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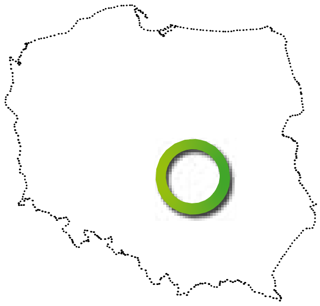
SILURIAN SUCCESSION OF THE HOLY CROSS MOUNTAINS



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The Holy Cross Mountains (HCM) are a unique area in southern Poland that belongs to the major tectonic zone of Europe, i.e., the Trans-European Suture Zone (Fig. 1; Berthelsen, 1992). The Palaeozoic rocks exposed in this hilly area are traditionally called the Palaeozoic core, subdivided into the Łysogóry Region in the north and Kielce Region in the south, separated by the Holy Cross Fault (Fig. 1). They reveal differences in tectonic and sedimentary evolution and in their stratigraphic records, enhanced by gaps of various spatial and temporal extent. These units are surrounded by a Permian-Mesozoic cover that in some localities overlies the Palaeozoic rocks along the Variscan unconformity. The Łysogóry Region is supposed to be a passive margin of Baltica (East European Craton), whereas the Kielce Region belongs to the Małopolska Block, which is considered to be a proximal terrane relocated dextrally along the present SW margin of Baltica (Dadlez et al., 1994; Kowalczewski, 2000; Nawrocki et al., 2007). Deep seismic sounding data display a crustal structure for the Małopolska Block, similar to that of the East European Craton (Malinowski et al., 2005). Palaeontological data indicate that in the Early Palaeozoic both the Małopolska Block and Łysogóry Region were located in the marginal part of Baltica (Cocks, 2002), contrary to suggestions of a Gondwanan provenance (Belka et al., 2002). Furthermore, paleomagnetic reconstructions clearly show that since at least the Mid-Ordovician the relative position of the Małopolska Block with respect to Baltica was similar to that of the present day (Schätz et al., 2006; Nawrocki et al., 2007).

The Cambrian system in the HCM is represented by a thick (up to 3000 m) siliciclastic succession dated by trilobite fauna and acritarch microphytoplankton (Żylińska, 2001, 2002; Szczepanik, 2009; Żylińska and Szczepanik, 2009). Shallow-water sandstones with numerous trace fossils dominate in stratigraphic intervals corresponding to the Series 2/3 and Furongian, and are widespread mostly in the western part of the HCM, whilst mudrock facies predominate in eastern localities. The Cambrian rocks of older age were deformed prior to the Furongian-Tremadocian time interval, as can be inferred from the angular unconformity between the Furongian sandstones/mudstones and underlying folded mudstones/shales corresponding to the Cambrian Series 2/3, detected in the eastern part of the Kielce Region (Szczepanik et al., 2004). The topmost part of the Cambrian section in the Łysogóry Region is made up of upper Furongian/lower Tremadocian black shales (up to 150 m thick) corresponding to the Scandinavian alum shales, and documenting continuous sedimentation across the Cambrian/Ordovician boundary.

There is a conspicuous angular unconformity at the Cambrian/Ordovician boundary recognized in the Kielce Region and documented by the upper Tremadocian glauconite-bearing sandstones and mudstones resting on folded sandstones and mudstones of the Cambrian Series 2/3. However, in the eastern part of this area the stratigraphic gap related to the Cambrian/Ordovician boundary narrows to the lower Tremadocian strata (Szczepanik et al., 2004). The layout of the Ordovician facies in the HCM shows a tripartite pattern, enhanced by the occurrence of Tremadocian to Katian sandstones and condensed limestones/dolostones (~50 m thick) in the Kielce Region surrounded by upper Darriwillian to Katian black and green/grey shales (~200 m thick) in the Łysogóry Region and SW localities of the Kielce Region (Dzik and Pisera, 1994; Trela, 2006). However, a few stratigraphic gaps were also documented in the Ordovician sedimentary record of the HCM (Trela, 2006; and references therein). The deposition of the Upper Ordovician condensed limestones took place on a central submarine elevation, under the influence of upwelling induced by winds of the westerlies zone (Trela, 2005, 2008). The adjacent mudrock facies were developed in a deeper-water shelf basin and record a pronounced change from intermittent dysoxic/anoxic to oxic conditions (Trela, 2007; Zhang et al., 2011). The topmost part of the Ordovician system in many localities in the HCM is made up of mudstones and sandstones (~6 m thick) corresponding to the global Hirnantian regressive event. The Hirnantian microphytoplankton community of these deposits is accompanied by exotic Middle Ordovician acritarch specimens of *Frankea* that appear to be redeposited from the Avalonian terrane that collided with Baltica in the Late Ordovician (Trela and Szczepanik, 2009).

In the Silurian both regions of the HCM displayed a similar evolution. The sedimentary record is represented by the Rhuddanian – Gorstian mudrock facies (up to 150 m thick) passing gradually into a thick succession of greywacke sandstones (Tomczyk, 1962; Malec, 2006; Kozłowski, 2008). The base of the Silurian succession consists of the Rhuddanian black shales and radiolarian cherts that represent only a small fraction of the mudrock facies. The Rhuddanian black shales in the Łysogóry Regions were part of the facies pattern developed along the present SW margin of Baltica, which was positioned at the northern margin of the Rheic Ocean (Podhalańska and Trela, 2007). They are coeval with the organic-rich "hot shales" deposited along the Gondwana shelf during the latest Hirnantian-Rhuddanian post-glacial transgression (Lüning et al., 2000). In the case of the HCM, the sedimentary environment was controlled by a shallow upwelling generated along a submarine elevation by the SE trade winds, which is supported by black radiolarian cherts in the Kielce Region (Kremer, 2005; Trela and Salwa 2007; Trela 2009). Black shale deposition returned close to the Llandovery/Wenlock boundary in response to a global transgressive episode after the Aeronian and Telychian period of overall climate cooling and water column mixing (Trela and Podhalańska, 2010; Page et al., 2007). Deposition of greywackes was initiated in late Ludlow times and resulted in the filling-up of the foredeep basin that extended from the Łysogóry Region to the present SW margin of Baltica (Poprawa et al., 1999; Narkiewicz, 2002). Kozłowski et al. (2004) postulated that the source area for greywackes was an arc-continent orogen located westward of the HCM (the Łysogóry Region was in a more distal position towards this orogen than the Kielce Region).

A diabase sill was intruded close to the boundary of the Silurian shales and greywackes (Fig.1; Kowalczewski, 2004; Krzemiński, 2004; Nawrocki et al., 2007). Based on chemical composition the diabase has been classified as of olivine tholeiite type (Krzemiński, 2004). This sill was considered to be an intrusive body corresponding to the post-Ludlow and pre-Emsian time interval (Kowalczewski and Lisik, 1974); however, recent ^{40}Ar-^{39}Ar data (422+418 Ma) indicate a late Ludlow age (Nawrocki et al., 2007).

In the Kielce Region the greywacke succession is unconformably overlain by Lower Devonian siliciclastic deposits, generated during the Late Caledonian orogeny. However, in the Łysogóry Region shallow water greywacke facies continue across the Silurian/Devonian boundary (Kozłowski, 2008). The Lower Devonian siliciclastics (~550 m thick) display a progression of the sedimentary environment from continental to marginal marine settings, including deposition in storm- and wave-dominated nearshore zones (Szulczewski 1995a; Kowalczewski et al. 1998; Szulczewski and Porębski 2008). Close to the Lower/Middle Devonian boundary, siliciclastic deposition was replaced by the development of a carbonate platform that revealed a three-phase evolution, including peritidal to bank and reef deposition followed by a post-reef phase of disintegration and drowning (Racki, 1993; Szulczewski, 1995a, 2006). The stepwise drowning of the carbonate platform was controlled by eustatic sea-level rise, accompanied by syndepositional block-faulting driven in turn by tectonic extension (Szulczewski et al., 1996). The worldwide biotic crises and anoxic black shale (or limestone) horizons were recognized within sections related to the drowning of the carbonate platform (Racki, 2006; Marynowski and Filipiak, 2007; Marynowski et al., 2010; Racka et al., 2010).

The facies layout in Early Carboniferous times was controlled by tectonic horsts and grabens inherited from the Late Devonian syndepositional block faulting (Szulczewski et al., 1996). The Carboniferous system in the HCM is represented by deposits of the lower Mississippian series, detected only in the Kielce Region. Palaeohighs were sites of local non-deposition at the Devonian/Carboniferous boundary.Alternating shales and lime mudstones were deposited on or close to the elevated blocks, whereas the adjacent basins were dominated by deposition of black shales, cherts with some participation of phosphorite nodules (Żakowa, 1981; Skompski, 2006). Anoxic shale facies buried the elevated blocks in the late Tournaisian and prevailed in the Visean across the entire basin. Subordinate facies are lime breccias and redeposited limestones of sub-marine fans derived from a hypothetical carbonate platform located to the south (Bełka et al., 1993). The deposition of shales with fine-grained greywackes closed the Carboniferous succession in the HCM. They are interbed-

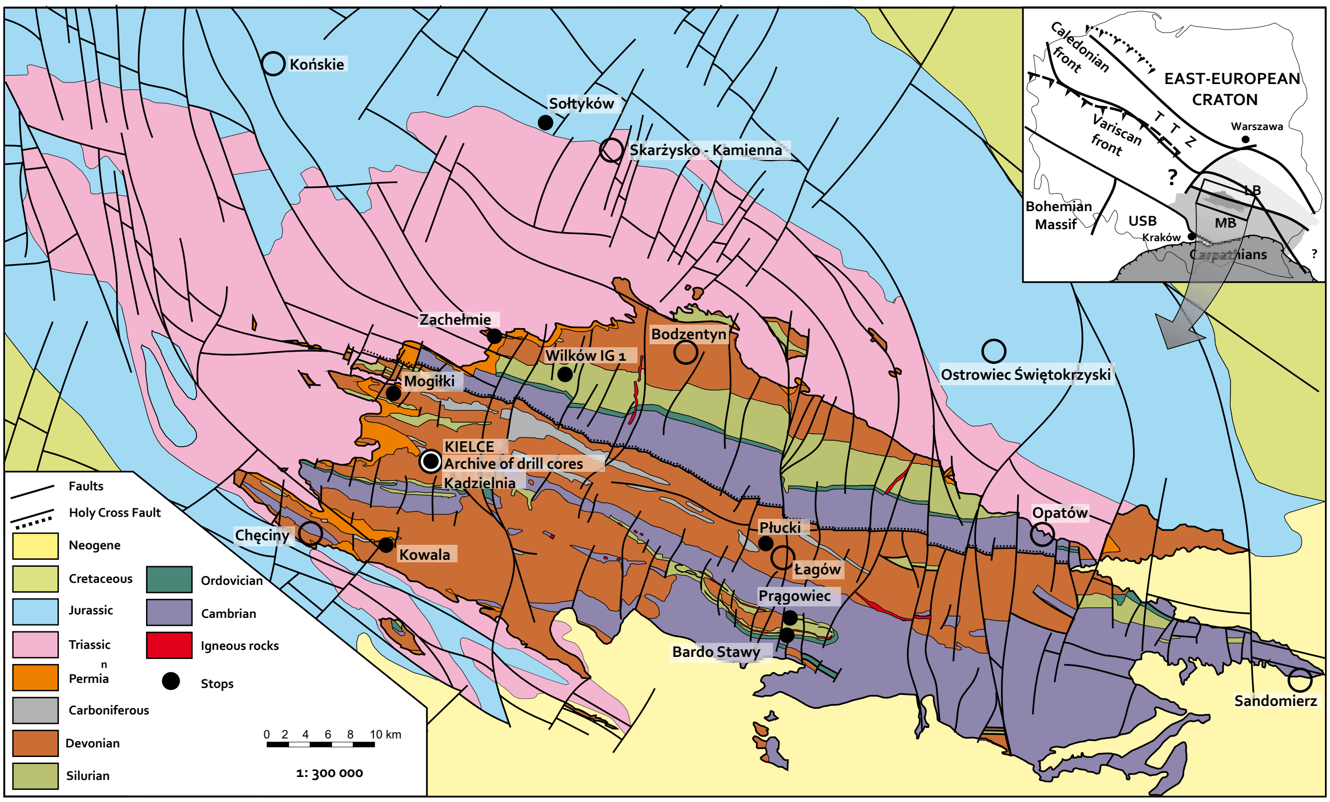


Fig. 1. Simplified geological map of the Holy Cross Mountains (after Rühle, 1977; Kowalczewski, Romanek and Studencki, 1990). USB – Upper Silesian Block, MB – Małopolska Block, LB – Łysogóry Block, TTZ – Teisseyre–Tornquist Zone

ded with numerous tuffite beds recording acid volcanic activity (Migaszewski, 1995). A pronounced stratigraphic gap in the Upper Palaeozoic sedimentary record of the HCM includes the uppermost Mississipian, Pennsylvanian and most of the Permian. It resulted from Variscan folding and faulting that took place in the post-Visean times. During the late Carboniferous, the Cambrian deposits of the Łysogóry Region were overthrust onto the Devonian strata of the Kielce Region along the Holy Cross Fault (Kowalczewski, 2004). It was, therefore, the time interval when the tectonic framework for development of the Permo-Mesozoic cover was established.

The Permian deposits in the HCM, referred to the upper Lopingian (Zechstein), rest on folded Palaeozoic rocks along the angular Variscan unconformity. Coarse-grained breccias and conglomerates composed of local material occur both at the base of the Zechstein succession and as intervals of various thickness interrupting red mudstones with calcrete horizons. These deposits are associated with alluvial fan or fan delta environments (Zbroja et al., 1998; Kuleta and Zbroja, 2006). The most conspicuous lithologies within these continental deposits are limestones, dolostones and evaporites (anhydrite nodules) documenting the incursion of marginal marine settings.

Lower Triassic deposits are represented by red sandstones, mudstones and shales, with subordinate carbonate interbeds. They document a wide spectrum of continental environments including: alluvial plain, eolian and lacustrine settings, accompanied, however, by subordinate shallow marine deposits (Senkowiczowa, 1970; Kopik, 1970; Kuleta and Zbroja, 2006). Middle Triassic limestones and dolostones occurring in the south-western, south and north-eastern localities of the Mesozoic cover were deposited in marginal to open marine settings of the carbonate platform (Senkowiczowa, 1970; Trammer, 1975). The Upper Triassic is represented by red beds of continental environments (fluvio-lacustrine settings) associated with a general marine regression on the HCM area. A conspicuous unconformity delineates the Triassic/Jurassic boundary.

Jurassic deposits of the HCM were formed in the eastern arm of the Jurassic European epicontinental basin (Pieńkowski, 2008). The lower part of this system is dominated by a siliciclastic succession of continental (alluvial plain and lacustrine) and marginal to shallow marine environments (Pieńkowski, 2004). The overlying Middle Jurassic sandstones, mudstones and heteroliths accumulated under the influence of relative sea-level changes. A thick carbonate succession, deposited on the carbonate ramp, dominates the Upper Jurassic rock record of the HCM (Pieńkowski, 2008). In some places, the Cretaceous sandstones rest on Upper Jurassic limestones along the erosive surface.

In post-Cretaceous times the HCM emerged due to tectonic inversion and uplifting, which resulted in partial removal of Mesozoic strata and exposure of Palaeozoic rocks (Kutek and Głazek, 1972). In the Miocene, the south-eastern periphery of the HCM was located in the marginal part of the Carpathian Foredeep, formed in response to northward overthrusting of the Alpine front.

Stop 1. Kowala – Famennian black shale horizons and Devonian/Carboniferous boundary (Figs 2–4)

Leszek Marynowski, Wiesław Trela, Sylwester Salwa

The Upper Devonian succession exposed in the active Kowala quarry is more than 350 m thick and is located in the southern limb of the Gałęzice Syncline at the southern margin of the Kielce Region (Fig. 1). This succession provides insights into the worldwide anoxic events associated with recurrent black shale horizons occurring in the Famennian part of the Kowala section and the Devoinian/Carboniferous boundary in the HCM (Fig. 2; Marynowski and Filipiak, 2007). The black shale horizons are referred to as:

- the Upper Famennian Annulata black shale (Bond and Zatoń, 2003; Racka et al., 2010),
- the Dasberg black shale (Marynowski et al., 2010),
- the enigmatic, previously unreported from the Famennian sections, ca. 20 cm thick Kowala black shale (Marynowski and Filipiak, 2007),
- the Hangenberg black shale (Marynowski and Filipiak, 2007)

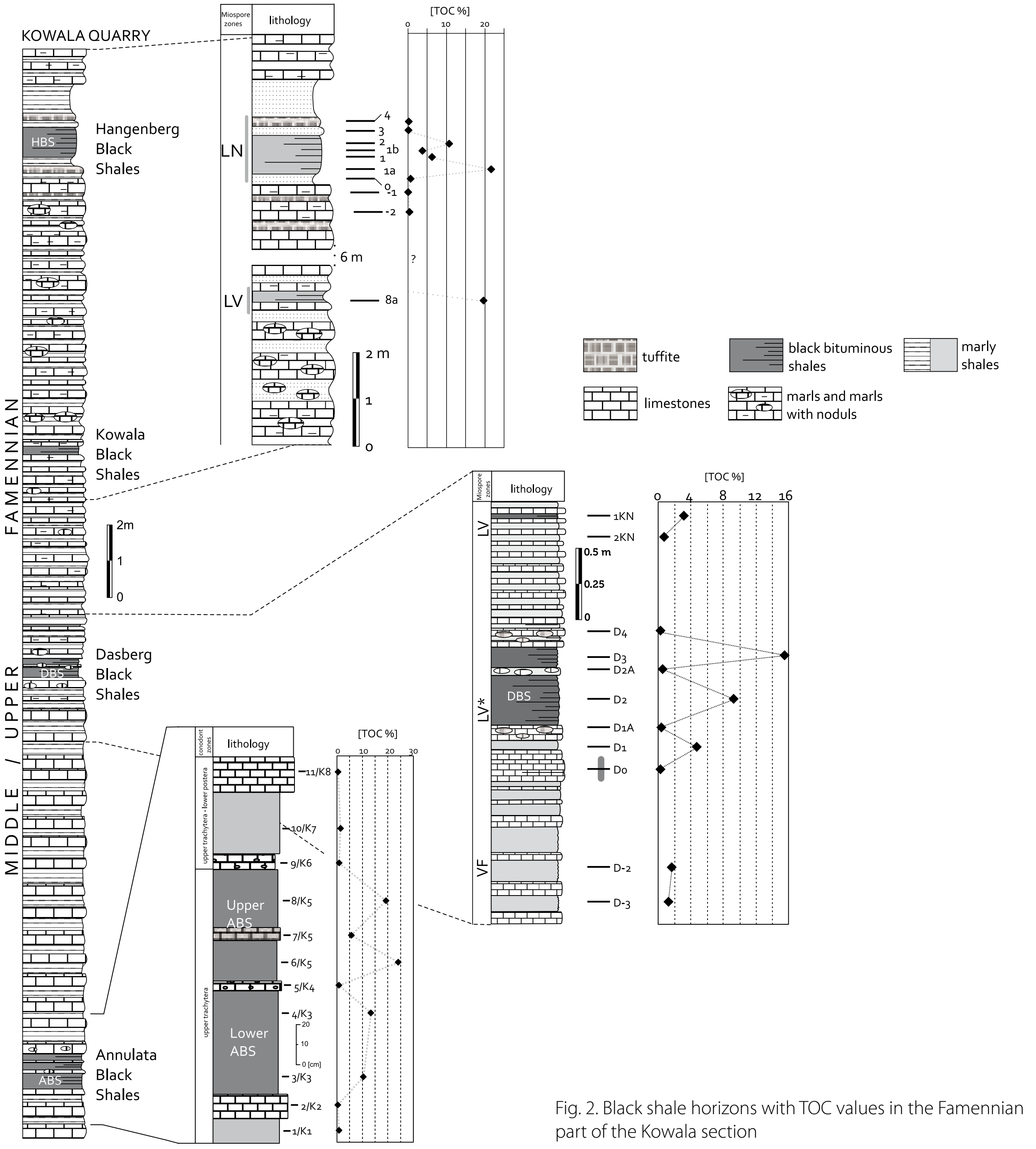


Fig. 2. Black shale horizons with TOC values in the Famennian part of the Kowala section

The Annulata black shale (ABS), up to 100 cm thick, is a bipartite horizon with thin nodular and black limestone interbeds (Fig. 2), dated to the upper part of the upper *Palmatolepis trachytera* conodont Zone, corresponding to the *Diducites versabilis–Grandispora famenensis* miospore Zone (Racka et al., 2010). The ABS in the upper part reveals a TOC content up to 23 wt. % (Racka et al., 2010). The lower black shale horizon developed under dysoxic, or intermittent anoxic, bottom-water conditions, whereas the upper one relates to a mainly anoxic environment. In both horizons euxinic conditions were at least intermittently present in the water column, as documented by the identification of isorenieratan and other biomarkers of green sulphur bacteria (Racka et al., 2010).

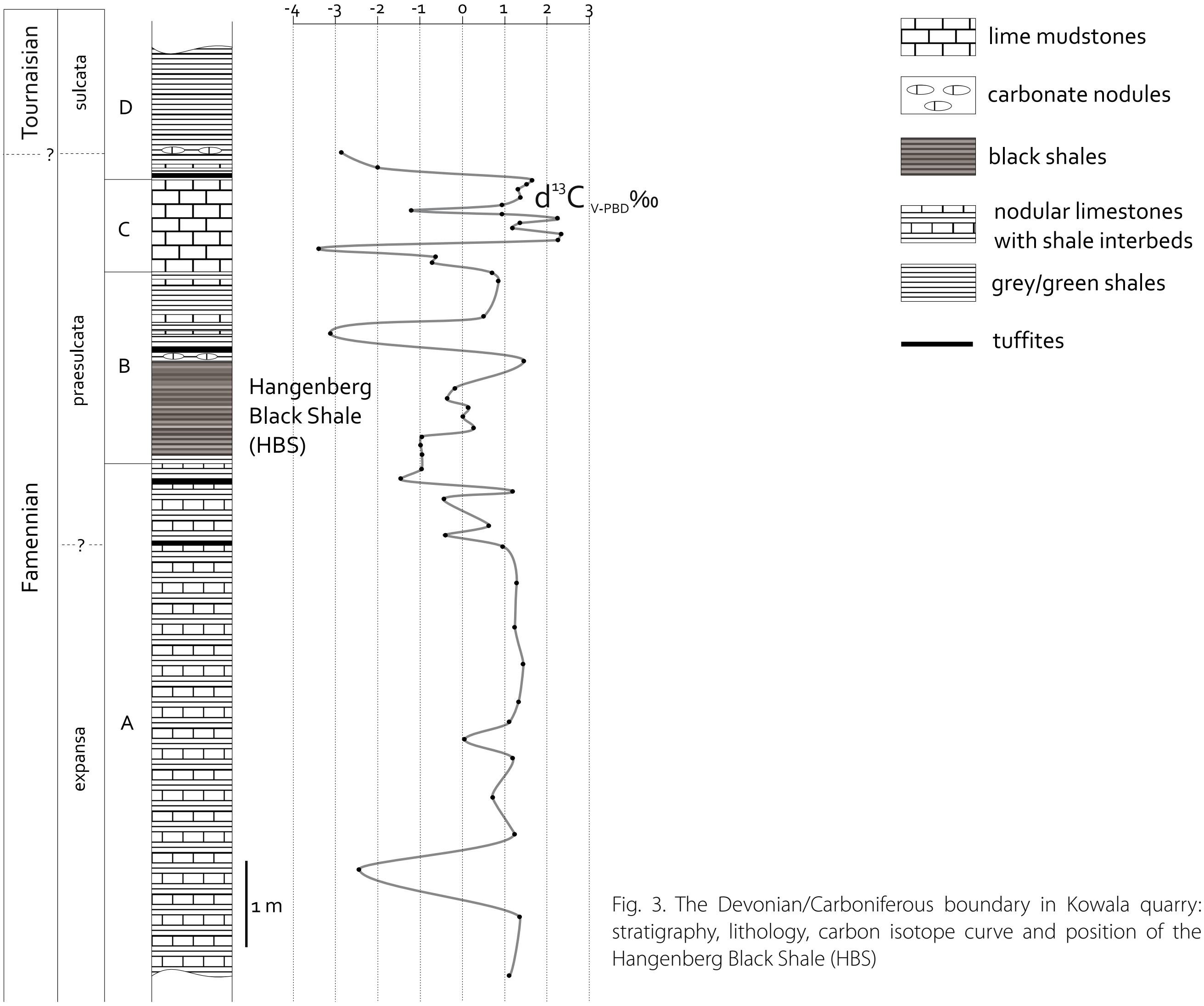


Fig. 3. The Devonian/Carboniferous boundary in Kowala quarry: stratigraphy, lithology, carbon isotope curve and position of the Hangenberg Black Shale (HBS)

The development of the Dasberg black shale (DBS), dated by the occurrence of VF (*Diducites versabilis–Grandispora famenensis*) and LV (*Retispora lepidophyta–Apiculiretusispora verrucosa*) miospore Zones, is very similar to that of the Annulata black shale. In the case of ca. 55 cm thick Dasberg event (Fig. 2), two black shale horizons were also described, with creamy nodular limestone sandwiched between them. Another typical feature of the Kowala's Dasberg section is a thinner (c.a. 5 cm) dark layer above the DBS identified also in the Effenberg Quarry, Germany, where DBS was also recognised (Hartenfels and Becker, 2009).

As in the ABS, the upper horizon of the Dasberg event was characterized by an elevated TOC content (up to 15%; Fig. 2) and taking into account data for the organic and inorganic proxies, sedimentary conditions here were also suboxic or intermittently anoxic in the lower DBS and mainly anoxic in the upper DBS (Marynowski et al., 2010).

The uppermost Famennian and lowermost Tournaisian rock record in the Kowala section can be divided into four sedimentary units (Fig. 3), including:

- a monotonous and fossiliferous nodular limestones interbedded with marly shales (A) corresponding to the *expansa* and lower *preasulcata* conodont zones (Malec, 1995; Dzik, 1997),
- a bipartite shale horizon (B) consisting of black shales (~ 0.9 m) identified as the Hangenberg black shale (HBS) grading upwards into brown-grey shales (~1,2 m),
- thin- to medium-bedded limestones (wackestones) with thin shale interbeds, up to 1.0 m thick (C), dated by conodonts of the middle/upper *preasulcata* zone (Malec, 1995; Dzik, 1997),
- a grey and cherry claystone succession with limestone nodules and thin tephra partings (D) referred to the lowermost Tournaisian.

The Upper Famennian miospore zone LV (*Retispora lepidophyta–Apiculiretusispora verrucosa*) was documented in the HBS horizon, revealing a TOC content up to 22.5 wt.% (Marynowski and Filipiak, 2007). A mass extinction of ostracod, conodont and ammonite faunas was recorded in the shale horizon exposed in the trench adjacent to the northern margin of Kowala quarry (Dzik, 1997; Olempska, 1997). This extinction was preceded by the disappearance of *Woclumeria* fauna in the topmost part of the underlying nodular limestones (Malec, 1995; Dzik, 1997). This faunal turnover was coeval with the deposition of the HBS in Kowala quarry, documenting water column euxinia and wildfires on land (Marynowski and Filipiak, 2007). A prominent positive $\delta^{13}C$ excursion, up to 2.7‰ (trench) and 2.54‰ (quarry), was detected within the limestone unit overlying the HBS (Fig. 3; Trela and Malec, 2007). These $\delta^{13}C$ data are comparable to a similar excursion interpreted by Buggish and Joachimski (2006) as a result of the Late Devonian relative sea-level fall. In the middle part of the HBS and below and above the black shale, volcanogenic material (tuffite) has been identified on the basis of mineralogical (Środoń, pers. inf) and geochemical (Marynowski et al., in preparation) compositions.

The Famennian deposits of the Kowala section reveal in some intervals strong tectonic deformation (Salwa, 2000). The most common structures include parasitic F_1 folds of various scale developed due to lithological contrast. Two zones of tectonic deformation (both above 20 m thick) in the quarry, show horizontal, mostly similar F_1 folds. Their axes are horizontal in the E-W direction and their axial surfaces show both S and N vergence (Fig. 4). The F_1 folds are located above thrust faults or reverse faults, strike generally in the E-W direction and dip towards the N (Fig. 4). These structures were produced by tectonic compression in a N-S direction. Folds and thrust faults are cut by transverse, dextral strike-slip faults (Fig. 4). Thick limestone layers contain numerous syntaxial calcite veins.

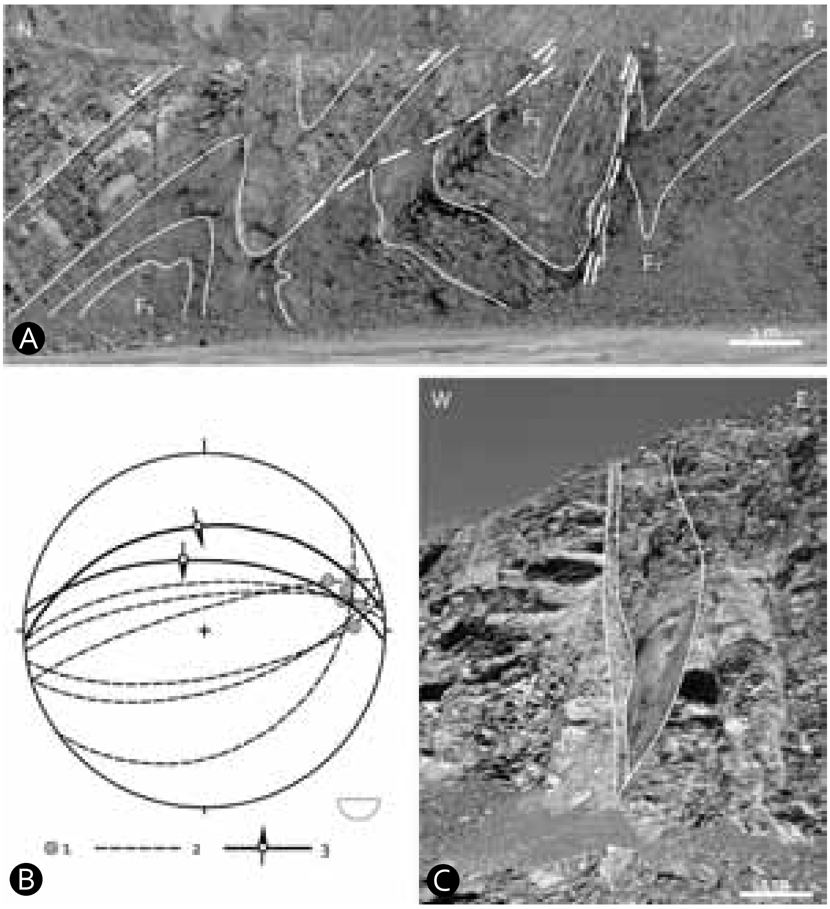


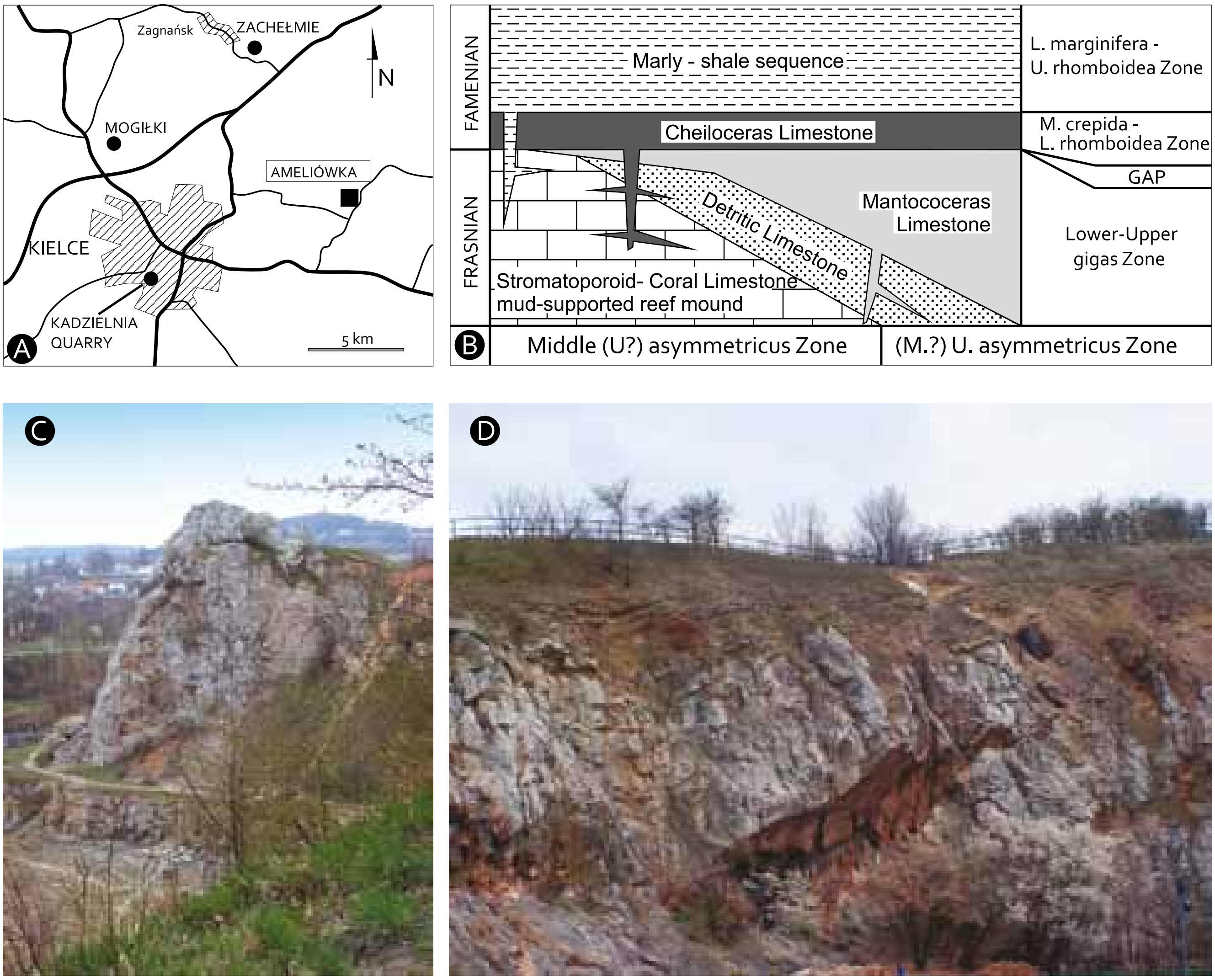
Fig. 4. Tectonic structures in Kowala quarry. A – general view of tectonically deformed part of the section with F_1 folds and thrust faults. B – spatial orientation of fold axis (1), axial surfaces (2) and thrust faults (3). C – transverse strike slip fault

Stop 2. Kadzielnia – Upper Devonian limestones and marly/shale cover (Fig. 5)

Wiesław Trela, Jan Malec

Kadzielnia quarry in the southern part of Kielce was set up on a hill composed of Upper Devonian limestones (Fig. 5). The bulk of the exposed succession is made up of inclined Frasnian limestones overlain by Famennian condensed limestones and marly/shale deposits (Szulczewski, 1978, 1981; 2010 and references therein).

Fig. 5. A – location of Kadzielnia quarry. B – lithostratigraphic scheme of the Upper Devonian limestones in the quarry (after Szulczewski, 1981). C – the "Geologist's Rock", composed of the Kadzielnia Limestone Member which is interpreted as a mud-supported microbial to reef mound. D – the Famennian marly limestone/shale succession overlying Frasnian and Famennian limestones in Kadzielnia quarry ↓



The Kadzielnia succession is divided into five lithostratigraphic units (mostly informal) that include:

- The Kadzielnia Limestone Member, interpreted as a mud-supported microbial to reef mound (~50 thick; Fig. 5) composed of massive boundstones with stromatactoid structures (Narkiewicz et al., 1990; Hoffmann and Paszkowski, 1992; Szulczewski, 2010). The sheet-like and tabular stromatoporoids are the main bounding organisms of the Kadzielnia mound. They are accompanied by tabulate and rugose corals, brachiopods, pelmatozoans, gastropods and trilobites (Szulczewski, 1981, 2010)
- Detritic Limestone (Fig. 5) represented by thick-bedded calcarenites and calcirudites consisting of stromatoporoids, corals, brachiopods, pelmatozoans, foraminifers, ostracods and calcispheres occurring together with *Renalcis* that in some cases form small build-ups (Szulczewski, 1981). The carbonate detrital material was supplied from the top of the Kadzielnia mound and deposited on its slope.

- Manticoceras Limestone (Fig. 5) occurring as thick-bedded biomicrites intercalated by detrital limestones and intraformational breccias that are dated by conodonts of the lower *rhennana* zone recognized at the base of this unit (Szulczewski, 1981, 1995a). The pelagic fauna consists of goniatites, orthocone nautiloids, conodonts, entomozoid ostracods, whilst the benthic organisms are represented by solitary rugose corals, gastropods and pelamotozoans.
- Cheiloceras Limestone forms a condensed interval (~1m thick) consisting of a pelagic and benthic fauna similar to that recognized in the Manticoceras Limestone (Szulczewski, 1995a). This unit rests disconformably on the Frasnian strata and is separated from the Manticoceras Limestone by a brief stratigraphic gap (Fig. 5) related to the Fransian/Famennian boundary (Szulczewski, 1981, 2010). The gap increases up to 11 conodont zones at the immediate contact of the Cheiloceras Limestone and Kadzielnia Limestone Member (*op.cit*).
- A marly-shale succession made up of alternating thin-bedded marly limestones and shales (Fig. 5) yielding various benthic organisms represented by rugose corals, brachiopods, crinoids, ostracods and blind phacopid trilobites accompanied by nectic and nectobenthic representatives (Szulczewski, 1981, 2010).

The Kadzielnia Limestone Member and Detritic Limestone are regarded as prograding deposits related to relative sea-level fall, whilst the overlying pelagic Manticoceras Limestone is associated with eustatic sea-level rise (Narkiewicz, 1988; Szulczewski, 2010). The Kadzielnia Member and Detritic Limestone are cut by fissures and neptunian dykes formed and infilled during an extensional tectonic regime responsible for the disintegration, fracturing and drowning of the carbonate platform in the HCM (Szulczewski, 1981; 2010).

Stop 3. Mogiłki – Giventian to Frasnian limestone succession (Figs 6–7)

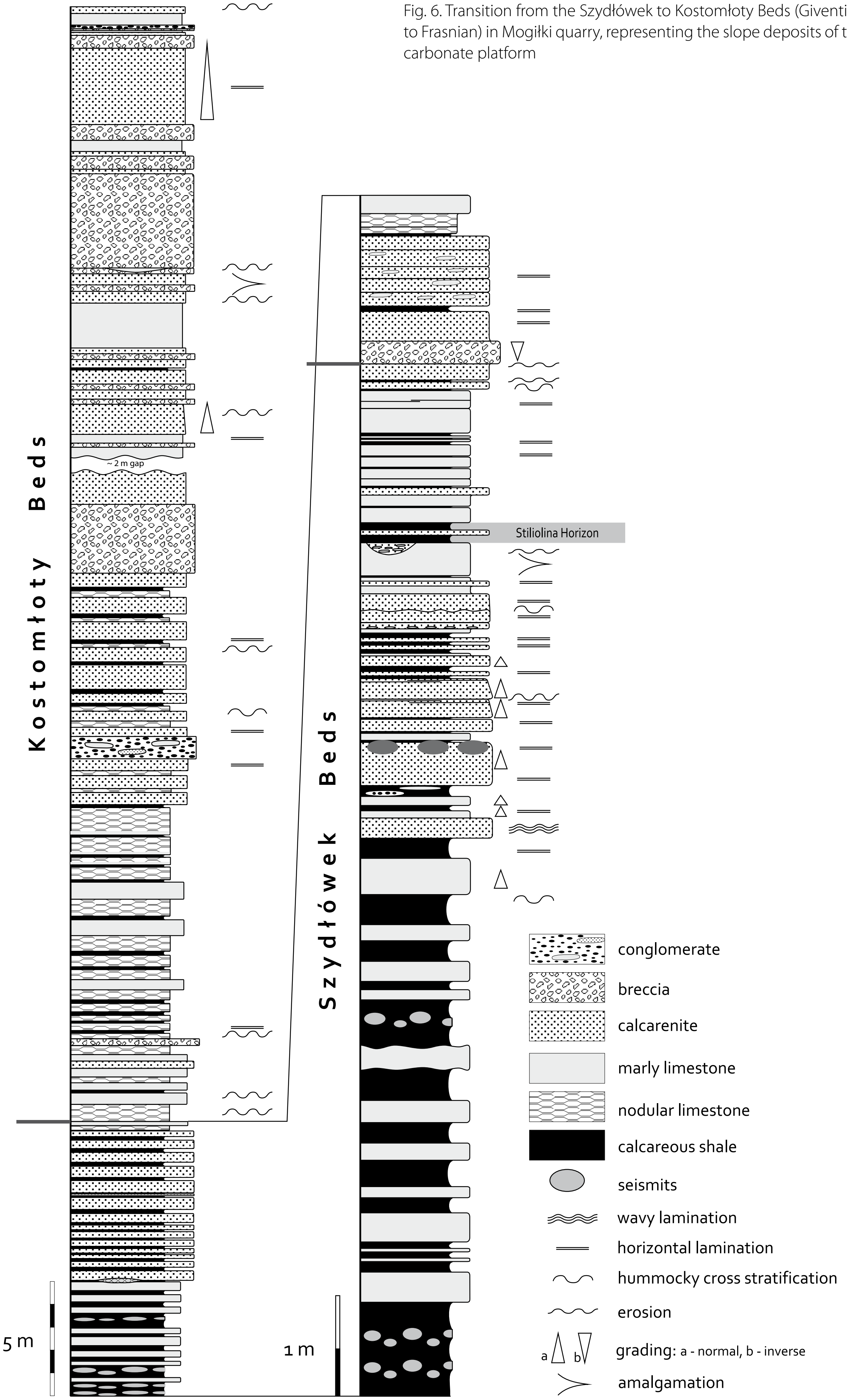
Wiesław Trela, Sylwester Salwa

The inactive Mogiłki quarry is located NW of Kielce in the Kostomłoty Hills, on the southern limb of the Miedziana Góra Syncline (Kielce Region; Fig. 1). The whole carbonate succession exposed in Mogiłki is referred to the upper Givetian to Frasnian Szydłówek Beds and a transition to the overlying Kostomłoty Beds that was thoroughly studied in stratigraphic, sedimentological and geochemical terms (Racki and Bultynck, 1993; Racki et al., 2004; Vierek, 2008; and references therein). The Mogiłki succession represents the transitional facies zone between the shallow water carbonate platform and deep-water Łysogóry basin (*op. cit*).

The Szydłówek Beds are dark grey to black thin- to medium-bedded micritic and marly limestones (Fig. 6) interbedded with calcareous shales yielding common styliolinids and some *Amphipora* branches (Racki et al., 2004). They contain also large limestone nodules. However, a few fossil-poor calcarenites containing many allochthonous lagoonal microbiotic indicators (calcispheroids and other microproblematics) were also detected (Racki, 1993). Deposition of the lower portion of the Szydłówek Beds took place in a dysoxic environment and conditions of overall sediment starvation supported by the Th/U ratio, the size of pyrite-framboids, the predominance of a laminated fabric and the scarcity of infauna (Racki et al., 2004). A thin black shale horizon (4 to 10 cm thick) with graded styliolinid-brachiopod coquinoid thin beds (*Styliolina* Horizon) occurring 2 m below the top of the Szydłówek Beds (Fig. 6) records a short-term benthic oxygen deficiency produced by higher carbon burial due to a high productivity event (Racki et al., 2004). Limestones above this horizon (~1 m thick interval) show a $\delta^{13}C$ excursion, up to 3.3‰, reflecting increased biotic productivity (*op. cit.*). The upper part of the Szydłówek Beds consists of calcarenite, calcirudite and coquaina beds interpreted as storm-induced tempestites (Vierek, 2008).

The overlying Kostomłoty Beds are composed of nodular limestones interbedded with conglomerates and horizontally laminated calcisiltites/calcarenites (Fig. 6). Conspicuous black to green shale partings intercalated with the limestone beds occur in the lower part of the unit. An increase of carbonate breccias and turbidites is a conspicuous lithological feature observed upwards through the section (Fig. 6). They were delivered both from the edge of the platform and its slope. This is confirmed by fragments of deep-water marly limestones within breccias and by the shallow water faunal communities, including brachiopods, echinoderms, gastropods, foraminifers, algae and cyanobacteria recognized within some carbonate fragments (Szulczewski, 1968). The breccias are related to redeposition of coarse-grained material by submarine gravity flows on the carbonate slope (*op. cit.*).

Fig. 6. Transition from the Szydłówek to Kostomłoty Beds (Giventian to Frasnian) in Mogiłki quarry, representing the slope deposits of the carbonate platform



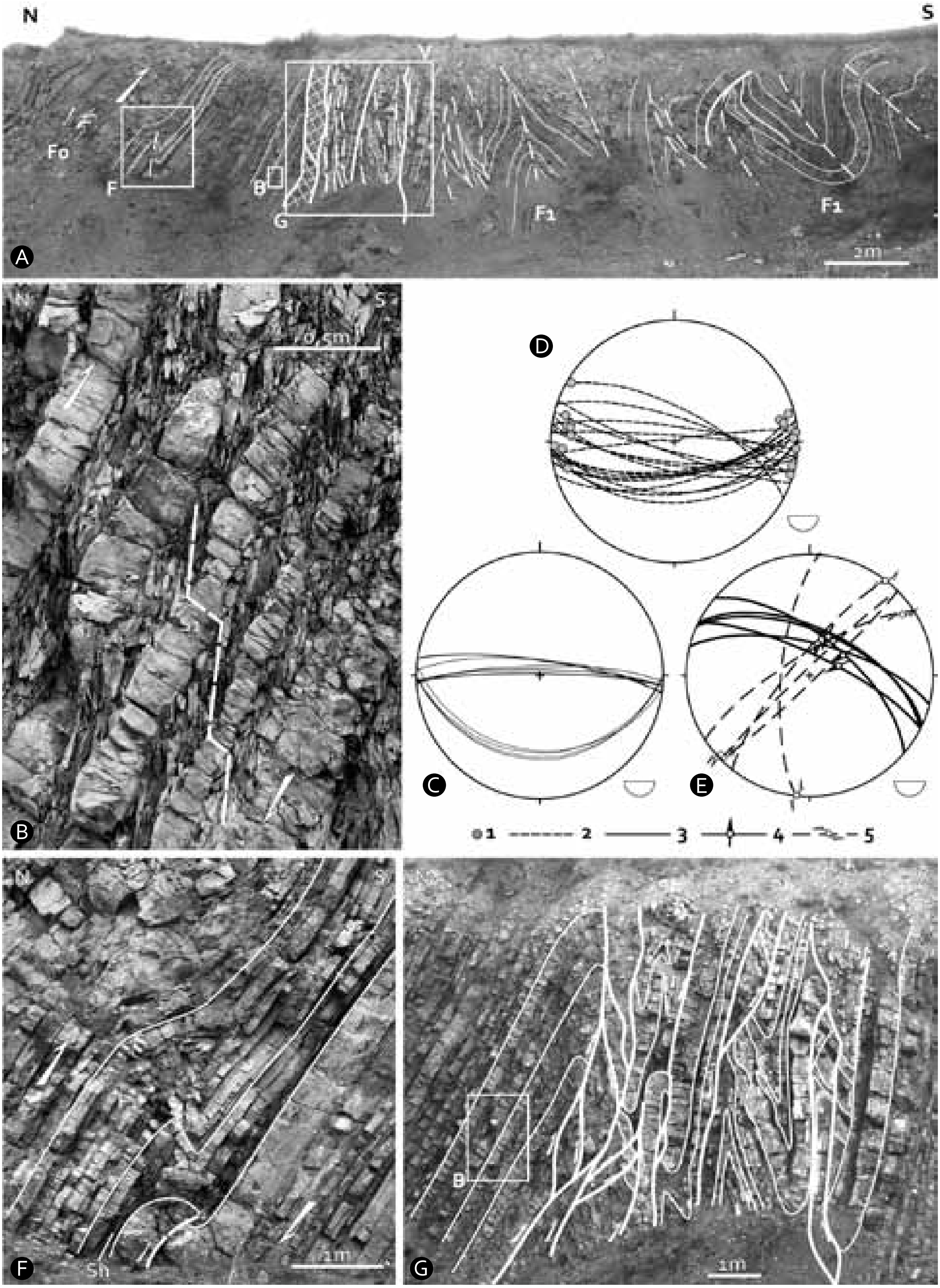


Fig. 7. Tectonic structures in Mogiłki quarry. A - General view of tectonically deformed part of the Szydłówek Beds (the eastern wall). B – refracted cleavage S_1. C-E – spatial orientation of the cleavage (C), F_1 fold elements (D) and faults (E). F – parasitic F_1 folds (Sh – Styliolina horizon). G – shear zone with sheared F_1 folds inside. Explanations: 1 – fold axis, 2 – fold surface, 3 – cleavage, 4 – reverse fault, 5 – strike-slip fault

The lowermost (southern) part of the Mogiłki section within the Szydłówek Beds shows pronounced tectonic deformation (Salwa, 1998, 2004, 2009; Konon, 2004, 2006), including seismites, synsedimentary folds F_0, and imbricated fans (Fig. 7A). The vergence of upright to slightly inclined F_0 folds (Fig. 7A) indicates NNE tectonic transport. They were produced by movement of weakly consolidated sediments in response to earthquakes. The refracted cleavage S_1 (Fig. 7B) and small scale contractional duplexes are the oldest tectonic structures in the section. The cleavage surfaces dip steeply in the marly shales and gently in the limestones (Fig. 7B,C). Numerous F_1 folds reveal almost horizontal axes in the E-W direction and axial surfaces showing mostly S or N to NNE vergence (Fig. 7D). They were formed during the main tectonic phase. Parasitic folds are present on their limbs, whilst in the hinge zones a poorly visible axial plane cleavage S_2 is sometime reported. The upper part of the Szydłówek Beds is less tectonically deformed and shows only a few small-scale parasitic F_1 folds (Fig. 7F). In the middle part of the quarry, a thick shear zone (~10 m) with several strongly sheared F_1 folds inside is visible (Fig. 7F,G). These deformational structures are related to the tectonic movement in a NNE-SSW direction. The folded rocks are cut by numerous transverse and oblique, almost vertical strike-slip faults. The first set are dextral and the second sinistral (Fig. 7G). Numerous calcite, calcite-dolomite and barite veins with metal sulphides are present.

