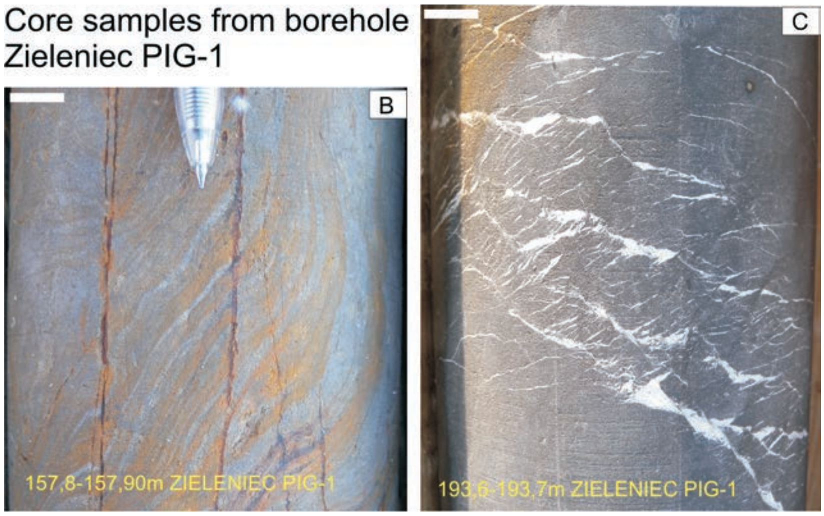


Fig. 7. Core samples from borehole Zieleniec PIG-1. **A** – core section from a depth of 149.1–149.5 m: subhorizontal, ~30 cm thick zone of tectonic breccia (cf. Fig. 2) in the footwall of the inferred Zieleniec thrust; note mica-schists overlying Upper Cretaceous marls; **B** – core section from a depth of 157.8–157.9 m: psammitic marls with folded, steeply to vertically disposed sedimentary lamination; **C** – core section from a depth of 193.6–193.7 m: fractured psammitic marls; note network of calcite veins indicating kinematics of minor reverse faulting. Scale bar is 1 cm long in all photographs.

mudstones with organic matter occur only in a narrow section at a depth of 179.40–182.30 m b.g.l.. Biostratigraphic analyses of rocks from Zieleniec PIG-1 well revealed presence of foraminifera, some elements of sponges, fragments of bryozoans and ostracods (Kozdrój *et al.*, 2011). The forams belong to an Upper Turonian assemblage of *Archeoglobigeryna cretacea* and *Dicarinella covcavata*.

The Upper Cretaceous rocks at the contact zone with the overlying mica schists, down to a depth of 194.40 m b.g.l. are strongly tectonised. This is manifested by steep or vertical dip of bedding planes (Fig. 2B) and common, irregular fracturing, cataclasis and brecciation. Weathered, “rusty” rocks testify a profound circulation of Fe-rich waters. This dense fracture network is locally healed with calcite veins. In spite of rich evidence of brittle fracturing, any additional features (fault geometry, slickensides) which would help to determine the transport direction are lacking. In rare places, where kinematics could be identified, only small signs of late reverse movement might be recognized (Fig. 7C). The bottom section of the borehole (194.40–200.00 m b.g.l.) is composed of fresh, massive clay-siliceous marls with no traces of bedding and showing deformation confined to tiny fractures only.

To explain the unquestionable presence of metamorphic rocks over Cretaceous sedimentary rocks in Zieleniec PIG-1 borehole, two alternative explanations may be taken into account. The apparently simplest one assumes thrusting which would bring basement mica schists to lie upon brecciated and folded marls (Fig. 7). Unfortunately, this explanation is not supported by any clear tectonic marker which might prove that tectonic stresses were relaxed in the compressional regime by thrusting localized within and slightly over the breccia horizon. Neither such brittle thrusts nor fault-related folds are evidenced anywhere in metamorphic basement and Cretaceous cover in the region. Moreover, the observed deformation below the inferred thrust plane is inconsistent with the principles of faulting mechanism, which predicts that deformation is usually localized along the fault plane and in the hanging wall over it but never in the footwall. Nonetheless, it the steepening of bedding planes and brecciation of Cretaceous marls might have taken place during early early stages of basin inversion along normal faults that were later taken over by thrusting. Such a scenario would be in accordance with the model of the NG evolution proposed by Don & Gotowała (2008), assuming the first stage of normal N–S faulting in the extensional regime and the second stage of reverse rebuilding along NW–SE trending faults in the shortening regime.

An alternative explanation proposed by A. Żelaźniewicz (pers.comm.) further explores the two-stage model and suggests that the flat contact of mica schists with brecciated marls (Figs 2, 7) was brought about by gravitational sliding down the steep eastern slope of the Orlica step in basement rocks, which was described by Badura & Rauch (2014) who recognized repeated tectonic activity in the region. What is observed in borehole Zieleniec PIG-1 is just a foothill fragment of a landslide. It moved downslope a mass waste of metamorphic rocks over weak marls which were brecciated and steepened during earlier event of normal faulting that affected both the basement and Cretaceous cover during multi-stage basin inversion. Such explanation is not in conflict with facts observed in the borehole and does not exclude the reverse tectonic activity along the fault that separates gneisses and marls on the western slope of the Strążyska Valley, south of Duszniki (Fig. 1), below the location of borehole Zieleniec PIG-1. This fault acted at the beginning as a normal fault and at the later stage was rejuvenated as a reverse fault (Żelaźniewicz, 1977). Such scenario is supported by the geometry of joint-drag folds observed in marls adjacent to the fault line (Żelaźniewicz, 1977) and is also consistent with the model of Don & Gotowała (2008).

CONCLUSIONS

In summary, the results obtained from the new boreholes prove that the zones of "frame dislocations" bordering the NG are complex structures with complicated and diversified tectonic evolution. In all the studied boreholes, Upper Cretaceous rocks invariably show signs of multiple tectonic deformation, which confirms multi-stage evolution of the Nysa Kłodzka Graben, first under extensional and then under compressional regime with duly changing kinematics.

The presence of thrusts and reverse faults, along which blocks of crystalline basement were moved over the Upper Cretaceous sedimentary rocks, as observed in Zieleniec PIG-1 borehole and in other localities (Młoty, Krosnowice, Czerwoniak Hill, Hronov-Pořici), seem to be significant, constitutive factor for the present-day topographic relief of the NG and its vicinity. The Zieleniec thrust as well as other similar structures in the Kłodzko region, originated under conditions of regional compression caused by the ongoing Africa–Europe converegence. The same process caused inversion of the Mesozoic Polish Basin to the north of the Sudetes Mts. (Krzywiec, 2000, 2002, 2005; Mazur *et al.*, 2005; Scheck-Wenderoth *et al.*, 2008; Cacace *et al*,. 2009; Sippel *et al.*, 2009).

At that time, owing to horizontal, N–S oriented stresses, the variously disposed, steep or low-angle fault planes with important strike-slip component were activated within the NG, which locally resulted in uplift and transfer of metamorphic rocks over Mesozoic platform cover. This view is supported by the observation made in the studied boreholes that the small reverse faults are associated with tectonic slickensides, which are not aligned parallel to the dip of the fault planes but rather close to their strike.

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