Stop 4. Płucki – Frasnian/Famennian boundary and Kellwasser event (Fig. 8)

Piotr Szrek

Two outcrops of Frasnian and Famennian limestones of the Łagów Beds situated SE of Płucki near Łagów (Fig. 1) provide evidence of a Late Devonian (Kellwasser) anoxic event in the HCM. Two horizons of black bituminous limestones reported from this locality probably correspond to the Lower and Upper Kellwasser Limestones (LKW and UKW, respectively) known from western Europe (e.g. Bad Wildungen) and the Moroccan Meseta. The Frasnian-Famennian boundary was located in the middle of the upper horizon (Fig. 8) (Szrek and Ginter, 2007 and reference herein). This is the easternmost locality of the Kellwasser facies in Europe. Both Kellwasser horizons, occurring below a thin cover of soil, and especially the UKW, were previously uncovered several times in trenches in the fields and on the cliff of the Łagowca river valley. Numerous publications, starting with Makowski (1963), have described the geology and fauna of these horizons (Racki et al., 2002; Woroncowa-Marcinowska, 2006; Szrek and Ginter, 2007).

The LKW is only temporarily exposed in excavations because of its difficult location in the field. For analysis only the UKW is permanently excavated; moreover the site is protected by law as a documentary point (looking for fossils is allowed).

The UKW itself is a richly fossiliferous, dark bituminous limestone (ca. 30-50 cm thick) and is a composite of three subunits. The lower, entirely Frasnian subbed (up to 30 cm), has a marl at the bottom which gradually changes upwards into limestone, so that many fossils occur partly in the marl and partly in the limestone. The fauna is relatively rare and dispersed, mostly consisting of epiplanctonic *Buchiola* bivalves, a few large (up to 20 cm long) nautiloid shells, and fish, of which the heavy armour of placoderms (*Aspidichthys*) is the most spectacular. The middle subbed (10 cm) is the most fossiliferous, and yielded particularly abundant goniatite specimens and minute arthrodire placoderms (several complete skulls have been found). The Frasnian-Famennian boundary is probably situated within this limestone bed (Fig. 8). In thin section, a micro-scale erosional boundary is observed. It may be speculated that sediment below the erosional boundary is Frasnian, and above it is Famennian. The uppermost subbed (10 cm), belonging to the Famnennian part of UKW (confirmed by conodonts), contains fewer goniatites but much more abundant oriented orthocone nautiloid shells (Fig. 8). *Buchiola* gives way to large benthic bivalves, such as *Loxopteria*. The placoderm fauna generally remains the same.

In several outcrops spanning the Frasnian-Famennian boundary beds in the Holy Cross Mountains, e.g., Wietrznia quarry, an evident stratigraphic gap occurs on the boundary. If such a gap exists in the UKW at Płucki, it is negligible and probably impossible to trace with the available biostratigraphic tools. Thus, the Płucki outcrop can be considered the best locality documenting the Frasnian-Famnennian transition in Poland.

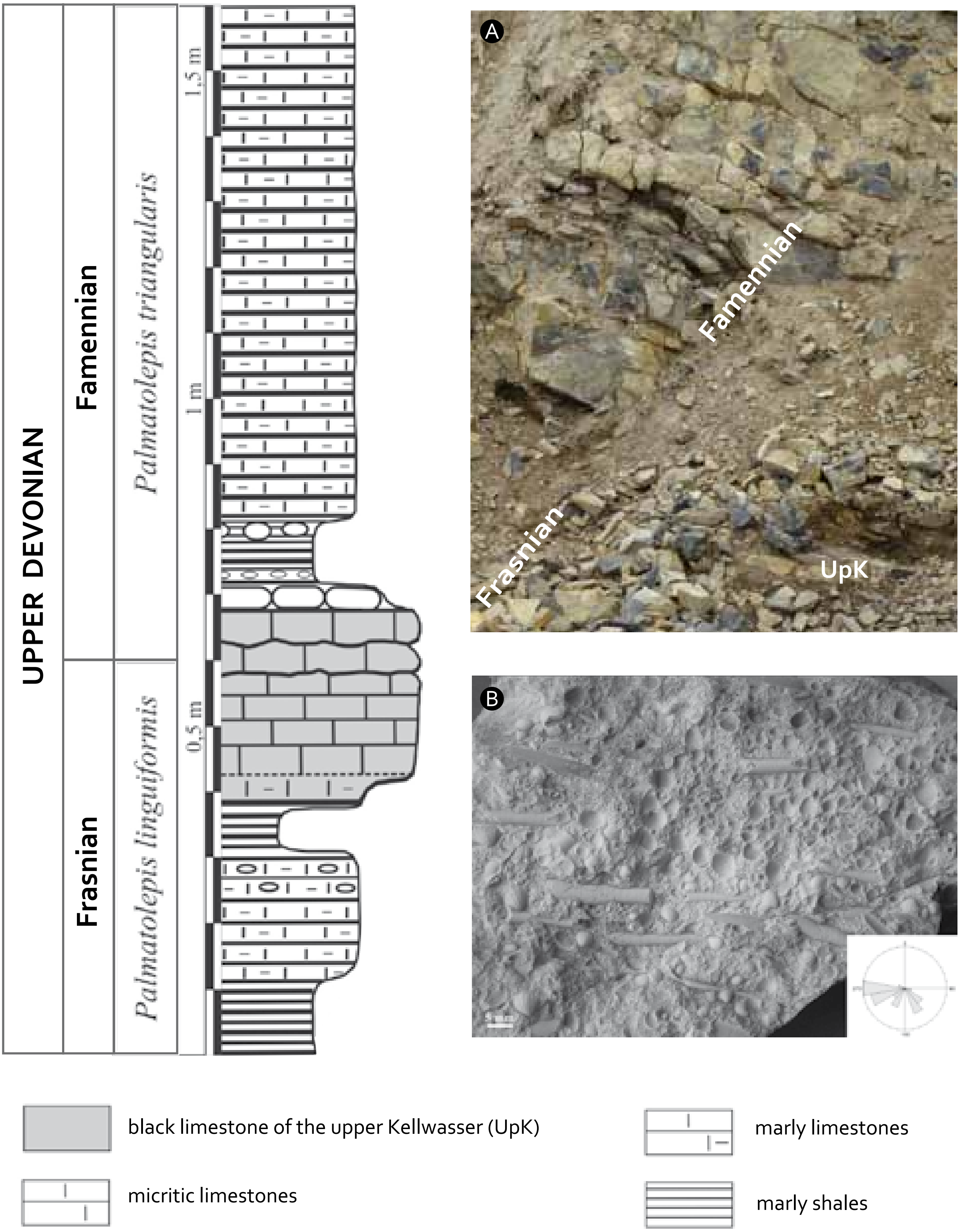


Fig. 8. A – Lithology and stratigraphy of the Frasnian/Famennian boundary in Płucki and position of the upper Kellwasser horizon.
B – Oriented orthocone nautiloid shells together with representatives of *Buchiola* bivalves

Stop 5. Bardo Prągowiec – Wenlock and Lower Ludlow shales (Fig. 9)

Wiesław Trela

The Prągowiec ravine in the northern limb of the Bardo Syncline (Kielce Region, Fig. 1) provides a natural outcrop of the upper Wenlock and lowermost Ludlow shale succession. The stratigraphy of this section was worked out by Tomczyk (1962), Kowalczewski and Tomczyk (1981), Porębska (2002 a,b) and Masiak (2007).

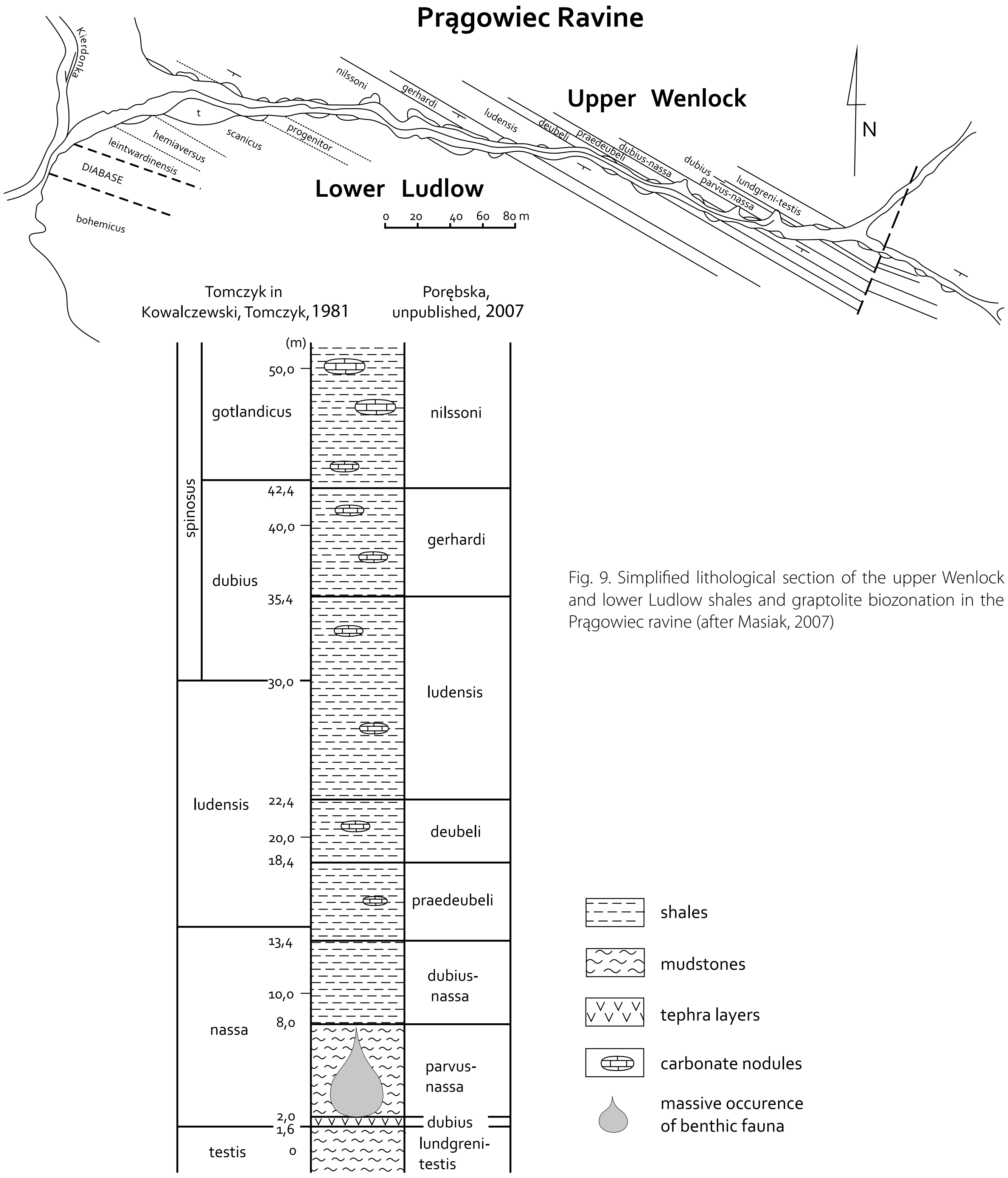


Fig. 9. Simplified lithological section of the upper Wenlock and lower Ludlow shales and graptolite biozonation in the Prągowiec ravine (after Masiak, 2007)

The oldest rocks occur in the northern part of the ravine and are yellow and grey mudstones (~1.6 m) with horizontal burrows. They are dated by graptolites of the *lundgreni-testis* zones with index taxa and numerous *Monograptus priodon*, *M. flemingii Pristiograptus dubiu* and *Cyrtograptus* sp., accompanied by nautiloids, crinoids, ostracods and bivalves (Masiak, 2007). This interval is overlain by a green tephra layer (Fig. 9), up to 0.4 m thick, with rhabdosomes of *Pristiograptus dubius* (Porębska, 2002a,b). The next stratigraphic interval (up to 6 m thick), coeval with the *parvus – nassa* graptolite zones, comprises yellow, bioturbated mudstones with tephra beds. Numerous trilobite, brachiopod and bivalve specimens occur at the base of this interval (~55 cm) referred to as the "Trilobite Bed" with representatives of *Odontopleura ovata* (Fig. 9; Tomczykowa, 1957; Kowalczewski and Tomczyk, 1981). This horizon records a regional colonization event corresponding to a mass occurrence of trilobite fauna in Baltica during the Mulde Event (Porębska et al., 2004; Calner, 2008).

The yellow mudstones grade upwards into grey, laminated shales, up to 35 m, which have yielded numerous graptolites indicative of the *dubius-nassa* to *nilssoni* zones (Fig. 9); however, the uppermost part of this interval is hidden under the Quaternary cover. The subordinate but distinctive lithology within these shales is related to calcareous nodules (a few to several cm) occurring in the *preadeubeli* graptolite zone and upwards through the section. The graptolite data from Bardo Prągowiec provide insight into the worldwide *lundgreni* event (Porębska, 2002a,b), considered to be the most spectacular mass extinction of the graptolite fauna in Silurian times. The three phases of this event include: 1) extinction recorded at the top of the *lundgreni–testis* zone, 2) a survival phase lasting from *dubius* to *dubius–nassa* zones and characterized by appearance of *Pristiograptus dubius* co-occuring in the middle part of this phase with *Gothograptus nassa* and *P. parvus*; 3) a recovery phase starting with the mass appearance of *P. praedeubeli* (Porębska, 2002 a,b).

The Silurian shales in the Prągowiec ravine are in contact with the diabase sill intruded close to the boundary of the lower Ludlow graptolite shales (Fig. 9) and the upper Ludlow Niewachlów greywackes.

Stop 6. Bardo Stawy – Ordovician/Silurian boundary and Rhuddanian black cherts and shales (Figs 10–11)

Wiesław Trela

The natural outcrop in Bardo Stawy in the southern limb of the Bardo Syncline (Kielce Region, Fig. 1) provides the complete section of Rhuddanian rocks in the HCM and the continuous sedimentary transition from the underlying strata of the uppermost Ordovician (Fig. 10; 11A).

The uppermost Ordovician is made up of grey/green and yellow mudstones, sandy mudstones with subordinate shales and sandstones of the Zalesie Formation (~6 m thick, Fig. 10), interpreted as regressive deposits related to the early Hirnantian glacio-eustatic event (Trela, 2007). They are dated by trilobites of *Mucronaspis mucronatus* (Brongniart) and *Mucronaspis olini* Temple (Kielan, 1959) and brachiopods of the Hirnantia fauna (Temple, 1965).

The overlying Bardo Formation, corresponding to the uppermost Hirnantian and Rhuddanian, is divided into the Rembów and Zbrza Members (Fig. 10; Trela and Salwa, 2007). The base of the Rembów Member consists of light brown shales (~80 cm; Fig. 10), with some admixture of silt-size quartz grains, which have yielded graptolites of the upper Hirnantian ?*persculptus* zone, including *Normalograptus parvulus* (Lapworth), *N.* cf. *persculptus* (Elles i Wood), *N. miserabilis* (Elles i Wood), *N. avitus* (Davies), and *N. normalis* (Lapworth) (Masiak et al., 2003). They grade upwards into thinly bedded, black radiolarian cherts, up to 6 m thick (Fig. 10; 11A), with graptolites of the *ascensus/acuminatus* zones represented by index taxa *Akidograptus ascensus* Davies, *Parakidograptus acuminatus* (Nicholson) and *P. primarius* Li, *Cystograptus ancestralis* Štorch and normalograptids (Bednarczyk and Tomczyk, 1981; Masiak et al., 2003).

The chert beds reveal a more or less regular, sub-millimetre, horizontal lamination (clearly visible on weathered surfaces), with rare white laminae (up to 10 cm long) and lens-like nodules, up to 0.8 cm thick (Fig. 11B). The cherts are made up of numerous radiolarian ghosts filled by microcrystalline quartz with subordinate fine spherulitic chalcedony (Fig. 11C), some admixture of muscovite, rare scolecodonts, chitinozoans and sponge spicules (Kremer, 2005). Moreover, they contain an amorphous organic matter and aggregates/clusters of very small globular bodies (1.5-3.5 µm in diameter), interpreted as the remnants of degraded coccoid cyanobacteria forming benthic microbial mats (Kremer and Kaźmierczak, 2005). In turn, the white laminae/nodules are composed of cryptocrystalline quartz, some organic matter, degraded acanthomorphic acritarchs, graptolites, chitinozoans, radiolarians and phosphate sediment (Fig.11C; Kremer, 2005).

The Rhuddanian black radiolarian cherts are interpreted as transgressive deposits related to marine flooding initiated during the latest Hirnantian (*persculptus* zone). Palaeogeographic reconstructions indicate that during the considered time span the HCM, as a part of Baltica, was positioned at the northern margin of the Rheic Ocean (Podhalańska and Trela, 2007). It is postulated that accumulation of black radiolarian cherts was influenced by an upwelling system (Kremer, 2005) generated by SE trade winds along the submarine paleo-high located in the central HCM (Trela and Salwa, 2007; Trela, 2009). These conditions generated large blooms preserved as white laminae and nodules within chert beds (Kremer, 2005).

The overlying graptolite siliceous shales of the Zbrza Member (~6 m thick; Fig. 11D) are largely horizontally laminated and interbedded with rare thin chert layers (up to 2 cm thick) displaying a faint lamination. Numerous graptolites indicative of the *vesiculosus* and *cyphus* zones were identified in this shale unit (Bednarczyk and Tomczyk, 1981; Masiak et al., 2003). The graptolite assemblage of the *vesiculosus* zone consists of the index taxon *Cystograptus vesiculosus* and numerous normalograptids: *Normalograptus medius*, *N. rectangularis* and *N. balticus*, accompanied upwards in the section by species of *Atavograptus, Huttagraptus*, *Dimorphograptus*, *Pseudoorthograptus*, *Neodiplograptus*, *Diplograptus, Raphidograptus* (Masiak et al., 2003). Light-coloured mottled bioturbations occur on some bedding planes and in most cases do not disturb the lamination.

The sandstone horizon (~0.8 m thick) overlying the chert/shale succession of the Bardo Formation (Fig. 10) appears to correspond to the post-Rhuddanian regressive event (Trela and Salwa, 2007).

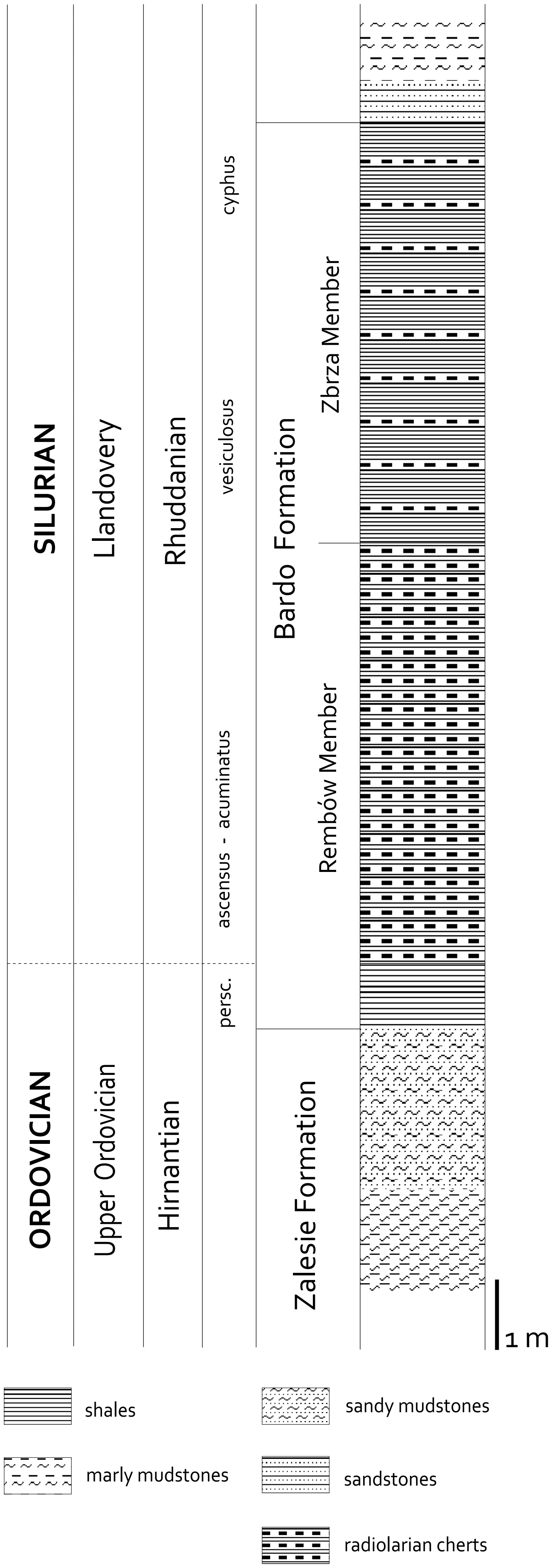


Fig. 10. Lithology and stratigraphy of the Ordovician/Silurian boundary in Bardo Stawy (graptolite biozonation after Bednarczyk and Tomczyk, 1981; Masiak et al., 2003), persc. – *perscuplus* graptolite zone

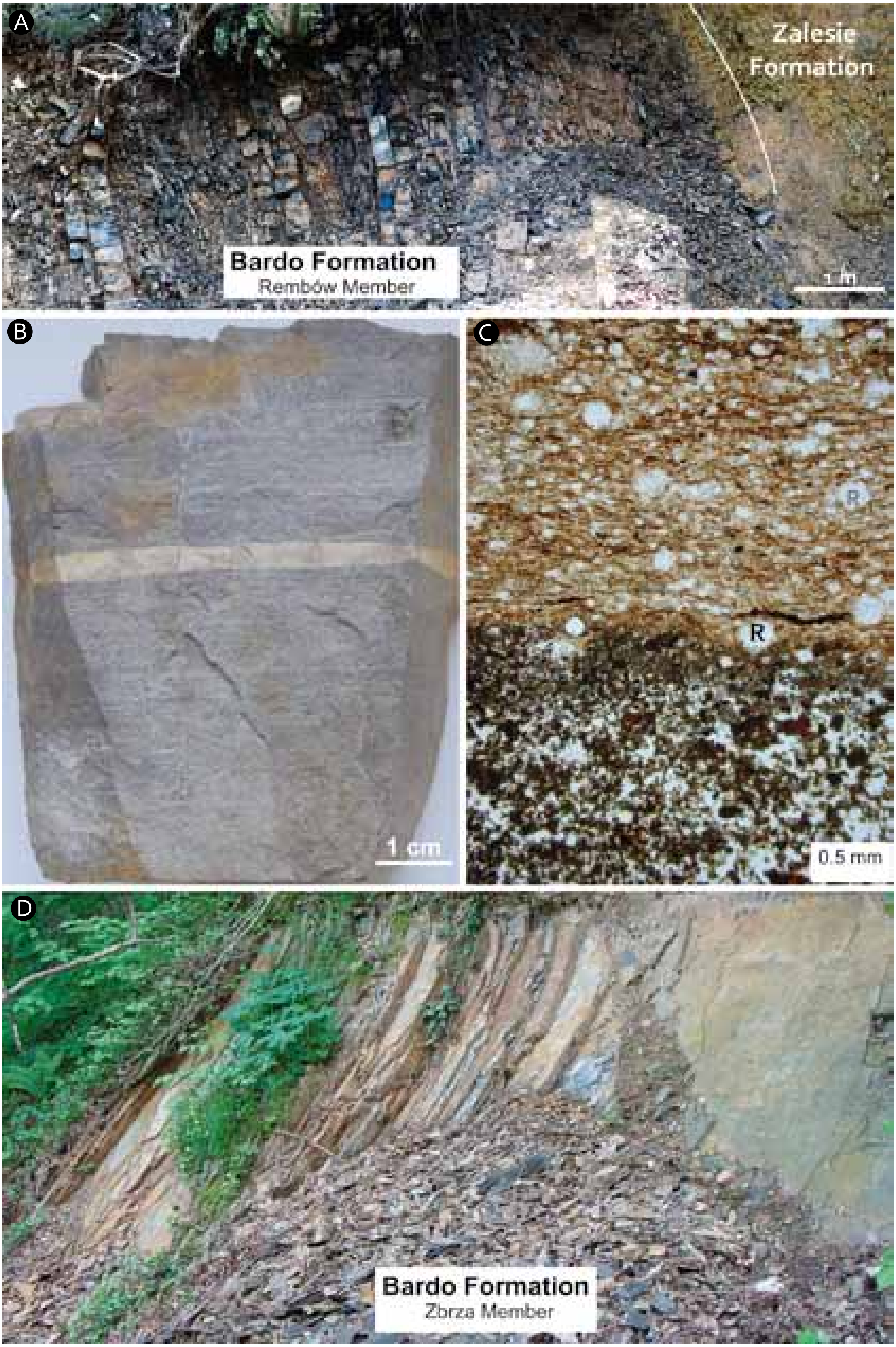


Fig. 11. A – the Ordovician/Silurian boundary in Bardo Stawy showing Hirnantian mudstones of the Zalesie Formation overlain by Rhuddanian black radiolarian cherts of the Rembów Member. B – laminated radiolarian black chert of the Rembów Member with thin white chalcedony laminae. C – photomicrograph of chert bed showing radiolarian tests (R) filled by microcrystalline quartz; and the contact with white chalcedony lamina enriched in organic matter; plane-polarized light. D – Rhuddanian siliceous graptolite shales of the Zbrza Member

Stop 7. Kielce (Wilków IG 1 well) – Furongian, Upper Ordovician and Silurian mudrock facies (Figs 12–13)

Wiesław Trela

The Wilków IG 1 well is located in the northern segment of the HCM (Fig. 1) and provides information on the Furongian to Silurian shale succession in the Łysogóry Region. The thickness of this succession in the drill-core is up to 950 m; however, some intervals are tectonically deformed.

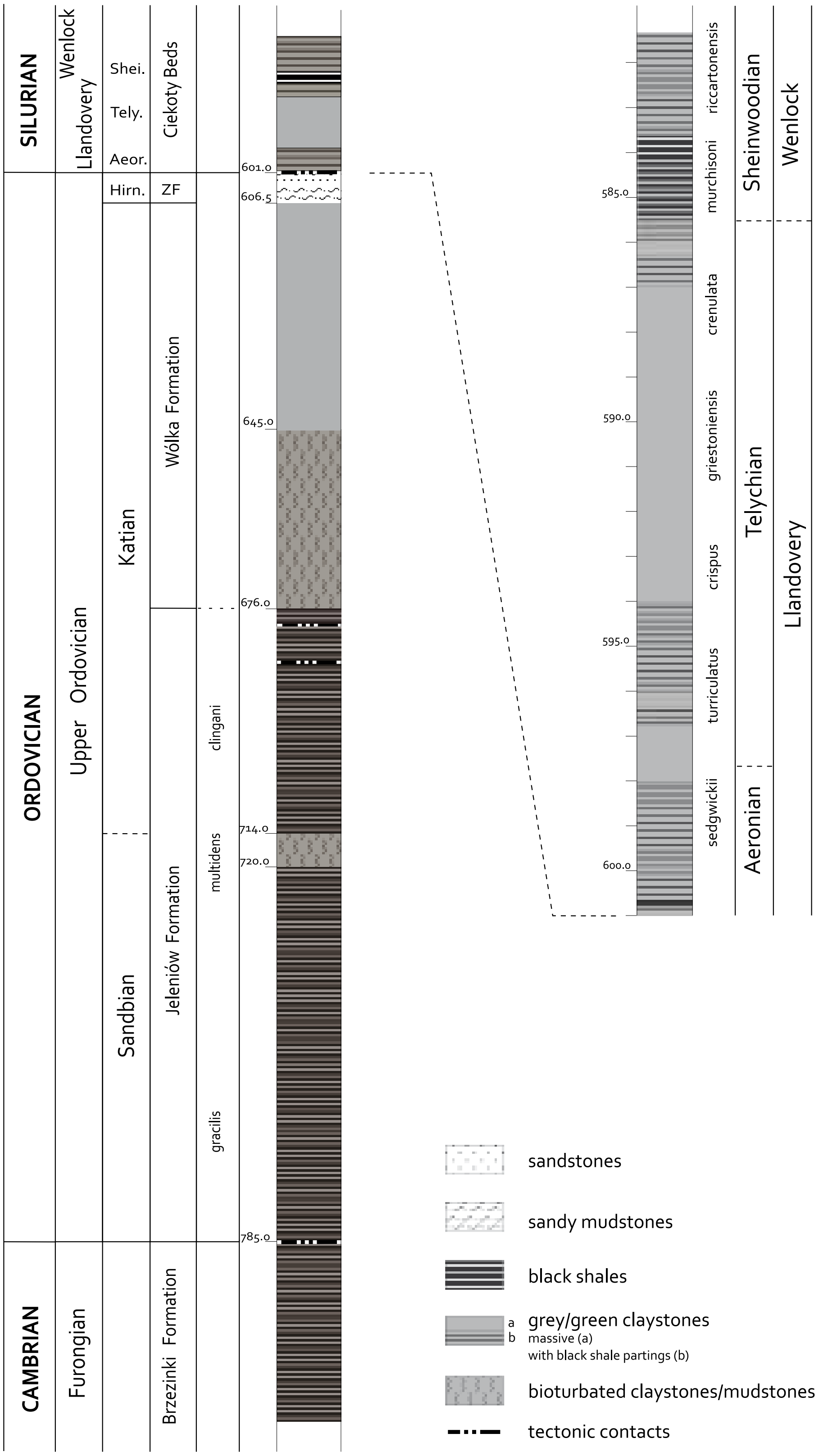


Fig. 12. The Furongian to Wenlock mudrock succession in the Wilków IG 1 well (graptolite biozonation after Deczkowski and Tomczyk, 1969; Trela and Podhalańska, 2010). Hirn. – Hirnantian, Aeor. – Aeronian, Tely. – Telychian, Shei. – Sheinwoodian, ZF – Zalesie Formation

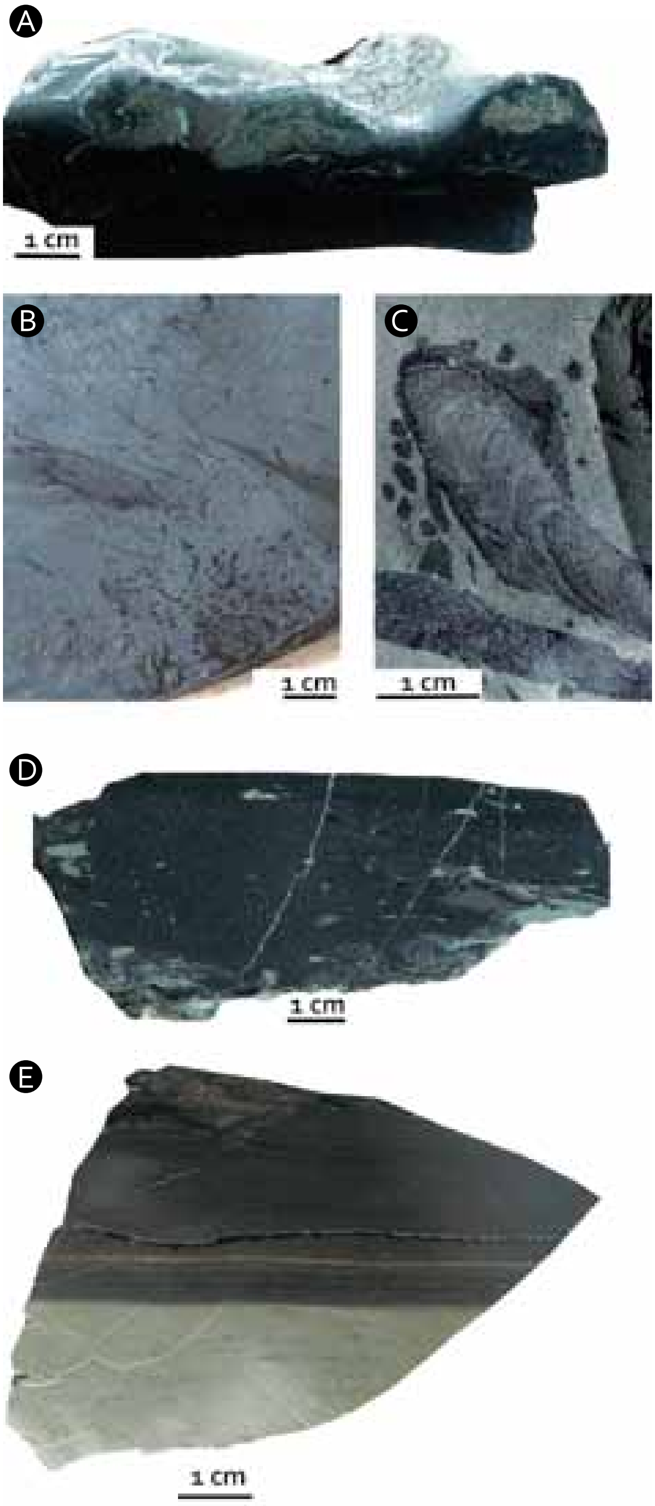


Fig. 13. A – thin microbial calcareous/phosphate mat overlying black claystone; the Wilków IG-1 well (depth 774.0 m, lower (?) Sandbian, the Jeleniów Formation. B – small *Chondrites* emplaced into a homogenous grey/green claystone background (bedding plane); the Wilków IG-1 well (depth 642 m, upper Katian, the Wólka Formation). C – meniscate backfill structure with slightly asymmetrical laminae (bedding plane surface), large *Chondrites* and non-compartmentalized, homogeneous backfill structure; the Wilków IG-1 (depth 658 m, upper Katian, the Wólka Formation). D – massive fine-grained sandstone of the Zalesie Formation with mudstone rip-up clasts, the Wilków IG 1 well (depth 604,2 m, Hirnantian). E – sharp contact between green bioturbated claystones and black shale, the Wilków IG 1 well (depth 599,1 m, Aeronian, the Ciekoty Beds)

The Furongian part of the Wilków section is represented by a 172.8 m thick succession referred to as the Mąchocice Beds and Brzezinki Formation (Łysogóry Beds in Tomczykowa, 1968); however, the drill-core did not reach the base of this mudrock succession. The Mąchocice Beds are made up of mudstones and dark shales which are in places intensely bioturbated and intercalated with thin sandstone beds. The Brzezinki Formation is represented by dark and black shales with the trilobite species of *Leptoplastides*, *Parabolina* and *Peltura*, accompanied by brachiopod species of *Lingulella* (Tomczykowa, 1968; Tomczykowa and Tomczyk, 2000). They have been correlated by Żylińska (2002) with the *Acerocare sensu lato* Zone and seem to be coeval with the Scandinavian alum shales.

There is a tectonic contact between the Furongian Brzezinki Formation and the overlying Sandbian – lower Katian monotonous dark to black shales of the Jeleniów Formation (Fig. 12; Trela, 2006, 2007). The lower boundary of the Jeleniów Formation is diachronous and in the Łysogóry Region extends from the uppermost Darriwillian to Sandbian stages (*teretiusculus* to *gracilis/foliaceus* graptolite zones), whereas its upper boundary is within the lower Katian stage (*clingani* graptolite zones) (Tomczykowa, 1968; Bednarczyk, 1971; Tomczykowa and Tomczyk, 2000). The shales are homogenous, revealing in places, however, a sub-millimetre horizontal lamination and discrete bioturbational mottling confined to individual laminae and subordinate fine lenticular and wavy-crinkly fabrics (Trela, 2007). Phosphate-rich nodules and thin phosphate-carbonate microbial mats (Fig. 13A) occur as subordinate lithologies in the lowermost part of the Jeleniów Formation. Locally, light-coloured discrete trace fossils, represented by small *Chondrites* accompanied by rare oval burrows with a discrete meniscate structure, are emplaced in the dark host sediment. Shales contain abundant pyrite that forms macroscopic small aggregates and more or less indistinct laminae and lenses. In thin section the pyrite occurs as framboids and microscale aggregates. A relatively thin sequence of grey/green bioturbated claystones (up to 6 m) divides this monotonous succession into two horizons (Fig. 12). The Jeleniów shales developed during the time interval characterized by the global predominance of greenhouse conditions in the Ordovician (see Page et al., 2007), that favoured decreased ocean circulation and a salinity-stratified water column (Railsback et al., 1990). They point to dysoxic/anoxic bottom waters in the HCM in response to the global climatic and oceanic conditions (Trela, 2007; Zhang et al., 2011). A relatively short-term oxygenation event interrupted this long-lasting oxygen-poor interval as can be inferred from the grey/green bioturbated claystones dividing the thick succession of Jelniów shales.

The Jeleniów Formation passes upwards into the Wólka Formation (Trela, 2006, 2007) comprising grey to green bioturbated claystones/mudstones (Fig. 12). Three types of bioturbation structures in these deposits include: 1) grey to dark biodeformational structures, 2) trace fossils showing a definite shape and distinct outlines, and 3) diffuse burrow mottles with indistinct outlines (Trela, 2007). The trace fossils are generally flattened due to compaction. Most conspicuous in the distinct trace fossil assemblage is *Chondrites,* displaying both small- (up to 1 mm) and large-diameter (2-4 mm) spots and root-like branches (Fig. 13B). The second, less common but distinct type of trace fossils are straight or slightly winding, unlined and unbranched meniscate burrows resembling *Taenidium* isp.; however, in cross sections this trace fossil shows a blade-like spreite structure comparable to the ichnogenus *Teichichnus* (Fig. 13C; Trela, 2007). The trace fossils are accompanied by *Planolites* isp. and *Palaeophycus* isp. The upper portion of the Wólka Formation is dominated by massive green claystones/mudstones with sparse biodeformational structures (Fig. 12). An increase of benthic oxygenation level in the HCM and colonization of the sediment by soft-bodied burrowers recorded in the Wólka Formation were consequences of a major change in ocean circulation due to polar cooling and associated thermohaline circulation at the beginning of the late Katian (Trela, 2007; Page et al., 2007; Zhang et al., 2011).

The topmost part of the Ordovician section in the Wilków IG 1 well, as in other HCM localities, is composed of sandy mudstones, sandstones interbedded with marls and shales of the Zalesie Formation (up to 6 m thick; Fig.12, 13D) referred to the Hirnantian regressive event (Trela, 2006; Trela and Szczepanik, 2009).

There is a stratigraphic gap between the Upper Ordovician Zalesie Formation and overlying Silurian strata that includes the Rhuddanian and most of the Aeronian stages (Fig. 12). The upper Aeronian and Telychian in the Wilków section are represented by grey/green carbonaceous shales referred to as the middle Ciekoty Beds, up to 15 m thick (Fig. 12 ; Tomczyk, 1962). The graptolite community recognized in these deposits includes species indicative of the *sedgwickii* to *crenulata* zones (Trela and Podhalańska, 2010). A subordinate lithology includes pyrite-enriched black laminated shales, occurring either as relatively thick intervals (up to 0,4 m) or thin laminated interbeds (a few cm). Lighter laminae within these shales show in some cases discrete bioturbation and a fine lenticular and wavy-crinkly fabric. The contact of the thin black shale beds and the host grey/green claystones is largely sharp (Fig. 13E); however, a gradual transition between these two lithologies has also been observed. The grey/green shales are apparently massive but in thin section they reveal a discrete horizontal lamination (sometimes inclined) enhanced by silt-size quartz grains. Nevertheless, in some cases discrete biodeformational structures are visible at both the macro- and micro-scales. The Aeronian and Telychian succession has a TOC content ranging from less than 1.0 wt% in grey/green claystones up to 2.61 wt% (usually 1.5–2.0 wt%) in black shales.

The Aeronian and Telychian sedimentary record in the Wilków IG 1 well can be referred to the Early Palaeozoic climate model and post-Rhuddanian cooling (Page et al., 2007). The black shale intervals appear to represent short-term transgressive events (see Loydell, 1998) referred to greenhouse periods (Page et al., 2007). On the contrary, the grey/green claystones of the Ciekoty Beds were deposited during icehouse periods, facilitating an increase of the benthic oxygenation level due to mixing of the water column. These conditions enabled bioturbation of the substrate by organisms inhabiting the soft-ground (or even soup-ground). Thin black shale partings in the grey/green claystones appear to record periods of seasonal stratification of the water column and related benthic oxygen deficiency during an overall icehouse climate state.

The Llandovery shales grade upwards into a monotonous succession of Wenlock and lower Ludlow grey shales (~150 m thick) yielding graptolites indicative of the *murchisoni* to *scanicus* zones (Deczkowski and Tomczyk, 1969; Tomczykowa, 1968). The Sheinwoodian black shale horizon (~2.0 m) with the index taxon of *Cyrtograptus murchisoni* marks the base of this succession (Fig. 12). The subordinate faunal species in this interval include *Orthoceras* and *Cardiola* (Deczkowski and Tomczyk, 1969). In the Wilków IG 1 well there is a continuous sedimentary transition from the graptolite shales to the upper Ludlow shales intercalated by mudstone and greywacke beds (~400 m thick). These deposits are dated by graptolites of *Pristiograptus bohemicus*, *P. longus*, *Seatograptus leintwardinensis*, accompanied by less frequent bivalves, ostracods, cephalopods and crinoids (Deczkowski and Tomczyk, 1969).

Stop 8. Zachełmie – Middle Devonian *Tetrapod* trackway and Variscan unconformity (Fig. 14)

Piotr Szrek, Wiesław Trela

The abandoned Zachełmie quarry is located NW of Kielce (Fig. 1) and is prominent locality due to the Variscan unconformity between the Middle Devonian and uppermost Permian/Lower Triassic strata, and the oldest (Middle Devonian) *Tetrapod* trackways (Fig. 14).

The Devonian dolostones belong to the Wojciechowice Formation of Eifelian age, as supported by conodont data (Niedźwiedzki et al., 2010). The lowermost part of the Devonian dolostones exposed in the quarry is composed of laminites and laminated stromatolites with spectacular shrinkage cracks on bedding surfaces related to the supratidal environment considered to record the earliest stage in development of the Middle-Upper Devonian carbonate platform in the HCM (Skompski and Szulczewski, 1994). The *Tetrapod* trackways were detected on bedding planes of this laminated part of the Eifelian section (Niedźwiedzki et al., 2010). Discoveries at Zachełmie show that tetrapods moved onto land at least 18–15 million years earlier than was previously supposed. In addition, they did not live in rivers and lakes as thought, but on the shores of warm, shallow seas. Those discoveries also help to make sense of the enigmatic Upper-Silurian tracks from other places (eg. Australia). These could be the oldest walking or jumping tracks made by a lobe-finned fish, perhaps an ancestor of the Middle and Upper-Devonian elpistostegids. They are also the best evidence that the animal which left them could move on land or in shallow water. Based on an analysis of the tracks and the surface of the deposit on which they were preserved, it is possible to reconstruct in detail the conditions prevailing at the time the tracks were made. Such tracks, quite independently of bone fossils, deliver much valuable information concerning, indirectly, the structure of the manus (hand) and pes (foot) bones

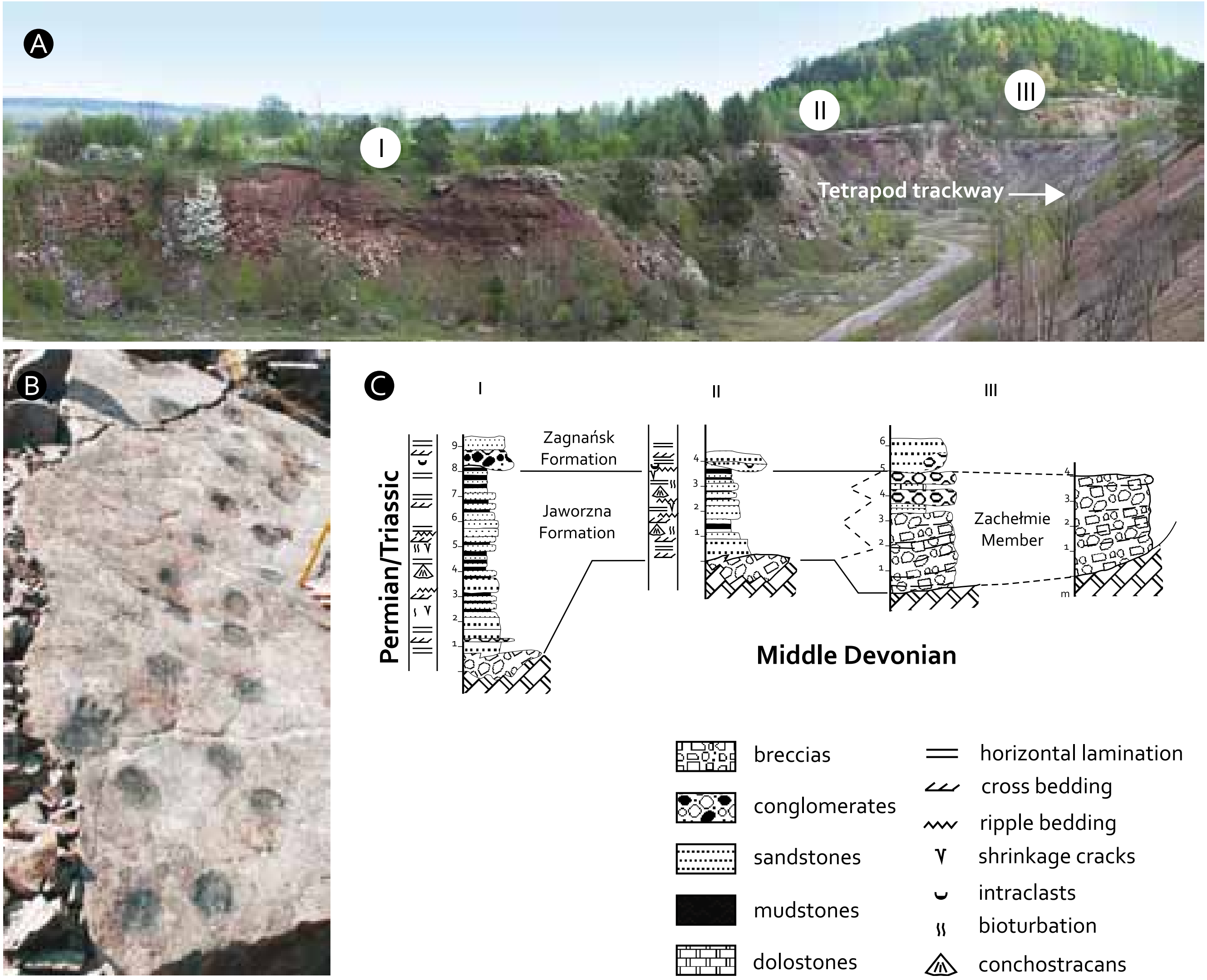


Fig. 14. A – general view of Zachełmie quarry with the Variscan unconformity. B – *Tetrapod* trackway on bedding plane of the Eifelian dolostone. C – correlation of the uppermost Permian/Lower Triassic deposits across Zachełmie quarry

of the animals which left them, and, directly, the way in which they moved. The tracks show that in the area of the present-day HCM, in extensive marine shallows of the Middle Devonian there lived animals with four walking limbs and digits! The animal which left the tracks could even have been up to about 2.5 metres long - we know this from the size of the largest tracks. The absence of body or tail drag marks proves that this creature moved efficiently through the mud, using its limbs to raise its body above the surface sediment. And as befitted a form of life descended from fish, it could no doubt also swim well.

The Middle Devonian rocks are cut by a prominent Variscan unconformity that reveals small scale topographic lows filled by a poorly sorted and clast-supported breccia (up to 1 m thick; Fig. 14) interpreted as the regolith developed upon the emergent surface probably during the Late Permian.

Crudely stratified conglomerates/breccias of the Zachełmie Member (up to 6 m thick) resting upon the Middle Devonian dolostones outcrop in the eastern part of the quarry. In the upper part they are intercalated with red sandstones. Besides local dolostone boulders this coarse-grained unit also contains fragments of the breccia from the topographic lows of the Variscan unconformity. These deposits are interpreted as an alluvial fan (Szulczewski, 1995b) developed in close proximity to a morphological rise built of Middle Devonian dolostones.

The bulk of the uppermost Permian/Lower Triassic succession in the Zachełmie quarry is made up of the Jaworzna Formation (Fig. 14), consisting of thin- to medium-bedded red sandstones and mudstones with shale partings. In nearby boreholes, the spore-pollen assemblage of the Lower Buntsandstein *Lundbladispora obsoleta - Protohaploksypinus panti* zones was identified in the Jaworzna Formation (Fijałkowska, 1994). These biostratigraphic data are supported by magnetostratigraphic data indicating that the deposits correspond to the basal Triassic normal polarity zone (Nawrocki et al., 2003). The occurrence of conchostracan carapaces of *Falsisca postera* Kozur & Seidel in the lower portion of the Jaworznia Formation and *Falsisca* cf. *verchojanica* (Molin) in its upper part suggests that the Permian/Triassic boundary is located within this unit (Ptaszyński and Niedźwiedzki, 2004). The sandstone beds show small-scale cross bedding, horizontal lamination, rare ripple marks and desiccation cracks. Moreover, root traces, plant remains, rare fish scales and vertebrate footprints have been recognized within these sediments, as well as invertebrate trace fossils corresponding to the *Scoyenia* and *Mermia* assemblages (Kuleta et al., 2006). The Jaworzna Formation is interpreted as sheet flood deposits (Szulczewski, 1995b) or even a fan delta succession entering a lake (Kuleta et al., 2009).

The overlying grey/pink sandstones of the Zagnańsk Formation (Fig. 14) are multistory and amalgamated channel deposits of a braided river system (Szulczewski, 1995b; Kuleta et al., 2006). In Zachełmie quarry two channel routes can be seen truncating the Jaworzna Formation and locally the Middle Devonian dolostones. The undulating erosional surfaces of sandstone beds are locally covered by thin channel lag deposits consisting of dolostone pebbles and red mudstone clasts. The common sedimentary structures in these sandstones include large scale trough and tabular cross-bedding.

Stop 9. Sołtyków – Lower Jurassic (Hettangian) continental deposits and dinosaur footprints (Fig. 15)

Grzegorz Pieńkowski, Wiesław Trela, Leszek Marynowski

The abandoned clay pit in Sołtyków (Fig. 15) is a natural reserve providing insighs into a Hettangian mixed meandering/anastomosing alluvial plain and lacustrine environments and to related invertebrates and vertebrates (Pieńkowski, 2004; Gierliński et al. 2004; Pieńkowski and Niedźwiedzki, 2008, 2009, 2011; and references therein). Based on palynomorphs, the age of the sediments was shown to be Hettangian-Early Sinemurian (Wcisło-Luraniec 1991; Ziaja 2006). Sequence stratigraphy correlation (Pieńkowski 2004; Gierliński and Pieńkowski 1999) allowed its range to be narrowed to the Early Hettangian. The recent discovery of the conchostracan *Bulbilimnadia killianorum* Kozur and Weems 2005 (Kozur and Weems, 2005, 2010) fully confirms the earliest Hettangian age.

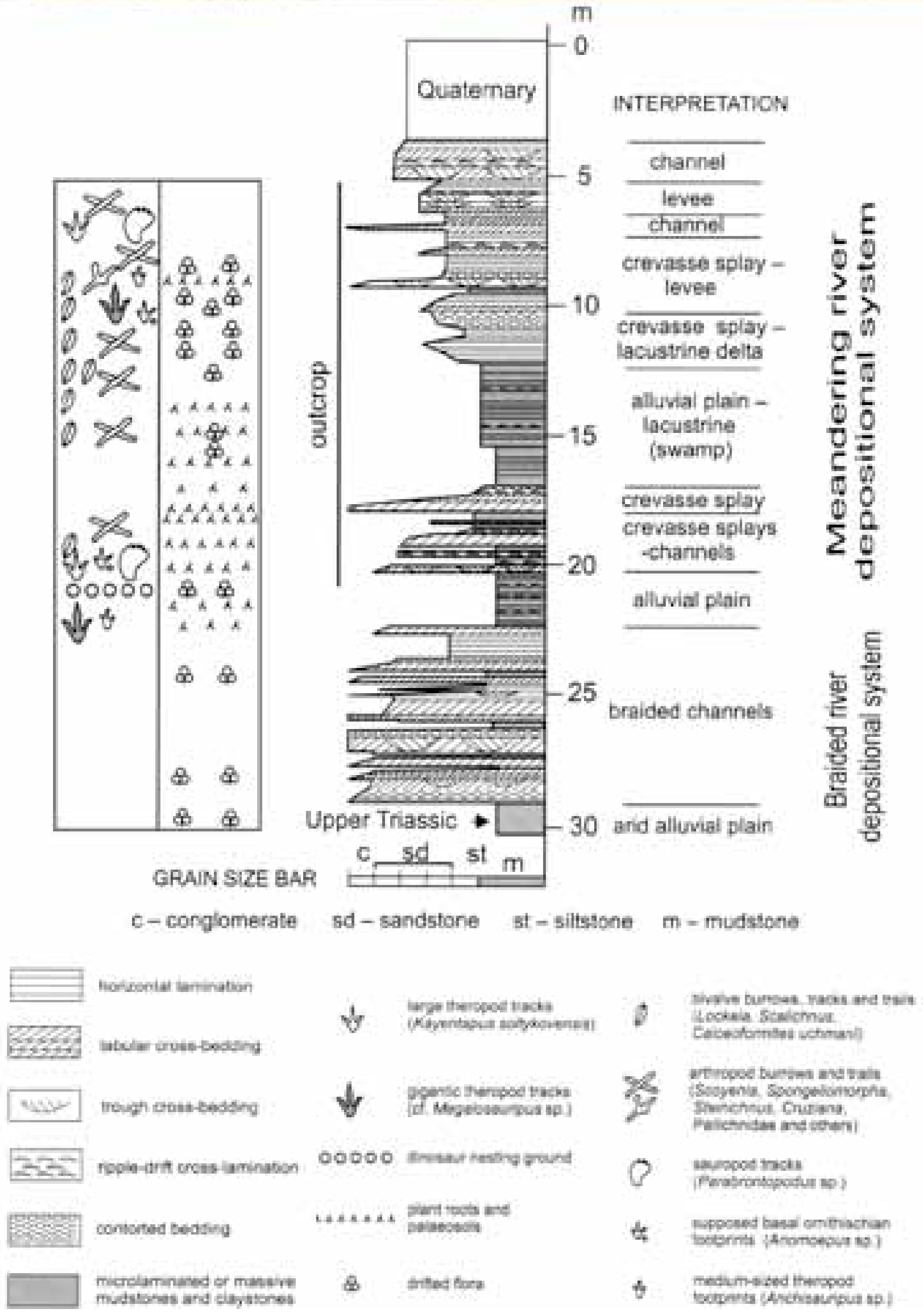
The sedimentary subenvironments described in this exposure by Pieńkowski (2004) include:

- Channel-related medium- to poorly- sorted light grey sandstones showing trough-cross bedding (Fig. 15).
- crevasse splay deposits represented by fine-grained sandstones (Fig. 15) with a large number of plant debris and mud clasts, which form thinner units than the channel sandstones. They occur as bodies with sharp bases or reveal gradational contacst with the substrate, which resulted accordingly from the sudden incursion of sediment-laden water or unconfined flow of a minor mouth bar/crevasse channel couplet. Some sandstone bodies reveal reactivation surfaces characteristic of multistage fill of channelized crevasse splays.
- lacustrine lithofacies represented by dark, organic-rich, laminated mudstones (Fig. 15) with numerous plant roots and palaeosols of podzol and gleysol types. They form a relatively thick package in the middle part of the outcrop, suggesting permanency of the lake/swamp area. The invertebrate trace fossils recognized in Sołtyków includes *Mermia* ichnofacies as well as *Scoyenia* and *Coprinisphaera* ichnofacies (Pieńkowski and Niedźwiedzki, 2008). The lacustrine and crevasse splay environments contain a relatively abundant trace fossil suite produced largely by bivalves (*Lockeia*, *Calceoformites*, *Scalichnus* isp.) and characterized by a variable ethological diversity, e.g., resting, locomotion, dwelling and escape structures (Pieńkowski and Niedźwiedzki, 2009). Most conspicuous is a locomotion (repichnion) trace fossil, *Ptychoplasma conica,* which is composed of chains of hypichnial mounds (Pieńkowski and Uchman, 2009). Its occurrence is limited to amalgamated crevasse sandstones. The trace fossil is associated with fresh water bivalves belonging probably to the Unionidae. This trace fossil reflects rhythmic (?diurnal) movement of the trace-maker in accordance with the direction of flow in the crevasse channel, where the forward movement took place in the shallow part of a sandstone layer and was interrupted by resting episodes in deeper sediment layer along the mud-sand interface. Episodic flood events forced bivalves to produce escape structures, moving from deeper (previous) to upper (later) levels of lateral movement. The exposed part of the crevasse splays, levees and dry places of the alluvial plain were colonized by crustaceans and/or insects that left burrows and chambered nests. The channel subenvironment has a less varied ichnoassemblage with bivalves and arthropods as dominant trace makers.

The Sołtyków outcrop is famous for the dinosaur footprints left by sauropods and theropods and ornitischian footprints, accompanied by reptilian, pterosaur and mammalian footprints (Pieńkowski and Gierliński, 1987; Gierliński et al., 2004; Niedźwiedzki, 2011). The trackways in Sołtyków indicate herding behavior among juvenile sauropods and possibly their escape from a hunting theropod (Gierliński and Pieńkowski, 1999). The most common theropod footprints preserved in Sołtyków belong to *Kayentapus soltykovensis* Gierliński, 1999 (up to 40 cm long) made presumably by *Dilophosaurus* (Gierliński and Ahlberg, 1994). Abundant and well preserved plant fossils have been recognized in the sedimentary record of Sołtyków including various ferns, *Neocalamites*, coniferns with *Hirmeriella* dominating in the Early Jurassic forests (Wcisło-Luraniec, 1991; Reymanówna, 1991; Barbacka et al., 2010). In the whole Sołtyków section charcoal fragments and elevated concentrations of polycyclic aromatic hydrocarbons have been found (Marynowski and Simoneit, 2009). They record lower Hettangian wildfires and indicate fire intensity near the Triassic/Jurassic boundary, most probably caused by the elevated atmospheric CO_2 levels and climate-driven shift (Belcher et al., 2010).

Fig. 15. Lithology and sedimentary environments of the Lower Jurassic (Hettangian) section in Sołtyków clay pit (after Pieńkowski, 2004) →


crevasse splay facies
channel facies
lacustrine facies


m
0
5
10
15
20
25
30
Quaternary
INTERPRETATION
channel
levee
channel
crevasse splay – levee
crevasse splay – lacustrine delta
alluvial plain – lacustrine (swamp)
crevasse splay
crevasse splays -channels
alluvial plain
braided channels
arid alluvial plain
Meandering river depositional system
Braided river depositional system
outcrop
Upper Triassic
c sd st m
GRAIN SIZE BAR
c – conglomerate
sd – sandstone
st – siltstone
m – mudstone
horizontal lamination
tabular cross-bedding
trough cross-bedding
ripple-drift cross-lamination
contorted bedding
microlaminated or massive mudstones and claystones
large theropod tracks (Kayentapus soltykovensis)
gigantic theropod tracks (cf. Megalosauripus sp.)
dinosaur nesting ground
plant roots and palaeosols
drifted flora
bivalve burrows, tracks and trails (Lockeia, Scalichnus, Calceoformites uchmani)
arthropod burrows and trails (Scoyenia, Spongeliomorpha, Steinichnus, Cruziana, Palaeophycus and others)
sauropod tracks (Parabrontopodus sp.)
supposed basal ornithischian footprints (Anomoepus sp.)
medium-sized theropod footprints (Anchisauripus sp.)

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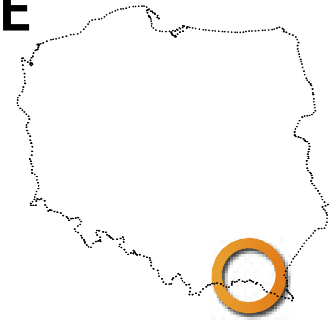
Carpathians

Field trip

THE CARPATHIANS – MENILITE SHALE AS THE MAIN OIL SOURCE IN THE CARPATHIANS



Leaders: Michał Krobicki [1,2], Jan Golonka [2] with contribution of Andrzej Ślączka [3]

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Itinerary: Warszawa – Rzyki – Poznachowice – Kobielnik – Żegocina – Lipnica Murowana – Brodziński Tors (Kamienie Brodzińskiego) – Znamirowice – Folusz – Iwonicz Zdrój – Równe – Bóbrka – Ciężkowice – Kraków

Main objectives: Cretaceous and Paleogene flysch deposits of the Silesian Nappe, Outer Carpathians, Poland; accretionary prism; Cretaceous organic-rich shales of the Cisownica Member, the Hradište Formation and Veřovice Formation, the Piechówka Member of the Hradište Formation. Reservoir rocks of the Istebna Formation and the Ciężkowice Sandstone Member, sandstone tors in the Outer Carpathian flysch, Oligocene organic-rich shales of the Menilite Formation, sedimentology of Menilite and Krosno formations, petroleum systems in the Polish Carpathians, history of the oil industry.

Outline of Geology

The Polish Carpathians form the northern part of the Carpathians (Figs 1-2). The Carpathian overthrust forms the northern boundary. The southern goes along the Poland-Slovakia national border. The Outer Carpathians are built of a stack of nappes and thrust-sheets showing different lithostratigraphies and tectonic structures. The Outer Carpathians nappes were thrust over each other and onto the North European Platform and its Miocene-Paleocene cover (Figs 3-6). The present authors provided a systematic arrangement of the lithostratigraphic units according to their occurrence within the original basins and other sedimentary areas.

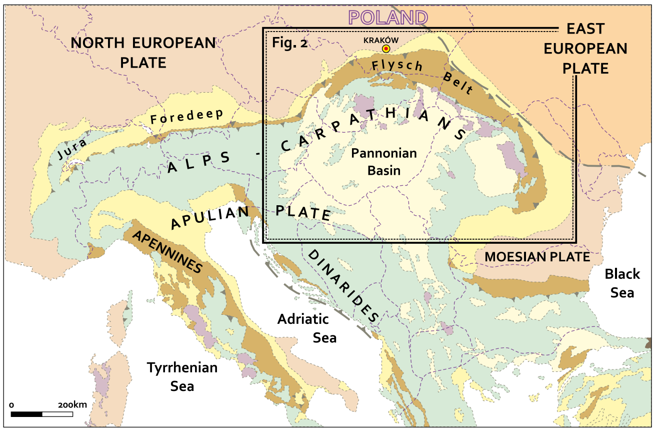
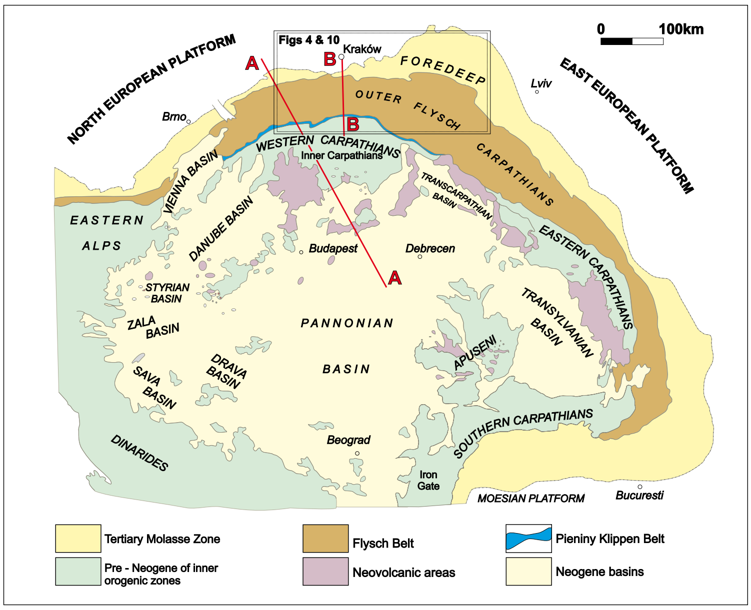


Fig. 1. Sketch of Alpine geology in Europe (modified after Picha, 1996)



This paper focuses also on the plate tectonic elements important to understanding the geology of the Polish Carpathians. The Inner Carpathian Terrane is a continental plate built of continental crust of Hercynian (Variscan) age and a Mesozoic-Cenozoic sedimentary cover. The uppermost Mesozoic sedimentary sequences of this plate are folded and thrust into a series of nappes (Figs 4-6).

The large continental plate, amalgamated during Precambrian and Paleozoic times, is known as the North European Platform. Proterozoic, Vendian (Cadomian), Caledonian, and Variscan fragments occur within the platform. The southern part of the North European Platform, adjacent to the Alpine Tethys is known as Peritethys (paleogeographical sketches – see Figs 7-9).

Fig. 2. Tectonic sketch map of the Alpine-Carpathian-Pannonian-Dinaride basin system (modified after Kováč, 1998; Plašienka et al., 2000) with the locations of generalised cross-sections across the Carpathian-Pannonian region (**AA**) (after Picha, 1996) and the Polish Carpathians (**BB**) (after Golonka et al., 2005a) (see – Fig. 3)

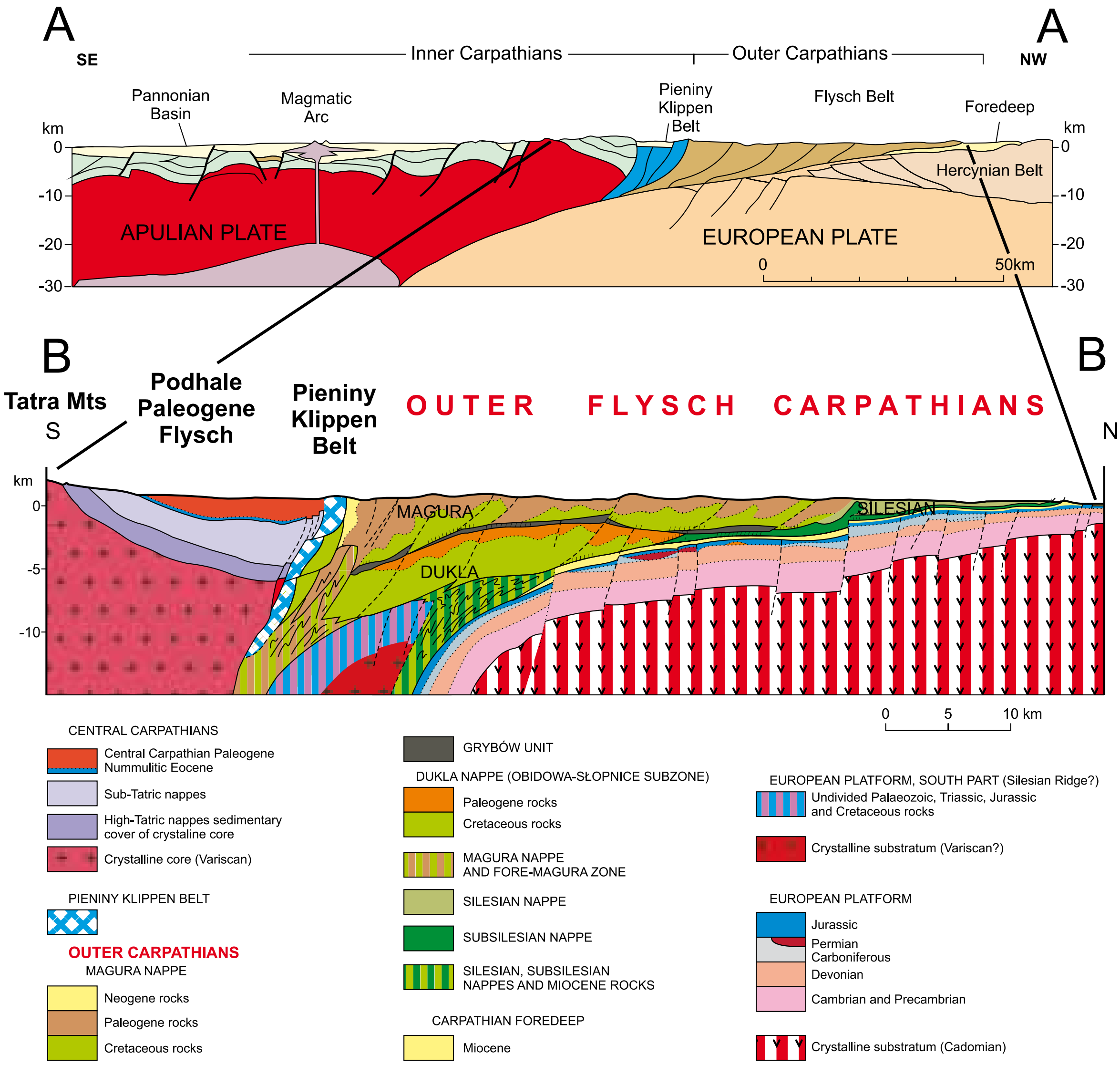


Fig. 3. Generalized cross-sections across the Carpathian-Pannonian region (**AA**) (after Picha, 1996) and the Polish Carpathians (**BB**) (after Golonka et al., 2005a) (for location of cross-sections, see Fig. 2)

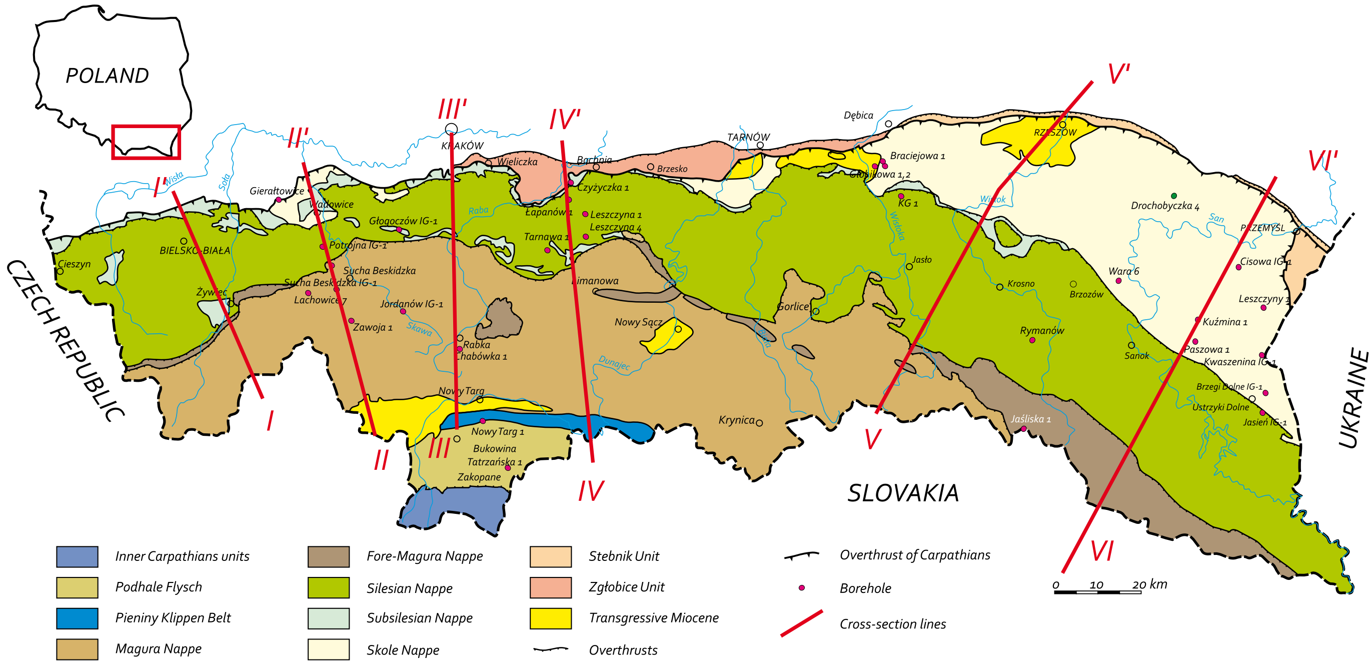


Fig. 4. Map of the Polish Outer Carpathians with the locations of cross-sections (see Figs 5, 6) (after Żytko et al., 1989; Golonka et al., 2011, modified)

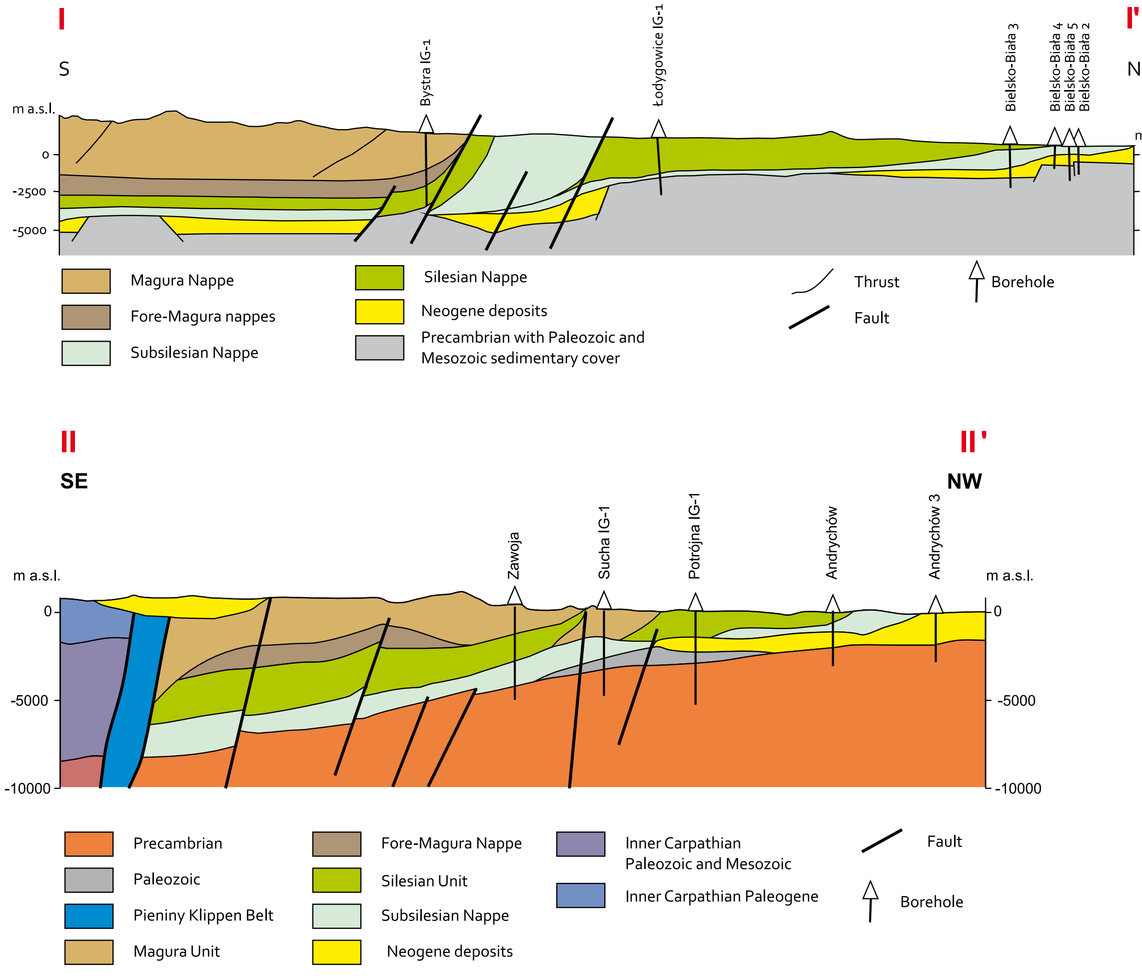


Fig. 5. Cross-sections through the western part of the Outer Carpathians and their foreland (after Golonka et al., 2011, modified). Cross-section locations on Fig. 4

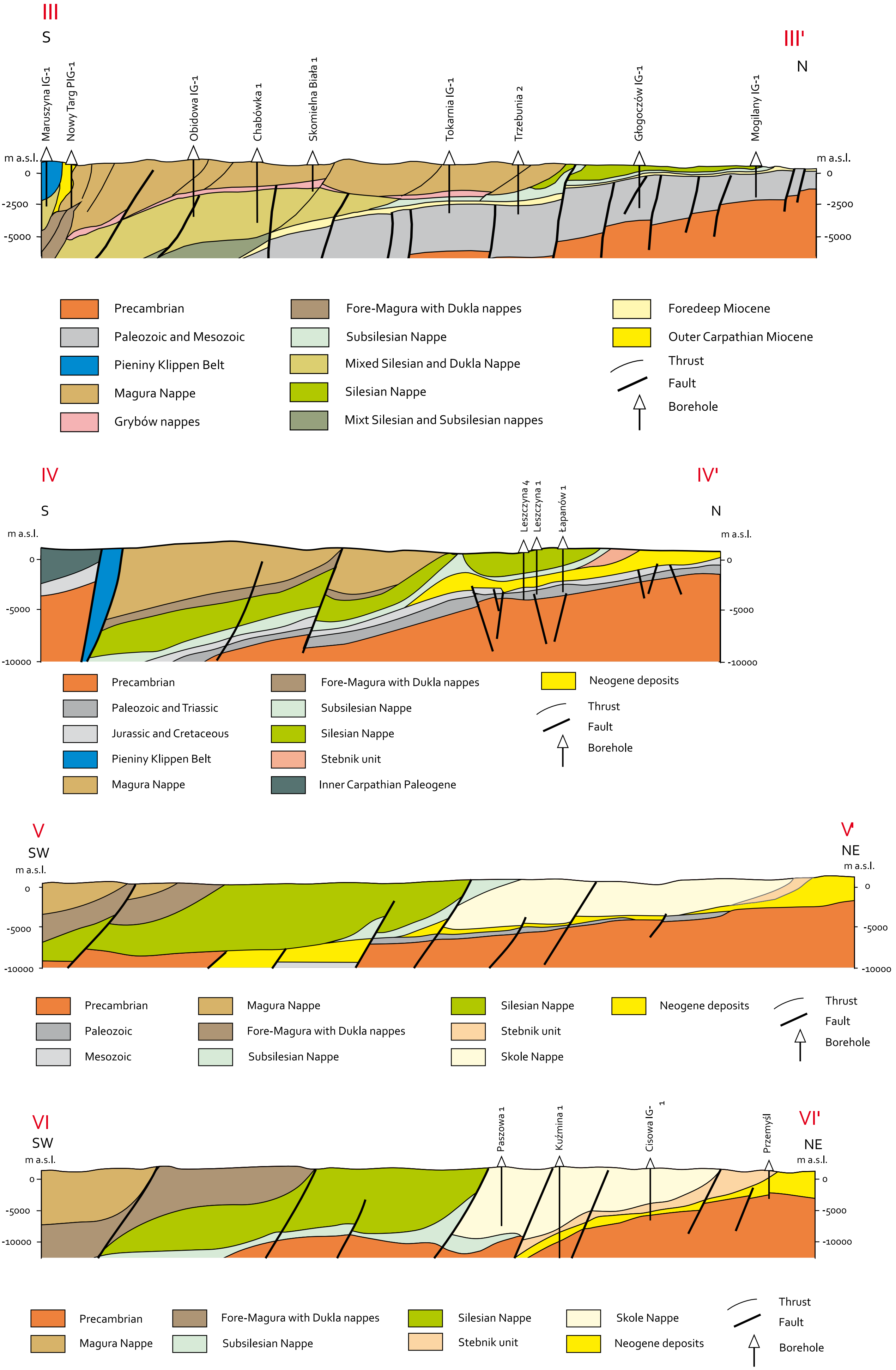


Fig. 6. Cross-sections through the western part of the Outer Carpathians and their foreland (after Golonka et al., 2011, modified). Cross-section locations on Fig. 4

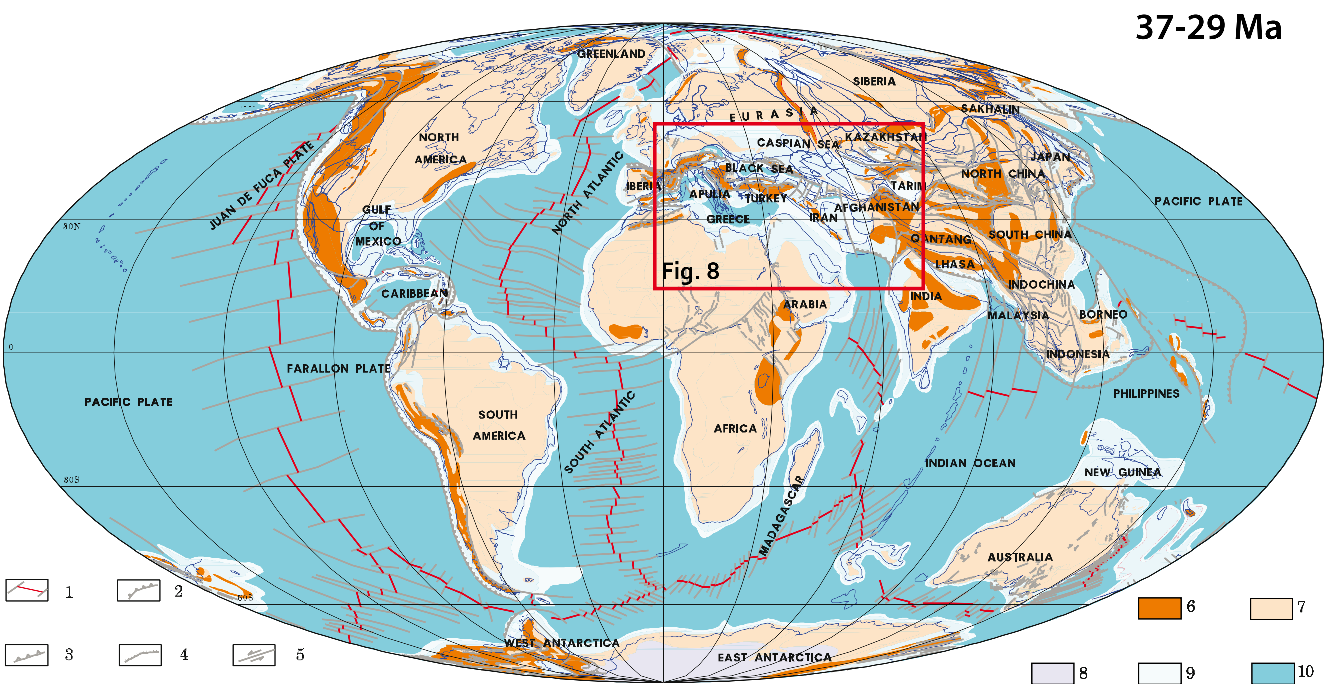


Fig. 7. Global plate tectonic map for the Oligocene. Explanations: 1 – oceanic spreading center and transform faults; 2 – subduction zone; 3 – thrust fault; 4 – normal fault; 5 – transform fault; 6 – mountains; 7 – landmass; 8 – ice cap; 9 – shallow sea and slope; 10 – deep ocean basin (from Golonka, 2000; Golonka et al., 2006; modified)

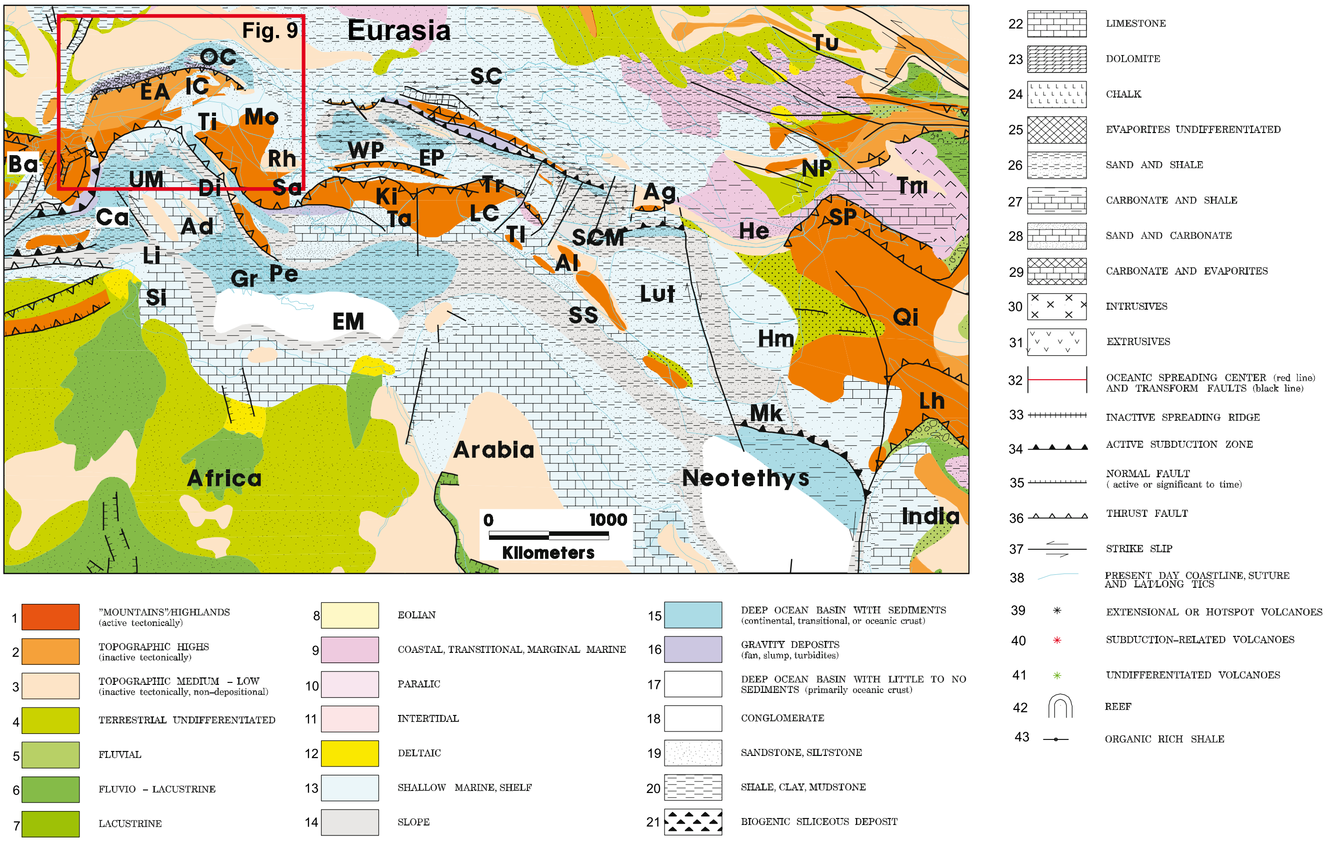


Fig. 8. Paleogeography of the southern margin of Eurasia with lithofacies of the circum-Carpathian/Caspian areas during Oligocene time (plate positions about 30 Ma) (after Golonka, 2004; slightly modified). Abbreviations of oceans/seas and plates names: Ad – Adria (Apulia); Ag – Aghdarband (southern Kopet Dagh); Al – Alborz; Ba – Balearic; Ca – Calabria-Campania; Di – Dinarides; EA – Eastern Alps; EM – Eastern Mediterranean; EP – Eastern Pontides; Gr – Greece; He – Heart; Hm – Helmand; IC – Inner Carpathians; Ki – Kirsehir; LC – Lesser Caucasus; Lh – Lhasa; Li – Ligurian (Piemont) Ocean; Mk – Makran; Mo – Moesia; NP – North Pamir; OC – Outer Carpathians; Pe – Pelagonian plate; Qi – Qiangtang; Rh – Rhodopes; Sa – Sakarya; SC – Scythian; SCM – South Caspian microcontinent; SI – Sicily; SP – South Pamir; SS – Sanandaj-Sirjan; Ta – Taurus terrane; Ti – Tisa; Tl – Talysh; Tm – Tarim; Tr – Transcaucasus; Tu – Turan; UM – Umbria-Marche; WP – Western Pontides

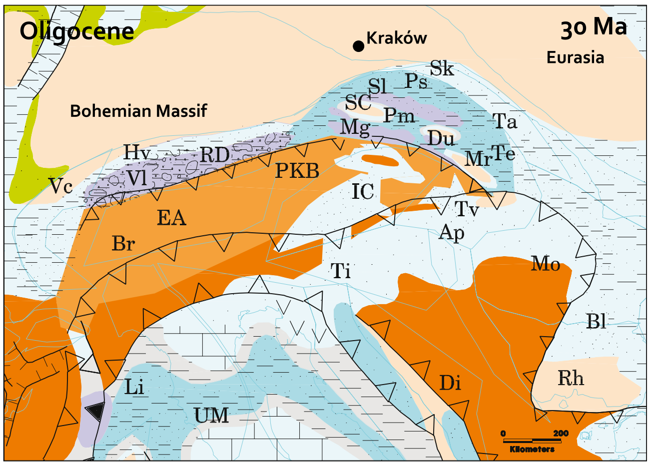


Fig. 9. Paleogeography, paleoenvironment and lithofacies of the circum-Carpathian area in the Oligocene (plate positions about 30 Ma) (after Golonka et al., 2000, 2006b; slightly modified). Abbreviations: Ap – Apuseni Mts; Bl – Balkan Basin and fold belt; Br – Briançonnais terrane; Di – Dinarides; Du – Dukla Basin; EA – Eastern Alps; Hv – Helvetic shelf; IC – Inner Carpathians; Mg – Magura Basin; Mo – Moesia plate; Mr – Marmarosh Massif; PKB – Pieniny Klippen Belt Basin; Pm – Fore-Magura Basin; Ps – Subsilesian Ridge and slope zone; RD – Rhenodanubian Basin; Rh – Rhodopes; SC – Silesian Ridge (Cordillera); Sl – Silesian Basin; Sk – Skole Basin; Ta – Tarçau Basin; Ti – Tisza plate; Te – Teleajen Basin; Tv – Transylvanian Basin; UM – Umbria-Marche; Vc – Vercors zone; Vl – Valais trough. For other symbols and colors, see Fig. 8

The Alpine Tethys constitutes important paleogeographic elements of the future Outer Carpathians, developed as an oceanic basin during the Jurassic as a result of the break-up of Pangea. The Czorsztyn submerged ridge (Pieniny Klippen Basin) was a part of the Alpine Tethys dividing the oceanic basin into two sub-basins. The southern sub-basin and the ridge are traditionally taken to constitute the Pieniny domain. Its sequences are involved in the Pieniny Klippen Belt – a strongly tectonized structure about 800 km long and 1-20 km wide, which stretches from Vienna in the west to the Poiana Botizii (Maramures, NE Romania) in the east (Figs 2, 10). The largest part of the northern sub-basin forms the Magura Unit, traditionally taken as belonging to the Outer Carpathians.

The Protosilesian or Severin-Moldavidic Basin developed within the North European Platform as a rift and/or back-arc basin. Its basement is represented by the attenuated crust of the North European plate with perhaps incipient oceanic fragments. The sedimentary cover is represented by several sequences of Late Jurassic–Early Miocene age belonging to the Dukla, Silesian, Subsilesian, Zdanice, Skole tectonic units in Poland and Czech Republic.

The oldest rocks of the North European Platform are Precambrian-Lower Paleozoic rocks belonging to the Bruno-vistulicum and Małopolska blocks. They are covered by Cambrian, Silurian, Devonian, Carboniferous, Permian, Triassic,

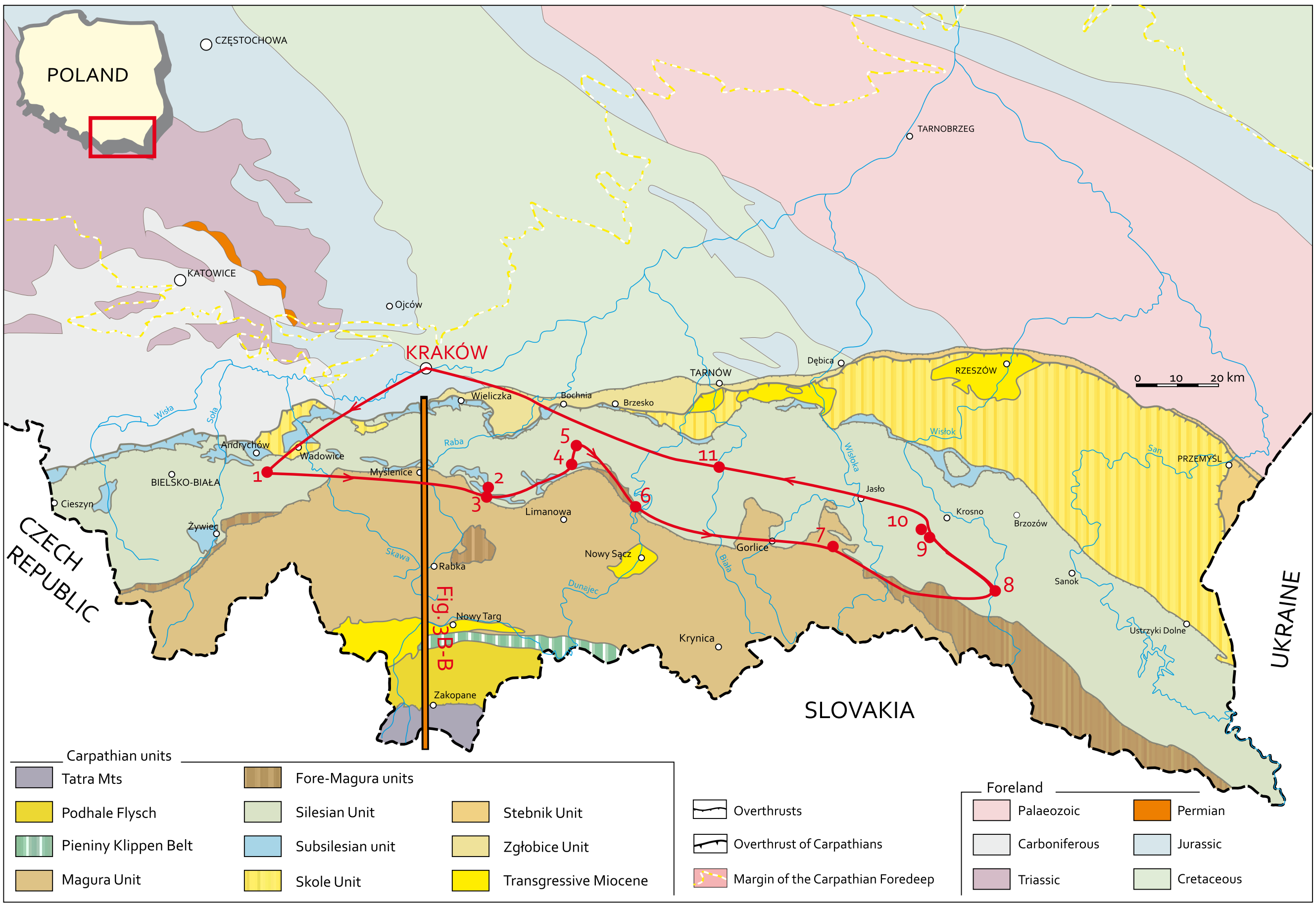


Fig. 10. Geologic map of the Polish Carpathians, Carpathian Foredeep and Foreland (after Żytko et al., 1989; Golonka et al., 2005) with location of the field trip stops and localations of cross-sections (Fig. 3BB)

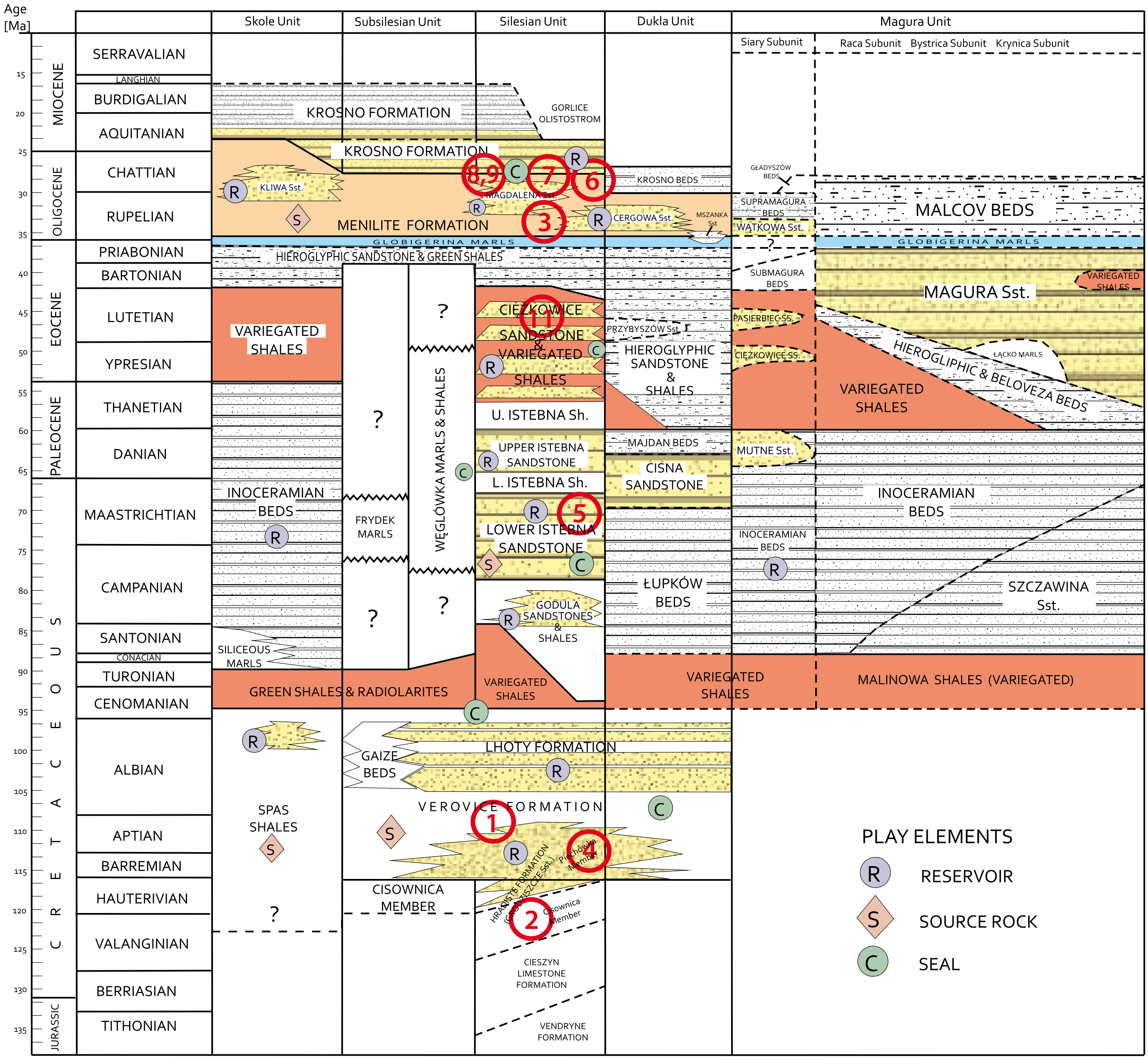


Fig. 11. Simplified lithostratigraphy of the Outer Polish Carpathians (after Dziadzio et al., 2001; Koszarski et al., 1985, modified) with the position of field trip stops

Jurassic, Cretaceous and Neogene sedimentary sequences. The thickness of the Jurassic carbonates exceeds 1000 m.

The sedimentation of the Outer Carpathian allochthonous rocks started during the Jurassic. The oldest time interval comprises the Jurassic and Early Cretaceous. The Protosilesian Basin was divided into the Dukla, Chornohora, Silesian, Subsilesian and Skole zones. The sedimentary rocks of the Silesian and Subsilesian zones include the Vendryne, Cieszyn, Hradiste (divided into Cisownica and Piechowka members), Verovice and Lhoty Formations (comp. Fig. 11). The Spas Formation with the Bełwin and Kuźmina members represents the Skole Basin.

The second time interval comprises Cretaceous-Paleocene times. The Foremagura Basin was formed at this time. It includes the Dukla and Grybów zones. The Silesian Basin included the Silesian zone with the Lhoty, Barnasiówka, Godula, Istebna formations, Ciężkowickie Sandstones and Variegated Shales. The Żegocina marls, Węglówka marls, Variegated Shale, Frydek marls, Gorzeń and Szydłowiec sandstones belong to the Subsilesian zone. The Skole included the Skole, Skyba and Boryslav-Pokutian zones and is only a small fragment in Poland. The Ropianka Formation and Variegated Shales represent the deposits of the Skole Zone. The Skyba and Boryslav-Pokutian zones contains the Spas shales.

The third time interval comprises Eocene times. The sedimentary rocks of the Magura Basin include the Łabowa, Beloveza, Łącko, Magura and Makow formations. The Foremagura Basin is represented by Variegated Shales, Hieroglyphic Beds, and the Luzna limestones and Grojec sandstones. The Silesian Basin includes the Hieroglyphic Beds, Variegated Shales, Przysietnica sandstones and Globigerina Marls. The Skole-Skyba Basin contained the Hieroglyphic and Bystrica formations, Variegated Shales and Globigerina Marls.

The last time interval comprises Oligocene-Early Miocene times. Two basins were present: Magura and Krosno. The Magura Basin included the Magura, Malcov and Makow formations. The Menilitic and Krosno formations dominated the Krosno Basin. In addition, the Cergova Sandsones, Kliwa sandstones and Polanycia Formation were present.

An attempt has been made to divide the Carpathian deposit into supersequences using sequence stratigraphy methods. The Jurassic–Early Cretaceous formations of the Severin-Moldavidic basin correspond well to the global sequence stratigraphy. The formations within other time intervals also fit to these scheme; however, the topic requires further investigation.

During Late Oligocene and Miocene orogenesis several nappes corresponding to the lithostratigraphic units were formed with a prevalent northerly direction of thrusting in the West Carpathians, north-easterly and easterly in the East Carpathians (Figs 2-9). In the Western Carpathians from the south they are: the Magura Nappe, Fore-Magura Group of nappes, the Dukla, Silesian, Subsilesian and Skole Nappe. The Magura Nappe forms the largest tectonic unit of the northern Outer Carpathians. It has been completely uprooted from its substrate and thrust over the Fore-Magura and Silesian nappes, at least 20 km, and perhaps up to 50 km, during orogenic movements. So-called tectonic windows, showing out-of-sequence Fore-Magura nappes, are related to the major fault zone, cutting the basement and allochthonous flysch nappes.

The Dukla Nappe stretches from the Polish to the Ukrainian Carpathians. It is thrust over the Silesian and dips under the Magura Nappe. In the Polish and Slovakian parts within the Dukla Nappe two subunits can be distinguished: Internal and External. The folds within the internal subunit are generally dip gently towards the south-west, whereas within the external subunits folds are steep and often with a reversed (south-western) vergence.

The Silesian Nappe thrust over the Subsilesian and Skole nappes dip under the Dukla, Magura or Fore-Magura nappes. The thrust magnitude reaches 40 km. The nappe west of the Wisłok river is built of several gently folded structures. The eastern part of the Silesian Nappe, east of the Wisłok river, plunges towards the south-east and is represented by a synclinorium (Central Carpathian Synclinorium) which is built mainly of Oligocene deposits. The Central Carpathian Synclinorium is built of several long, narrow, imbricated, thrust-faulted folds which are often disharmonic. The Central Carpathian Synclinorium passes into the Krosno Zone in the Ukraine. Southeast of the town of Sanok, the amplitude of marginal thrusts of the Silesian Nappe and of the Sub-Silesian Nappe diminish and eventually terminate and this zone passes into a normal fold. Therefore, the prolongation of the boundary between the Silesian and Skole units towards the southeast is not so clear as in the west. In the frontal part of the Silesian Nappe, south of the town of Rzeszów, the Subsilesian Nappe is exposed in the Węglówka area. Seismic surveys and wells connected with the Węglówka oil field show that it is steeply thrust over the Skole Nappe. The diapiric-type migration of the less competent formations of the Subsilesian Nappe along the strike-slip fault forms this so-called tectonic window or out-of-sequence thrust zones.

The Skole–Skyba Nappe forms a large, 40 kilometers wide, portion of the eastern part of the Northern Carpathians and is thrust over Miocene sediments that cover the North European Platform. The most distinctive structural feature of this nappe is the occurrence of large thrust-folds “skybas” (duplexes) thrust over each other in a north-easterly direction and traced for several hundreds of kilometers along the length of the Carpathian Arc. The width of such “skybas” is from single kilometers up to 12 km. South-west of the town of Przemyśl the folds create a sigmoidal arc which reflects a similar sigmoidal bend of the Carpathian margin (Figs 4, 10). Near Rzeszów the marginal part of the Skole Nappe is covered by Miocene molasse, which form a piggy-back basin. Farther towards the west, near the town of Pilzno, the northern part of the Skole Nappe is probably folded together with the Miocene cover. The inner part of the Skole Nappe is a synclinal area built of several folds with broad synclines composed of the Oligocene/Lower Miocene Krosno Formation. The thrust-plane of the Skole Nappe changes from very gentle to very steep, whilst in the internal zone they are represented by the Lower Miocene Krosno Formation.

The Cenomanian – Late Eocene collisional stage is characterized by the formation of subduction zone along an active margin, partial closing of an oceanic basin and the development of main flysch basins associated with rifting on the platform (passive margin) with attenuated crust. Several basins became distinctly separated within the Outer Carpathian realm. Each basin had a specific type of clastic deposits, and sedimentation commenced at different times. The northward movement of the ALCAPA (ALpine-CArpathian-PAnnonian) Terrane during Eocene-Early Miocene times and oblique collision with the North European plate led to the development of the accretionary wedge of the Outer Carpathians. During the Priabonian and Rupelian, there was a prominent uplift in the Outer Carpathian basin. Tectonic movements caused final folding of the basin infills and created several imbricated nappes, which generally reflect the original basin configurations. During the overthrusting, the marginal part of the advanced nappes was uplifted, whereas in the inner part sedimentation continued in the remnant basin. Big olistoliths often slid down from the uplifted part of the nappes into the adjacent, more outer basins. The nappes became uprooted from the basement and the Outer Carpathian allochtonous rocks were overthrust northward in the west and eastward in the east onto the North European platform for distances of 50 km to more than 100 km. Overthrusting migrated along the Carpathians from the west towards the east. In front of the advancing Carpathians nappes, the inner part of the platform, in the eastern and with the marginal parts of the flysch basin, started to downwarp and a tectonic depression formed during the Early Miocene. Thick molasse deposits filled up this depression. At the end of the Burdigalian, that basin was overthrust by the Carpathians and a new, more external one developed. Clastic and fine-grained sedimentation of Carpathian and foreland provenance prevailed, with a break during the Late Langhian to Early Serravallian when a younger evaporite basin developed. Locally olistostromes were deposited, with material derived from the Carpathians and the inner margin of the molasse basin. During the Langhian and Serravallian, part of the northern Carpathians collapsed and the sea invaded the already eroded Carpathians. The foreland basin and its depocenter migrated outward and eastward, contemporaneously with the advancing Carpathians nappes. As a result the Neogene deposits show diachrony in the foreland area. In the west sedimentation had terminated in the Langhian but in the east lasted till the Pliocene. These events mark the postcollisional stage in the evolution of the Outer Carpathians.

Passage from Warszawa – Rzyki

The field trip starts in the parking lot of the Polish Geological Institute in Warszawa. Warszawa is located in the Polish Lowlands, a vast area filled mainly with glacial, fluvioglacial and fluvial deposits. These deposits contain numerous erratic blocks, mainly crystalline, brought by glaciers from Scandinavia. One such block is exposed in front of the Polish Geological Institute – National Research Institute building. The bus goes south, following the Warszawa-Cieszyn international highway. After leaving the lowlands, the route enters a highland area; the part of this area in the vicinity of Częstochowa is known as the Polish Jura Chain or Kraków-Częstochowa Upland. This upland contains many hills built of Upper Jurassic, mainly Oxfordian limestones. The famous Częstochowa monastery (Jasna Góra) is located on one of these hills. This is the site of the famous ancient picture of Saint Mary known as Black Madonna. Many historians believe that this picture was painted by Saint Luke. The Saint Mary shrine is a destination of numerous pilgrimages from Poland and other European countries. The monastery is situated within the fortress, which was effectively defended against a huge Swedish army in the XVII century during the Polish-Swedish war known as "Deluge".

After passing Częstochowa, the trip leads through the Silesian Highlands, built of Triassic and Paleozoic deposits, a cradle of the Polish mining industry. Many coal, lead, zinc and silver mines exist in this area. After passing Oświęcim, the site of the infamous German concentration camp Auschwitz (now a museum visited by millions of tourists), the route leaves the highlands and crosses the Carpathian Foredeep filled with Neogene deposits. In the vicinity of Andrychów, the route crosses the Outer Carpathian Main Thrust. The Outer Carpathian nappes are thrust over the Carpathian Foredeep Neogene rocks in this area. This part of the Outer Carpathians is known as the Beskid Mały Mountains. These mountains, exceeding 900 meters in height, are built mainly of Cretaceous and Paleocene proximal flysch with thick sandstone bodies belonging to the Godula and Istebna formations. The first geological stop is located 5 kilometers south of Andrychów in the village of Rzyki (Figs 10, 12).

Stop 1. Rzyki (Veřovice Formation) (Figs 12-15)

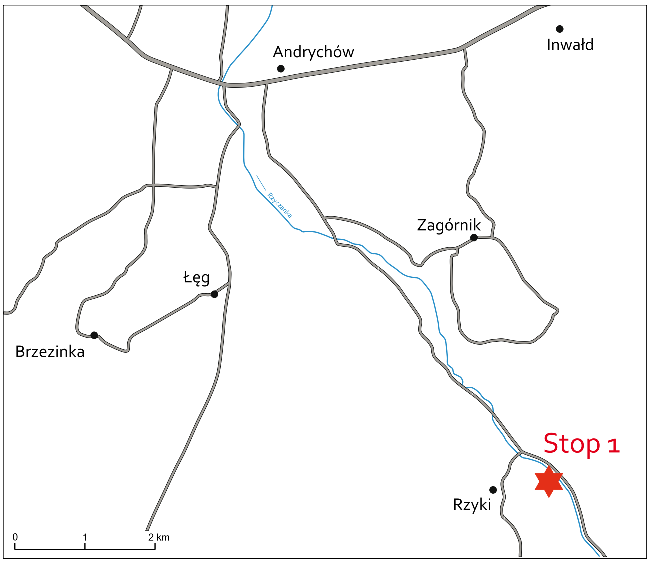


Fig. 12. Location of the village of Rzyki (with field trip Stop 1)

This classic site in the Polish Outer Carpathians, containing organic-rich rocks – the source rocks for generation of oil, is exposed in the Wieprzówka waterfall site in Rzyki (Figs 13, 15). This site is located near the town of Andrychów, about 80 km from Kraków Balice Airport and close to Wadowice. Wieprzówka waterfall site is easily accessible by tourists coming with their cars, bikes, buses or by public transportation. It can serve as an object illustrating geological processes such as the Oceanic Anoxic Event for the general public. From time to time in Earth history, Oceanic Anoxic Events (OAE) happen. These events occur when the Earth's oceans become severely depleted of oxygen. During an anoxic event conditions in the vast areas of the oceans are similar to those existing today in the Black Sea. Much organic matter gathers on the bottoms of seas and oceans. It is believed that oceanic anoxic events are linked to specific paleogeographic and paleoclimatic conditions, changing oceanic current circulations, volcanic activity, and an increase of greenhouse gases and the subsequent global warming. Most of the Earth's oil and gas originated from organic-rich source rocks deposited during OAEs. The end of the Early Cretaceous represents one of these OAEs (Bralower et al., 2002; Kratochvílová et al., 2003; Golonka et al., 2008b).

The global sea-level was more than 200 hundred meters above today's level, close to the maximum 1st-order highstand for the entire Earth history. This was also a period of increasing continental submergence. Volcanism activity release enormous amount of greenhouse gases, especially CO_2. Global greenhouse conditions prevailed. Hot, equable climates occurred, with generally humid continental interior settings.

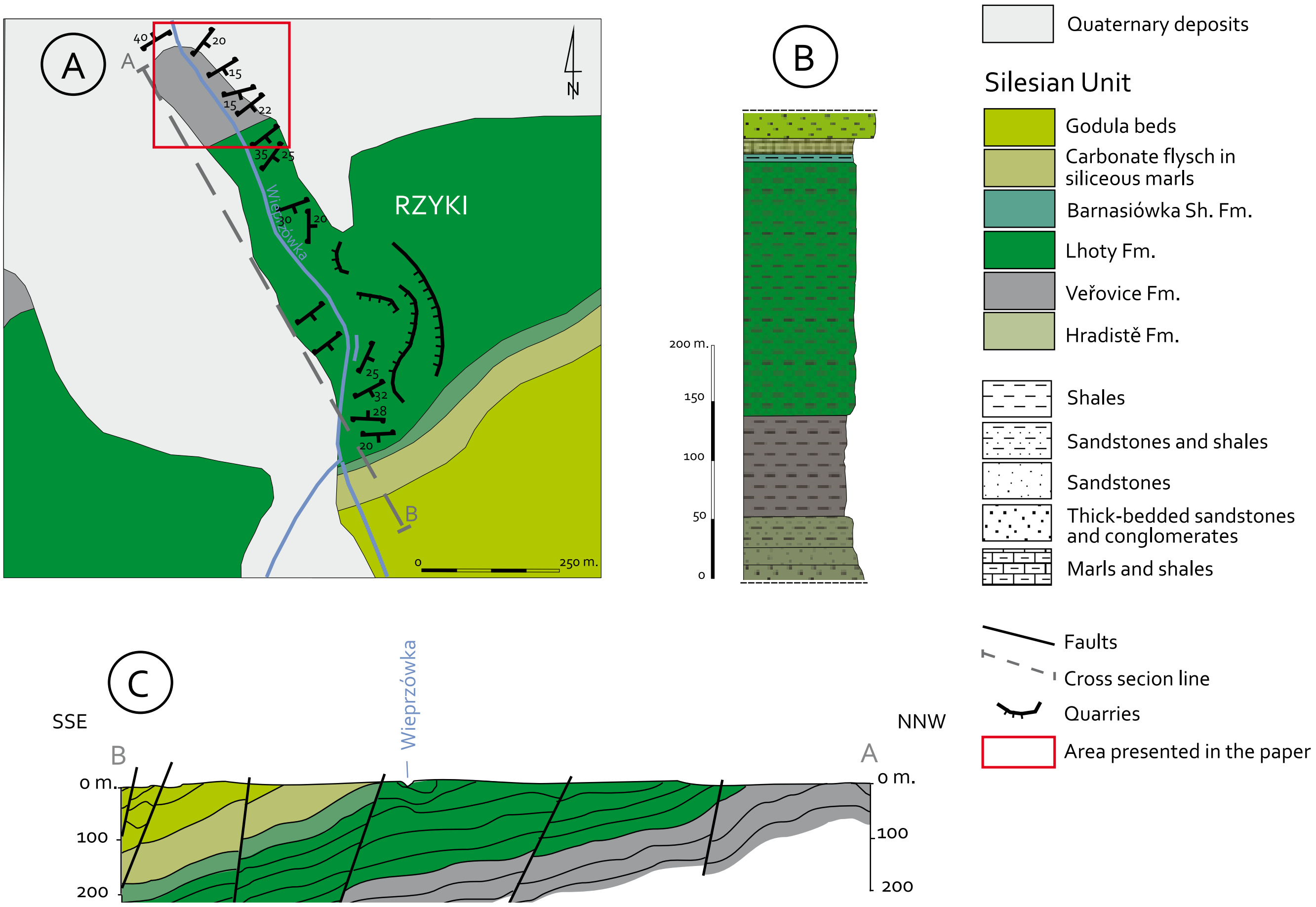
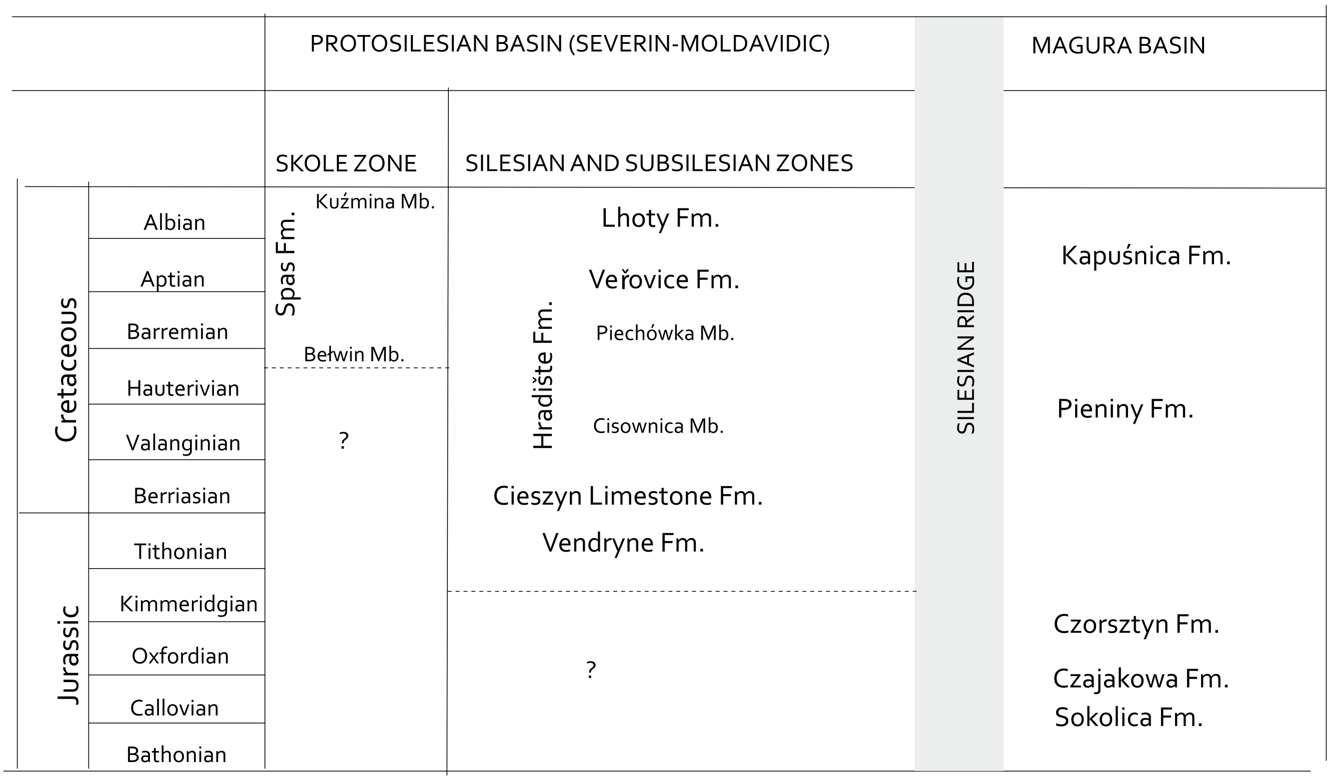


Fig. 13. Geological location of the Veřovice Formation's reference section in Rzyki. **A** – simplified geological map of the northern part of Rzyki (after Książkiewicz, 1951; Uchman & Cieszkowski, 2008, modified) – as in part B; **B** – geological log of the Cretaceous deposits showing the lithostratigraphic position of the Veřovice Formation in Rzyki; **C** – geological cross-section observed in northern part of Rzyki



		PROTOSILESIAN BASIN (SEVERIN-MOLDAVIDIC)		SILESIAN RIDGE	MAGURA BASIN
		SKOLE ZONE	SILESIAN AND SUBSILESIAN ZONES		
Cretaceous	Albian	Spas Fm. Kuźmina Mb.	Lhoty Fm.		Kapuśnica Fm.
	Aptian		Veřovice Fm.		
	Barremian	Bełwin Mb.	Hradište Fm. Piechówka Mb.		
	Hauterivian	?			Pieniny Fm.
	Valanginian		Cisownica Mb.		
	Berriasian		Cieszyn Limestone Fm.		
Jurassic	Tithonian		Vendryne Fm.		
	Kimmeridgian		?		Czorsztyn Fm.
	Oxfordian				Czajakowa Fm.
	Callovian				Sokolica Fm.
	Bathonian				

Fig. 14. Jurassic-Lower Cretaceous lithostratigraphy of the Outer Carpathian basins in Poland

Organic-rich sediments were deposited in many marine basins worldwide. Typical OAE deposits are dark-grey or black; this color is caused by the high amount of carbon, measured as so-called Total Organic Carbon (TOC). Shales of the Veřovice Formation represent typical OAE-deposited rocks (Bralower et al., 2002; Kratochvílová et al., 2003, Golonka et al., 2008b).

The Veřovice Formation (Golonka et al., 2008a, b and references therein) comprises typical black Cretaceous organic-rich deposits of the Silesian Series (Fig. 14). Its stratotype is located in the village of Veřovice in the Czech Republic; the Rzyki profile serves as a reference section. The formation age, evaluated from assemblages of dinoflagellates (Cieszkowski et al., 2001, 2003; Skupien, 2003; Golonka et al., 2008a, b) and foraminifera (Bieda et al., 1963; Nowak, 1976; Szydło, 1997), is Barremian-earliest Albian. In the lithostratigraphic profile of the Silesian Series the Veřovice Formation is underlined by the Hradište Formation (Late Valanginian – Hauterivian) and stratigraphically covered by the Lhoty Formation (Albian – Early Cenomanian) (see Golonka et al., 2008a and references therein). This formation is tectonically deformed as a part of the Silesian Nappe. As mentioned above, rocks of the formation were deposited during the Early Cretaceous, under OAE conditions. Transgressions related to the highest Phanerozoic sea-level and upwelling contributed to the excessive nutrient supply. The Carpathian basins produced a large amount of organic matter, preserved due to the sedimentary conditions and to the limited supply of terrigeneous material. A Rock-Eval analysis of the Veřovice Formation from Rzyki revealed Total Organic Carbon – TOC content reaching 2.31 wt%. Organic-rich deposits are widespread in the Silesian Basin, with TOC values reaching 3-3.5 wt% in the Veřovice Formation in Moravia and in the Zasań area south of Kraków (Golonka et al., 2008b). These rocks were buried under a thick pile of younger, Upper Cretaceous and Paleogene flysch deposits, deformed into the imbricated series of nappes. This development led to the maturation of organic matter and expulsion of oil, as indicated by the T_{max} values.

The section at the Wieprzówka waterfall, forming Lower Cretaceous deposits of the Silesian Nappe, is located in the Beskid Mały "block" (Książkiewicz, 1977) (Fig. 13). Its geological surroundings were first depicted on the map by Książkiewicz (1951). Later the section was described by Ślączka & Kaminski (1998), Cieszkowski et al. (2001, 2003), Uchman (2004), Uchman & Cieszkowski (2008). Zieliński (2003) described the natural diversity and various, rich natural attractions of the whole Wieprzówka stream valley. He also noted the beauty of the waterfalls formed in the northern part of Rzyki.The stream valley of Wieprzówka in Rzyki was deeply dissected by fluvial erosion (Fig. 15), probably as a result of extraction of

Fig. 15. The Veřovice Formation close to Rzyki. **A** – stream erosion has formed a kind of canyon a few meters deep within the Veřovice Formation; **B** – series of small waterfalls built of black shales and laminated sandstones in the upper part of the Veřovice Formation. The shales display lower amounts of Total Organic Carbon, between 1–2 wt% in this part of the profile. Behind on the left is visible a steep eastern slope of the Wieprzówka stream valley built of deposits of the Lhoty Formation; **C** – shales at the beginning of the Veřovice Formation section displaying the highest amount of Total Organic Carbon (TOC), reaching 2.31 wt%; **D** – Black and dark grey, partly siliceous shaly mudstones of the Veřovice Formation form the canyon walls. Mudstone layers form here an anticline

gravel from the stream beds (Ślączka & Kaminski, 1998) and/or remodeling of the stream bed by the great flood in 1997 and later events. The stream erosion formed a kind of canyon a few meters deep, with a series of scenic waterfalls and erosional potholes in the riverbed, and revealed the detailed development of the Lower Cretaceous Veřovice and Lhoty formations (Fig. 13). These formations are gently folded and dip gently toward the south-southeast. They are cut by a system of meso-scale faults. Most faults included within the system are normal, with down-thrown northern flanks, but some are reverse with northern thrust vergence. Transform faults, usually NNW-SSE oriented, also exist in this section. Fluvial erosion exploited the fault system, when forming the canyon. The uppermost part of the Veřovice Formation and the lower part of the Lhoty Formation are exposed in the waterfall.

In the northern part of Rzyki, bordering on the NE with the village of Zagórnik, the section begins with the gently folded Veřovice Formation (uppermost Barremian – Aptian – earliest Albian). The upper part of the formation is exposed in the section, while the lower is covered by Quaternary fluvial deposits. The outcropping part of the Veřovice Formation is represented by carbonate-free black and dark grey, partly siliceous shaly mudstones with intercalations of thin- and very thin-bedded laminated coarser siltstones, fine-grained sandstones (Fig. 15). The sandstones are quartzitic, gray, with parallel or cross-ripple lamination. They have presumably been deposited by bottom currents in an abyssal plain sedimentary environment. Up the section, a few meters thick, shaly-sandstone packages with thin- or medium-bedded sandstones are present within the mudstone and siltstone sequence. Some of the sandstones display features of turbidites. At the steep transition between the Veřovice and Lhoty formations sandstones are more common. Occasional siderites and/or ankerites form thin layers, lenses, or oval concretions within black shales. In some places shales with siderites are disturbed by sub-marine slumps. Small aggregates of pyrite are also visible in the shales.

While the black shales of the Veřovice Formation at Rzyki are Lower Cretaceous anoxic deposits, trace fossils occur there occasionally (Ślączka & Kaminski, 1998; Cieszkowski et al., 2001, 2003; Uchman & Cieszkowski, 2008), indicating that living conditions periodically improved and that the sea-floor was colonized by animals. The trace-fossils were figured by Uchman (2004), Uchman in: Cieszkowski et al. (2001, 2003) and Uchman & Cieszkowski (2008). The trace fossils *Phycosiphon incertum*, *Chondrites intricatus*, *Planolites*, *Paleophycus* and locally *Thalassinoides* forms occur within some thin layers of usually lighter pelitic deposits. *Protovirgularia* traces have also been found in the section. It was supposedly produced by chemosymbiotic bivalves that could burrow in anoxic sediment. A Barremian – Early Albian age of the Veřovice Formation in Rzyki was previously estimated from micropaleontological data on foraminifera from other sections in the Outer Carpathian and on the superposition of this formation in the lithostratigraphic profile of the Silesian Series (Cieszkowski et al., 2001, 2003; Uchman & Cieszkowski, 2008). Recently dinocysts *Cerbia tabulata, Kiokansium polypes, Odontochitina operculata, Pseudoceratium gochtii, Pseudoceratium polymorphum* were determined by P. Skupien from the lower part of the Rzyki section. This assemblage indicated a Late Barremian – Aptian age.

Up the section the Veřovice Formation passes into the Lhoty Formation, Albian – Early Cenomanian in age. The Lhoty Formation here (Książkiewicz, 1951; Cieszkowski et al., 2001, 2003, Uchman & Cieszkowski, 2008) is developed as thin- and medium, and occasionally thick-bedded, quartzitic, dark sandstones with distinct parallel and cross lamination, inter-bedded with black, dark grey and greenish, often spotty shales.

At the beginning of the Veřovice Formation section the shales display the highest content of TOC, reaching 2.31 wt%. Upstream, at places where we encounter a series of small waterfalls built of black shales and laminated sandstones, the shales display lower contents of TOC, between 1-2 wt% in this part of the profile. TOC_{max} values from the Veřovice Formation in the Wieprzówka waterfall profile indicate that a significant amount of oil was expelled, probably at the peak of orogenesis during Miocene times. The rocks in the profile were buried at that time by Carpathian imbricated nappes. This burial enhanced maturation and expulsion. Today the Wieprzówka rocks are exposed at the surface, therefore the maturation process has ceased entirely.

As mentioned above, the Veřovice Formation hosts a variety of tectonic deformations. We can easily identify rather small-scale faults and folds of different geometry. There is also visible a net of complementary joints clearly marked by white veins of calcite within black mudstones and gray sandstone. In some place coulisse or horse systems are presented. All the tectonic deformation resulted from the Miocene Alpine tectonism, which formed the Silesian Nappe as part of the Carpathian Mountains domain.

Passage from Rzyki – Poznachowice

From Rzyki, the route returns to Andrychów and turns eastwards. Near Andrychów several deep boreholes penetrated the Carpathian flysch and reached a Neogene substratum at depths ranging from 1-2 km (Cieszkowski & Ślączka, 2001). From Andrychów, the route enters Wadowice, John Paul II country. The late Pope was born in Wadowice, and now this small town is visited by millions of tourists. On the right, we can see hills built of thick-bedded sandstones of the Upper Cretaceous Godula and Istebna formations. On one hill, in Kalwaria Zebrzydowska, there is a beautiful XVII century cloister built in a baroque style. The cloister, together with the Stations of Cross, is on the list of UNESCO World Heritage. The picturesque Lanckorona contains the remnants of a medieval castle and a beautiful town square with architecturally interesting wooden houses. In the town of Myślenice the route passes the Myślenice tectonic window and leads along the River Raba and the Dobczyce artificial lake. The lake is the main reservoir of fresh water for the city of Kraków. From Dobczyce, another small town with a medieval castle, the route turns south toward Poznachowice.

Stop 2. Poznachowice [Grodziszcze (Hradište) Formation]

(Figs 16-18)

Fig. 16. Location of the Poznachowice section and the Kobielnik abandoned quarry (with field trip Stops 2 and 3)

Along the River Krzyworzeka, a section of the Cisownica Member is exposed. This member, formerly known as the Upper Cieszyn shales, belongs to the Hradište Formation (Golonka et al., 2008a). This 300-meter thick unit, Valanginian-Aptian in age, consists of alternating black marly shales and calcareous, micaceous, thin- and medium-bedded, fine-grained siliciclastic sandstones, rarely calciturbiditic sandstones (see Fig. 18), sometimes with beds and lenses of clayey siderites (Burtan, 1978). The sedimentation rates were low, rocks were deposited below CCD, the detrital material was transported from the northwest, and no longer supplied the basin. The sandstones display horizontal, oblique and convoluted lamination. Intercalations of beds and lenses of clayey siderites are numerous, and were mined in the last century, forming the economic base for the iron industry in this area. The benthic foraminiferal assemblage suggests that the sediments were deposited at upper to middle bathyal depths. The upper part of the Cisownica Member was deposited under anoxic conditions. Similar rocks in the Czech Republic contain up to 2.5% of Total Organic Carbon (TOC).

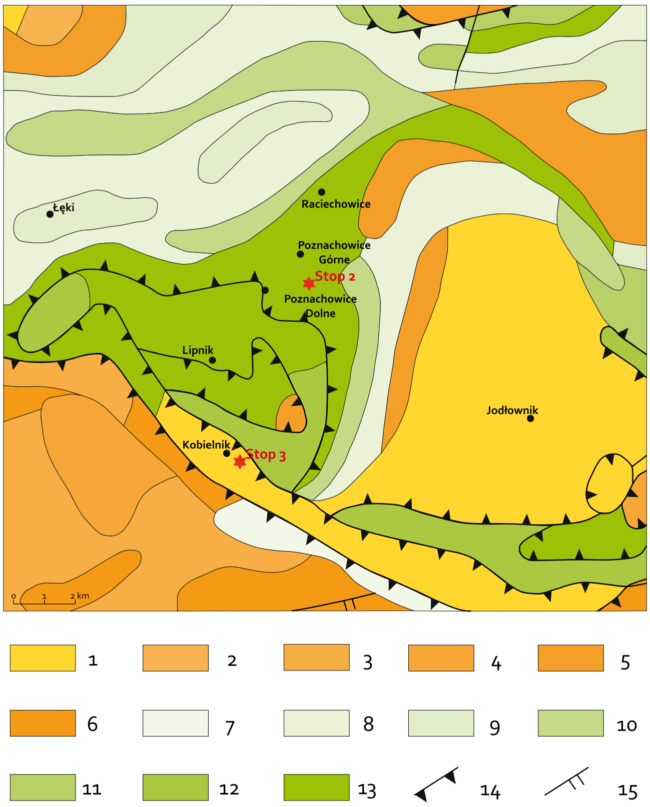
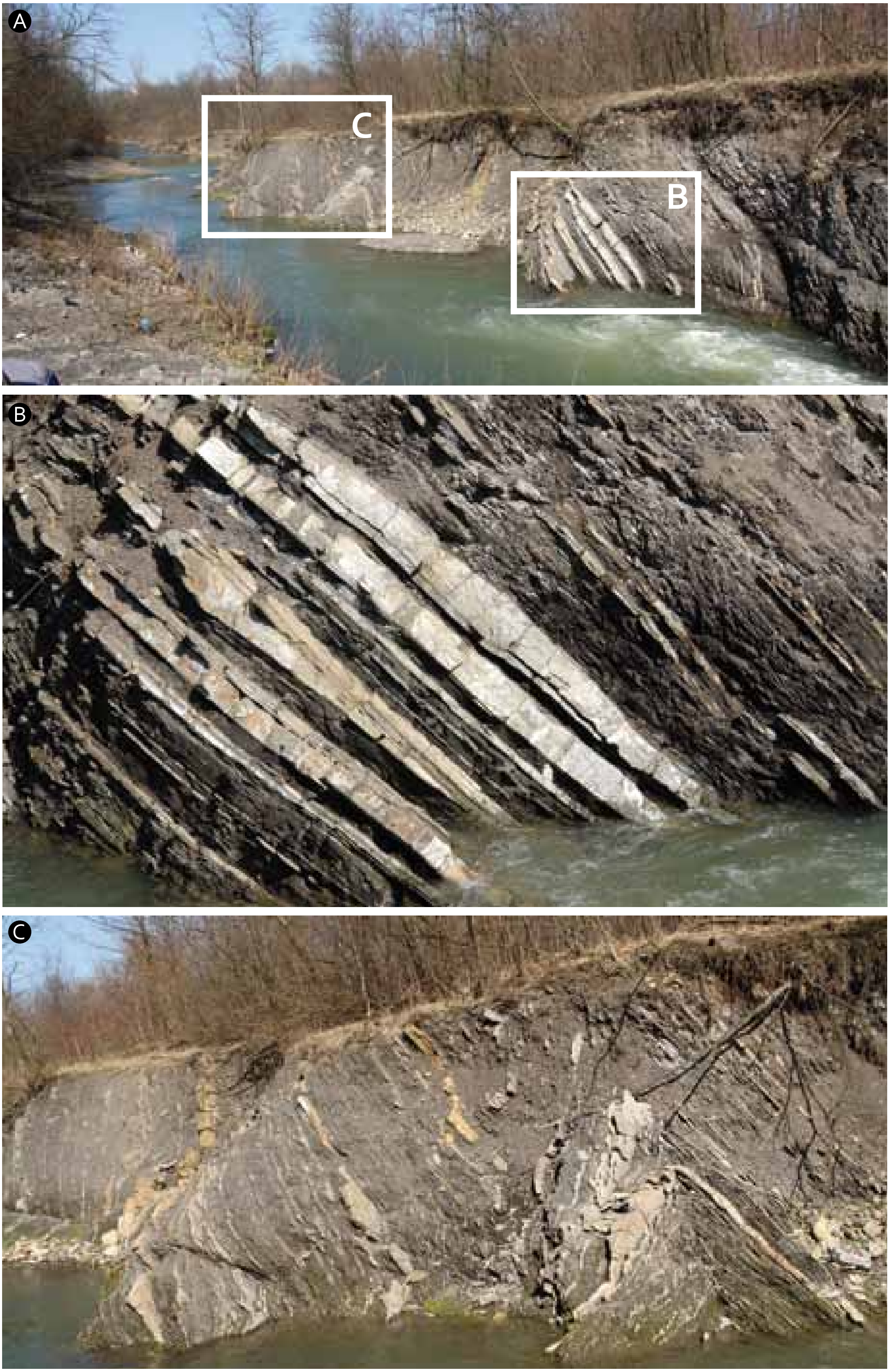


Fig. 17. Sketch of geological map of the Poznachowice and Kobielnik vicinities (after Lexa et al., 2000). Explanations: 1 – Menilite and Krosno formations; 2 – Sub-Magura and Supra Magura members; 3 – Pasierbiec and Osielec Sandstones; 4 – Hieroglyphic Formation; 5 – Ciężkowice Formation; 6 – Beloveza Beds; 7 – Inoceramian Formation; 8-10 – Istebna Formation; 11 – Lhota Formation; 12-13 – Cieszyn-Hradište formations; 14 – first order overthrust lines; 15 – second order overthrust lines


A
C
B
B
C

Stop 3. Kobielnik (Menilite Formation)

(Figs 16, 17, 19)

In the Kobielnik abandoned quarry thin-bedded flyschoidal rocks crop out. The oldest part is calcareous fine-grained sandstones and marls with numerous cherts. The main part of the quarry is occupied by the Menilite Formation, thin-bedded, brown, grey and black siliceous marls and shales intercalated with rare coarse-grained sandstones/fine-grained conglomerates. Large fragments of Upper Carboniferous coal are common in these beds (exotic clasts). In some places natural seeps of bituminous oil occur on joint surface of sandstones (Fig. 19). On several bedding surfaces we can observe abundant fish scales characteristic of the clupeids (Szymczyk, 1978).

Some remarks on the Menilite Formation

The Oligocene sequences commenced with dark brown bituminous shales and cherts with locally developed sandstone submarine fans or a system of fans up to several kilometers long. The upper boundary of the bituminous shales is progressively younger towards the north and shales pass gradually upwards into a sequence of micaceous, calcareous sandstones and grey marls, thinning upwards. The rocks representing this time interval belong to Lower Tejas III from the sequence stratigraphy point of view (Golonka & Kiessling, 2002; Cieszkowski et al., 2006). Two basins were present during these times: Magura and Krosno. The Menilite Formation dominated within the Krosno Basin (Oszczypko, 1991; Oszczypko et al., 2005; Cieszkowski et al., 2006; Ślączka et al., 2006).

The Menilite Formation was deposited during favourable conditions for organic-richness. The major processes responsible for such richness are: high biologic productivity, non-dilution of organic richness by clastic sedimentation, and preservation of organic matter within its depositional environment (Golonka et al., 2009; Kotlarczyk & Uchman, 2012, with literature cited therein).

← Fig. 18. General view (**A**) and more details (**B**, **C**) of the Early Cretaceous deposits of the Hradište Formation (Cisownica Member) in the Poznachowice section

PROCESSES FOR ENHANCED ORGANIC RICHNESS

BIOLOGIC PRODUCTIVITY
(Nutrient Concentrating Processes and Settings)
- A. Enhanced Nutrient Concentrations
  - 1) Terrestrial Input of Nutrients
  - 2) Coastal Upwelling
  - 3) Open Water Upwelling
- B. Evaporitic Settings
  - 1) Silled Basins
  - 2) Shelf/Platform Depressions
  - 3) Rifts on Flooded Continental Platforms
  - 4) Mid and High Latitude Deserts
- C. Restricted Geographic Configuration
- D. Terrestrial Kerogen Influx
- E. High Latitude Effect (Oceanic Convergence)

DEPOSITIONAL PRESERVATION
(of Organic Material in Depositional Environment)
- A. Actively Subsiding Depocenter at Time of Deposition
- B. Maintenance of Anoxia
  - 1) Positive Water Balance (Fresh-Water Influx)
  - 2) Salinity Stratification
  - 3) Thermal Stratification
  - 4) High Productivity
  - 5) Restricted Circulation (Deep, Narrow Trough or Silled Basin)
- C. Isolation Factor
  - 1) Distance of Basin from Paleo-Shoreline (Coastlines, Shelves, Epeiric Seaways)
  - 2) Local Uplift Deflecting Drainage away from Basin (Rifts)

NON-DILUTION OF SEDIMENTED ORGANIC MATTER
(Low Sedimentation Rate)
- A. Proximity to Orogenic Belts during Interval of Source Rock Deposition
- B. Drainage Conduits into Depocenter from Uplifted Areas
- C. Rate Influence by Climatic Belts, e.g. Wet Zones

Much of the organic matter produced in the oceans eventually settles into deeper water. A greater part of this material is oxidized during settling, consumed by benthic or planktonic organisms, or undergoes strong degradation in the sediments. A variable part of the primary production, however, is buried and preserved. The relative importance of these processes depends on the level of organic matter production, the depth of the water column, the rate of sedimentation, and the availability of oxidants (Golonka et al., 2009).

High or increased levels of primary production of organic matter by photosynthesis within single-celled marine algae in the surface waters of the ocean supports an increased flux

Fig. 19. Abandoned quarry in the village of Kobielnik. **A** – general view of the Menilite Formation; **B**, **C** – cherty marls in the lower part of the Menilite Formation; **D** – thin bed of coarse-grained conglomerates as intercalations within the Menilite Formation; **E** – thin bed of fine-grained sandstones with Upper Carboniferous clasts of coal; **F** – natural efflux of bituminous oil on joint surface of sandstone

of organic carbon to the sea floor. This process is invoked as one of the primary controls on the origin of organic-rich sediments. The primary production of organic matter by planktonic organisms is governed by solar radiation and nutrient supply. Light attenuation restricts photosynthesis to the euphotic zone, which ranges in depth from 100-120 meters in clear, open oceans to only a few meters in turbid and near-shore areas. The euphotic zone is also limited to a depth of only about 20-35 meters in plankton-rich, stagnant areas like the Azov and Black Seas. The euphotic zone usually has low concentrations of dissolved nutrients, because these are consumed by the phytoplankton. Deeper water, below the euphotic zone, is enriched in nutrients by bacterial degradation of organic debris (fecal pellets and dead organisms) as it sinks to the ocean floor. Sustained primary production can occur only if the nutrient supply into the euphotic zone is maintained. Nutrients can be supplied to the euphotic zone by wind-driven mixing of deeper water, by upwelling of intermediate water beneath areas of surface water divergence, and in coastal areas by lateral inflow of nutrient-rich river waters. The origin of many organic-rich rocks has been attributed to upwelling. This is because upwelling zones are rich in dissolved nutrients necessary to sustain high organic productivity (Picha & Stranik, 1999; Golonka et al., 2009).

The Krosno Basin during Oligocene times fulfilled the conditions for organic productivity. Paleoclimate modelling indicates wind directions favorable to open water upwelling, symmetric and circular. The computer modeling was confirmed by actual observations from the Czech Republic (Picha et al., 2006). According to the quoted authors the Menilite Formation was deposited in a zone of proliferation of marine life (diatoms). Nutrient supply was caused by upwelling of nutrient-rich deep waters under anoxic conditions. The siliceous phyto- and zooplankton production is accompanied by nektonic organisms, mainly fish (Jerzmańska & Kotlarczyk, 1976; Kotlarczyk et al., 2006; Picha et al., 2006; Bieńkowska-Wasiluk, 2010). The depositional environment of the formation may be compared to that which existed along the active margins of coastal California, where the Monterey Formation of Miocene age formed in the paleoenvironmental conditions favorable to the deposition of organic-rich diatomites. Restricted geographic conditions also enhanced these processes.

The most important factor operating to preserve organic matter in sediment is the reduction or removal of oxygen from the bottom layers of water on the sea floor. Most major source rocks, with the exception of prodelta shales and some turbidites and upwelling-related source rocks, show evidence of having been deposited in anoxic or suboxic conditions known also from Carpathian basins, especially from the Krosno Basin (e.g., Picha & Stranik, 1999; Golonka & Picha, 2006; Kotlarczyk & Uchman, 2012). Even though oxidation occurs in both oxic and anoxic conditions at similar rates, anoxia at the bottom of the water column can help to preserve organic matter. This is done through restriction (due to a lack of oxygen) of deposit feeders, which represent a major catalyst to oxidation efficiency. Another way anoxic pore water aids preservation is that many organic molecules (liquid hydrocarbons, lipids, lignins) are more stable in anaerobic conditions and are resistant to anaerobic degradation (Golonka et al., 2009).

In general, as the rate of deposition of fine-grained sediment increases, the organic matter content of the sediment also increases. This general rule holds when the sedimentation rate is not excessive and follows from the above relationships and because rapid sedimentation decreases the time organic matter is exposed on the sea floor or in the top few meters of the sediment column (Golonka et al., 2009). Most of the Menilite Formation represents fine-grained sedimentation. With the passage toward the sandy Krosno Formation, the organic richness disappears.

A critical control on the content of organic matter in marine sediments is the rate of organic matter accumulation on the ocean floor versus the rate of sedimentation of terrigenous and skeletal mineral matter. The organic carbon concentration in sediments is then ultimately determined by the amount that the organic matter is diluted by inorganic sediment. For rich source rocks the sedimentation rate of organic matter exceeds that of mineral matter, which is usually very low. Preservation of the record of organic productivity is also associated with very limited influx of detrital material both from the foreland and the orogenic belt to the Krosno Baisn during the sedimentation of the Manilite Formation shales (Picha et al., 2006). This non-dilutional factor contributed to the final organic richness of the Manilite Formation.

The actual geochemical characteristics of the Menilite Formation were outlined by Kotarba & Koltun (2006), Lewan et al. (2006) and Kotarba & Nagao (2008). According to these authors the Total Organic Carbon (TOC) content ranges from 0.18 to 17.25% (mean 4.48%) in the deposits occurring now within the Silesian Nappe. Type II, algal oil-prone kerogen dominates throughout the formation; types I and III are less frequent. Organic production caused by algae (mainly dinoflagelates and diatoms) is indicated by biomarkers and stable carbon isotope analyses. Some biological markers were derived from gymnosperms and angiosperms. It indicates the influx of terrigenous organic matter from ridges surrounding the Krosno Basin (Kotarba & Koltun, 2006).

Passage from Kobielnik – Żegocina

The route approaches Żegocina common (Fig. 20), the administrative district of Bochnia County. Its seat is the village or small town of Żegocina, which lies approximately 21 kilometres south of Bochnia and 46 km south-east of Kraków (Fig. 10). Żegocina was named Villa Żegota by the Kraków Prince Bolesław Wstydliwy in the XIII century. He passed the rights to this village to the knight Żegota, whose coat of arms Topór (the battle axe) is now the official coat of arms of the town. Several interesting cultural sites are located in Żegocina common, including a XV century wooden church in Rozdziel.

Traditionally the Żegocina area (Fig. 21) was considered as a long tectonic window, where the more external units crop out from beneath the Silesian Nappe (Skoczylas-Ciszewska, 1960; Ślączka & Kaminski, 1998). The beds comprising the window are strongly folded into several narrow faulted folds. Several exposures of Maastrichtian grey marls, locally with thin laminated sandstones, are known. Some marls display slump structures, and it is also possible to find a block of olistolites, including Jurassic andesites. An exposure of whitish marly limestones (Żegocina Marls) of Turonian to early Senonian age is located near the market place in Żegocina. The marly deposits originated within the Subsilesian sedimentary area. The Żegocina Marls are micritic limestone, *Maiolica*-type, strongly lithified, and containing brown chert nodules.

Stop 4. Żegocina quarry [Grodziszcze (Hradište) Formation]
(Figs 20–24)

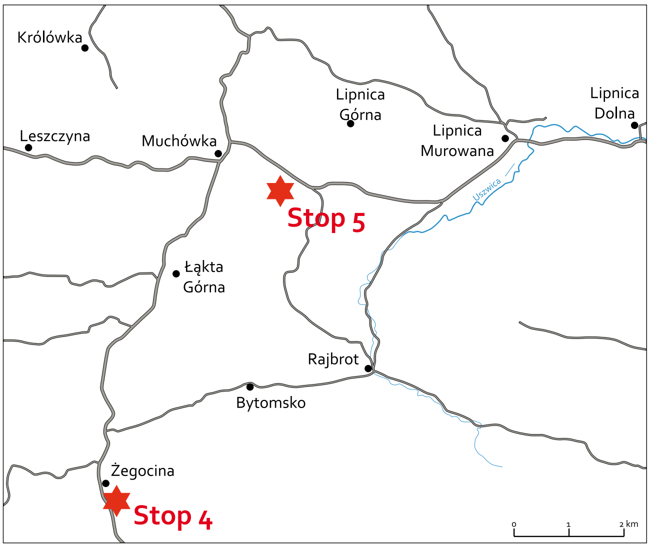


Fig. 20. Location of the Żegocina abandoned quarry (with field trip Stop 4) and Brodziński Tors (Kamienie Brodzińskiego) (with field trip Stop 5)

An excellent outcrop of the Outer Carpathian deposits is located in an abandoned quarry on the east bank of the Żegocina stream (Figs 20, 21), opposite the petrol station. The flysch rocks exposed in the quarry belong to the Grodziszcze Formation (Kamieński et al., 1963; Unrug, 1969; Malik & Olszewska, 1984; Ślączka & Kaminski, 1998), deposited during Early Cretaceous times in the Protosilesian basin (Fig. 24). The whole Grodziszcze Formation is about 300 m thick and was formed by deposition of clastic material in a marine basin 2000 m to 3500 m deep. Probably they were derived from the Silesian Ridge, which separated the Protosilesian Basin from the Magura Basin (Fig. 24). The material was derived from the shallow near-coastal zone and was transported by turbidity currents toward the slope and continental rise parts of the basin. Turbidity currents are masses of water, rich in sediment, that flow down the continental slope. As more and more sediment builds up, a continental rise forms. The continental rise lessens the degree of the continental slope. The currents move because they display higher densities than the fluid through which they flow. Gravity forces enable the currents to move down the slope with an increased carrying capacity of clastic material. When the basin slope increases, the speed of the current also increases and draws up more sediment. The increase of sediment load increases the current density and its velocity can reach over 100 km per hour. When the current reaches the continental rise it loses its high energy, slows down, and deposits the suspended material into the submarine fan. The gradual decrease of velocity causes a gradual deposition of the transported material and upward diminishing of the particle size. This mechanism results in the following sequence of deposits: sandstone-mudstone-shale.

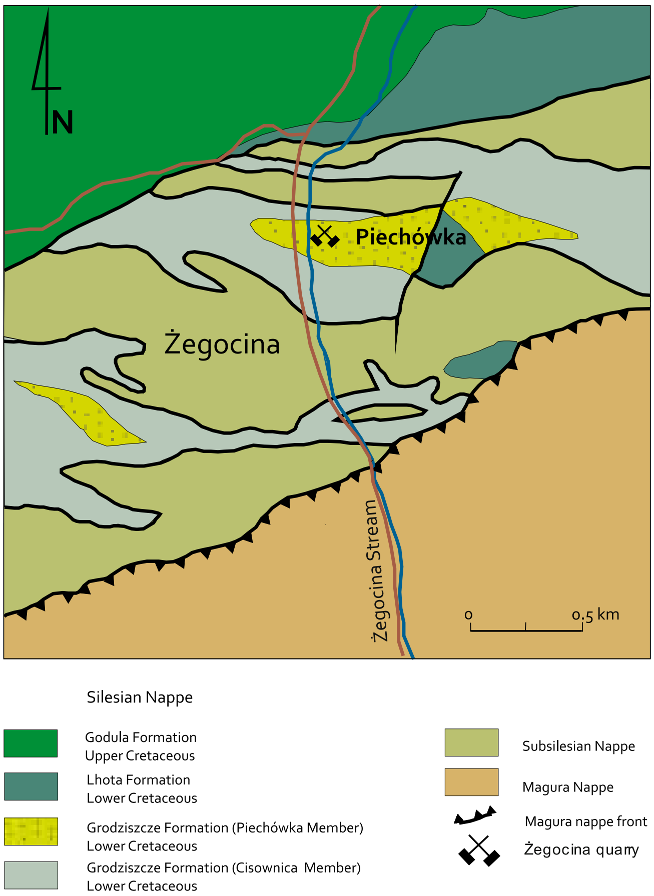


Fig. 21. Geological map of the Żegocina area (after Leśniak, 2008 in Krobicki et al., 2008, slightly changed)

Different sedimentary structures, such as bedding, lamination and fractional grain-sizes, can be observed in turbiditic deposits (Fig. 23). In the case of the rapid loss of velocity and rapid deposition of the clastic material, the fractional sorting does not occur and the deposits display massive or chaotic structure with exotic-bearing gravelstones (Fig. 23E) or sandstones. All such sedimentological features and processes are present on the geotouristic board in Żegocina quarry (Fig. 23A). This quarry, named "Geological Park in Żegocina" (http://www.zegocina.pl/aktual/2005/pazdziernik/kamieniolom/park-kamieniolom.htm), belongs to the so-called "Ecomuseums of Bochnia Region". Additionally, it is possible to estimate the frequency of the turbidity currents during the deposition of the Grodziszcze Formation in Early Cretaceous times. One current every 20,000 years gives 2-3 metres of accumulation every 100,000 years or 0.5–1 mln for the whole series in the quarry. Sometimes the submarine slumps occurred on the basin slope, especially during times of seismic activity. These slump deposits are characterized by a chaotic distribution of material and often deformation of older unconsolidated deposits.

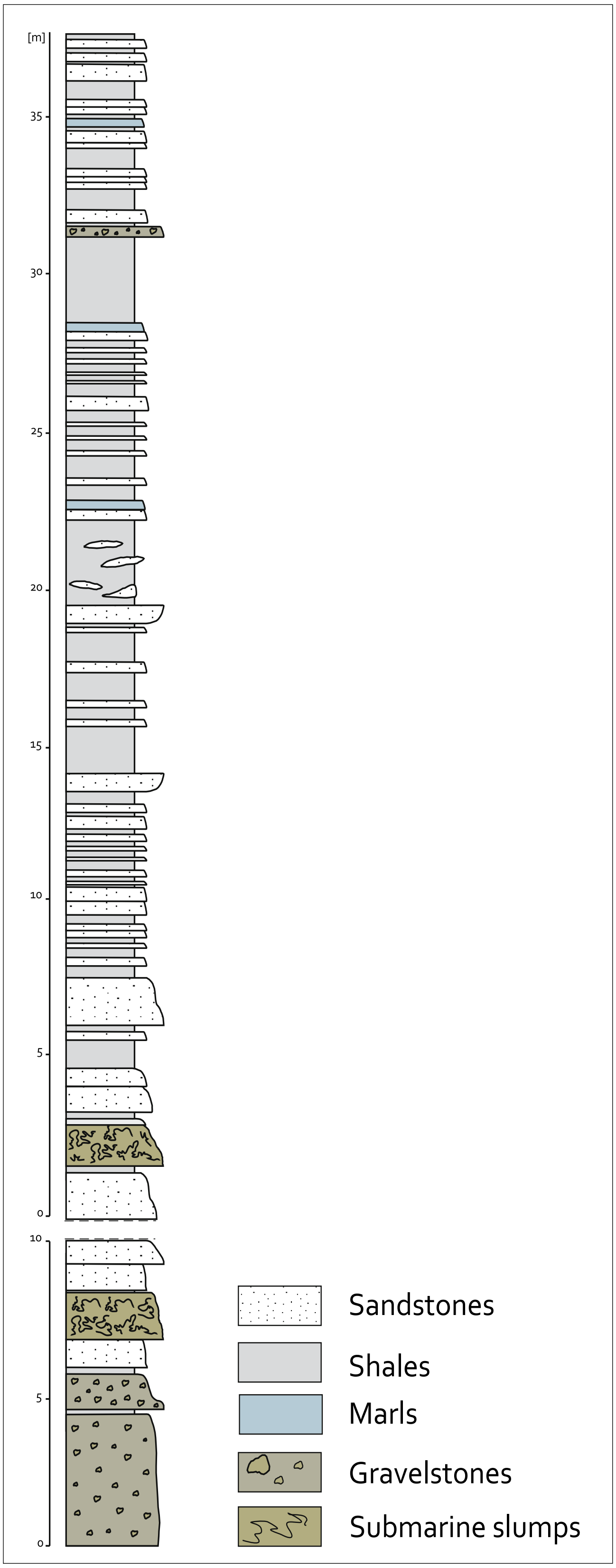


Fig. 22. Lithological profile of the Grodziszcze Formation (Piechówka Member)

The profile (Fig. 22) begins within the Żegocina stream bank, where two layers deposited by high density turbidity currents are visible. They begin with turbiditic sandstone layers and pass upwards into a chaotic body containing fragments of shales and Carboniferous coal (Malik & Olszewska, 1984) The sequence then passes upwards to a complex of thin and medium bedded, calcareous sandstones. The thickness of the sandstone layers is 8-25 cm, rarely 3-5 cm and 30-40 cm. Sedimentological and palentological investigations recognized several lithofacies with different types of foraminifers. These turbidites show flow structures and flute marks indicating a northeastward direction of transport. A slight increase in the density of flowing suspensions and striking of the bottom by objects carried by turbidity currents promotes the development of flute marks. In the central part of the left quarry wall a unique coarse-grained clastic dyke can be observed. Unconsolidated and water-saturated flysch sandstones are subject to liquefaction and intrude upwards and downwards into fissures in the deposits, forming such sandstone dykes. This liquefaction was perhaps caused by submarine earthquakes. The sandstone dykes lack primary sedimentary structures. Higher up in the section there are several lensoid layers that appear to resemble channel fill deposits. However, the lack of any trace of erosion below them suggests that they represent dune or sand wave structures with convex upper surfaces. The sandstones are intercalated with grey shale containing agglutinated foraminifera. Fragments of aptychi have also been found.

The modern approach to the stratigraphy of the Protosilesian basin, based on the correlation between Czech and Polish Carpathians, is distinguishing these formal Upper Jurassic – Lower Cretaceous lithostratigraphic formal units (Golonka & Waśkowska-Oliwa, 2007; Golonka et al., 2008a):

The Vendryně Formation (Oxfordian-Tithonian)
The Cieszyn Limestone Formation (Tithonian-Lower Valanginian)
The Grodziszcze Formation (Valanginian-Aptian)
The Veřovice Formation (Aptian-Albian)

The Grodziszcze Formation (Eliaš et al., 2003) was formerly known as the Upper Cieszyn Beds and Grodziszcze Sandstones (e.g. Ślączka et al., 2006) or Tesin-Hradište Formation (Picha et al., 2006). Two members are proposed with the Grodziszcze Formation: the Cisownica Member (Upper Cieszyn Beds) and the Piechówka Member (Grodziszcze Sandstones). The name of the latter unit is derived from the Piechówka hamlet in Żegocina near the visited quarry (Fig. 21). The quarry is the type locality for this new lithostratigraphic unit. This area is also the type locality for the Żegocina Marl Formation. The Protosilesian basin sedimentary units were later incorporated into the Silesian, Subsilesian and Skole tectonic nappes. During the final orogenic stages, Africa converged with Eurasia. A direct collision of the supercontinents never happened, but their convergence lead to the collision of intervening terranes, leading to the formation of the Alpine-Carpathian orogenic system. Throughout the Miocene, tectonic movements caused the final folding of the basin fill and created several imbricate nappes which generally reflect the basin margin configurations after the Cretaceous reorganization and Paleogene development of the Carpathian accretionary prism. The Silesian Ridge was destroyed totally and is known only from olistolites

Fig. 23. Abandoned quarry in Żegocina. **A** – general view; **B** – well-bedded flysch deposits of the Grodziszcze Formation; **C** – detail of the Grodziszcze Formation deposits with characteristic flyschoidal features (convolute lamination); **D**, **E** – gravelstones of the Grodziszcze Formation, full of exotic pebbles

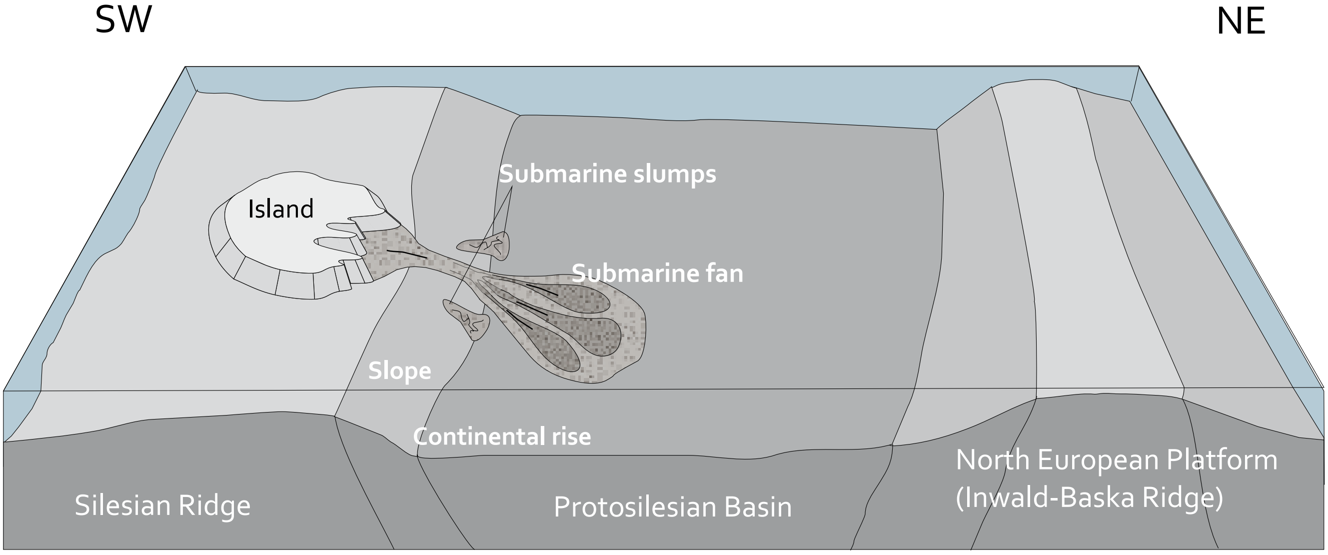


Fig. 24. Sedimentological model of the deposition of the Grodziszcze Formation. Not to scale

and exotic pebbles in the Outer Carpathian flysch (Fig. 23E). Their destruction was related to the advance of the accretionary prism. The flysch rocks and the ridge's basement rocks form olistostromes and exotic pebbles within the Menilitic-Krosno flysch (Oligocene time) (comp. Fig. 9). Perhaps such a huge olistostostrome was formed in the Żegocina area, including elements of Silesian, Subsilesian sedimentary rocks, as well as basement rocks, andesites and Upper Jurassic reef limestones of Štramberk-type limestones.

The Żegocina abandoned quarry in the Protosilesian basin is one of the sites included in the Polish database constructed by the Polish Academy of Sciences Institute of Nature Preservation as a part of the IUGS Global GEOSITES project, carried out by the European Association for the Conservation of the Geological Heritage (ProGEO) (Alexandrowicz, 2008, editor - http://www.iop.krakow.pl/geosites/, see also Alexandrowicz et al., 1999). The whole database contains descriptions of 175 sites (areas) arranged in order of physiographical regions of Poland. The database is open and should be supplemented in the future. It is the first such English edition in Europe destined for the Internet and prepared according to the format proposed by ProGEO. Further additions are expected, because similar databases of representative geosites in particular European countries will have an important advantage in the development of geoconservation at an international level. An information board is located at the entrance to the quarry (Fig. 23A). It contains a detailed description of the site's history and geology. The text presented here is partly based on this information (Lesniak, 2008 in Krobicki et al., 2008)

Passage from Żegocina – Lipnica

Lipnica Murowana is a small town, founded in the XIV century by the Polish king Władysław Łokietek. According to legend, when in the region of Lipnica, old king Łokietek went hunting in a forest with his son Kazimierz. The old king chased an animal with a spear and disappeared into the forest. He got tired and felt a sleep under a lime tree. When his people found him he thrust his sword into the tree and said to his son – "We shall set a new town here and we shall call it LIPNICA" (Lipnica from lipa, lime tree in Polish). So, the coat of arms shows a lime tree and the sword of King Władysław Łokietek. Lipnica Murowana displays a unique preserved medieval architecture in the town market and surrounding streets. The wooden church of St. Leonard was included in the UNESCO list of World Cultural heritage belonging to the Wooden Churches of Southern Little Poland (Małopolska) (http://whc.unesco.org/archive/advisory_body_evaluation/1053.pdf). According to the UNESCO page the wooden churches of Małopolska are outstanding examples of different aspects of medieval church building traditions in Roman Catholic culture.

Built using the horizontal log technique, common in eastern and northern Europe since the Middle Ages, the buildings were sponsored by noble families and also became a symbol of prestige, representing a highly qualified wooden alternative to the masonry structures in urban centres. The church of Lipnica Murowana was built at the end of the 15th century. It has been renovated many times, but this has not significantly affected its form or spatial arrangement. It contains the XVI century ornamental polychrome decoration of the ceiling and walls painted in the XVII and XVIII centuries. On Palm Sunday, proceeding Easter, an unusual procession is held in Lipnica Murowana. Some 25 metre-tall Easter "palms" soar up over the crowd. Made of wicker and wood, decorated with paper flowers, these palms are slender and surprisingly solid. There is a competition for the highest palm.

Stop 5. The Brodziński Tors (Kamienie Brodzińskiego) (Istebna Beds)
(Figs 20, 25, 26)

This interesting educational trail is located west of Lipnica Murowana (Figs 20, 25) and south of the village of Muchówka. It starts at the parking lot near the country inn (Karczma – "Gospoda pod Kamieniem Brodzińskiego") which offers delicious regional specialities. The trail heads southwards across woods covering Paprotna hill (elevation 436 m). The stops on the trail describe the characteristic biota of these woods. The scenic tors are located on the top of the hill. These were named „Kamienie Brodzińskiego" (Brodziński Tors) (Fig. 26) after the famous XIX century Polish poet, who lived and wrote his poems in this area and also frequently visited this scenic site. One of the trail stops describes his life and achievements.

The shape of the tors has depended on the lithology and lamination of sandstones, the direction of jointing and on their position with respect to the morphological elements (Alexandrowicz, 1978; Alexandrowicz & Brzeźniak, 1989). The differentiated bedding of the deposits, the domination of coarse-grained material and the traces of submarine erosion characterise the rocks as fluxoturbidites (Fig. 26), accumulated by high density turbidite current and debris flows. Features of these sediments are particularly well visible on the tor walls subjected to selective weathering. The area is a classic study site and has high didactic value, especially for demonstrating rock relief, sedimentary structures typical of fluxoturbidites, and the geological setting of tors in the zone of Istebna Formation sandstones, as well as the lithostratigraphic position in the succession of deposits of the Silesian Unit. The Istebna Formation was deposited during Late Cretaceous – Paleogene times. The lower member of this formation contains thick fluxoturbiditic sandstones. It is worthwhile mentioning that the rocks in the Istebna Formation exposure gave the famous sedimentologist Kuenen (in Ślączka & Kaminski, 1998) the idea to introduce the term "fluxoturbidites" for the part of a turbidite characterised by a thick homogenous interval connected with a sand flow. The most significant feature of the very thick beds is their homogeneity, with discernible grain segregation only. In the lowermost part of the layers we observe a gradation or concentration of coarser material. Within several layers blocks of mudstones of local origin are observed, some of them occuring with gravels. At the top of beds B, and sometimes C&D, intervals of the Bouma sequence are visible. Very often the laminae are rich in carbonised plant remnants. Some beds display lensoid shapes. The lower surface of the majority of beds is erosional, and channels of different size are visible (Fig. 26C). The erosion of lower beds leads to an amalgamation of the beds. Sometimes flute marks are visible, showing that the sandstone had to be already compacted.

These types of rocks are a perfect example of the reservoir for oil in the Carpathians (Fig. 11).

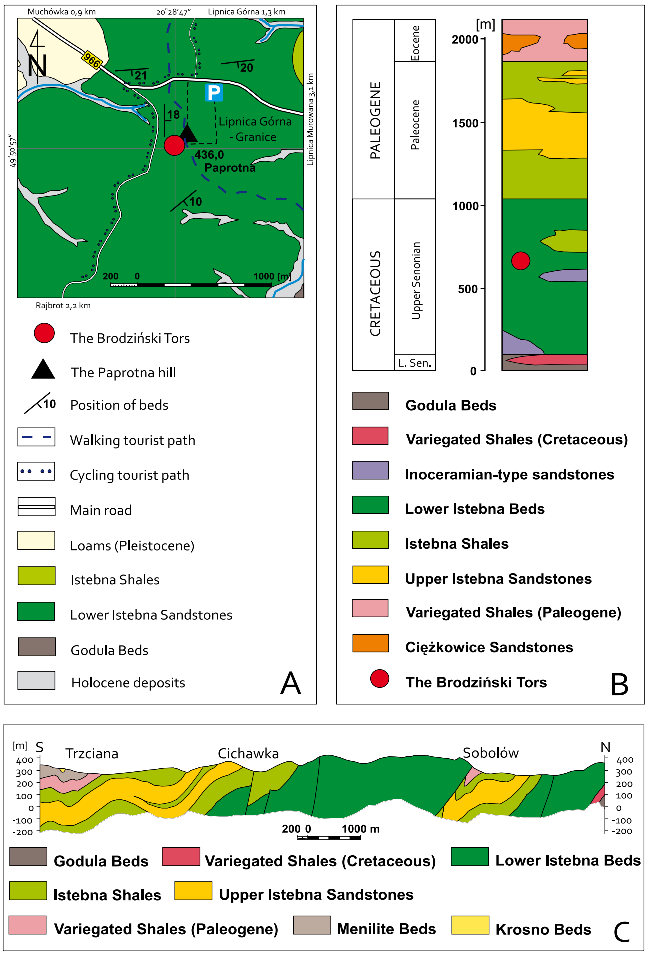


Fig. 25. Geological sketch of the vicinity of the Br odziński Tors (**A**) (Stop 5) with portions of the lithostratigraphic scheme of Silesian Unit "(**B**) and a schematic cross-section through the Silesian Nappe west of Paprotna hill (**C**) (after Skoczylas-Ciszewska & Burtan, 1954, slightly modified)

Passage from Lipnica – Znamirowice

From Lipnica, the route leads eastward. In the village of Tymowa it turns south, following the Kraków-Nowy Sącz highway along the Dunajec River and Czchów reservoir toward the next geological site at Znamirowice.

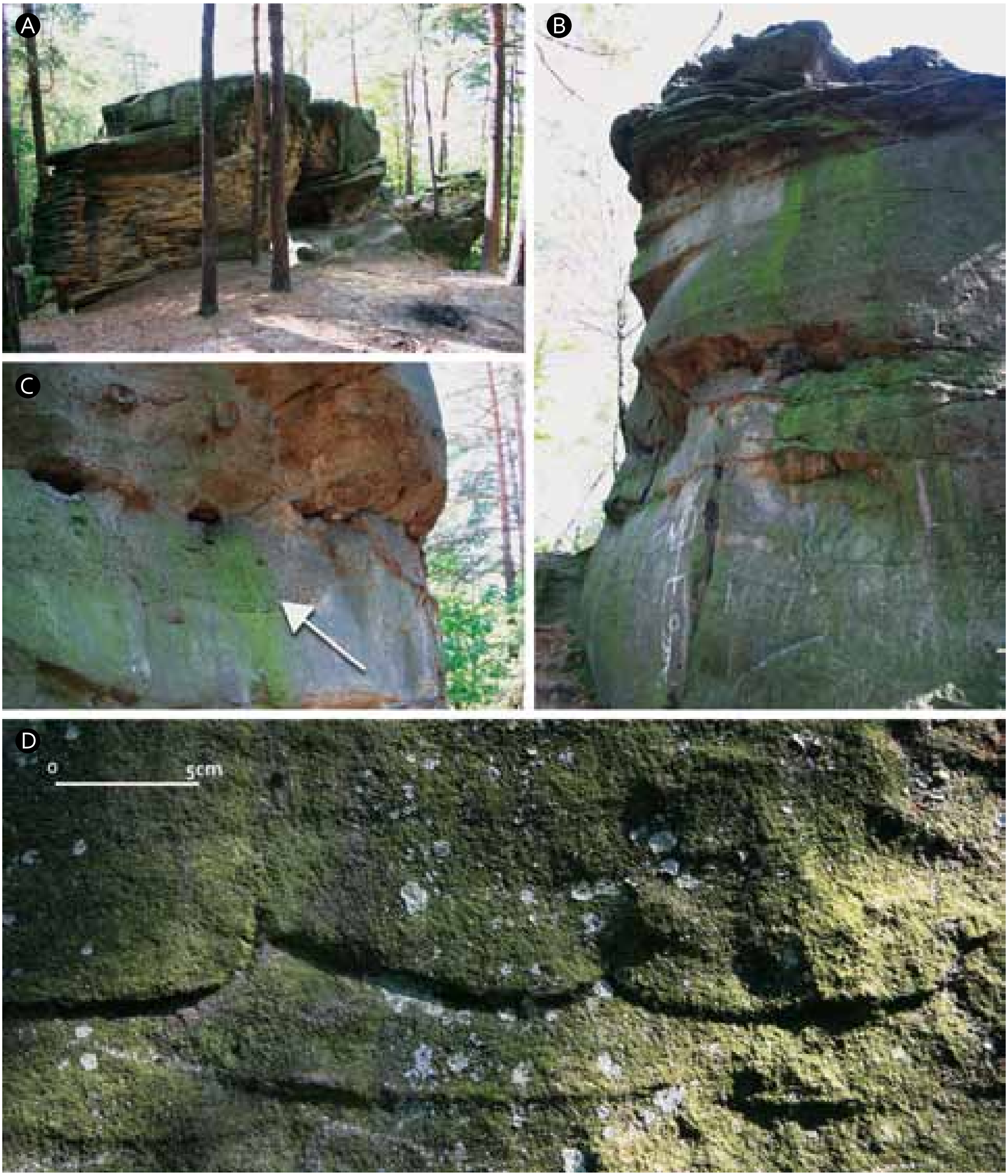


Fig. 26. Two of the Brodziński Tors klippen (**A**, **B**) – thick bed of sandstones of the Lower Istebna Sandstones with erosive channel with sharp sole boundary (arrow) between coarse- and fine-grained sandstones (**C**) and escape structures (**D**)

Stop 6. Znamirowice (i.a. Menilite Formation)
(Figs 27-29)

Fig. 27. Location of the village of Znamirowice over the artificial Rożnów Lake (with field trip Stop 6)

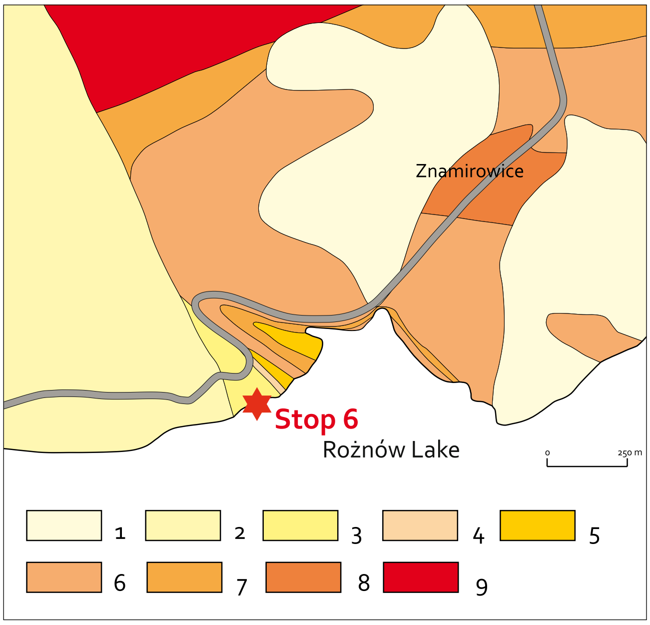


Fig. 28. Geological sketch of the Znamirowice area and location of the section of the Menilite Formation (arrow) (after Leszczyński, 1996, modified). Explanations: 1 – Quaternary; 2 – Krosno Formation; 3 – Menilite Formation; 4 – Sub-Menilite Globigerina Marl; 5 – Hieroglyphic Formation; 6 – Ciężkowice Sandstone; 7 – Variegated Shales; 8 – Upper Istebna Shales; 9 – Upper Istebna Sandstones

Outcrops in the Znamirowice area are located on the western slope of the Rożnów artificial lake (Ślączka & Kaminski, 1998; Leszczyński, 1996, 1997, 2008). The Rożnów reservoir was formed after construction of the dam on the River Dunajec in 1935. This 22 km long lake covers 16-20 square kilometers and is visited by many tourists. A yacht club marina is located in Znamirowice. The lake level fluctuates. The oucrops are clearly visible during lower water level. Eocene–Oligocene deposits belonging to the Silesian Nappe, Rożnów anticline, are exposed in the Znamirowice outrops. The older Eocene rocks belongs to the Hieroglyphic Formation. They are represented by typical flysch deposits – gray and green shales interbeded with thin sandstones. The Hieroglyphic Formation is underlain by Eocene Ciężkowice Sandstones and Paleocene Upper Istebna Beds (the Ciężkowice Sandstones will be examined at Stop 11).

The thin-bedded flysch of the Hieroglyphic Formation passes upwards into yellowish, poorly exposed marls belonging to the sub-Menilite Globigerina Marls; they contain abundant planktonic foraminifera and calcareous nannoplankton (Ślączka & Kaminski, 1998; Leszczyński, 1996, 2008). This horizon is known all over the Carpathians and also has equivalents in the entire Alpine region. The rocks were deposited during a dramatic drop in global temperature, marking the onset of Antarctic glaciation (Ślączka & Kaminski, 1998; Golonka & Kiessling, 2002, Golonka et al., 2006). According to Ślączka & Kaminski (1998) the Globigerina Marls represent the P16/17 and NP 20/21 Late Eocene micropaleontological zones. A detailed biostratigraphic study of the Globigerina Marls in Znamirowice (Van Couvering et al., 1981) revealed that the unit straddles the P16/17 and NP20/21 zonal boundaries, based on the concurrent ranges of *Globigerina linaperta, G. ampliapertura,* and *Turborotalia pomeroli* (which overlap in Zone P17). The disappearance of both *Discoaster oarbadiensis* and *D. saipanens* within the Globigerina Marl indicates that the NP20/21 zonal boundary lies with it. According to the biochronology of Berggren et al. (1995), the LAD of *saipanensis* is at 34.2 Ma, which was about 0.5 Ma before the Eocene/Oligocene boundary. Using a variety of lithological and micropaleontological evidence, Leszczyński (1996) estimated that the Globigerina Marls at Znamirowice were deposited during a single 400 ky eccentric cycle. Lithological variations within the marls, visible as marl-claystone couplets at the base of the unit, have been interpreted as representing Milankovitch-frequency variations in calcareous nannofossil productivity (Krhovsky er et al., 1993; Leszczyński, 1996).

The Lower Oligocene Menilite Formation covers the Globigerina Marls in the entire Silesian Nappe. This formation is well exposed at the Znamirowice site and is the subject of our examination. The deposition of this formation marks an anoxic event in the remnant Menilite-Krosno Basin (Ślączka & Kaminski, 1998). The anoxic event was related to specific wind directions, causing concentric upwelling conditions (e.g. comp. Kotlarczyk & Uchman, 2012).

The lower part of the formation is represented mainly by sandstone with intercalations of dark brown shales, siliceous marls, tuffites and cherts (Ślączka & Kaminski, 1998).

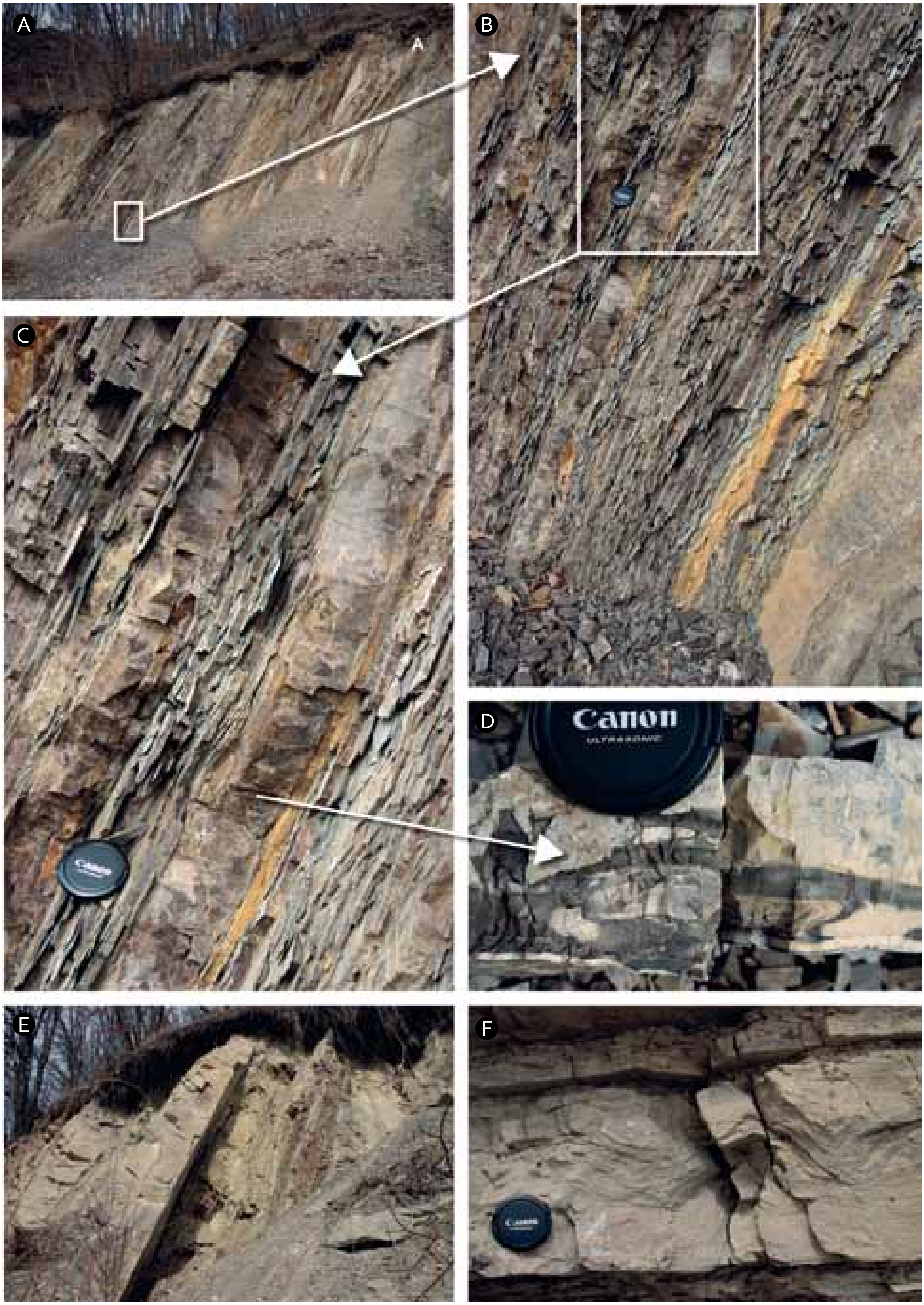


Fig. 29. Middle part of section (**A**) with thin-bedded brown, grey and black shales (**B**, **C**), sandstones, marls and cherts (**C**, **D**) of the Menilite Formation and intercalations of the medium-bedded Krosno-type sandstones (**E**) with convolute structures (**F**)

The silica mineral menilite gives the name to the formation. The sandstones are covered by brown shales, representing organic-rich rocks typical of this formation. The Menilite Formation is covered by the Krosno Formation. The contact is tectonically disturbed. The basal part of the Krosno Formation comprises thick-bedded, medium-grained calcareous sandstones with mica flakes. Gradation is developed and layers are mostly structureless. These can be considered medium-grained fluxoturbidites. The current structures show that material was brought from the southwest, from the Silesian Ridge. The thick sandstones pass upwards into a series of medium- and thin- bedded, laminated, fine-grained sandstones intercalated with grey marly shales. They display T_{bcde}, T_{cde} and rarely T_{bce} Bouma sequences. The current structures (cross-bedding and flute casts) indicate NW-SE directions, but higher up in the profile part of the sandstone layers show the opposite, which can be an effect of vortices or reflection of currents (Ślączka & Kaminski, 1998).

Passage from Znamirowice – Folusz

From Znamirowice the itinerary leads southwards; near a bridge on the River Dunajec it crosses a tectonic window where the Fore-Magura (Grybów) Unit is exposed. Part of the succession, thick-bedded sandstones of Oligocene age (Cergowa Sandstones), is visible in the Dąbrowa quarry on the left side of the road. Here the Cergowa Sandstones are developed in a proximal facies and form thick amalgamated beds. The route then crosses the flat terrain of the Nowy Sącz intramontaine tectonic basin, filled with 500 meters thick continental and marinę deposits of Neogene age (Ślączka & Kaminski, 1998). In the center of this trough lies the town of Nowy Sącz, founded in 1292, with its Gothic church and a few houses from the XV century. Later we pass through the centrum of Stary Sącz, founded in 1273, with churches and a cloister going back to XIII-XIV century. From Nowy Sącz, the route leads east, following the Nowy Sącz - Przemyśl highway. It passes the town of Grybów, the type locality of the Grybów Unit, the marginal part of the Magura Nappe with the small tectonic window of Ropa situated in the valley of the river Ropa, the village of Szymbark (where we can visit a XVIII century wooden Baroque church and a fortified Renaissance minor house from the XVI century), and eventually reaches the town of Gorlice. This town was founded in 1417 and is renowned by the fact that the first experimental petroleum distillery in the world was built here in 1853 by a local chemist, Ignacy Łukasiewicz. A plaque on the City Council building in the market square commemorates the spot where Łukasiewicz first distilled petroleum in the basement of his chemist shop. The city museum, located on a side street leading west from the main square, holds a collection of memorabilia relating to the early petroleum industry in the Gorlice district, including the original experimental still that Łukaszewicz used (Ślączka & Kaminski, 1998).

Stop 7. Folusz (Jasło Limestones)

(Figs 30–32)

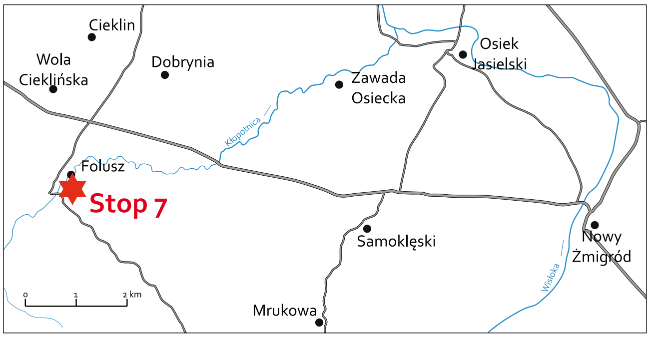


Fig. 30. Location of the Folusz village (with field trip Stop 7)

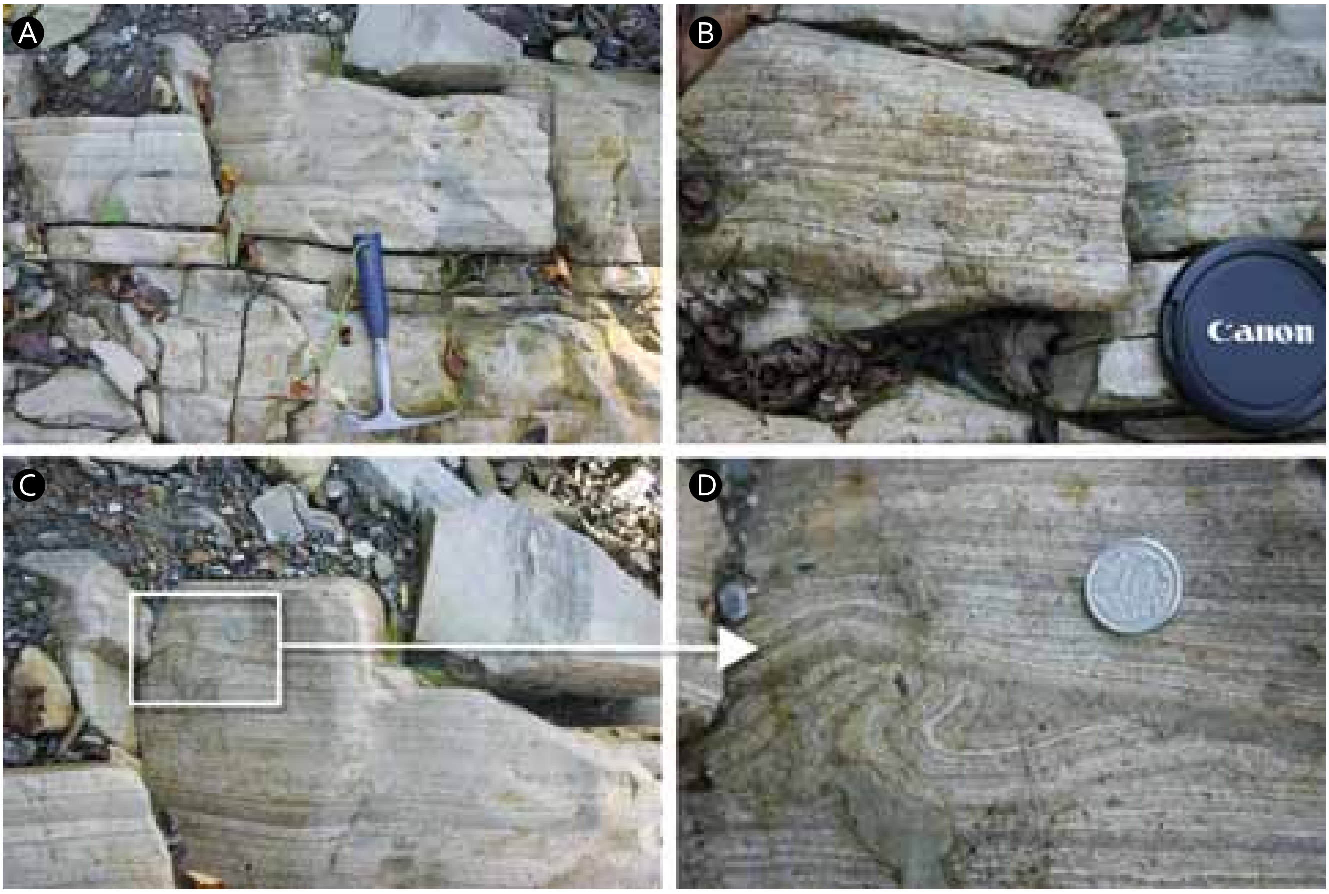
In the small stream in the village of Folusz, one of the most spectacular outcrops of the so-called Jasło shales (truly, limestones) occurs. These are very thin-laminated limestones full of coccoliths and are a record of a bloom of these fossils (Haczewski, 1989). They are also a useful chronohorizon in Carpathian stratigraphy (Fig. 32) (cf. Koszarski & Żytko, 1961; Jerzmańska & Kotlarczyk, 1976; Kotlarczyk et al., 2006).

Passage from Folusz – Iwonicz Zdrój

From Folusz the route returns to the Gorlice – Dukla highway and turns east. Before Dukla there is a perpendicular valley leading south towards the Valley of Death. This area was the site of one of the bloodiest mountain battles of the Second World War, in which 500,000 soldiers took part and nearly 100,000 were killed or injured. The town of Dukla was founded in 1380 along the important wine route from Hungary. It is worth seeing the parish church from the XVIII century decorated with a Roccoco interior, and also the XVIII century Park with its palace founded in the XVI century and rebuilt in the XIX century (Ślączka & Kaminski, 1998).

From Dukla our route follows the main road in the direction of Krosno. In Miejsce Piastowe it turns south towards the Klimat hotel in Iwonicz Zdrój (location of dinner and overnight stay).

If times allows we can visit another Menilite Formation outcrop at Rudawka Rymanowska, about 30 kilometers from Iwonicz Zdrój.



→ Fig. 31

Fig. 31. Jasło Limestones in Folusz village with typical thin-laminated structures (**A**-**E**) and synsedimentary slump-type features (**C**-**E**)

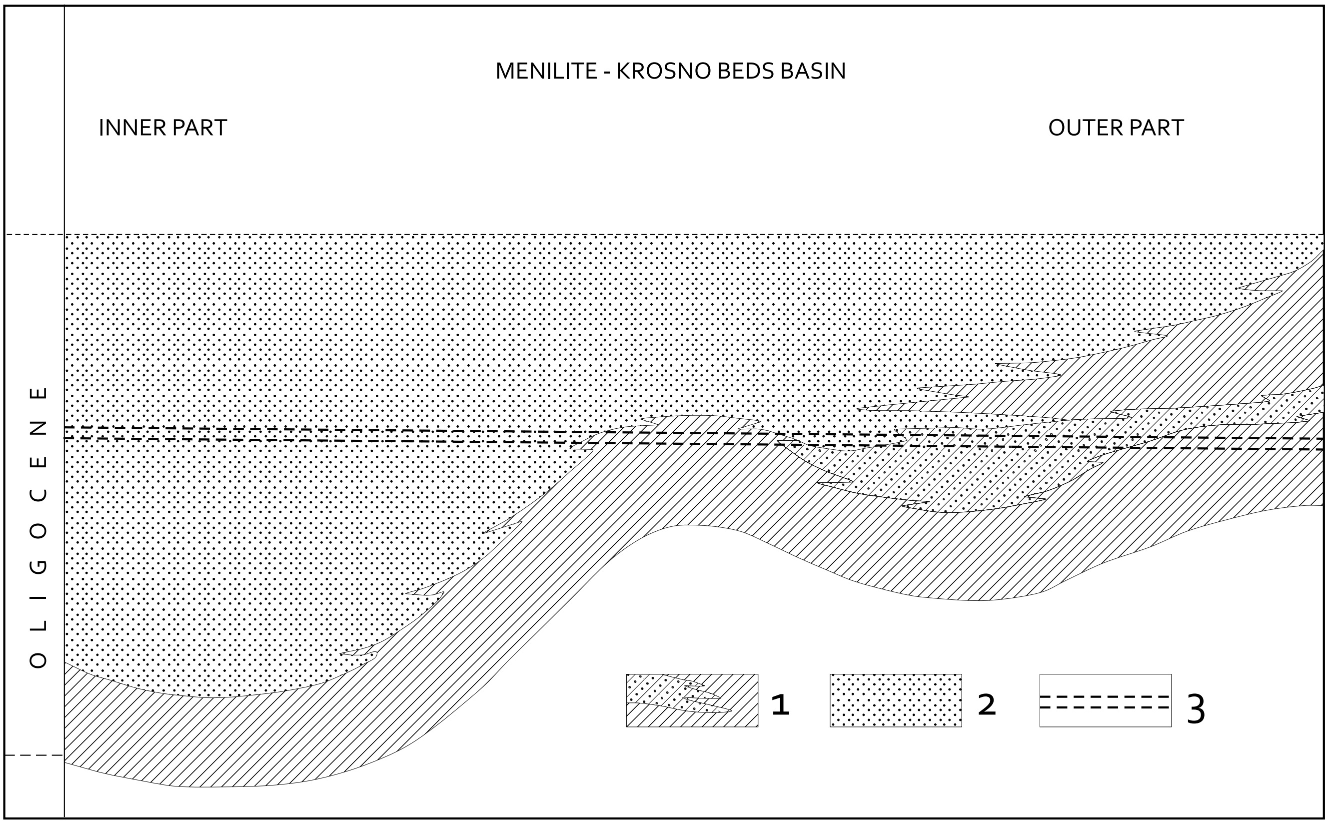


Fig. 32. Ideogram of the facies changes in the Oligocene sedimentary basin of the Outer Carpathian Basin (adopted from Jerzmańska & Kotlarczyk, 1976). Explanations: 1 – Menilite shales with the Kliwa sandstones; 2 – Krosno Formation; 3 – Jasło Limestones (chronohorizon)

Stop 8. Rudawka Rymanowska (Menilite and Krosno formations)
(Figs 33–36)

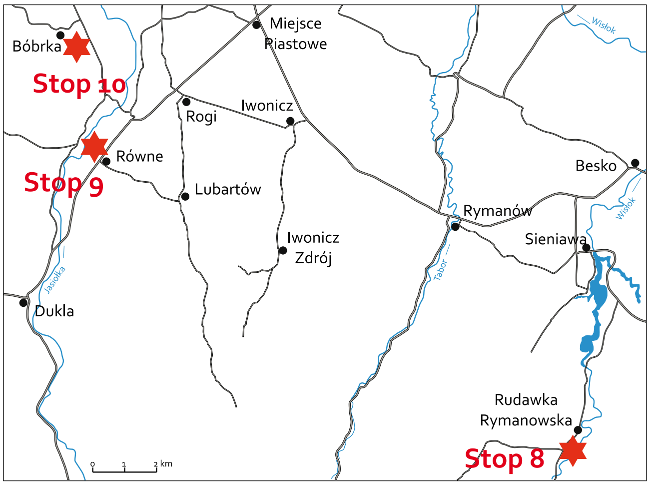
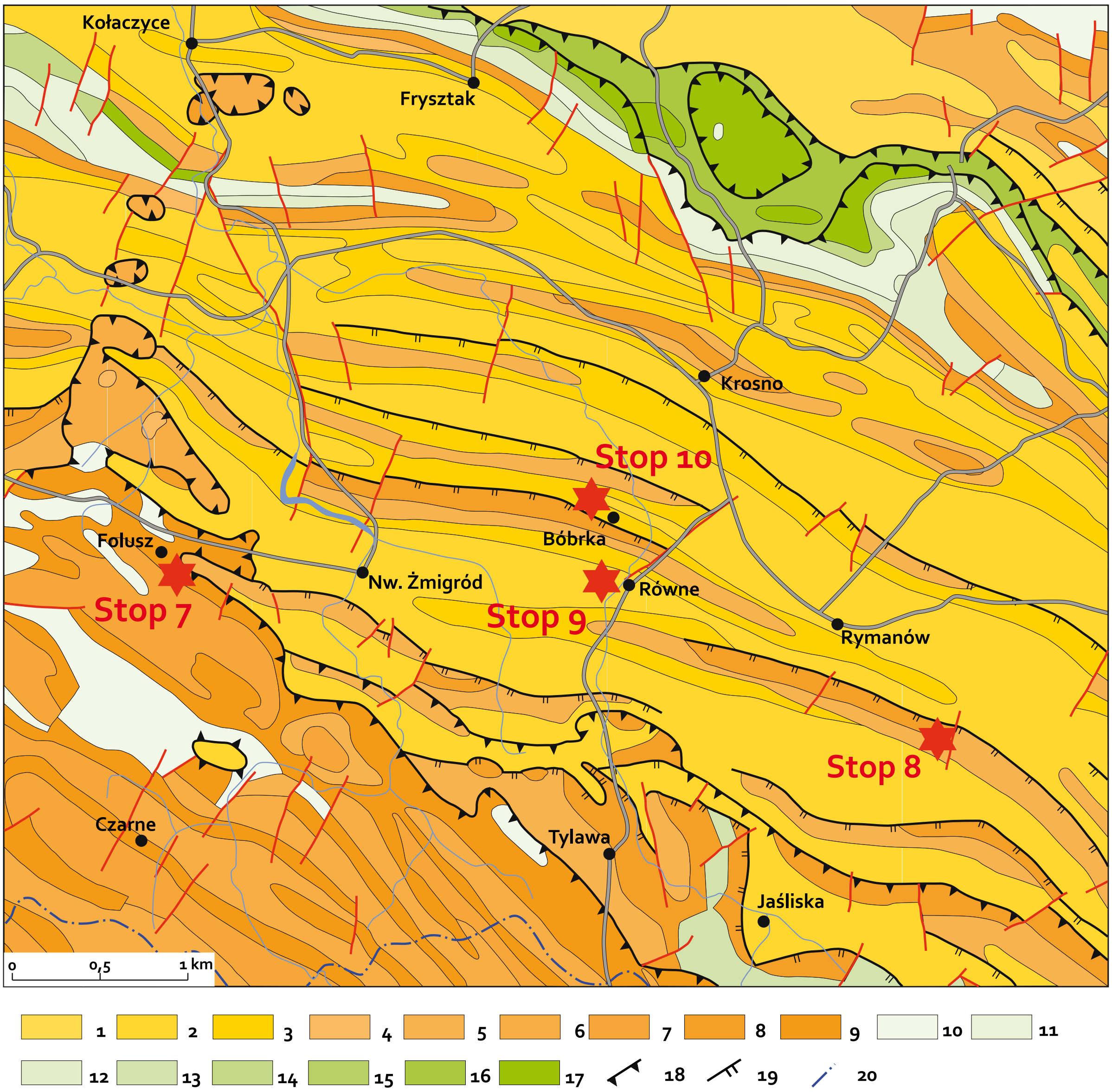


Fig. 33. Location of the village of Rudawka Rymanowska, Iwonicz Zdrój Spa, Równe section and Bóbrka Museum (with field trip Stops 8-10)

In one of the largest natural exposures in the Polish Outer Carpathians, strongly folded dark brown and rusty Menilite Shales are exposed. Most beds start with a sandstone or mudstone layer and represent sediment deposited by muddy density currents. On the left side of the exposure, and also on the left side of the river, several intercalations of black cherts are visible. Thin intercalation of the so-called Tylawa limestones (coccolithes limestones – Ciurej, 2009) occurs also between thin-bedded shales. In this exposure several tectonic structures connected with the main anticline

Fig. 34. Geological map of the Nowy Żmigród – Rymanów region with location of field trip Stops (8-10) (after Lexa et al., 2000). Explanation: 1-9 – from Istebna up to Krosno formations of the Magura and Silesian units; 10-17 – from Cieszyn up to Menilite-Krosno formations of the Silesian and Subsilesian units; 18 – first order overthrust lines; 19 – second order overthrust lines; 20 – national boundary ↓



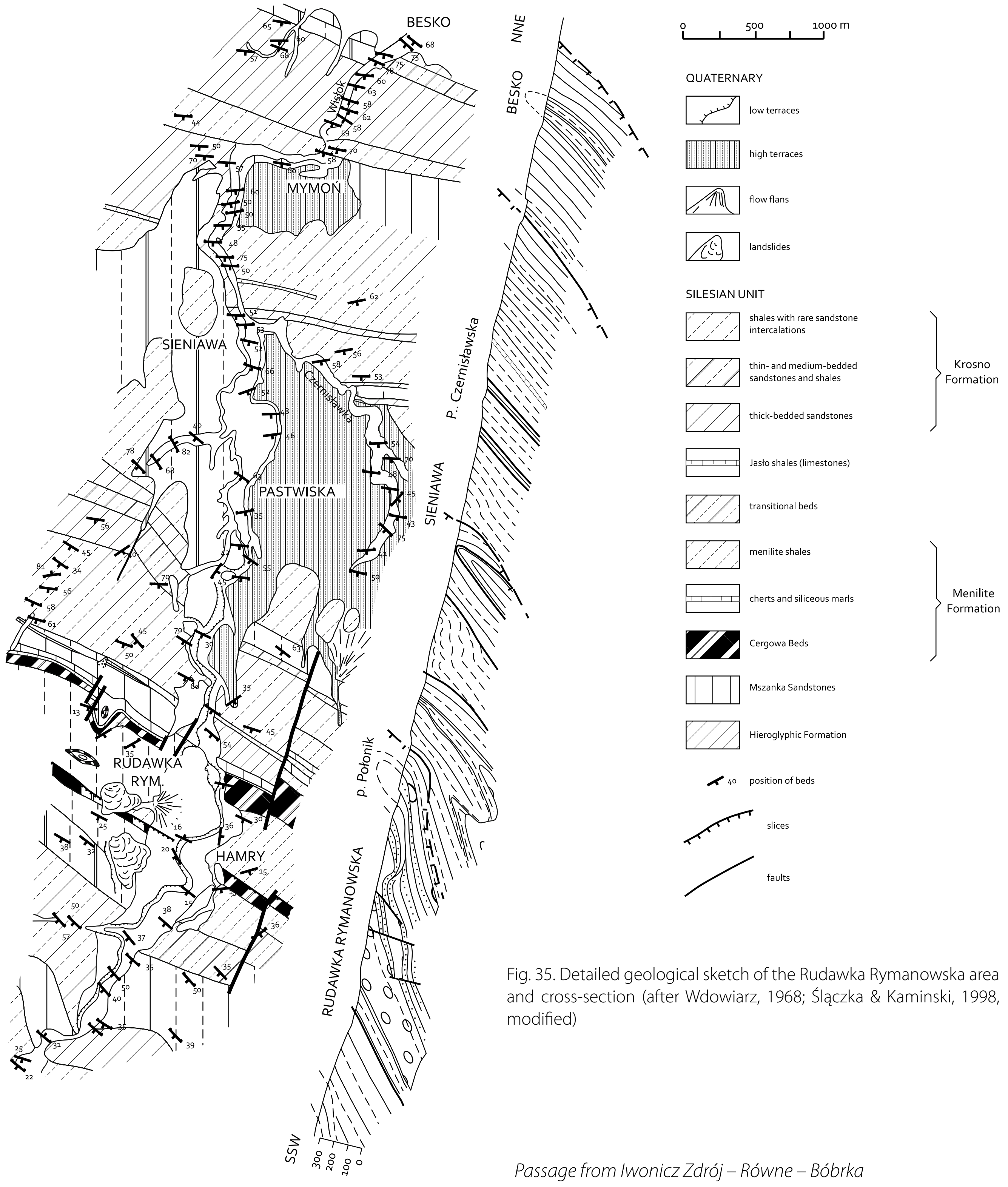


Fig. 35. Detailed geological sketch of the Rudawka Rymanowska area and cross-section (after Wdowiarz, 1968; Ślączka & Kaminski, 1998, modified)

can be observed, such as secondary folds with box of oblique faults, etc. At the bottom of the exposure the anticline is closed by sandstone banks in the anticline axis. Going upwards the anticline becomes more open and shifted towards the left (Ślączka & Kaminski, 1998). The river is difficult to cross and without rubber boots it is possible only to admire the outcrop from a distance, taking pictures.

Passage from Iwonicz Zdrój – Równe – Bóbrka

The picturesque old spa Iwonicz Zdrój is a popular tourist resort. The town centre, with its wooden houses, is preserved almost intact from the XIX century. The mineral waters from here were first described in 1587. The mineral waters available at the "Pijalnia wód" derive from formation waters accompanying a small oil fieid. They contain a variety of dissolved salts, including bromine and iodine. It is also possible to take a forest path to a spring in the forest called "Bełkotka", known at least from the beginning of the XIX century, in which we see bubbles of natural gas.

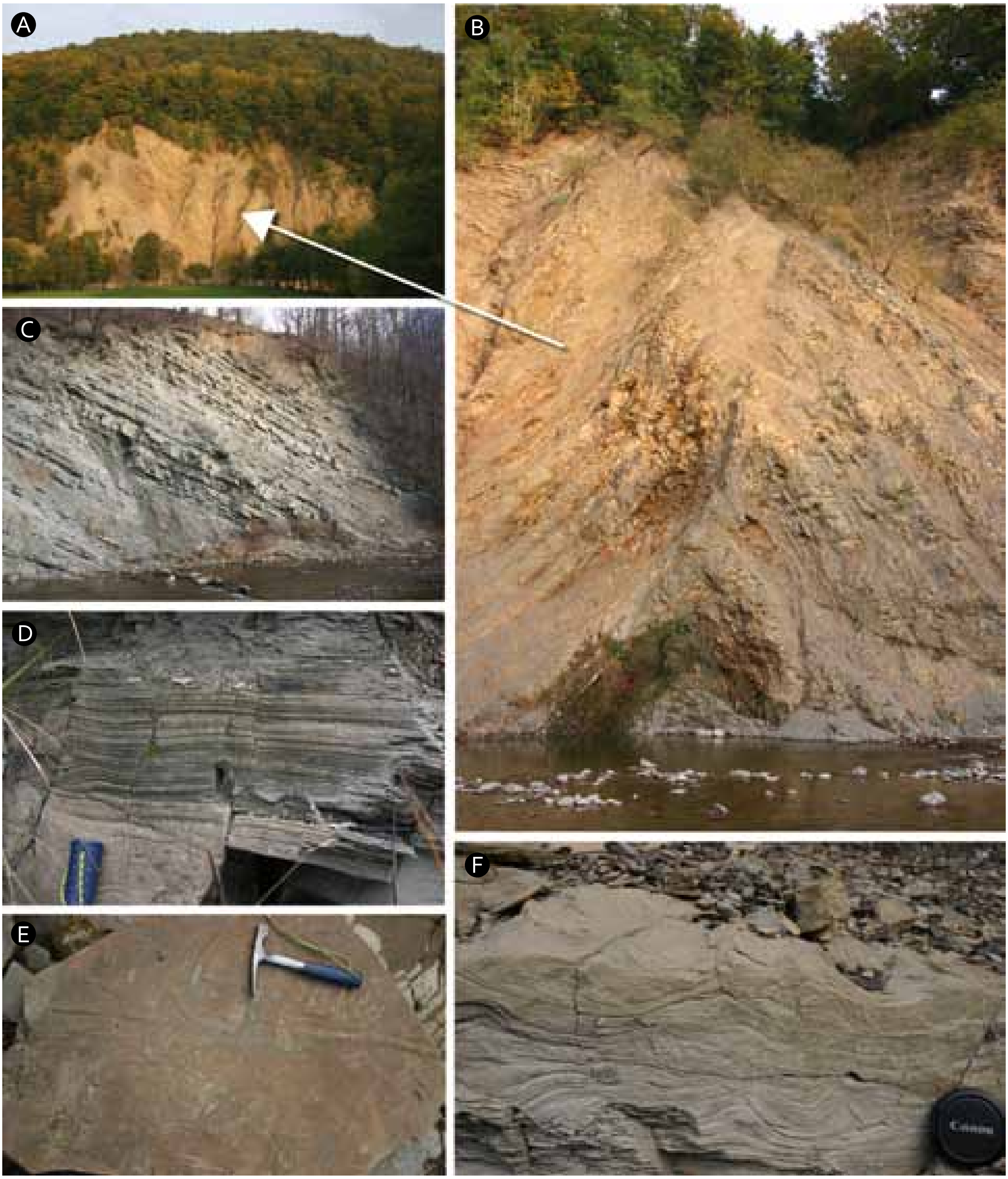


Fig. 36. Main part of the Rudawka Rymanowska outcrop with strongly folded thin-bedded Menilite Formation (**A**, **B**) and thin- and medium-bedded Krosno Beds (**C**, **D**) with typical turbiditic features – sole marks (**E**) and convolute structures (**F**)

From Iwonicz Zdrój the route returns to Miejsce Piastowe and the Miejsce Piastowe – Dukla highway.The next geological stop is located near the highway in the vicinity of the Równe Oil Field and Bóbrka Museum of Oil Industry.

Stop 9. Równe (Menilite Formation)
(Figs 33, 34, 37)

The Menilite Formation is well exposed in an abandoned quarry. Thin-bedded brown, grey and black marls and siliceous marls with cherts crop out in the main part of the quarry. There are numerous thin chert intercalations in the middle part of the central wall, and fine-grained sandstones with grading features and convolute mudstones which are characteristic of the distal type of flyschoidal sedimentation. Some fish fragments can be found in the lower part of the outcrop (Fig. 37E).

Stop 10. Bóbrka (Museum of Oil Industry)
(Figs 33, 34, 38)

The Open Air Museum of Oil Industry is located within the oldest industrial oil field of Bóbrka-Rogi. The entrance to the museum is at a small cluster of oil rigs at the crossroads. The Open-Air Museum and Petroleum Museum in Bóbrka was founded in 1961 to commemorate the centenary of the oldest Carpathian oil field, Bóbrka-Rogi. This oil field was leased in 1854 by Ignacy Łukasiewicz, the founding father of the oil industry (Ślączka & Kaminski, 1998).

Ignacy Łukasiewicz was born in 1822 in Zaduszniki, at that time Galicia, the Austro-Hungarian monarchy. He studied pharmaceutics at the Jagiellonian University in Kraków and worked in the Lvov pharmacy of Piotr Mikolasch called "Under the Golden Star"(Sozański et al., 2006). He spent his pastime investigating the properties of crude oil, common in seeps of the Carpathian region and used as medicine for curing baldness. He worked together with the other pharmacist Jan Zeh on the distillation of crude oil. They were successful in 1853, obtaining kerosene. The first lighting of kerosene lamps in a Lvov hospital was recognized as the beginning of oil industry. In 1854 the petroleum company Łukasiewicz – Trzecieski (Łukasiewicz – Trzecieski – Klobassa since 1861) was established later, starting its operations by exploiting oil wells in the Bóbrka-Rogi oilfield (Sozański et al., 2006). A series of oil wells was dug by hand to depths as great as 140 m. The "Małgorzata" well dug in 1862 yielded 4,000 litres of crude oil per day. In 1862 the Austrian Mining Engineer Henryk Walter arrived at Bóbrka, and introduced a method of drilling boreholes by the use of hand-operated percussion rigs. Three years later in the nearby village of Chiorkówka, Łukasiewicz built the first large-scale petroleum refinery to supply the local kerosene lamp industry (Ślączka & Kaminski, 1998). In the Open Air Museum, examples of different oil rigs, jacks, and tools have been assembled to illustrate the petroleum industry in the Carpathians. Of special interest are two hand-excavated wells "Franek" and "Janina", which have been producing oil since 1853 and 1878, respectively. In its 140 year history the Bóbrka field has produced over 1.2 million tonnes of oil, and production continues on a small scale today. At the museum it is possible to see a smithery from 1854 and a workshop from 1864, both of which were in use at the Bóbrka oil field, as well as Łukasiewicz's house (Ślączka & Kaminski, 1998). The modern museum building exibits the history and the present-day activity of the petroleum industry.

The Bóbrka oil field is an anticlinal structure that is subdivided into separate blocks by faults and dislocations. The main petroleum reservoirs are the four horizons of the Ciężkowice Sandstones capped by the impermeable variegated shale horizons that occur between the sandstone lenses. These rocks were investigated by another famous Polish scientist, Józef Grzybowski, the founding father of applied micropaleontology. Józef Bolesław Grzybowski (1869-1922) began his geological studies at the Jagiellonian University in Kraków in 1893, under the supervision of Władysław Szajnocha. His goal was to accomplish a series of monographs documenting the foraminiferal faunas of the Carpathians. He began with a study of Oligocene foraminifera from Dukla, and spent the next seven years studying foraminifera from the Wadowice, Krosno, and Gorlice regions. Grzybowski (and his student Maria Dylążanka) described 127 new species of foraminifera, and the authorship of an additional 20 species was later transfered to him under the rules of zoological nomenclature. His collection housed at the Jagiellonian University is perhaps the single most important reference collection of Carpathian deep-water agglutinated foraminifera. In 1894 while Grzybowski was busy with his Ph.D. thesis on the foraminifera from Wadowice, Henryk Walter arrived at the Jagiellonian University with drilling mud samples from boreholes in the Krosno area. Prof. W. Szajnocha decided the subject warranted further study, and Grzybowski was given the task of studying the microfossils. After a preliminary report dealing with the taxonomy of foraminifera he recovered, by 1898 Grzybowski had been able to demonstrate that foraminifera can be used to correlate subsurface strata in wells drilled for petroleum exploration. His paper was entitled *"Microscopical investigations of borehole muds of oil fields. I. The Potok - Krosno Well II. General Remarks".* In this paper and the following monograph "Foraminifera from the oil-bearing beds in the vicinity of Krosno" Grzybowski explained his methods of using microfauna for correlation, and produced the new famous cross-sections showing the subsurface formations in the Potok Oil Field, the location of his foraminiferal zones, and the oil-bearing horizons. Grzybowski continued this line of research with a study of the foraminifera from the Gorlice region (published in 1901). After earning his habilitation based on a study of Peruvian molluscs, he went on to become the first Professor of Paleontology at the Jagiellonian University (Ślączka & Kaminski, 1998).

Passage from Bóbrka – Ciężkowice

From Bóbrka, the route returns to Dukla and Gorlice. In Gorlice it turns northeastword to the last geological site in the famous Skamieniałe Miasto in Ciężkowice.

← Fig. 37. General view of the Równe section (**A**) with thin-bedded brown and grey marls (**B**, **C**) and cherts (**C**, **D**) of the Menilite Formation, sometimes with numerous fish remains (**E**) and rare intercalations of thin-bedded mudstones (**F**). The teleosteid fishes are well preserved in some outcrops (**G**, **H**) (Jamna Dolna and Rudawka Rymanowska respectively)

Fig. 38. The Ignacy Łukasiewicz Open Air Oil and Gas Industry Museum. **A** – drill ram for shallow drilling; **B** – big drill tower; **C** – classical pump oil machine, so-called "kiwon"

Stop 11. Ciężkowice (Ciężkowice Sandstones)
(Figs 39–40)

Fig. 39. Location of the famous Stone Town (Skamieniałe Miasto) in Ciężkowice (field trip Stop 11)

The Ciężkowice Sandstones are well known to petroleum geologists, forming the main reservoir in the Carpathian oil province (Fig. 11). The type locality of the Ciężkowice Sandstone Member is in the Skamieniałe Miasto (Stone Town) Nature Reserve in Ciężkowice. This reserve is visited by many tourists, containing a large number of picturesque sandstone tors and protected as the first in the Polish Carpathians.

The tors were shaped by weathering and erosion. Their shape has depended on the lithology and lamination of sandstones, the direction of jointing and on their position with respect to the morphological elements (Alexandrowicz, 1978; Alexandrowicz & Brzeźniak, 1989). The differentiated bedding of deposits, domination of coarse-grained material and traces of submarine erosion characterise fluxoturbidites accumulated by high density turbidite current and debris flows (Leszczyński, 1981). Features of these sediments are particularly well visible on tor walls subjected to selective weathering. The area is a classic study site and has high didactic value especially for demonstrating rock relief, sedimentary structures typical of fluxoturbidites, and the study of oil and gas reservoirs.

Fig. 40. Different shapes of tors as an erosional weathering effect (**A**, **B**) of thick-bedded, massive sandstones of the Ciężkowice Sandstone Member with fluxoturbidite features – sharp erosional contacts between massive beds (**C**, **D**) and parallel lamination (**D**)

From Ciężkowice the route turns west. After passing the scenic medieval castle Melsztyn and the River Dunajec, it reaches the Nowy Sącz – Kraków highway and turns north. In the vicinity of Brzesko, along this highway, we leave the Carpathian Mountains and enter the Carpathian Foredeep, filled with Miocene marine sediments. The thickness of these sediments varies from a few hundred metres in the western and northern parts to over 3000 metres in the eastern part of the Carpathian foreland. They consist mainly of clays, sands and evaporites (Krobicki et al., 2008).Two main tectonic units are distinguished in the foredeep:

1: an autochthonous unit, which is built of *in situ* sediments and cover the central and northern parts of the Carpathian foreland;
2: an allochthonous unit, which was folded in front of the Carpathian nappes and thrust from south to north over the autochthonous unit.

The allochthonous unit is also called the Zgłobice Unit. These tectonic features can be observed in numerous cross-sections through the marginal zone of the Miocene in front of the Carpathian thrust belt in Poland. As a result of these intense disturbances in the overthrust unit, strong deformation of salt layers resulting in an increase and decrease of their thickness, and even coarse breccias composed of salt clay with blocks of rock salt, can be observed. The final stage of these disturbances was uplift of the folded strata to the surface, resulting in the origin of the Miocene salt deposits (Krobicki et al., 2008).

The route passes the famous ancient salt mines of Bochnia and Wieliczka (Unesco World Heritage list) and enters Kraków. In Kraków and its vicinity the Jurassic and Cretaceous rocks of the North European Plate are exposed. The platform is dissected by numerous faults into several horsts and grabens. The grabens are filled with Miocene molasse deposits, whilst horsts elevate the Upper Jurassic and Cretaceous rocks. The Jurassic rocks are represented mainly by Oxfordian cyanobacterial-sponge build ups with associated nodular, chalky and micritic limestones. Oxfordian rocks build Wawel Hill with the Polish Royal Castle on the top visible from the bridge on the River Wisła. The Royal Castle was built in the X century and remodelled several times. The most important remodelling was done by Queen Bona and her team of Italian architects in the XVI century, giving the castle its Renaissance character. The limestones are shaped by karst phenomena. There is a cave inside the hill known as Smocza Jama. The name, which means Dragon Den, is derived from the Early Medieval legend about the dangerous dragon that terrorized the population of ancient Kraków. The dragon was killed by the young shoemaker Skuba, who fed the beast with sheep filled with sulfur and other chemicals. Today this dragon is a symbol of Kraków and present in every souvenir boot. Shoemaker Skuba is rather forgotten, perhaps because of his anti-ecological usage of chemicals against endangered/extinct species.

After passing Wawel hill the bus stops at the Kraków AGH University of Science and Technology parking lot, near the AGH Main Library. Our field trip ends. Participants have two options:

1. Leave the bus and stay in Kraków or depart to their destination from Kraków airport, railroad or bus stations;
2. Return with the bus to Warszawa.

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GeoShale 2012 ❯ field trip guidebook

Iwiczna Core Warehouse

Workshop

PARASEQUENCES IN MUDSTONE STRATA

Core Warehouse Workshop

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Main aim of this workshop is to examine core from the Tłuszcz IG-1 well and observe the wide range of physical, biogenic, and chemical attributes that, along with stratal surfaces and stacking patterns, record depositional conditions and provide insights into the distribution of rock properties essential to economic success.

Preface

Workshop will take place in one of the core warehouses of the Central Geological Archive in Iwiczna – a small town situated 5 km south of Warsaw. This workshop is a part of three trips focused on Lower Paleozoic Basin developed on the East European Craton:

(1) Holly Cross Mountains Field Trip; giving a chance for examining facies proximal to the Caledonian Orogeny with sandstones and mudstones.
(2) Core Workshop; examining sediments characteristic of distal, relatively deep area of the basin, dominated by claystone and mudstone.
(3) Western Ukraine Field Trip – Podole Region; visiting the eastern shoreline of the lower Paleozoic Basin developed as a carbonate platform cropping out along Dniest River.
(4) Each of these trips characterizes a different part of the basin, but all together give extraordinary insight into basin architecture, regional context, and a well-defined facies zonation. This zonation is strongly influenced by the character of the shoreline, eustasy, and tectonics.

The Lower Paleozoic deposits of the western margin of the East European Craton has been an object of detailed study since late fifties of XX century. Pasłęk IG-1 was the first well that started the regional study of Polish Lowlands in 1957. During this project tens of well were drilled, many with high core recovery, that can now help geologists understand and explore for shale gas/oil plays in Poland. In total, thousands of meters of continuous cores were taken and are accessible for study.

Recently Lower Paleozoic Basin (LPB) at the western margin of East European Craton was recognized as one of the most promising regions for shale gas/oil exploration in Europe. Based on North American experience, the large area of the LPB in Poland will be a hot topic for next years or decades.

Introduction

Fine-grained terrigenous clastic sedimentary rocks tend to get less attention than any other group of deposits despite the fact that they are volumetrically the most common of all sedimentary rock types. Mud and mudstones are the most widespread and abundant deposits on the Earth's surface both today and in most of the past and certainly deserve full attention. In the field, mudstone does not frequently show the clear biogenic and sedimentary structures seen in limestones and coarser clastic rocks. Exposure is usually poor because they do not commonly form steep cliffs, and they readily form soils supporting vegetation which covers the outcrop. This group of rocks therefore tends to be ignored but they can provide as much (or possibly more) information as any other sedimentary rock type.

The first definition of "shale" was given by Hoosen in 1747 in "The Miner's Dictionary" – it was the first recognition of mudstones as a separate class of rocks (Hoosen & Williams, 1747). Since this publication was printed mudstone study has been in progress, but still there is a gap between understanding of fine-grained sediments compared to coarser grained clastic or carbonate rocks. More than 100 years ago Henry Clifton Sorby mentioned the mud-dominated environment as a one of the most challenging topics. Sorby first started using thin-section for the study of mudstones (metamorphosed) and this situated him on the pioneer position in the mud geology (Sorby, 1853). Since then, there are some very important publications about mudstone study that mark crucial milestones of progress in fine-grained analysis:

(1) X-ray apply for clay minerals (Rinne, 1924),
(2) biomarkers in petroleum (Treibs, 1936),
(3) scanning electron microscopy (Bates, 1949),
(4) vitrinite reflectance applied to sedimentary rocks (Teichmuller, 1958),
(5) K-Ar analysis applied to mudstones (Hower et al., 1963),
(6) models of oxygen-dependent biofacies (Rhoads & Mores, 1971),
(7) sedimentology of Shale (Potter et al., 1980),
(8) shales and mudstones (Schieber, 1998).

Nowadays, fine-grained sediments attract a wide range of specialists because of high hydrocarbon potential as well as promising target for CO_2 sequestration and nuclear waste storage. Shale gas resources have changed the oil&gas business all around the world. A few years ago, recognition of shale potential reached Poland sparking a series of projects focused on shale gas/oil plays by major and smaller companies. Besides their economic potential, there is a serious possibility to further our understanding of the geological history of Poland using the fine-grained rocks. On the east side of a line connecting Słupsk-Warsaw-Zamość, Silurian deposits comprise the majority of the sedimentary record, making this particular interval the most important in terms of thickness and natural resource potential in Poland.

Geological Setting

During this workshop we will have an opportunity to examine core from the Tłuszcz IG-1 well. Our observation starts in the base of the Caradoc and goes continuously to Lower Ludlow, which in total is around 200 meters (Fig. 1).

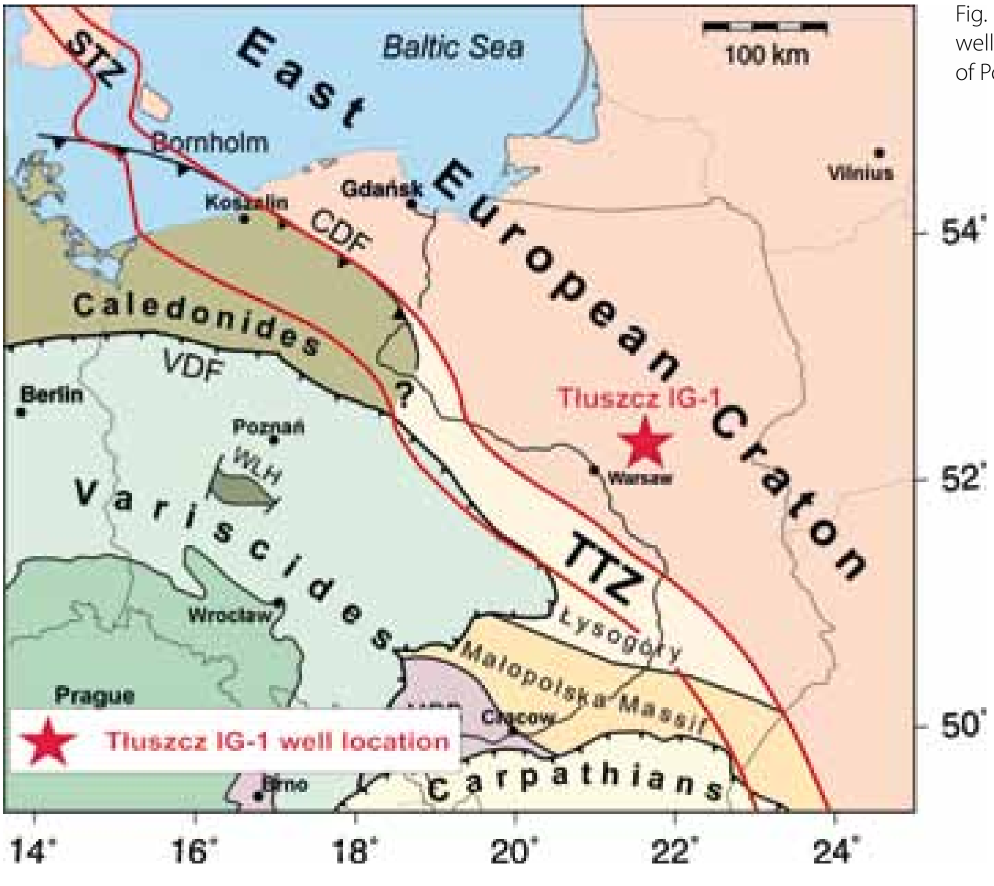

Fig. 1. Location map of Tłuszcz IG-1 well. Main sub-Permian tectonic units of Poland (after: Pożaryski et al., 1992)

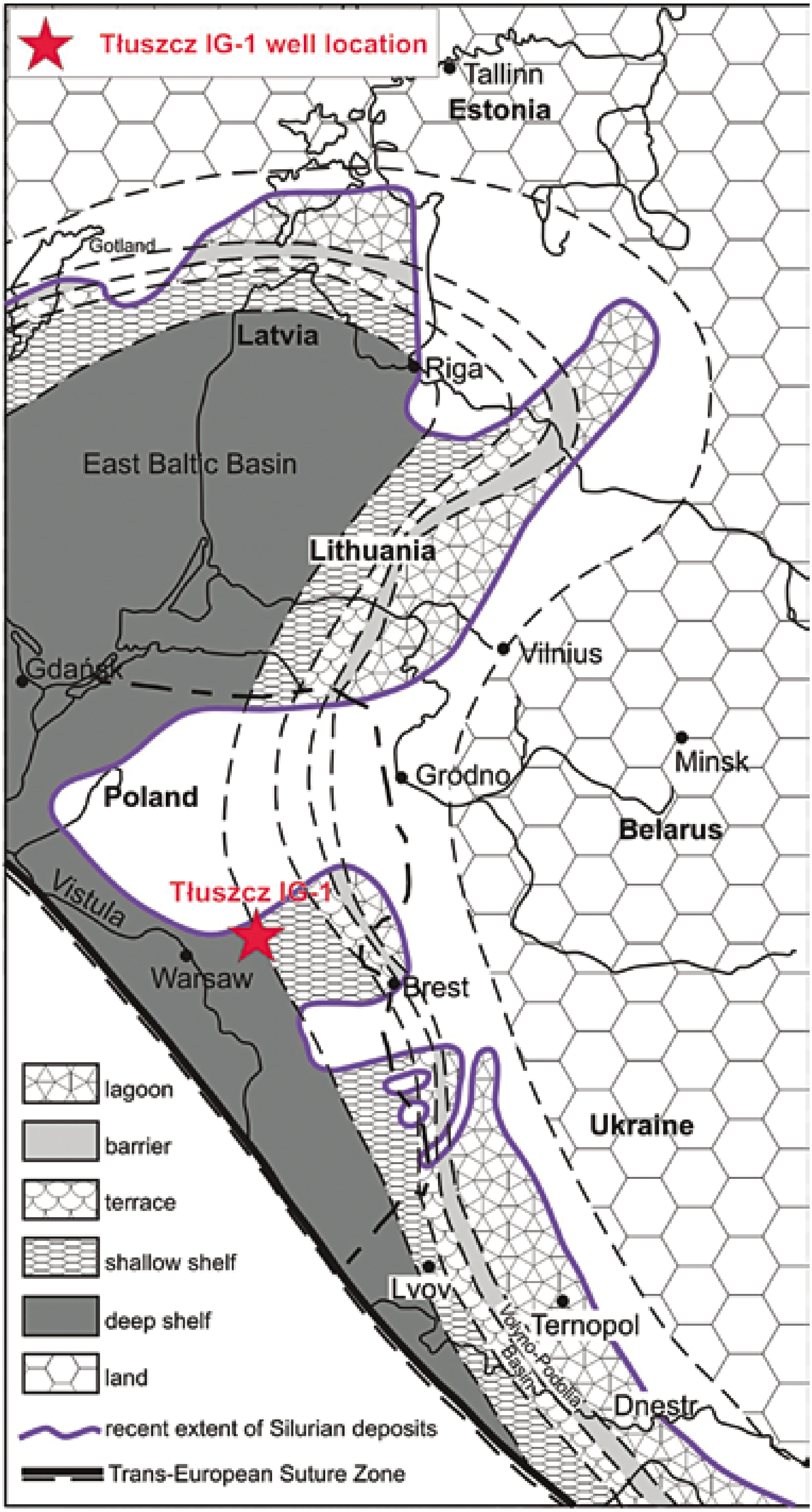

Fig. 2. Distribution of Silurian facies belts on the western margin of the East European Platform (Wenlock times); after Einasto et al. 1986, simplified

Lower Paleozoic organic-matter-rich mudstone was deposited on the western margin of the East European Craton (EEC). As a result of later processes and erosion, the basin was divided into three sub-basins: Baltic Basin in the north, Podlasie Basin in the east central area, and Lublin Basin in the southeastern part of Poland. Tłuszcz IG-1 well is located in the central part of the Podlasie Basin. Each of the sub-basins is characterized by comparable lithofacies development. In the period of time from late Ordovician to late Silurian deposition was driven by flexural bending of west martin of EEC, when Baltica converged with Laurentia to form Laurussia – the Caledonian Orogeny (Poprawa et al., 1999). During this event there was increasing sedimentation rates recorded in the vertical profile. Caledonian collisional zone provides sediment source to foreland basin from west to the east.

Upper Ordovician is characterized by high diversity of lithofacies development in the lateral extent. Caradocian deposits in the north consists mainly of mudstone, whereas in the south and east there are marls and limestones (Modliński, 1982) (Fig. 2). During the late Ordovician to early Silurian there was a significant climate event in the world connected with glaciations on the southern hemisphere – the Gondwana glaciations. As a result, there were changes in sea level (fall), water circulation in oceans, and content of CO_2 in atmosphere. Influence of Gondwana glaciations was certainly important for Baltica as well as for other continents. During Ashgill, the marly-carbonate platform expanded widely to cover the majority of the basin. Based on paleomagnetic data, the continent of Baltica traveled to the north during the Ordovician and Silurian (Cocks and Torsvik, 2004) (Fig. 3). Deposition in the Silurian started with claystone strata in the Podlasie basin. These so-called *hot shales* are characterized by highest TOC of any lithofacies in the basin (up to 17% present-day TOC; Lis et al., 2012). As a result of onlapping towards the east, the lower part of the Silurian deposits is absent in the Lublin Basin. In the Lublin region there is then continuous deposition from Silurian to lower Devonian. Thickness of Silurian deposits increasing significantly towards the western margin (Fig. 4).

Fig. 3. Late Ordovician paleogeography (after Cocks, 2000)

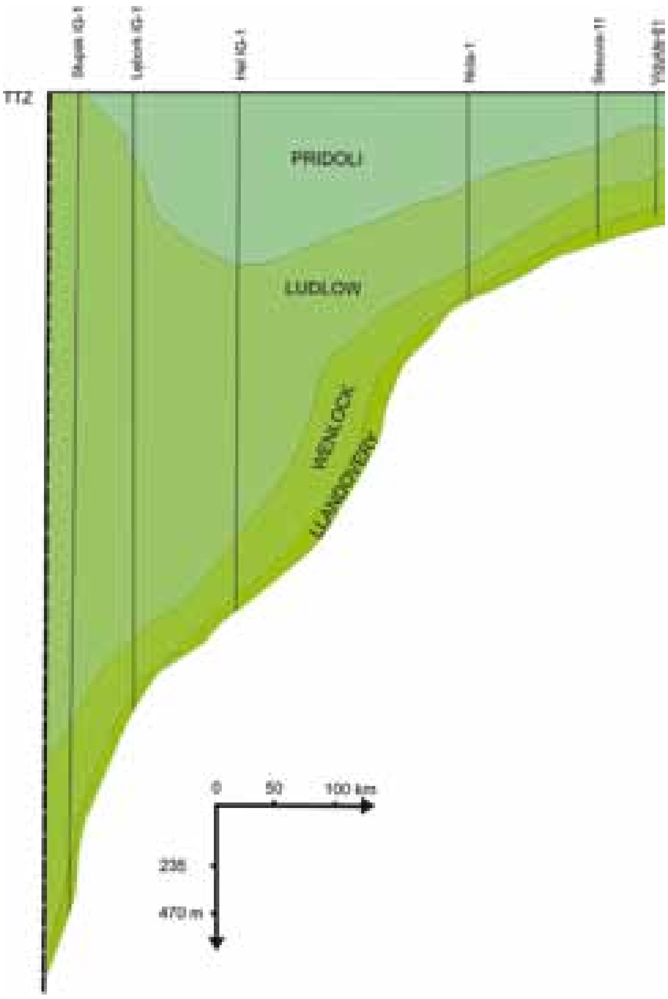

Fig. 4. General stratigraphic cross-section along Słupsk IG-1 – Lębork IG-1 – Hel IG-1 – Nida IG-1 – Sesuvis-11 – Vidukele-61 – Geluva-99 – Ledai-179 – Svedsasai-252 wells (after Lazaurskiene et al., 2003)

Tectonic style of the Baltic and Podlasie Basin is quiet (Fig. 5), whereas Lublin Basin is characterized by complex tectonic style with multiple generations of faults (Fig. 6).

Tłuszcz IG-1 well was targeted for drilling in 1959 as one of the first research project in the Polish Lowlands. An aim of this effort was to characterize the crystalline basement and sedimentary cover. Tłuszcz IG-1 well was drilled to 2953.8 m MD and was fully cored. In practice core recovery ranges from 10 to 100% with average around 70 %.

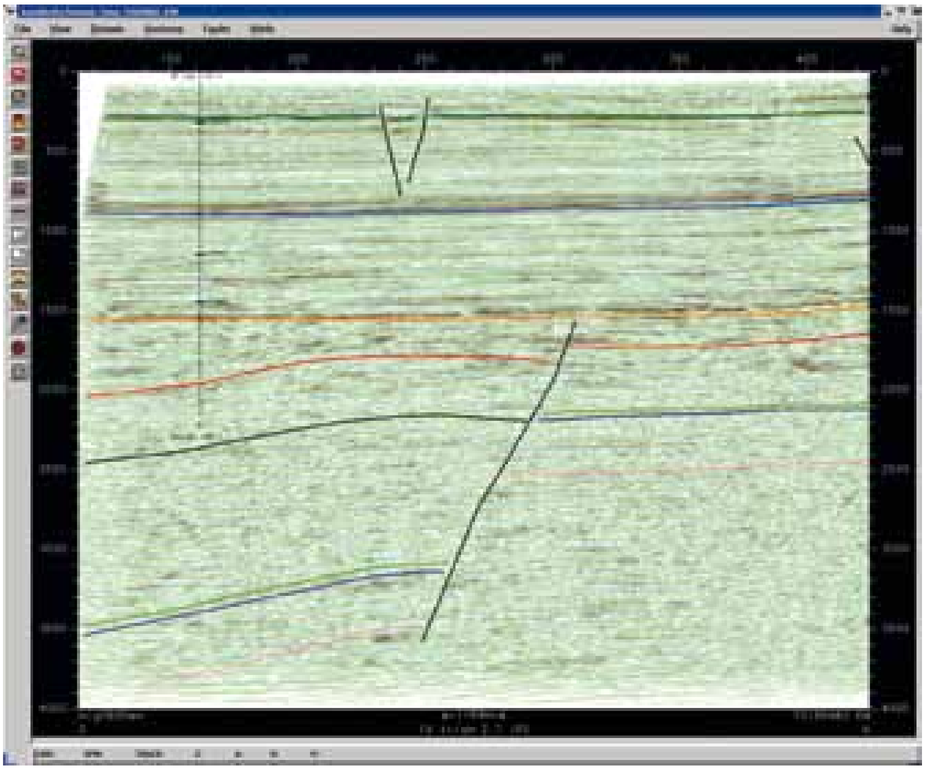

Fig. 5. Example of the seismic line in the Podlasie Basin (image courtesy of G. Wróbel)

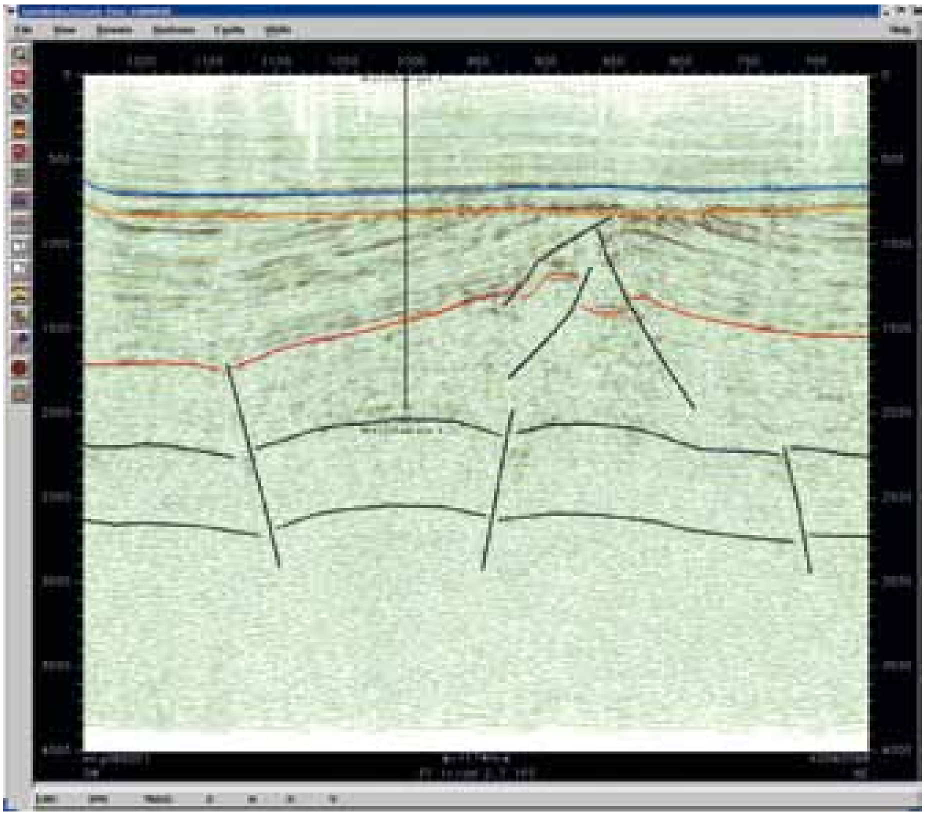

Fig. 6. Example of the seismic line in the Lublin Basin (image courtesy of G. Wróbel)

Tłuszcz IG-1 tops

Formation	Thickness (in m)	Top (in m)	Bottom (in m)
Ludlow	132	1668	1800
Wenlock	129	1800	1929
Llandovery	35	1929	1964
Ashgill	5	1964	1969
Caradoc	11	1969	1980

Mudstone Features

Based on experience from the North America, mud-dominated basins are widely diverse and demand detailed analysis. In terms of shale gas/oil plays, study of each analyzed and interpreted feature is essential and helps to recognize, define, and understand the play. Only integration among all observations can result in sophisticated and realistic basin model. Fine-grained sediments require more careful and patient study because of small scale of depositional features.

1. Grain Size

Although the terms clay, mud, silt and shale are generally recognized, their technical definition and usage have long been difficult and are not fully agreed upon. Clay is a textural term to define the finest grade of clastic sedimentary particles, those less than 4 µm in diameter. Individual particles are not visible to the naked eye and can only just be observed with a high-power optical microscope. Clay minerals are a group of phyllosilicate minerals which commonly consist of clay-sized particles. Silt is the name given to objects consisting of particles between 4 and 62 µm in diameter. The size range is subdivided, like in sand, into coarse, medium, fine, and very fine. In practice we can use this subdivision also for mudstone. The coarser grains of silt are visible to naked eye or with a hand lens. Finer silt is most readily distinguished from clay by touch, as it will feel gritty if a small amount is ground between teeth, whereas clays feels smooth. When clay and silt sized particles are mixed in unidentified proportion as the main constituents in unconsolidated sediment, we call this material *mud*. The common term *mudstone* can be applied to any consolidated sediment made up of silt and/or clay. Regarding on proportion between particles we can call it (Fig. 7):

- Claystone (Fine Mudstone)
- Mudstone (Medium Mudstone)
- Siltstone (Coarse Mudstone)
- Sandy Siltstone
- Sandy Mudstone
- Sandy Claystone
- Muddy Sandstone

(see Lazar et al., 2010, for a further discussion of this topic and practical guidelines for application to core or hand samples)

Fig. 7. Textural triangle illustrating grain-size classification (from Lazar et al, 2010)

The term *shale* is from time to time applied to any mudstone but it is proper to use this expression only for mudstones that show a fissility that is a direct inclination to break in one direction, parallel to the bedding.

During study of fine-grained rocks, grain size is one of the most important and basic observations, which gives us an idea about the place in the basin, distance from the provenance area (proximal, medial, distal).

2. Lamination

From smallest to largest, the component layers of a sedimentary body are laminae, lamina set, beds, and bedsets. Different arrangements of these layers characterize different types of sedimentary bodies and identify different depositional processes. Genetically a lamina is a small bed (a) relatively uniform in composition and texture; (b) is never internally layered (at least megascopically); (c) has a smaller areal extent than the enclosing bed, except in some instances where laminae parallel bedding surface; and (d) forms in a shorter period of time than the encompassing bed. In addition, the thickness of a laminae is usually measured in millimeters; although laminae in some cross-laminated, coarse-grained beds may be as thick as 25 cm (Campbell, 1967).

Lamination is the dominant structure of fine-grained rocks even though much is commonly destroyed by burrowing. Although lamination occurs in many forms, crucial formative requirements for lamination are repetitive variations of terrigenous, chemical or biological supply rates all in exceedance of bioturbation rates. Typically, individual laminae are separated one from another by sharp contacts caused by abrupt changes in grain size, possibly by concentrations of coarse micas, heavy minerals, or fine organic matter, but contacts may also be gradational. Laminae can be continuous or discontinuous – such discontinuous lamination can result from primary sedimentation of thin migrating ripples moving

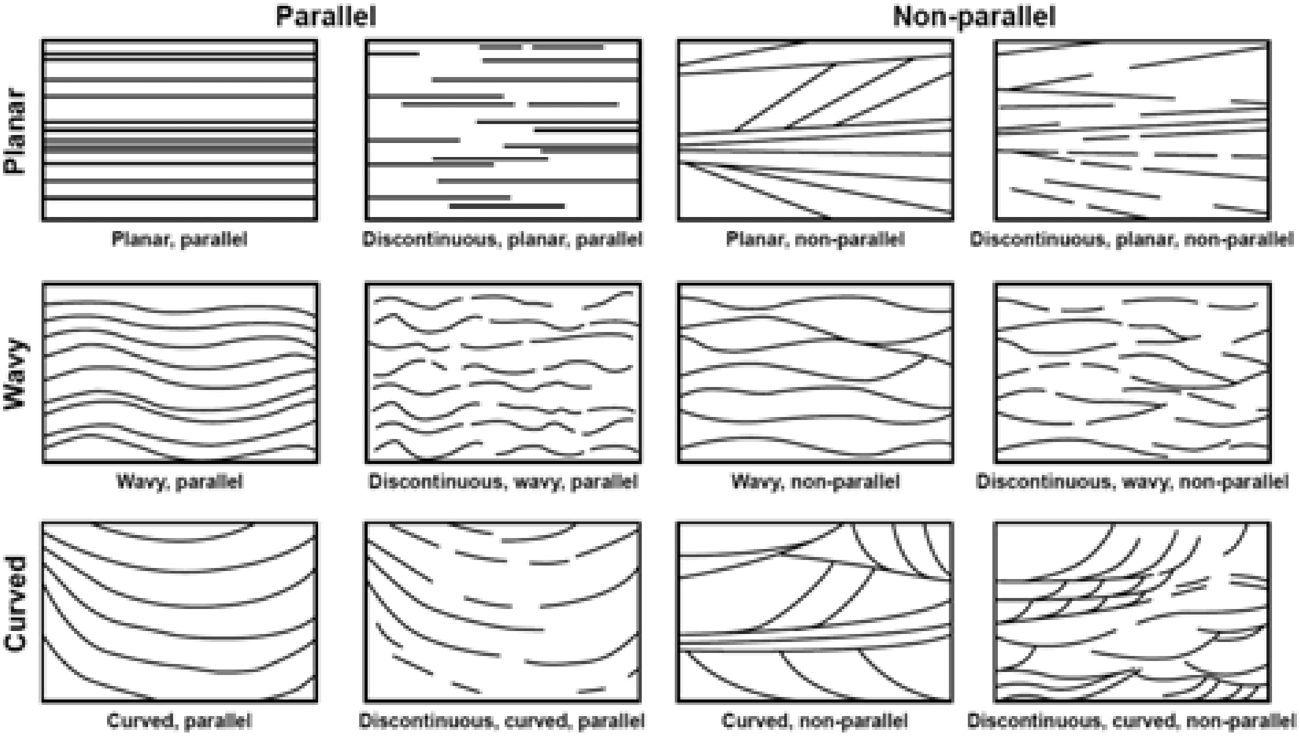

Fig. 8. Descriptive terms for beds, laminae and laminasets (after Campbell, 1967)

along cohesive clayey bottom to form commonly observed flaser bedding (Fig. 8). Wavy, curved, or planar, parallel or non-parallel can reflect energy of the bottom current. Laminae are also present in pure mud, where it is defined by slight grain-size variations reflecting hemipelagic rain of particles of terrigenous, biogenic, or chemical origin. In this situation, laboratory work (X-ray radiography, back-scattered electron images, or computed tomography – CT) are necessary to define lamination. In muds dominated by terrigenous provenance, laminae can result from the tail of turbidity currents that deposited siltstone and sandstone up dip. Biological and chemical laminae commonly represent either seasonal or such exceptional conditions as algal blooms in the upper part of the water column, as important for TOC distribution.

Lamination definition gives us insights for several levels of interpretation:

(a) Energy of environment: As a first end member, continuous-wavy-parallel lamination tends to record low-energy suspension settling, whereas the opposite end member would be discontinuous-curved-non-parallel laminae recording bedform migration.
(b) Level of oxygen just above basin floor (defining by *epifauna*) and oxygen level just below basin floor (defining by *infauna*). When oxygen level is high bioturbation index (BI) is high and lamination poor (non preserved), whereas if oxygen level is low BI is low and original lamination is preserved (at equivalent sediment accumulation rates).
(c) Seasonal or exceptional conditions, like: algal blooms, volcanic eruption, ash storm.

3. Sedimentary Structures

Sedimentary structures in mudstone vary quite widely, however, detailed study and careful observations are required because of the scale. These structures are more readily seen where silt or fine sand laminae are deposited along with mud. When naked eye cannot observe structures, X-ray radiograph, computed tomography (CT), or thin sections of core usually reveals structures hidden to the eye. In general those sedimentary structures which occur in sandstones are present also in fine-grained sediment, but at a different scale. The majority of deposition in the muddy environment is due to tractional current, and not pelagic suspension as used to be interpreted in majority of basins. One of the most important property of mud accumulation is sticking together of relatively small particles to create aggregates-floccules (Schieber et al., 2007). Flocculation is a phenomenon which comprise group of chemical and physical properties, such as settling velocity, particle size, ion exchange behavior, and organic content (Schieber et al., 2007).

The most typical and common sedimentary structures found in the Lower Paleozoic succession in Poland are (Fig. 9):

(a) Current ripples
(b) Wave ripples
(c) Wave-enhanced sediment gravity flow beds (WESGFs)
(d) Graded beds
(e) Water escape structures
(f) Scours
(g) Hummocky cross-stratification
(h) Gutter casts

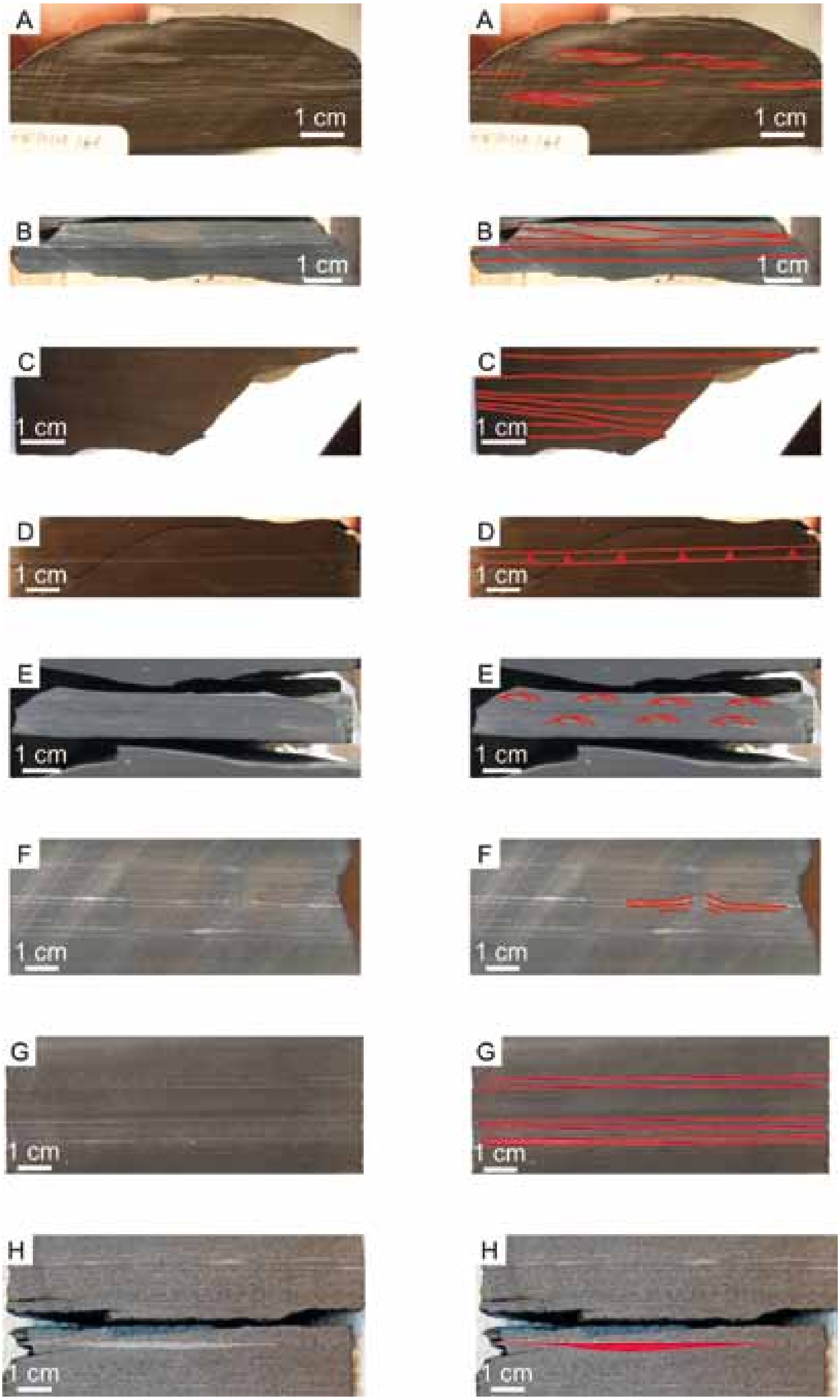

Fig. 9. Sedimentary structures in deposits of the Podlasie-Lublin Basin: a) Current ripples, b) Scour, c) Hummocky cross-stratification, d) Graded bed, e) Wave ripple, f) Water escape structure, g) Wave-enhanced sediment gravity flow beds (WESGFs), h) Gutter cast

4. Diagenetic Features

(a) *Glauconite*

This iron potassium phyllosilicate clay mineral with characteristic green color is considered to be indicative of continental shelf marine depositional environments with slow accumulation rate, and might be related to omission surfaces. Glauconite is deposited in not fully oxygenated water column. Therefore these diagenetic mineral is good indicator of maximum flooding surfaces in relatively proximal areas (Potter et al., 2005) (Fig. 10).

Fig. 10. Glauconite layer in Tłuszcz IG-1 core

(b) *Pyrite*

Is the most common of the sulfide minerals. The formation of pyrite in muds requires three components: organic carbon, iron, and sulfate (in marine sediments is always abundant). Lack of pyrite can indicate that either carbon or iron was a limiting factor. Pyrite is present in mudstone deposits in many types: accumulations (framboids, poly-framboids-effect of early diagenesis), burrow infills, or as a dispersed crystals (Fig. 11).

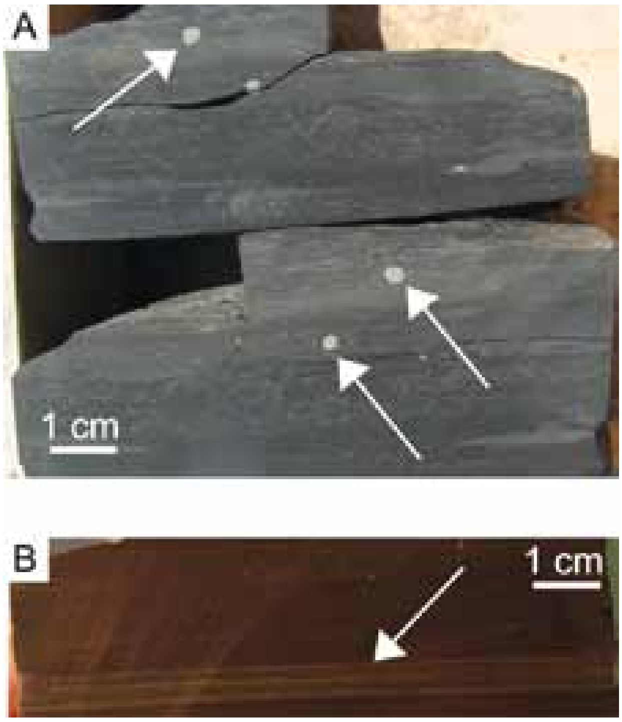

Fig. 11. Pyrite; A – pyrite framboids, B – pyrite laminae

(c) *Early CO_3 cementation*

Early calcite cementation is an effect of early microbially mediated diagenesis and is good indicator of flooding surfaces in rock record. The relative development and size of nodules are indications of the amount of time recorded and the sediment accumulation rate. In Lower Paleozoic succession in Poland nodules ranges from few mm to 50 cm in size (Fig. 12).

Fig. 12. Early carbonate cementation in Tłuszcz IG-1 well; FS – flooding surface

5. Biogenic Structures

The organisms living on or in the sediment leave a record of their activities as *trace fossils (ichnofossils)*. Those organisms are the most important enemy of lamination and sedimentary structure preservation. On the other hand, they record information about substrate conditions and animal behavior. *Trace fossils* are the tracks, trails, or burrows and borings left by organisms as they move around. Bottom dwellers construct well-defined holes by eating sediment, reproduction activity, or as a concealment from predators. In general animals are not preserved, but only their traces. The main important control on the diversity of burrowing is the oxygen level just above and below the sea floor. Trace fossils are both paleontological and sedimentological entities, indicating type of environment in the stratigraphic record. There are also other uses of trace fossils: they can help in defining how animals use space in time, the firmness of the sediment, help identify intervals of slow (horizontal, vertical and inclined borrows) or rapid sedimentation (mostly horizontal borrows), and they are also indicating depth of the basin. Identification of trace fossils in cores is based mostly on their appearance in vertical cross-section. Simple vertical borrows will be under-represented in core description (probability of a core to intersecting a burrow with a long axis parallel to the core is less than the probability of the core cutting across a horizontal burrows). In general, more than one view is necessary to guarantee an accurate trace description.

The most common borrows in Lower Paleozoic section at the western margin of east European Craton are (Fig. 13):

(a) Chondrites

Chondrites is a complex root-like borrow system of regularly branching feeding tunnels of similar diameter which never anastamose, nor cut across one another. *Chondrites* is a typical element of the *Cruziana* ichnofacies. When in the sedimentary record there are only *Chondrites* environment is interpreted as recording low oxygen levels. It represents a complex feeding behavior and is therefore usually associated with fully marine conditions.

(b) Anconichnus

Irregularly meandering, black-cored burrows with a light halo of coarser silt. In cross-section, the burrows are sub-circular, U-shaped in the longitudinal profile. *Anconichnus* represents the grazing of worm-like organisms and is common element of the *Cruziana* and *Skolitos* ichnofacies on a normal marine shallow shelf.

(c) Helminthoida/Helminthopsis

Regular meandering (*Helminthoida*) or non-regular meandering (*Helminthopsis*) burrows which never branch. *Helminthopsis* is a common element of the distal *Cruziana* ichnofacies and proximal *Zoophycos* ichnofacies on a normal marine shallow shelf.

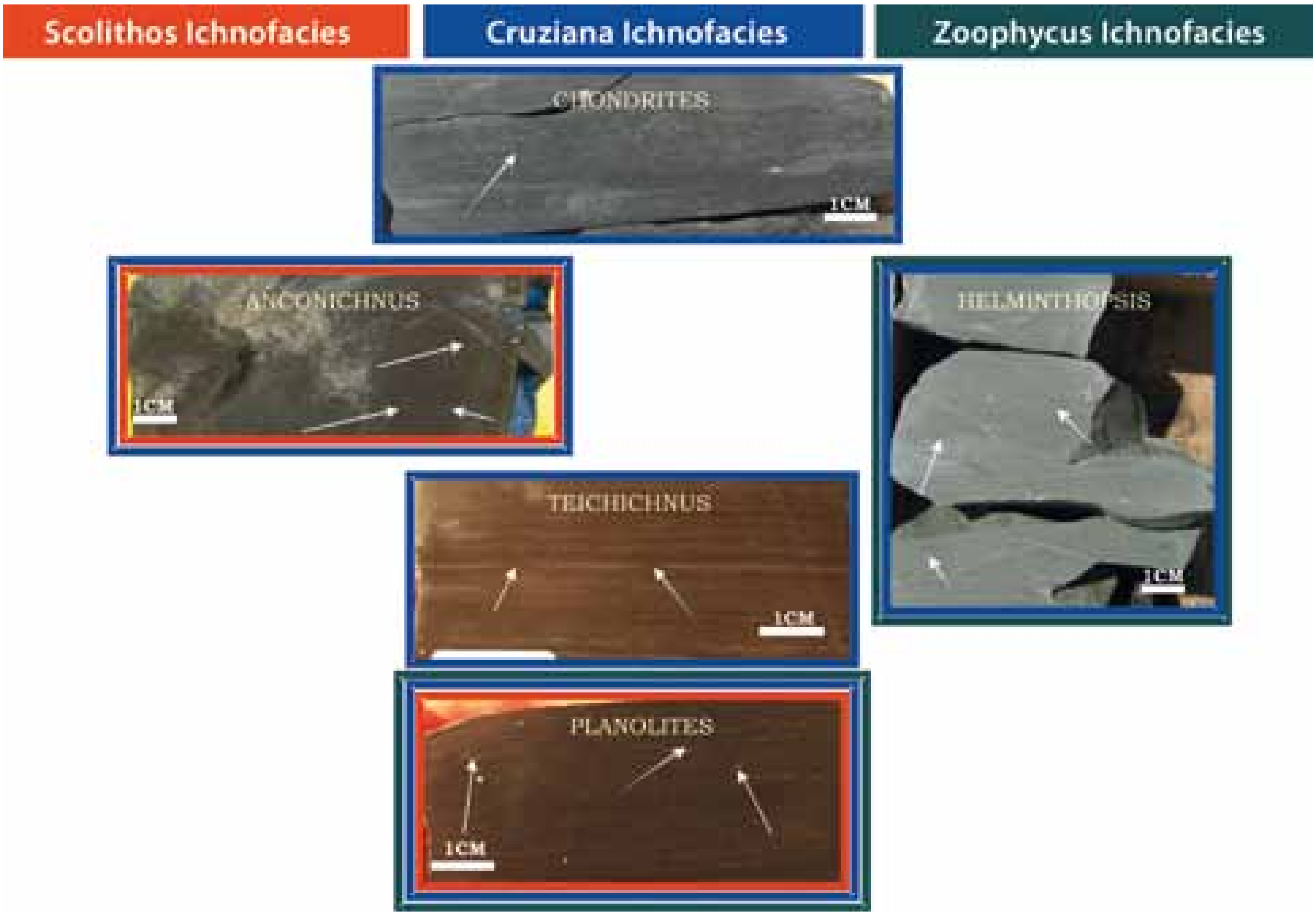

Fig. 13. Typical Lower Paleozoic bioturbations in Podlasie-Lublin Basin

(d) Teichichnus

Appears on vertical surfaces as a vertical series of closely packed concave-up or concave-down, crescentric laminae. *Teichichnus* is generally found in lower shoreface to offshore environments associated with *Cruziana* ichnofacies.

(e) Planolites

The most common burrow found in the Lower Paleozoic section. *Planolites* appears as a unlined, rarely branched, smooth or irregularly walled burrows, and circular in cross-section. This kind of burrow occurs in all environments from freshwater to deep marine.

6. Body Fossils

Shelves are areas of oxygenated water occasionally brushed by different types of currents to bring in nutrients. This particular environment is a place for many organisms which may live swimming in water column (*planktonic*) or on the sea floor (*benthic*). Terrigenous clastic shelf deposits may contain a wide range of organisms, whose diversity depends on the energy and oxygen level.

In core observation not only type or species of organisms is important, but also characteristic of their deposition, abundance, and preservation (taphonomy) in sedimentary record. Good preservation may indicate quiet environment, whereas broken parts would be typical for high energetic processes as gravity flows or mass movement. The majority of the graptolites deposited in these mudstone strata are chaotically oriented, although some settled down in aligned order as an effect of unidirectional currents.

The most common and characteristic body fossils for the Lower Paleozoic succession are:

(a) *Graptolites*

Those colonial animals are common fossils and have worldwide distribution. They are an important index fossil for dating Paleozoic rocks as they evolved rapidly with time and form many different species. They are deposited on the basin floor of relatively distal/deep ocean with poor bottom circulation; this is a reason why they are widely found in mud-dominated environments. One of the most important contributions in graptolites characterization was work done by Roman Kozłowski – Polish geologist dealing with Ordovician and Silurian mudstones in Poland (ex. Kozłowski, 1949) (Fig. 14).

Fig. 14. Graptolites in core: A-broken, B-well-preserved

Fig. 15. Well-preserved brachiopod in Tłuszcz IG-1 well

Fig. 16. Well-preserved cephalopod in Tłuszcz IG-1 well

(b) *Brachiopods*

Most species avoided locations with strong current and waves, they typically occupy steep slope of the continental shelves and the bottoms of deep ocean. Brachiopods fossils are useful indicators of climate changes during the Paleozoic era. Where global temperatures were low as in much of the Ordovician, the large difference in temperatures of the ocean created different assemblages of fossils at different latitudes. On the other hand, warmer periods, such much of the Silurian, created smaller difference in ocean water temperatures, and resulted with widespread colonization by the same few brachiopod species (Fig. 15).

(c) *Cephalopods*

During the Early Paleozoic their range was restricted to sublitoral regions of shallow shelves of the low latitudes. In Ordovician, a more pelagic habit was progressively adopted. (Fig. 16)

Parasequence in Mudstones

The *parasequence* is a stratigraphic unit defined as a relatively conformable succession of genetically related beds or bedsets bounded by flooding surfaces (Van Wagoner, 1995).

Parasequence is a basic element of sequence stratigraphy. To construct a valid sequence-stratigraphic framework, detailed facies analysis is necessary. Careful description and analysis of entities mentioned above enable recognition of distinct lithofacies in the fine-grained rock record. Facies builds into facies associations whose stacking in vertical profile give insight into basin infill characterization.

Boundary of parasequence is flooding surface (Fig. 17). Flooding surfaces in mudstone strata can be subtly expressed, so for identification, the full range of all observations needs to be integrated. In general, flooding surface is a plane which bounds sediments deposited in shallower, generally higher-energy environment (below) from sediments deposited in deeper, generally lower-energy environment (above). For this identification listed below features are helpful:

Grain size

Fine-grained lithofacies representing more distal basin part, are present above flooding surface, and coarser deposits (representing more proximal part of the basin) is present below flooding surface. (In well-defined flooding surfaces sharp boundary is observed).

Lamination type

Continuous and parallel lamination is related to the rocks deposited above flooding surface, whereas discontinuous and wavy lamination is related to deposits below flooding surface. (In well-defined flooding surfaces, an abrupt change in lamination type is observed).

Sedimentary structures

Analysis of sedimentological structures is related to basin depth and environment energy. Not only type of features but also size and frequency observation can be crucial. Strata above a flooding surface generally record lower energy, slower sedimentation rate conditions than the interval just below.

Diagenetic features

Early diagenetic cements and nodules record such essential environmental indicators as: oxygen level (pyrite, glauconite), sedimentation rate and sedimentation breaks (early CO_3 cement).

Biogenic features (Bioturbation Index *BI*)

Directly records oxygen level, basin depth, and sedimentation rate. BI is higher below flooding surface and lower above. (In well-defined flooding surfaces, an abrupt decrease in BI is commonly observed).

Fossils

Type and abundance of animals indicate distance from the shoreline (water depth) and bottom conditions, resulting in typical assemblages that are characteristic of particular circumstances. Not only type of fossil but also their preservation and arrangement (taphonomy) are important.

Fig. 17. Part of drillcore displaying flooding surface and interval with early carbonate cementation. Most parasequences are thicker than this one, used for illustration

Color

Color is mostly connected with grain size, and subsequently is characterizing distance from the shoreline, water depth, or the influx of sediment from the Caledonian Orogen as it occurs in the Lower Paleozoic Basin at the western margin of EEC. Dark color is associated with fine-grained sediments (typically rich in very fine grained dispersed pyrite), whereas light color is associated with coarser sediments.

All listed features are cross-correlated, commonly occurring together, but sometimes only one may be present for parasequence definition. There are groups of features which are strongly associated and cross correlation between them is marked, as for example grain size and lamination type, or biogenic features and color.

Parasequences group into parasequence set defined by their stacking pattern: progradational, retrogradational, or aggradational. Based on initial examination of the Lower Paleozoic mudstones, parasequence sets can be correlated between wells across distances from a few to tens of kilometers (depending on interval).

When the deepest water facies are defined a widespread marine flooding surface - maximum flooding surface (*MFS*) is present. It usually displays evidence of slow deposition or condensation, such as hardgrounds, abundant burrowing, fossil accumulation and mineralization. Maximum flooding surfaces are related to the elevated TOC values.

Geologists dealing with fine-grained deposits have to keep in mind that muddy sediment can be eroded and transported laterally without showing obvious signs (Macquaker & Bohacs, 2007). Depending on particular place in the basin, energy of the environment, paleotopography, currents directions, bottom cohesiveness and gravity flows intensity of erosion may vary significantly. Fine-grained succession in the sedimentary record are much less complete than were previously interpreted.

Summary

The Lower Paleozoic Basin at the western margin of East European Craton in Poland is dominated by fine-grained sediments.

For mudstone analysis, detailed core observation is necessary

High diversity of lithofacies is observed

Parasequences and parasequences sets can be defined based on integration of physical, biogenic, and chemical attributes, lamina geometry, and stratal stacking.

Based on North America experience with shale gas/oil basins Polish Basin is only at the very beginning stage of study. They do share some similarities with other Paleozoic shale gas plays, but appear to have some significant differences as well.

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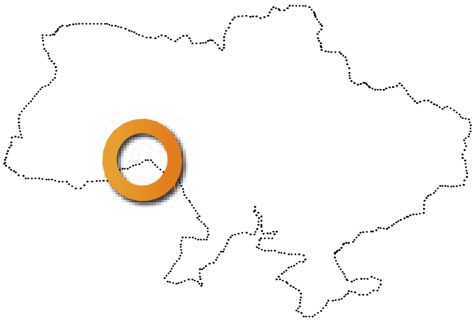
GeoShale 2012

field trip guidebook
Podolia

Field trip

SILURIAN SUCCESSION WITHIN THE LOWER PALEOZOIC BASIN OF PODOLIA



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Preface

The Ukrainian field trip is one of the trips focused on Lower Paleozoic sediments. The aim of the trips is to examine the basin along a cross section from the carbonate platform/ramp (Ukraine Field Trip) through mudstones interpreted as of relatively deep basin origin (Core Warehouse Workshop) to mudstones and sandstones of the Holy Cross Mountains.

In the deep basin (Polish location) there was deposition of hundreds of meters of mudstones derived from the Caledonian Front; there was no deposition on the side of the carbonate platform or very limited deposition of limestones (Ukrainian location). Isochronous intervals of Lower Paleozoic sediments are very thick in Poland and thin in Ukraine. Layers onlap between the Podlasie/Lublin Basin and Kamyanets Podilsky region and laterally change from claystone through mudstone and marls to limestones. Throughout Ordovician and Silurian times the shoreline went back and forth, causing migration of a marginal carbonate platform. In Caradocian and Ashgillian times the carbonate platform reached the Polish part of the basin (ex. Stadniki IG-1 well, Tłuszcz IG-1 well). Those changes are recorded in the sedimentation and by our ability to observe them in cores as well as at outcrop.

Introduction

The field trip offers a good opportunity to examine carbonate deposits of Lower Paleozoic shallow marine settings that can be defined as the platform side of the eastern margins of the basin. Participants will have a chance to observe carbonates in the deeply eroded Dniester River Valley, organized in third order cyclothems: elementary, mesocyclothems and macrocyclothems. The stratigraphic sequence comprises upper Vendian, Cambrian, Ordovician and Silurian. Towards the west, it is possible to observe an uninterrupted transition of the Silurian carbonate deposits to marly and shaly facies of the lowermost Devonian (Lochkovian) in the villages of Dnistrove and Mikhalkiv (Ustya). Farther to the west many sections provide a complete record of an upward transition from open-marine through marginal marine sediments to fluvial, siliciclastic mainly redbeds of Old Red Sandstone age at the Zalishchyky outcrop.

Geomorphological and geological background

Podolia (Ukrainian: Поділля, *Podillia*, Polish: *Podole*, English: *Podolia*) is a historical region in Eastern Europe, located in the south-western portions of Ukraine, south of Volhynia and extending between the rivers Dniester and Southern Buh.The name Podolia appeared in the 14th century and is derived from Old Slavic – ***po***, meaning "by or along or next to", and – ***dol,*** meaning "valley" or "lowland"; similar to Pomerania (***po****-****mare*** – by or along the sea).

The Podolian uplands are characterized by gently hilly plains dissected by deeply cut valleys and canyons.

Geologically the Podolian region represents the middle portion of the sedimentary Dniester Basin situated at the southwestern margin of the crystalline basement of the Ukrainian Shield (Fig. 1). The sedimentary cover is composed of differently preserved deposits from the Precambrian (Vendian), Palaeozoic (Cambrian, Ordovician, Silurian, Devonian), Mesozoic (Jurassic, Cretaceous) up to the Cenozoic (Neogene and Quaternary). An especially well exposed and essentially undeformed, continuous sedimentary sequence of Silurian and Devonian carbonates and shales has been intensively investigated since the XIX century (summarized in Kozłowski, 1929; Nikiforova and Predtechensky, 1968; Nikiforova et al., 1972; Nikiforova, 1977; Tsegelnjuk et al., 1983; Drygant, 1984, 2000; Abushik et al., 1985; Koren' et al., 1989). Upper Silurian and Lower Devonian fossiliferous sedimentary rocks cropping out at many localities in the Dniester canyon and its tributaries provide a complete record of the oceanographical, environmental, biotic and geochemical conditions in the early Palaeozoic ocean, and over the last decade have attracted many geologists for intensive palaeontological, sedimentological and biogeochemical studies in connection with global bio-events (Huff et al., 2000; Uchman et al., 2004; Kaljo et al., 2007; Małkowski and Racki, 2009; Małkowski et al., 2009; Łuczyński et al., 2009; Skompski et al., 2008; Skompski, 2010; Drygant, 2010; Baliński, 2010, 2012; Voichyshyn, 2011).

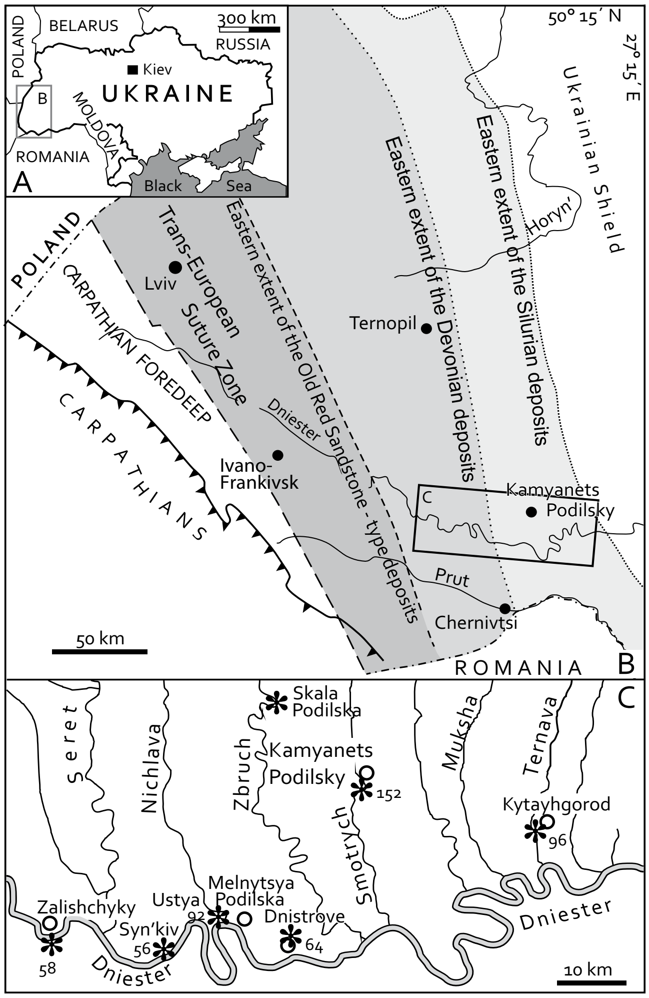


Fig. 1. Location map of SW Ukraine (A) and geological setting and distribution of the Silurian and Devonian deposits in Podolia (B). (C) outcrops (asterisks) in the vicinity of Dniester valley and its tributaries referred in the text (After Małkowski et al., 2009, modified). Outcrop numbers after Nikiforova et al. (1972)

Lithology and stratigraphy of the Silurian and Early Devonian of Podolia

The Silurian and Lower Devonian sequences form one continuous transgressive-regressive sedimentary complex on the southwestern margin of the East European Platform in the proximity of the mobile Teisseyre-Tornquist Zone (Fig. 1 and 3). The lowermost Silurian (Kytayhorod Formation) is separated from the Ordovician (Molodovo Formation, Suboch Member) by regional stratigraphical gaps. The Middle and Upper Silurian deposits, about 370 m to 430 m thick, are divided into four lithological and stratigraphical units (Fig. 2): the Kytayhorod, Bahovytsya, Malynivtsi and Skala formations/horizons, whilst the Devonian deposits clearly form two units: the open-marine, fossiliferous, calcareous-argillaceous Tyver Series, up to 530 m thick, and the near-shore, terrigenous, redbeds of the Dniester Series, up to 1200 m thick and with agnathan fish remains (Nikiforova et al. ,1972; Voichyshyn, 2011).

Kytayhorod Formation

The Silurian Kytayhorod Formation is subdivided into four units: the Restiv, Demshyn, Marianivka and Cherche members. The formation begin with the 5 - 10 m thick Restiv Member, comprising dark, greenish-gray marls intercalated with thin-bedded biodetrital limestones, which according to Tsegelnjuk et al. (1983) contain diagnostic conodonts and graptolites: *Monoclimacis crenulata*, *M. gracilis*, *Monograptus pridon*, *Cyrtograptus murchisoni*, *C. bohemicus*. The fossil assemblage indicates upper Llandovery and lowermost Wenlock (early Sheinwoodian) ages for the Restiv Member.

The Demshyn Member of nodular limestones intercalated with marls about 13 m thick contains fossils diagnostic of a lower Wenlock (Sheinwoodian) age and points to a continuation of the transgressive depositional phase. The fossil assemblage comprises brachiopods, trilobites, chitinozoans, tabulate *Favosites gotlandicus* and rugose corals *Syringaxon siluriensis* (Tsegelnjuk et al., 1983).

The Marianivka Member of monotonous nodular limestones, 24-26 m thick, contains abundant and diverse fossil assemblage of characteristic rugoses, solid halysitids and tabulates.

The Kytayhorod Formation is succeeded upwards by the Bahovytsya, Malynivtsi and Skala formations.

Bahovytsya Formation

The Bahovytsya Formation is aproximately 50 m thick and comprises only one unit, the Bahovytsya Member of monotonous nodular limestones; it represents the middle part of the Podolian Silurian (partly upper Homerian and Gorstian).

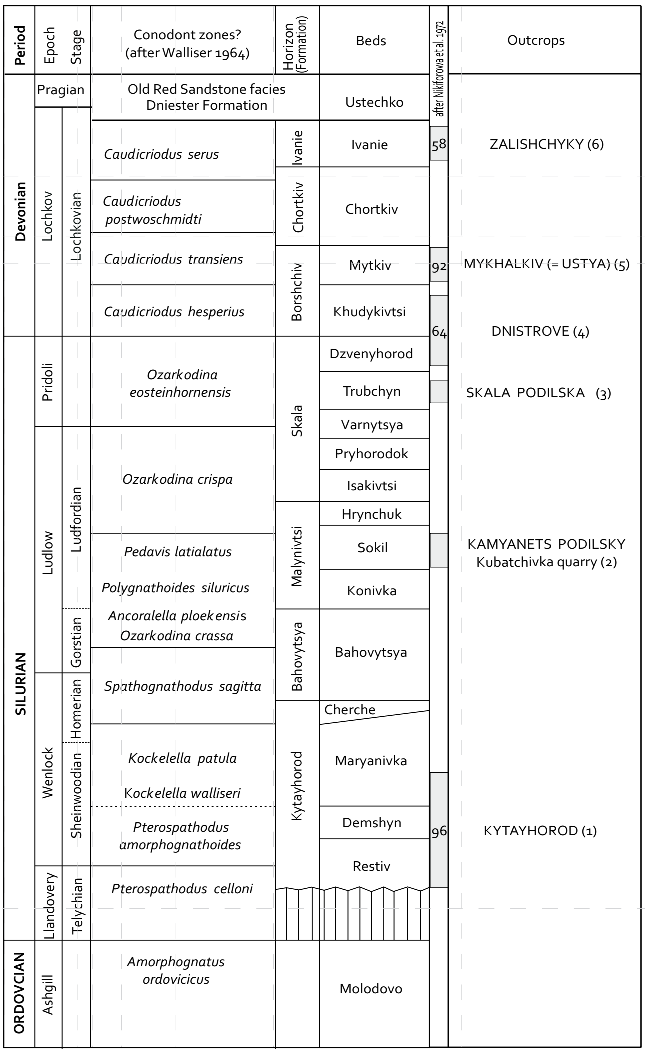
Malynivtsy Formation

The successively conformable Malynivtsy Formation is over 100 m thick and represents the middle part of the Ludlow series. The Formation is subdivided into three units, each of which represent a small-scale transgressive-regressive cycle: Konivka, Sokil and Hrynchuk Member (Nikiforova et al., 1972; Drygant ,1984, 2000).

The Konivka Member is composed of nodular, organodetritic limestones and marls about 25 m thick, partly dolomitised and with thin metabentonite on top. The limestones contain an abundant and diverse fossil fauna of rugose corals, stromatoporoids, tabulates, heliolitids and brachiopods (Tsegelnjuk et al., 1983; Skompski et al., 2008).

The Sokil Member is about 55 m thick, and comprises monotonous nodular limestones and marls with a number of thin metabentonite layers (Tsegelnjuk et al., 1983; Huff et al., 2000). The unit contains abundant tabulate and rugose corals, stromatoporoids, brachiopods and trilobites (Tsegelnjuk et al., 1983; Skompski et al., 2008; Łuczyński et al., 2009).

The Hrynchuk Member in the upper part of the Malynivtsi Formation is an about 20 m thick set of partly dolomitised nodular limestones and marls intercalated with organodetritic, crinoidal limestones and three thin metabentonite layers (Huff et al., 2000). The unit contains a fossil assemblage similar to the previous underlying deposits of the Sokil Member (Tsegelnjuk et al., 1983).



Period	Epoch	Stage	Conodont zones? (after Walliser 1964)	Horizon (Formation)	Beds	after Nikiforowa et al. 1972	Outcrops
Devonian	Pragian		Old Red Sandstone facies Dniester Formation		Ustechko		
	Lochkov	Lochkovian	*Caudicriodus serus*	Ivanie	Ivanie	58	ZALISHCHYKY (6)
			Caudicriodus postwoschmidti	Chortkiv	Chortkiv		
			Caudicriodus transiens	Borshchiv	Mytkiv	92	MYKHALKIV (= USTYA) (5)
			Caudicriodus hesperius		Khudykivtsi	64	DNISTROVE (4)
SILURIAN	Pridoli		*Ozarkodina eosteinhornensis*	Skala	Dzvenyhorod		
					Trubchyn		SKALA PODILSKA (3)
					Varnytsya		
	Ludlow	Ludfordian	*Ozarkodina crispa*		Pryhorodok		
					Isakivtsi		
			Pedavis latialatus	Malynivtsi	Hrynchuk		
					Sokil		KAMYANETS PODILSKY Kubatchivka quarry (2)
			Polygnathoides siluricus		Konivka		
		Gorstian	*Ancoralella ploekensis* *Ozarkodina crassa*	Bahovytsya	Bahovytsya		
	Wenlock	Homerian	*Spathognathodus sagitta*	Kytayhorod	Cherche		
		Sheinwoodian	*Kockelella patula* *Kockelella walliseri*		Maryanivka		
			Pterospathodus amorphognathoides		Demshyn	96	KYTAYHOROD (1)
					Restiv		
	Llandovery	Telychian	*Pterospathodus celloni*				
ORDOVCIAN	Ashgill		*Amorphognatus ordovicicus*		Molodovo		

Fig. 2. Stratigraphic scheme of the Silurian and Lower Devonian deposits of Podolia (compilation after Nikiforova et al. ,1972; Tsegelnjuk et al., 1983; Abushik et al., 1985; Koren' et al.,1989; Drygant, 2010)

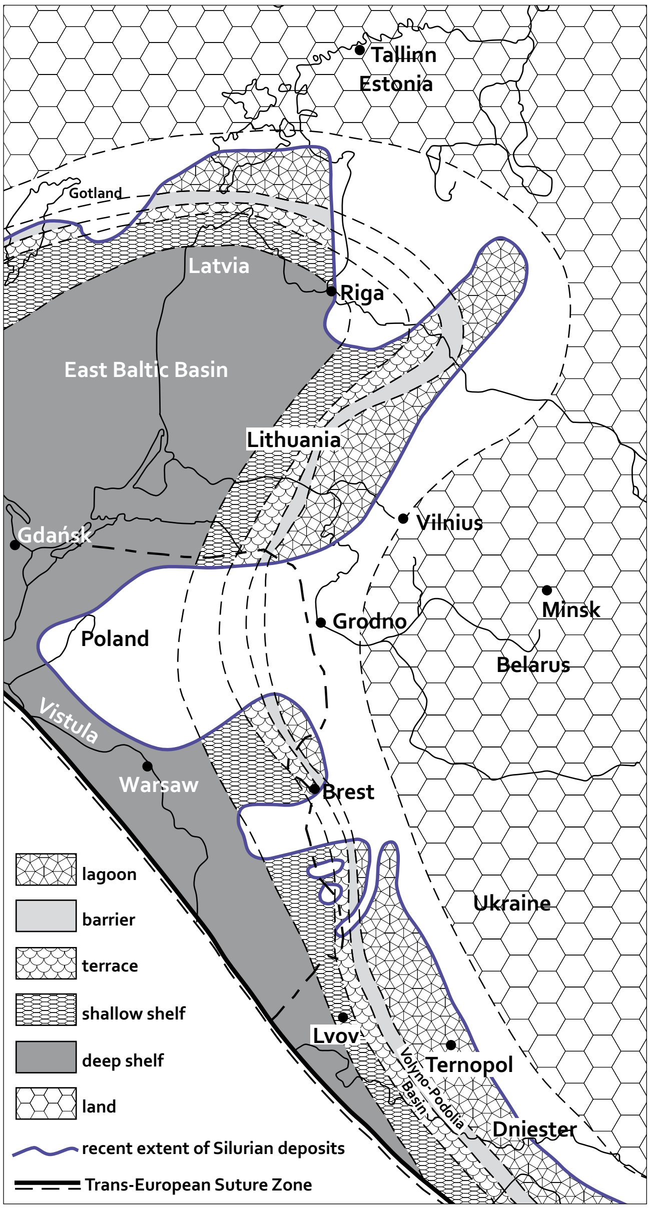


Fig. 3. Distribution of Silurian facies belts on the western margin of the East European Platform (Wenlock times); after Einasto et al., 1986, simplified

Skala Formation

The Skala Formation sequence is up to 190 m thick and has vertically different lithologies, which reflect cyclical facies development (Kozłowski, 1929; Nikiforova et al., 1972; Tsegelnjuk et al., 1983; Abushik et al., 1985; Skompski et al., 2008; Łuczyński et al., 2009). It is subdivided into five units: the Isakivtsi, Pryhorodok, Varnytsya, Trubchyn and Dzvenyhorod Members.

The Isakivtsi Member is represented by 12 m thick grey, fine-grained dolomites intercalated with limestones and dolomitic marls, and two metabentonite layers (Huff et al., 2000). The limestones contain, especially in the basal part of the unit, a scarce fauna such as brachiopods, trilobites and numerous ostracods. A characteristic feature of the unit is the presence of abundant dasycladacean algae (Nikiforova and Predtechensky, 1968).

The Pryhorodok Member is about 25 m thick and comprises laminated dolomitic marls, claystones and dolomites containing numerous surfaces with the polygonal pattern of desiccation processes. These are sedimentary features characteristic of lagoonal deposits (Skompski et al., 2008).

The Varnytsya Member is an about 60 m thick unit of dolomites, dolomitic marls and detritic and nodular limestones. The unit containan up to 35 cm thick metabentonite layer (Tsegelnjuk et al., 1983; Huff et al., 2000) and abundant and diverse assemblage of massive colonial tabulate and rugose corals (Skompski et al., 2008). Drygant (1971, 1984) found in the lower part of this member a conodont *Ozarkodina crispa* which allows to locate the Ludlow-Pridoli boundary about 20 m above the base of the Varnytsya Member.

The Trubchyn Member conformably overlies the Varnytsya Member and is an about 40 m thick unit of massive black limestones, which are in some places dolomitised, containing numerous bioherms and biostromes composed of tabulate and rugose corals, heliolitids, stromatoporoids, stromatolite and other calcified cyanobacteria (see Nikiforova et al., 1972; Koren et al., 1989; Skompski et al., 2008; Łuczyński et al., 2009). The unit yields also a very rich and diverse assemblage of brachiopods and trilobites (Tsegelnjuk et al., 1983).

The Dzvenyhorod Member is about 30 m thick and is represented by intercalations of marls, flaggy and nodular limestones with bioherms up to 2 m thick in the lower part of the unit and one thin metabentonite layer in the upper part. A rich and diverse fauna has been found in this member. The conodonts *Ozarkodina eosteinhornensis* and *Ligonodina elegans*, and trilobites *Acaste dayiana* and *Acastella spinosa podolica*, and chitinozoans *Eisenackitina barrandei*, *Linochitina klonkensis* and *Urnochitina urna* indicate a Pridolian age for the Dzvenyhorod Member (Tsegelnjuk et al., 1983; Drygant, 1984, 2010; Abushik et al., 1985; Wrona, 2008; Drygant and Szaniawski, 2012). The Silurian-Devonian boundary was established on the basis of the FAD (First Appearance Datum) of the graptolite index species *M. uniformis angustidens*and the chitinozoan index species *Eisenackitina bohemica*, and *Margachitina catenaria*, within the greenish-gray argillaceous shales and marls containing dark-gray limestone nodules typical of the Khudykivtsy beds, and the boundary line is placed 3.2 m above the top of the black flaggy nodular limestone interval, typical of the Dzvenyhorod lithology (see also Nikiforova et al., 1972; Nikiforova, 1977; Małkowski et al., 2009).

The Early Devonian deposits

Within the Lower Devonian succession in Podolia, two successive, broad lithostratigraphical divisions have been recognized (see Nikiforova et al., 1972):

1. An argillaceous-calcareous sequence representing an open-marine facies with abundant brachiopod, ostracod and tentaculitid faunas (see Abushik ,1971; Alth, 1874; Szajnocha, 1889; Kozłowski, 1929). The fossiliferous deposits, presently named the Tyver Series (Nikiforova and Obut, 1960; Nikiforova et al., 1972; Drygant, 2010), are an uninterrupted continuation of the Silurian marine deposition.
2. An Old Red-type siliciclastic succession, termed the Dniester Series (Gurevich et al., 1963; see Fig. 2), with fossil remains limited to numerous agnathan fish vertebrae occurring in many layers (Hamerska, 1923; Zych, 1927; Văscăuţanu, 1931; Dikenshtein, 1957; Narbutas, 1984; Drygant, 2010; Voichyshyn, 2011).

The Tyver Series, up to 530 m thick, is subdivided into three well-known horizons: Borshchiv, Chortkiv and Ivanie (Fig. 2). This fossil-rich, open-marine Lochkovian suite (see for details Alth, 1874; Kozłowski, 1929; Nikifirova and Predtechensky, 1968; Nikiforova et al., 1972; Shulha, 1974; Tsegelnjuk, 1994; Drygant, 1984, 2000, 2010), is replaced laterally by dolomitic and siliciclastic Old Red strata to the northwest (Ikva Formation).

The lower Lochkovian Borshchiv Horizon includes the Khudykivtsi and Mytkiv Members (180 m thick in total). The basal Devonian Khudykivtsi Member comprises variably interbedded dark-grey argillaceous shales, marls and marly to micritic limestones, intercalated with rare bioclastic limestones (mostly encrinites). The overlying Mytkiv Member is a thick succession of dark-grey argillaceous shales with rare and thin intercalations and lenticles of grey marly or biodetrital limestones. The well preserved marine fossils are very diverse and comprise corals, bivalves, brachiopods, nautiloids, crinoids and trilobites. Brachiopod coquinas are common (Małkowski et al., 2009; Drygant, 2010). The Khudykivtsi Member contains important graptolites (*Monograptus uniformis angustidens, M. n. uniformis)*, trilobites (*Warburgella rugosa*, *Acastella heberti elsana*, *A. tiro*), brachiopods (*Resserella elegantuloides*, *Clorinda pseudolinguifera*, *Glossoleptaena emerginata*, *Cyrtina praecedens)* and conodonts (*Ziglerodina remscheidensis*, *Caudicriodus cristaglli*) which represent the *Caudicriodus hesperius* Conodont Zone (Drygant, 2010). The Mitkiv Member fossil assemblage comprises brachiopods: *Lanceomyonia borealiformis*, *Plrctodonta maria*, *Cyrtina praecedens*; trilobites: *Warburgella rugosa*, *Homalonotus roemeri*; ostracods *Opistoplax gyratus*, *Phlyctiscapha podolica*; conodonts *Zieglerodina remscheidensis*, *Caudicriodus transiens*, *Caud. hadnagyi* (Drygant, 2010).

The Chortkiv Member, more than 200 m thick, is represented by alternating dark-grey argillaceous shales and thin (up to 20 cm) fine-grained limestones. In the upper, more carbonate-rich part, brownish and red-colored claystones, up to 3 m thick, appear for the first time in the Podolian succession. Brachiopods *Mutationella podolica*, *Howelella zaleszczykiensis*, bivalves, ostracodes *Cornikloedenia inornata*, *C. binata*, *Evlanella rubeli* and tentaculites are abundant and often occur in coquinas. The conodonts *Caudicriodus postwoschmidti* and *Ziglerodina mashkovae* indicate a Lochkovian age for the Chortkiv Member (Drygant, 2010). In addition to abundant marine fossils, numerous agnathan remains occur: *Thelodus oervigi*, *Podolaspis lerichei* (Nikiforova et al., 1972; Voichyshyn, 2011; Voichyshyn and Szaniawski, 2012).

Higher in the sequence, the Ivanie Member, approximately126 m thick, comprises dark, variably silty shales, with intercalations of thin, nodular, biodetrital limestones. The upper part of the interval is dominated by siltstone beds containing scarce fossil assemblages that include agnathans, ostracods *Leperditia tyraica* and podocopids *Cytherellina submagna* (Olempska et al., 2011); brachiopods *Multaionella podolica*, conodonts *Ziglerodina serrula*, *Caudicriodus serrus* and gigantostracans (Nikiforova et al., 1972; Drygant, 2010; Olempska et al., 2011). The passage into the overlying Old Red–type facies is typified by the appearance of thick-bedded red sandstones and sandy shales, representing inshore lagoon to fluvial-estuarine regimes (see Narbutas, 1984; Uchman et al., 2004). This non-fossiliferous red succession of interbedded mudstones and siltstones, with a variable admixture of quartz arenites (Dniester Series), up to 1800 m thick in the Trans-European Suture Zone, is widely distributed in the region due to progressive basinal shallowing (Zych, 1927; Dikenshtein, 1957; Narbutas, 1984; Uchman et al., 2004).

Palaeogeography of Podolia in the Silurian and Early Devonian

The Podolian Dniester Basin was located during the Silurian and Early Devonian close to the equator in the tropic zone (Tait et al., 2000; Baarli et al., 2003, Nawrocki and Poprawa, 2006). The sedimentation rate and facies extension of the Silurian and Lower Devonian of the Podolian Dniester Basin were strongly controlled by its location in the marginal belt of the East European Platform, near to the mobile Trans-European Suture Zone – the TESZ or Teisseyre-Törnquist Fault Zone (Drygant, 2000; Skompski et al., 2008; Małkowski et al., 2009).

Route: Lvov–Tarnopil–Terebovla–Skala Podilska–Kamyanets Podilsky–Kytayhorod–Kamyanets Podilsky

Stop 1. Outcrop: Kytayhorod section

(Figs 4–6)

Target: It is possible to observe exposed Upper Vendian, Lower Cambrian, Upper Ordovician (Molodovo Formation, Suboch Member), Middle Silurian (Telyachian and Sheinwoodian) sediments of the Kytayhorod Formation, and the Cretaceous.

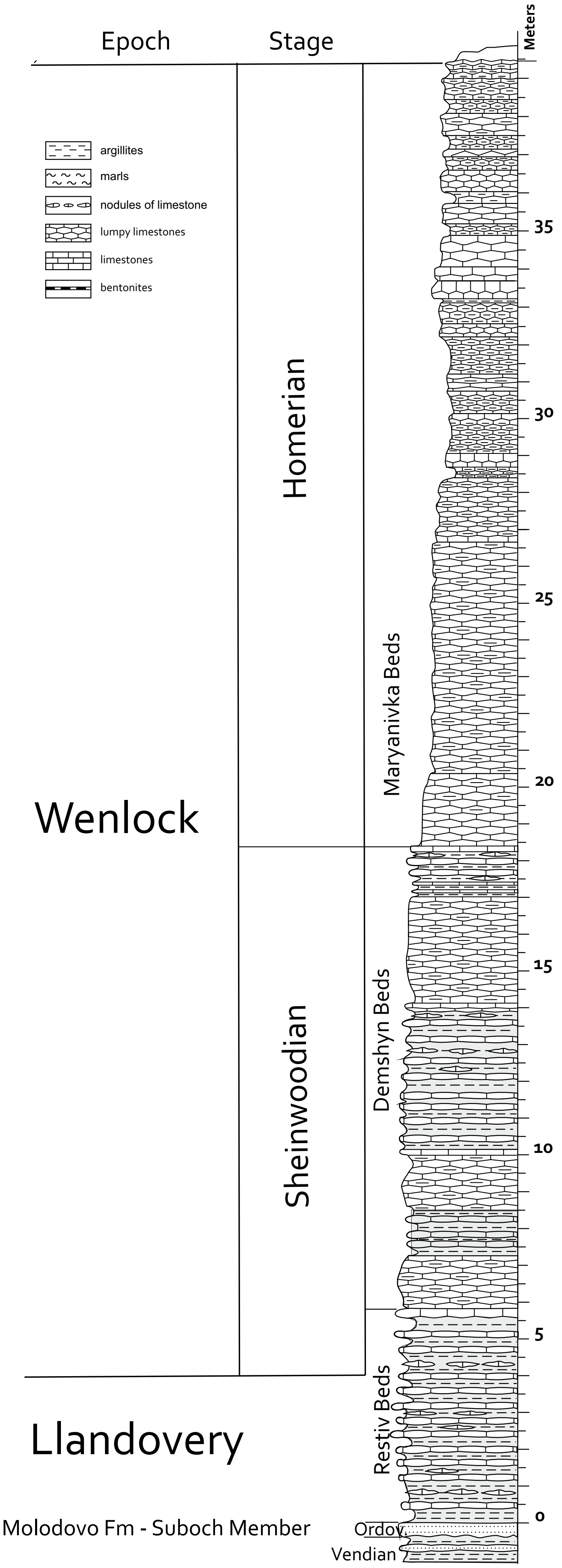
Description: The oldest sedimentary rocks in Podolia, the Vendian greenish-grey and dark-grey sandy argillaceous strata, about 7 m thick, are exposed at the Ternava stream level on the left side of a deep valley. They are overlain by glauconite sandstone assigned to the Baltic series of the Lower Cambrian. Recently Cambrian sandstones are usually covered by the dammed up Ternava and Dniester rivers, but sometimes exposed rocks are accessible in the middle of summer when the water level is low.

The Upper Ordovician sandy limestones, 0.4 m thick, assigned to the Suboch Member of the Molodovo Formation, overlie an eroded surface of Vendian or Cambrian rocks. Erosional blocks can be available in a deep gully running down directly below the church in the village of Kytayhorod. They contain conodonts: *Amorphognatus* sp., *Drepanodus homocurvatus* Lind. *Panderodus* sp., brachiopods *Pseudolingula quadrata* (Eichw.), *Platystrophia lutkevichi* Alich., *Vellamo verneuli* (Eichw.), *Triplesia insularis* Eichw., *Parambonites gigas* Schm., and chitinozoans *Desmochitina nodosa*, *Conochitina micracantha* Eis. *Lagenochitina prussica* Eis. (Laufeld, 1971). The Suboch Member is assigned to the Upper Ordovician (Ashgilian) and can be correlated with a Baltic Vormsi age (Tsegelnjuk et al., 1983). Their eroded upper surface is overlain by Silurian deposits of the Kytayhorod Formation.

Fig. 4. Typical view of naturally exposed Silurian strata in the steep left bank of the Ternava River at the village of Kytayhorod. Arrow points to the gully selected for detail examination see Fig. 5

Fig. 5. Section selected for sampling and detailed examination, located on the left bank of Ternava River. This is the same steep slope as shown in Fig. 4

Fig. 6. Kytayhorod profile. Lithology after Nikiforova et al., 1972 and Racki et al. 2012 *in press*, simplified →



The Kytayhorod Formation is subdivided into four units: the Restiv, Demshyn, Maryanivka and Cherche Members. The Kytayhorod succession in this outcrop is characterized by rather monotonous carbonate-marly lithologies evolving from platy rhythmic to non-bedded, nodular varieties representing only the three lowest of four recognized units (see Fig. 6).

The formation begins with the 5–10 m thick Restiv Member, represented by dark, greenish-gray marls intercalated with thin-bedded biodetrital limestones, which according to Tsegelnjuk et al. (1983) contain diagnostic conodonts: *Pseudoneotodus tricornis*, *Neoprioniodus subcarnus*, *Pterospatodusamorphognatus*, *P. procerus*, *Carniodus carinatus*, *Ozarkodina gaertneri*, *Pygodus lyra*, *P. lenticularis*, *Trichonodella papilio*; and graptolites: *Monoclimacis crenulata*, *M. gracilis*, *Monograptus pridon*, *Cyrtograptus murchisoni*, *C. bohemicus*; chitinozoans: *Angochitina longicollis* and *Conochitina proboscifera*, trilobites *Calymene restevensis*, *Bumastus barriensis*, *Proetus concinus*, and 14 species of brachiopods. Fossil assemblages indicate an upper Llandovery and lower Wenlock (Seinwoodian) ages for the Restiv Member. The very abundant and diverse fossil faunas found in the Kyatyhorod section have been recently re-examined and re-described by D. Drygant and H. Szaniawski (conodonts), A. Baliński (brachiopods) and R. Wrona (chitinozoans) (publications in press)

The Demshyn Member is 12 m thick, and comprises dark-grey, nodular, platy limestone intercalated with greenish-grey marls, yielding brachiopods represented by 18 species dominated by strophomenide, atrypides, and in the uppermost of the interval by a mass-occurrence of rhynchonellide; trilobites *Warburgella stokesii*, *Cheirurus insignis*, *Leonaspis marclini* and conodonts *Ozarkodina media*, *Ligonodina silurica*, *Peltodus dyscritus* and chitinozoans *Margachitina margaritana* (Tsegelnjuk et al., 1983, Drygant, 1984).

The major positive carbon isotope excursion associated with extinctions and changes in community structure has been recorded in this unit (Demshyn Member) at the beginning of the Wenlock and correlated with the global Ireviken Event (Kaljo et al., 2007; Racki et al., *in press*)

The Kytayhorod section is terminated by the Maryanivka Member, represented by approximately 20 m thick, monotonous, compact nodular limestones containing brachiopods *Atrypa reticularis*, *Dicoelosia biloba*, *Resserella elongatula*, *Plectatrypa imbricata*, *and Howellella* sp., and scarce rugose corals *Halacanthophyllum* sp., heliolitides and trilobites *Bumastus* sp., and chitinozoans *Conochitina pachycephala*.

The Silurian succession exposed at the village of Kytayhorod is overlain discordantly by Cretaceous deposits.

The succession of brachiopod fauna in the Kytayhorod section shows gradual and minor temporal changes. The most characteristic trend in the fauna is a change from stressed assemblages of prevailing small-dimension forms in the Restiv Member to medium- and large-sized forms in the Demshyn Member, and, particularly, Maryanivka Member (Baliński in Racki et al., *in press*). Conodont faunas exhibit two-step distributional pattern, characterized by low-frequency but relatively high diversity assemblages quickly replaced in the succession by a stable, but typically poor, *Panderodus* – dominated biota of overall increasing frequency (Drygant, 1984; Racki et al., *in press*). The organic-walled microfossils, Chitinozoans, in the Kytayhorod section show a moderately diverse (up to 13 taxa) *Margachitina*-dominated assemblage. Two rich assemblages with dominant species *Conochitina proboscifera* and *C. pachycephala*were found in the lowermost and topmost samples of the section, respectively. This fairly stable dynamic pattern differs from the abrupt changes in chitinozoan faunas at the Llandovery-Wenlock boundary, partly due to a stratigraphical gap (i.e., the *Margachitina margaritana* Zone *sensu stricto*), reported from Estonia by Hints et al. (2006).

The Restiv Member is ecologically distinctive in its unique co-occurrence of graptolites and macroflora (*Pseudosajania)*, associated with more widely distributed benthic groups: crinoids, gastropods, solitary rugose corals (*Orthopaterophyllum*), nautiloids and trilobites (*Acidaspis*; common in some layers). Assemblages from the lowermost part of the Demshyn Member include the five benthic groups and bivalves, with locally abundant solitary corals (*Orthopaterophyllum*, *Sverigophyllum*), whilst some higher beds (Nikiforova et al., 1972) are either unfossiliferous (nodular lithologies) or characterized by a bivalve fauna only, with *Grammysia* and *Mytilarca*. The abundant brachiopod fauna of the upper Demshyn Member is accompanied by a rather impoverished assemblage of trilobites, solitary corals (*Stereotactis*), crinoids and gastropods.

The Ireviken Event global isotope excursion identified in the Kytayhorod section was marked by well-defined temporal changes in detrital input, redox state and, supposedly, bioproductivity, but without correlative relations with the $\delta^{13}C$ pattern (Kaljo et al., 2007; Racki et al., *in press*). The environmental evolution, from outer shelf toward reefal platform, was forced mostly by the regional tectonic regime and generally regressive eustatic sea-level fluctuations (see Koren et al., 1989). Thus, the global biogeochemical perturbation was of minor significance in the sedimentary signature of this epeiric sea, as claimed also for other Laurussian sites in many other studies (see review in Calner, 2007; Cramer and Saltzman, 2007a, b; Munnecke et al., 2010).

Locality data: Exposure no. 96 (numbered according to Nikiforova et al., 1972); situated on the steep left bank of the River Ternava (left tributary of the Dniester) below the church in the village of Kytayhorod (Fig. 4); the most accessible gully (arrowed in Fig. 4) has been selected for detailed examination (Fig. 5); coordinates: N48°38´19.1˝ E26°47´18.,6˝.

Stop 2. Outcrop: Kubatchivka Quarry near Kamyanets Podilsky
(Figs 7– 8)

Target: The possibility of examining the Silurian (Ludfordian) Sokil Member succession of the Malynivtsi Formation, which consist of stromatoporoid-coral and crinoidal-stromatoporoid sequences representing the zone of shoals and barriers.

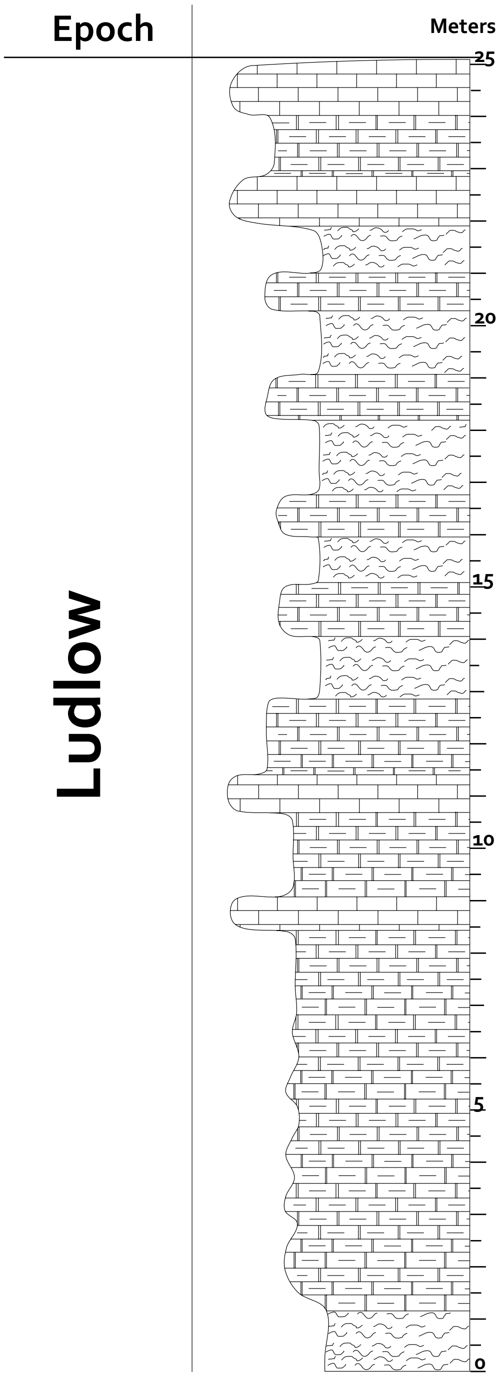
Description: The succession exposed in the quarry is over 30 m thick but only the lower part (10-15 m) is accessible for direct examination. The equivalent succession is also easily and fully available, although weathered and partially covered by soil and overgrowth, on the opposite (left) bank of the River Smotrych, at the complementary Tsybulivka locality (Fig. 7). The beds exposed in the quarry dip slightly to the west, and comprise three complexes (Skompski et al., 2008, Łuczyński et al., 2009). The lower complex forms massive stromatoporoid and stromatoporoid-coral limestones containing massive and branching (*Amphipora*) stromatoporids (often in life position); tabulates *Syringopora*, *Favosites pseudoforbesi*; rugose corals *Weissermelia lindstroemi* accompanied by crinoids, brachiopods: *Isortis* (*Arcualla*) *crassa*, *Shaleriella delicata*, *Morinorhynchus crispus*; trilobites: *Calymene spectabilis*, *Proetus signatus* (Tsegelnjuk et al., 1983; Skompski, 2008; Łuczyński et al., 2009). Skompski et al. (2008) and Łuczyński et al. (2009) interpreted the lower complex as representing an autoparabiostrome according to the classification of Kershaw (1994). This lower complex ends with black, marly-argillaceous shales containing nautiloid orthocones, crinoid steams, eurypterids, bivalves (*Petronitella* sp.), trilobites, brachiopods (*Craniops* sp., *Orbiculoide* sp.), gastropods, beyrichid and leperditicopid ostracodes, bryozoans and fish fragments (see also description in Skompski et al., 2008 and Łuczyński et al., 2009). The lower complex and its terminating shales have an eroded top surface covered by the light grey oncolitic-fenestral complex 0.6–0.8 m thick, which comprises partially laminated limestones yielding ostracods and fragmented stromatoporoids, tabulates and solitary corals. The upper part of the laminitie-fenestral complex also shows the effects of erosion and a separate lower stromatoporoid complex from the third overlying upper complex developed as massive stromatoporoid-crinoidal limestone which changes its character upwards into dark, nodular, marly, wavy-bedded

Fig. 7. General view of the eastern (left) canyon wall of the River Smotrych1 km south of Kamyanets Podilsky. The Cybulovka section (opposite river bank to Kubatchivka quarry) exposes strata of the Sokil Member of the Malynivtsi Formation, dated as Ludlow.

limestone with redeposited and fragmented stromatoporoids. This upper complex reaches more than a dozen meters and is clearly visible in the high-wall canyon (Fig. 7) of the River Smotrych (see also description in Skompski et al., 2008 and Łuczyński et al., 2009).

According to Skompski et al. (2008) and Łuczyński et al. (2009) the stromatoporoid-coral and the crinoidal-stromatoporoid complexes exposed in Kubatchivka probably represent the zone of shoals and barriers connected with tidal and peritidal conditions, and a diverse sedimentary environment with numerous high-energy events.

Locality data: Exposure no. 152 in Nikiforova et al. 1972; The Kubatchivka Quarry, about 1.5 km south of Kamyanets Podilsky down the River Smotrych on its western (right) bank; coordinates: N48o 38´ 54.1'', E26o36´ 09.1''



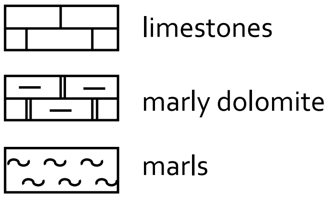


Fig. 8. Simplified section exposed in Kubatchivka Quarry near Kamyanets Podilsky

Route: Kamyanets Podilsky–Skala Podilska–Dnistrove –Mykhalkiv(Ustya) at Nichlava River–Zalishchyky

Stop 3. Outcrop: Skala Podilska Quarry

(Figs 9, 10)

Target: The uppermost part of the Trubchyn Member of the Skala Formation, is dated as Pridoli. We have the opportunity to examine different dolomite and biodetrital limestone successions representing cyclic sedimentation in a shallow lagoon that periodically dried out (Abushik et al., 1985; Skompski et al., 2008).

Description: The Trubchyn beds exposed in the quarry wall are clearly distinguishable into two different dolomitic and limestone complexes separated by light yellow-greenish slightly argillaceous clays about 0.8 m thick (Abushik et al., 1985: Fig. 6, bed no. 38 on the profile; Skompski et al., 2008). The lower dolomitic complex is barren of fossils, with rare ripply lamination accompanied by desiccation polygons. The dolomitic beds pass upwards into greenish clay deposits which probably contain metabentonites. The overlying upper complex is characterized by fairly well bedded stromatoporoid limestones (see also more detail description in Skompski et al., 2008). The sedimentary environment of the lower complex has been interpreted by Skompski et al. (2008) as being the shallowest of those in the Silurian of Podolia, and located in a shallow lagoon that periodically dried out and became subaerially exposed. The faunal remains, such as stromatoporoid fragmens, tabulate corals and crinoid ossicles, were supplied sporadically to the lagoon from zones further offshore (Skompski et al., 2008).

Locality data: The quarry is located in the southern part of the town of Skala Podilska, on the left side of the public road to Kamyanets Podilsky. Exposure no. 219 in Abushik et al., 1985.

Fig. 9. General view of Skala Podilska Quarry

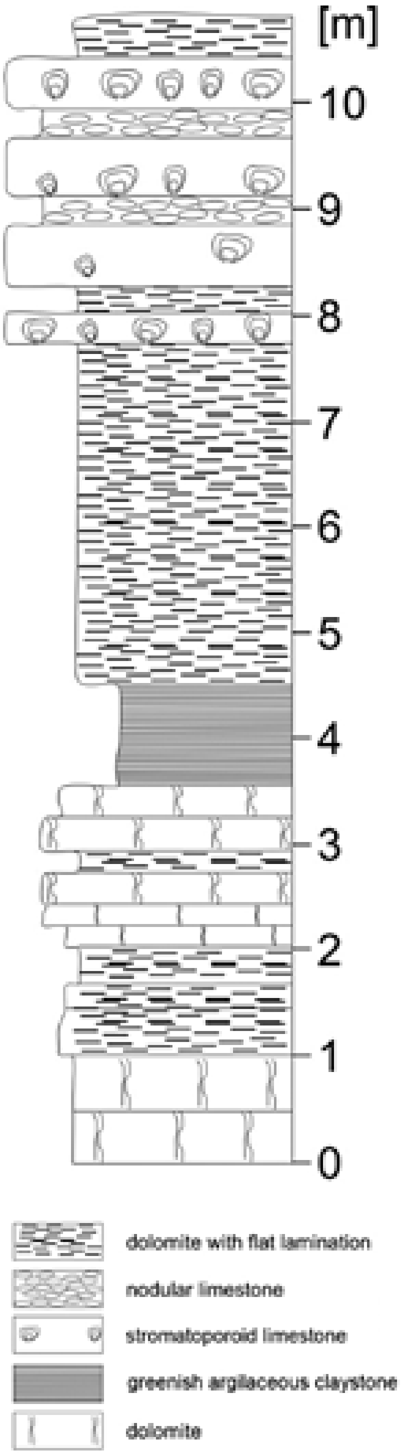


Fig. 10. Schematic lithological profile in Skala Podilska Quarry

Stop 4. Outcrop: A trench at the village of Dnistrove (formerly Volkivtsy) (Figs 11–12)

Fig. 11. Field photography of the trenched section of clayey-calcareous Silurian - Devonian boundary beds of the top Dzvenyhorod Member and basal Khudikivtsi Member at the village of Dnistrove (former Volkovtsy). Outcrop no. 64 in Nikiforova et al., 1972

Target: A detailed study through the Silurian–Devonian boundary beds at the key section in the Dniester Basin of Podolia (Fig. 11). The Silurian Dzvinohorod Member of the Skala Formation (dated as Pridoli) and the Devonian Khudykivtsi Member of the Borshchiv Formation (dated as Lochkovian).

Description: The trenched section exhibits the Upper Silurian Dzwenygorod Member of the upper part of the Skala Horizon (Figs. 11-12); dark, fossiliferous, nodular limestones, 19 m thick, predominate in the topmost interval, and contain many characteristic Silurian brachiopod, trilobite and particularly conodont species, including *Ozarkodina eosteinhornensis* and *Ligonodina elegans*. The Silurian-Devonian boundary is located 3.2 m above the top of the dark, nodular limestone interval, in the middle part of a sequence of interbedded greenish-grey argillaceous shales and marls containing dark-grey limestone nodules. The boundary is characterized by the first appearance of the trilobite *Acastella heberti*, brachiopods *Clorinda pseudolinguifera* and *Glossoleptaena emarginata* and the conodont *Ozarkodina remscheidensis*. The guide graptolite species *Monograptus uniformis angustidens* is found at the Dnistrove (formerly Volkovtsy) section only in shales interbedded within the nodular limestone layers (Fig. 12). These biostratigraphical data (see also Nikiforova et al., 1972; Nikiforova, 1977; Drygant, 2010) allow a fairly reliable correlation with the global boundary point in the Klonk stratotype section (Chlupač and Hladil, 2000). Furthermore, the conodont genus *Icriodus*, commonly considered as a guide fossil for the Early Devonian, is confirmed in the Podolian section by *Icriodus woschmidti*, which has been found 1.5 m below the S-D boundary (Mashkova, 1971; Drygant, 2010).

The oldest brachiopod in the Dnistrove section is *Daya behemica* which occurs in the topmost part of the Dzvenyhorod Member (for a detailed description of the brachiopod fauna see Kozłowski, 1929 and Baliński, 2012). The species occurs mainly in the thin bedded nodular limestone in nest-like clusters. *D. bohemica* is a characteristic species of the uppermost layers of the Prídolí Series of Estonia, Lithuania, and Latvia (Havlíček and Štorch, 1990; Rubel, 1977). Numerous athyridide *Dnestrina gutta* occur above the layer with abundant *Daya behemica*. Apart from Podolia, this species is known from the Přídolí of Moldavia, and Western Europe (Alvarez and Copper, 2002). The occurrence of *D. gutta* suggests a stressed and impoverished, low diversity, short-ranging assemblage of somewhat deeper water conditions than *Daya bohemica* (Baliński, 2012).

The main occurrence of atrypide *Gracianella (Sublepida) paulula* at Dnistrove has been revealed 40 cm above the S-D boundary and is correlated with the climax of the Klonk Event. Other brachiopods in the assemblage are small-sized *Resserella elegantuloides*, *Plectodonta (Plectodonta) pantherae*, *Pseudoprotathyris infantilis*, and *Howellella (Howellella) latisinuata*. The most characteristic brachiopod *G.(S.) paulula* co-occur with the guide graptolite *Monograptus uniformis angustidens* and it seems that this fauna represents a low-diversity high dominance, quiet-water *Gracianella* Community of Boucot (1975) recognised in the Silurian non-reef communities. In the succeeding 4 m of rhythmic marls and limestones, the brachiopod fauna is either very rare, poorly preserved or absent. However, at about 5.5 m above the S–D boundary appears diverse, well preserved, and distinctive brachiopod fauna dominated by medium-sized forms such as *Sepatrypa (Septatrypa) secreta*, *Plectodonta (Plectodonta) pantherae*, *Sphaerirhynchia gibbosa*, *Clorinda pseudolinguifera*, and *Talentella crassiformis*. The brachiopod fauna is associated with diverse benthic fauna represented by trilobites, crinoids, gastropods, bivalves, and nautiloids. The brachiopod assemblage is represented by a variety of morphological types and ecological adaptations (Baliński, 2012). The specimens are mostly articulated with the exception of *Clorinda pseudolinguifera* which possessed a hinge structure of deltidiodont type. The numerous strophomenide *P. (P.) pantherae* in this assemblage possess a color-pattern which probably performed a protective function through disruptive camouflage against the visual systems of potential predators and this implies the presence of a photic zone (Baliński, 2010). Moreover, the presence of numerous *S. (S.) secreta* suggests that the fauna may be compared to the Silurian non-reef quiet-water *Dubaria* Community of Boucot (1975). This corresponds to Havlíček and Štorch's (1990) opinion that in the Přídolí of Bohemia the *Dubaria* Community is related to aquiet, shallow-water plain. Thus, the inventory and character of the brachiopods and associated fauna from beds about 5 m above the S-D boundary at Dnistrove section probably indicate a setting near the lower limit of the photic zone (Baliński, 2012).

The limestone layers in the Dnistrove succession are very rich in conodonts: *Ziglerodina remsheidensis*, *Caudicriodus woschmidti*, *Caud. hesperius*, and *Delotaxis cristagalli*. Comparatively abundant are: *Ozrkodina typica, Parazieglerodina eosteinhornensis, Wurmiella excavata* and *Panderodus unicostatus*. Thus, despite somewhat irregular frequency trends, the less abundant faunas occur in the broadly-defined clay-enriched S-D boundary interval and in the uppermost part of the Dnistrove succession (Drygant and Szaniawski, 2009, 2012; Drygant, 2010).

A turnover in the faunas is recognized near the S–D boundary level, when four Silurian-type species have disappeared (e.g., *Delotaxis detorta, Parazieglerodina eosteinhornensis* and *Ozarkodina typica*), and more rich Devonian assemblage (up to six species), with *Zieglerodina remscheidensis, Caudicriodus*, and *Pandorinellina*, suddenly flourished in the shallowing epeiric sea (Drygant and Szaniawski, 2009; Drygant, 2010).

The occurrence of characteristic chitinozoan species such as *Urnochitina urna, Eisenackitina bohemica, Cingulochitina* ex. gr. *ervensis, Calpichitina velata, Margachitina catenaria*, and *Anthochitina* ex. gr. *superba* represents an accumulation zone within the S–D boundary interval at Dnistrove. The over abundance of the thick-walled vesicles of *Urnochitina* (Operculatifera) could have been effected by a cold water environment related to the cooling period preceding the S–D boundary event. The abundant occurrence of the similarly structured vesicles of *Eisenackitina barrandei* and *E. bohemica* at the boundary of both systems may well be analogous (Paris and Grahn, 1996; Wrona, 2009).

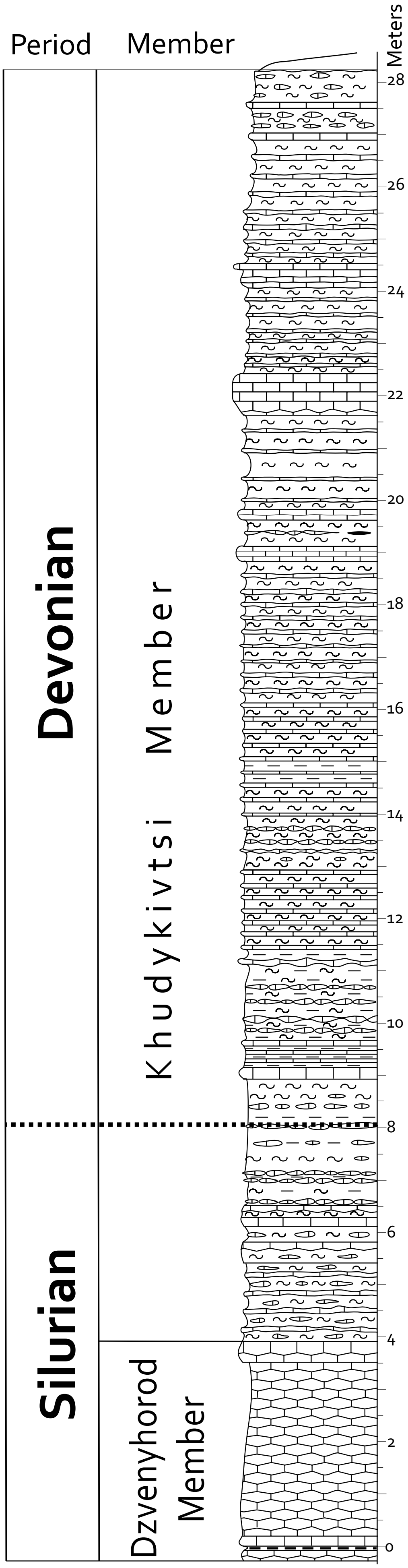


Fig. 12. Schematic profile of the Dnistrove outcrop. Lithology after Nikiforova et al., 1972, simplified

In the upper part of the section, in the Khudykivtsi Member an abundant and diversified chitinozoan assemblage, dominated by *Ancyrochitina* and *Angochitina* occurs again, There are species of a fundamentally different chitinozoan group belonging to the Prosomatifera, characterized by thin-walled highly ornamented vesicles, with spines, ramified processes and vellum. This abundance could have been a result of progressive warming during the Lochkovian in that area. In summary, the distribution of chitinozoans at Dnistrove demonstrates specific dynamics across the Klonk Event (see Paris and Grahn, 1996; Wrona, 2009).

The topmost exposed 1.6 m of the Silurian are characterized by the occurrence of crinoids, nautiloids, trilobites (*Proetus, Acastella*), and bivalves (see also Nikiforova et al. 1972; Koren et al. 1989). In particular, the remnants of the large floating crinoid *Scyphocrinites*, including bulb-shaped loboliths, are very abundant, forming several lenticular and locally graded bioclastic intercalations, up to 10 cm thick. Within the nodular and scyphocrinoid limestone layers, a thin shale horizon with abundant guide graptolite *Monograptus uniformis angustidens* was found (Figs. 11-12). Conversely, orthocone nautiloids are patchily distributed in a ca. 2 m interval around the system boundary.

Above the S–D boundary the brachiopod fauna is accompanied by rather rare but ubiquitous crinoid ossicles, trilobites *Acastellaherberti elsana, Warburgella regulosa;* nautiloids *Risoceras* sp.; and occasionally also bivalves *Pteria*sp., gastropods *Platyceras* sp., bryozoans, ostracods, and tentaculitids.

The Klonk Event identified in the Dnistrove section exhibits some temporal links with the sea-level rise across the S–D transitional beds and, regardless of specific causes, reflects a regional carbonate crisis linked with a tendency toward elevated eutrophication and oxygen deficiency (Małkowski and Racki, 2009; Racki et al., *in press*). The deepening and temperature drop at the S–D boundary time was clearly tied with heavy storms, recorded in crinoid bioclastic accumulation, and possibly also with upwelling currents (Racki et al. *in press*). The features collectively point to a uniqueness of the Klonk Event among the Silurian global events (see summary in Munnecke et al., 2010), and some similarities already to Devonian transgressive/anoxic episodes (see Walliser, 1996; Małkowski and Racki, 2009).

Locality data: No. 64 - numbering in Nikiforova et al. (1972). The village of Dnistrove (formerly Volkovtsy) on the left bank of the River Dniester. Exposure in a trench excavated in a gully with water spring, located upstream and about 300 m from the old orthodox church campanile; coordinates: N48°32´16.9˝ E26°14´21.4˝

Stop 5. Outcrop: the village of Mykhalkiv on the River Nichlava
(Fig. 13)

Target: Exposure of the typical lithology of the Mytkiv Member of the Borshchiv Formation (Fig. 13).

Description: Exposed on the left slope of the river are approximately 40 m thick monotonous, alternately bedded limestones – siltstones and clayey-calcareous shales representing the middle part of the Mitkiv Beds, which is the upper unit of the Borshchiv Formation. The brachiopod coquinas exposed just above water level contain *Clorinda pseudolinguifera*, *Howellella laeviplicatus*, *Lioclema gloria*, *Leptotrypella vulgata*, and *Minussina spinosoformis* (Nikiforova and Predtechensky, 1968). The argillites and clayey shales with scarce layers and lenses of limestones yielding rare brachiopod shells are predominant in the higher part of the section. In the upper part of the outcrop occur argillites, clayey marls yielding abundant fossils, mainly brachiopods *Resserella elegantuloids*, *Rhipidomella frequens*, *Amphistrophia podolica*, *Stropheodonta subinterstralis*, *Glossoleptaena emarginata*, and *Lanceomyonia borealiformis*; nautiloids, bivalves, trilobites:*Acastella tiro*, *Warburgella rugulos* and *Homalonotus roemeri*; ostracods: *Opistoplax gyratus*; conodonts: *Caudicriodus postwoschmidti*, *C. transgrediens*, *Zieglerodina mashkovae, Z. remsheidensis* (Drygant, 2010); as well as graptolites *Monograptus uniformis,*and chitinozoans: *Margachitina catenaria*, *Eisenackitina bohemica* and *Angochitina tsegelnjuki* (see Nikiforova and Predtechensky, 1968; Obut 1973; Paris and Grahn, 1996; Wrona, 2009). There are, in addition to abundant marine fossils, some scarce agnathan remains: *Thelodus oervigi*, *Podolaspis lerichei* (Nikiforova et al., 1972; Drygant, 1984, 2010; Voichyshyn, 2011).

Locality data: No. 92 - numbering in Nikiforova et al. (1972). Exposure in the village of Mykhalkiv (formerly Ustya) on the left side of the River Nichlava (the northern tributary of the Dniester River) opposite an abandoned mill; coordinates: N48°36´56.4˝ E26°05´19.3˝

Fig. 13. General view of the eastern (left) escarpment of the River Nichlava at the village of Mykhalkiv (former Ustia), exposing strata of the Mytkiv Member of the Borshchiv Formation

Route: Zalishchyky–Chortkiv–Terebovla–Ternopil'–Lvov

Stop 6. Outcrop: Zalishchyky on the right side of the River Dniester
(Figs 14–17)

Fig. 14. General view of the southern (right) steep bank of the Dniester at Zalishchyky. Exposed upper part of the Ivanie Formation (above the water level) and its contact with red-colored Dniester Formation, overlain at the top of the bank by white- Cretaceous and Neogene rocks

Target: Middle part of the Ivanie Formation and its contact with red-colored Dniester Formation. During long historical investigations of Podolian geology this contact was traditionally considered as the Silurian-Devonian boundary.

Description: The over 60 m high exposure on the steep right slope of the deep Dniester river valley is accessible for direct examination in two parts, separated by the main road and bridge. At the base of slope, about 2 m above the water line and just above the dirt road, are exposures of rhythmically altered, grey-colored shales and siltstones with thin nodular or lenticular intercalations of biodetrital limestones (Figs. 15-16). The fossil remains in these strata represent mainly ostracods *Leperditia tyraica* and brachiopods *Mutationella podolica*, which locally form coquinas associated with bivalves, nautiloids, tentaculitids, corals, crinoids, conodonts *Ziglerodina serrula*, *Caudicriodus serus* (Drygant, 1974, 2010) and fish remains (see Voichyshyn, 2011; Voichyshyn and Szaniawski, 2012); chitinozoans have also been reported here: *Ancyrochitina* sp,. *Sphaerochitina* sp. (Paris and Grahn, 1996).

The upper part of the section is accessible on the same right slope above the bridge and main road from Zalishchyky to Chernivtsy (Fig. 17). The upper sequence of the Ivanie Member is exposed, represented by bioturbated, grey to yellowish-green siltstone with rare limestone beds. The limestones contain a scarce fossil assemblage containing ostracods, brachiopods, agnathans and eurypterids (Nikiforova et al., 1972; Drygant, 2010; Voichyshyn, 2011). The overlying sandy shales and thick-bedded red sandstones represent inshore lagoonal to afluvial-estuarine, Old Red Sandstone facies of the Dniester Formation (Narbutas, 1984; Uchman et al., 2004; Drygant, 2010; Voichyshyn, 2011). The boundary between the Ivanie Formation and the Dniester Formation is clearly marked by the conversion of grey carbonate and siliciclastic deposits with marine fauna into the monotonous red beds (Narbutas, 1984). The white colored Cretaceous and Neogene deposits cover the eroded surface of the Old Red Sandstone at the top of section (Fig. 14).

Locality data: No. 58 – numbering in Nikiforova et al. (1972). Exposure about 2 m above the water line (just above the dirt road) in the lower part of the right escarpment of the River Dniester upstream from the main road bridge at Zalishchyky. (N48°37´58.3˝ E25°43´57.2˝). The upper part of the profile is available in exposures100 m downstream on the same right escarpment above the bridge and main road from Zalishchyky to Chernivtsy; coordinates: N48°40´45.0˝ E25°46´21.9˝

Fig. 15. Field photography of the middle part of the Ivanie Member showing the typical lithology of alternating bedded limestone and siltstone beds. Exposure in the lower part of right escarpment of the Dniester River upstream of the road bridge at Zalishchyky

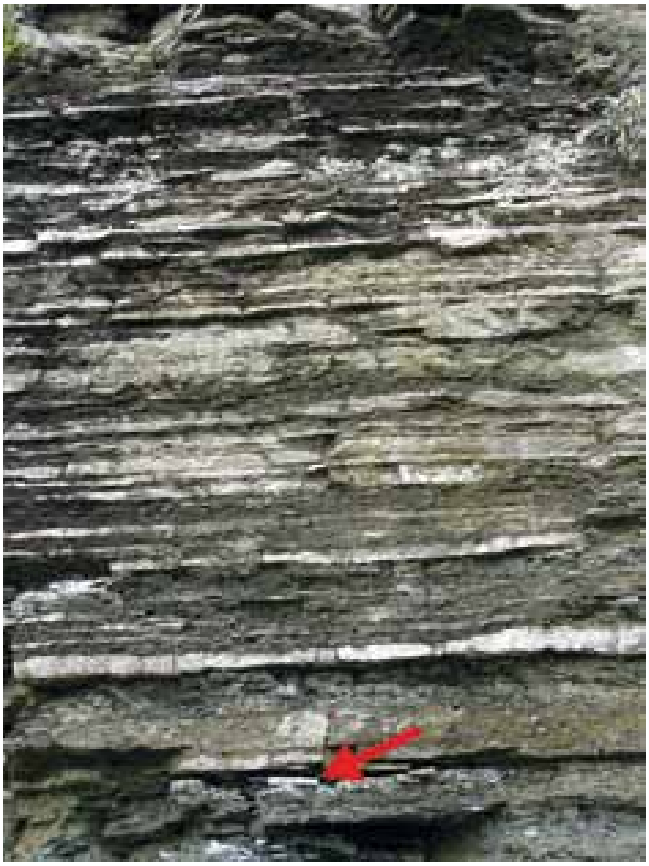


Fig. 16. Details of the same exposure as in Fig. 15, showing typical lithology of alternating thin-bedded limestones and siltstones

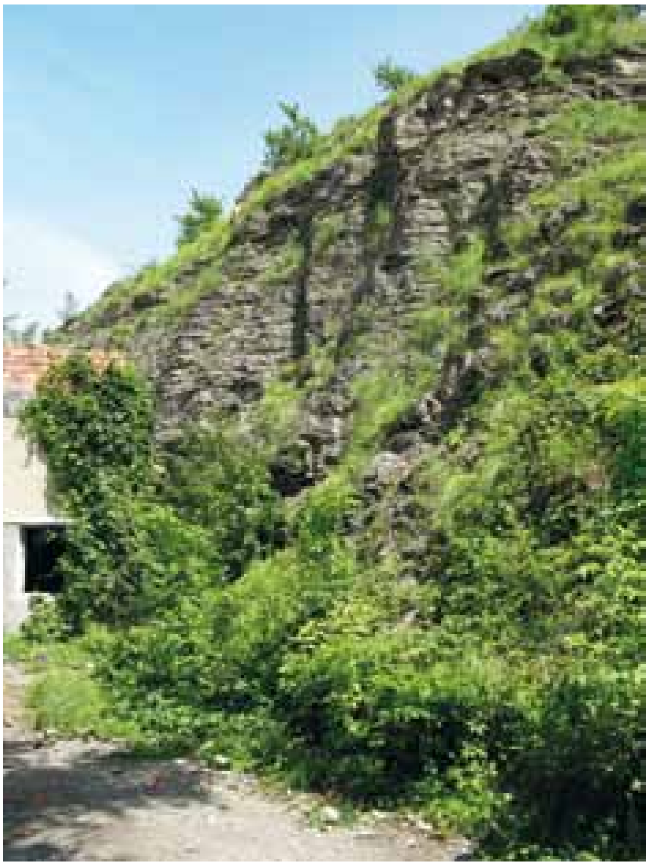


Fig. 17. Field photograph of the upper part of the Ivanie Member exposed in the upper part of the right escarpment of the Dniester River over the bridge and road from Zalishchyky to Chernivtsy

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