Silurian shales of the East European Platform in Poland – some exploration problems

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A b s t r a c t. The pericratonic Silurian shale succession in Poland, despite its reasonably well-constrained geological framework, entails a number of contentious issues that need to be resolved before this emerging shale gas play will enter a stage of successful development. The succession is thought to have originated in a Caledonian foredeep encroaching distally onto a pericratonic shelf ramp. However, the geochemical signature of the mudrocks is consistent with a cratonic rather than orogenic sourcing, the proximal part of the foredeep basin-fill is apparently missing, and the shale succession juxtaposes in part across the Teisseyre-Tornquist Zone against suspected terranes with no evidence of Silurian tectonism. Organic-rich Llandovery–Wenlock shales form a NW-SE striking central belt that is increasingly calcareous toward the craton (NE) and more silty toward the inferred orogen (SW), with the TOC content decreasing in both directions perpendicular to the strike. The TOC trend seems consistent with the deep-downlap model of black shale deposition suggested for many Paleozoic foredeep basins, but does not quite agree with the outer neritic to upper bathyal depths assumed for the shale deposition.

Preliminary results from three wells drilled by Orlen Upstream in the Lublin Basin indicate that the Llandovery–Wenlock shales were deposited on a distal shelf ramp sheltered from the craton by shelf carbonate shoals and periodically affected by weak storm-generated currents. The impact of storms on water column resulted in intermittent rises of oxygen content in the otherwise anoxic to dysoxic near-bottom conditions. The prospective interval is dominated by calcite-cemented clayey mudstones showing moderate to good reservoir qualities. It is cut locally by ENE- or NE-dipping, steep fractures favourable for fluid transmissibility, and a NE or SW direction is most advantageous for artificial fracturing. This interval is capped with a Ludlow calcite-cemented, laminated siltstone that forms a regional correlation marker and shows soft-sediment deformations attributable to gravitational collapse on a NE-dipping paleoslope. If correct, this interpretation might imply the encroachment of orogen-fed clinothem system onto the SW-inclined craton-margin shelf ramp.

Keywords: *Silurian, black shale, shale gas, unconventional play*

Silurian black shales form a non to weakly deformed 700 km long belt situated along the western margin of the East European Platform in Poland (Fig. 1). The evaluation of their presumably great potential as both source rock and reservoir for gas is currently under intense investigation by industrial, governmental and academic institutions.

Relationships between factors controlling the distribution, concentration and preservation of organic carbon in shales, as well as their geomechanical properties, such as porosity, permeability, strength, fractability, etc., must be well understood before this emerging gas play enters a successful development phase. This knowledge is crucial for proper planning and completion design of wells. Although the depositional, tectonic, and burial history of the Silurian shale belt seems to be reasonably well-constrained on a regional scale (Poprawa, 2010), there is an obvious need for both new high-quality subsurface data and integrated multidisciplinary conceptual models for predicting the occurrence of resource-quality shales within this continuous though remarkably heterogeneous reservoir. In this paper, we highlight some of the key, controversial and unresolved geological problems and present preliminary information from wells recently drilled by Orlen Upstream in the Lublin Basin (Syczyn-OU1 and Berejów-OU1) and in the Garwolin area (Goździk-OU1) (Fig. 2, 3).

TECTONIC SETTING

The lower Paleozoic shale belt in central Poland straddles the boundary between the Paleozoic Platform and the East European Platform founded on Proterozoic lithosphere. The substructure of the Paleozoic Platform is composed of a mosaic of terranes (East Avalonia, Małopolska Massif, Upper Silesia Block), which accreted to the southwestern margin of Baltica along a broad and structurally complex zone referred to as the Trans-European Suture Zone (TESZ) (Dadlez et al., 1994, 2005; Berthelsen, 1998; Pharaoh, 1999). The Teisseyre-Tornquist Zone (TTZ) constitutes the NE boundary of TESZ and limits the undeformed lower Paleozoic succession from the south-west (Fig. 1). From the NE towards the TESZ, the Silurian shale succession thickens from null to ca. 3000 m, its base plunges from 1050 m to more than 5000 m, and the thermal maturity of the organic-rich Llandovery–Wenlock shales extends through the wet to dry gas window and farther below (Poprawa, 2010). Results of subsidence analysis indicate that the western margin of the East European Craton after the late Proterozoic rifting evolved into a passive margin, which during the Middle(?) Ordovician–Silurian underwent flexural bending as a consequence of the collision between Avalonia and Baltica (Poprawa et al., 1999; Poprawa & Pacześna, 2002; Nawrocki & Poprawa, 2006). Therefore, the pericratonic

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Silurian mudrocks are interpreted to constitute the distal infill of a Caledonian foredeep (Poprawa, 2006). This notion is supported by the presence of a wedge of Wenlock–Ludlow silty turbidites in the western Baltic Basin (Kociewie Formation – Modliński & Podhalańska, 2010). The wedge is thinner and younger eastwards and was likely derived from the North German-Polish Caledonides (Jaworowski, 2000).

Nonetheless, it should be emphasized that the geochemical signature of these sediments indicates a stable, cratonic source (Krzemiński & Poprawa, 2006), and also the U-Pb SHRIMP zircon ages derived both from them and the folded Koszalin–Chojnice Zone are compatible with sources located in the East European Craton (Poprawa et al., 2006). It is worth mentioning that evidence for the Caledonian orogen is weak and restricted to the NW Poland, the proximal Caledonian foredeep is missing, and a considerable part of the pericratonic shale belt juxtaposes through the TTZ with the Łysogóry and Małopolska Massifs, which exhibit no signs of a late Silurian orogenic activity. The tectonic subsidence curves (Poprawa et al., 1999; Poprawa, 2006) show a distinctive increase of subsidence during the Ludlow and Pridoli. However, their older sections (Llandovery–Wenlock) are not unequivocally diagnostic, which makes the hypothesis of subsidence during post-rift thermal cooling still worth considering. All these apparent discrepancies clearly require further insights focusing primarily on the provenance signals in order to recognize better the relative role of cratonic and orogenic sources and to constrain better the tectonic setting of the Silurian shale deposition.

REGIONAL FACIES ZONATION

The paleogeographic map of the Wenlock (Fig. 2) depicts an arrangement of lithofacies in belts stretching NW-SE, with the central, NW-trending clayey shale belt, which is increasingly calcareous to the NE and increasingly contaminated with siliciclastic silt toward the SW (Modliński, 2010). Moreover, organic carbon content appears to attain the highest values in the central belt and decreasing laterally away from it (Poprawa, 2010). These facts indicate that the fine-grained clastic material was supplied from both, mixed carbonate-siliciclastic coasts of a pericratonic shelf in the east and from a hypothetical orogenic source in the

Fig. 1. Location of pericratonic Silurian basins within the main pre-Permian tectonic units of Poland (Mazur & Jarosiński, 2006, modified). Extent of the Trans-European Suture Zone marked by white, diagonal lines

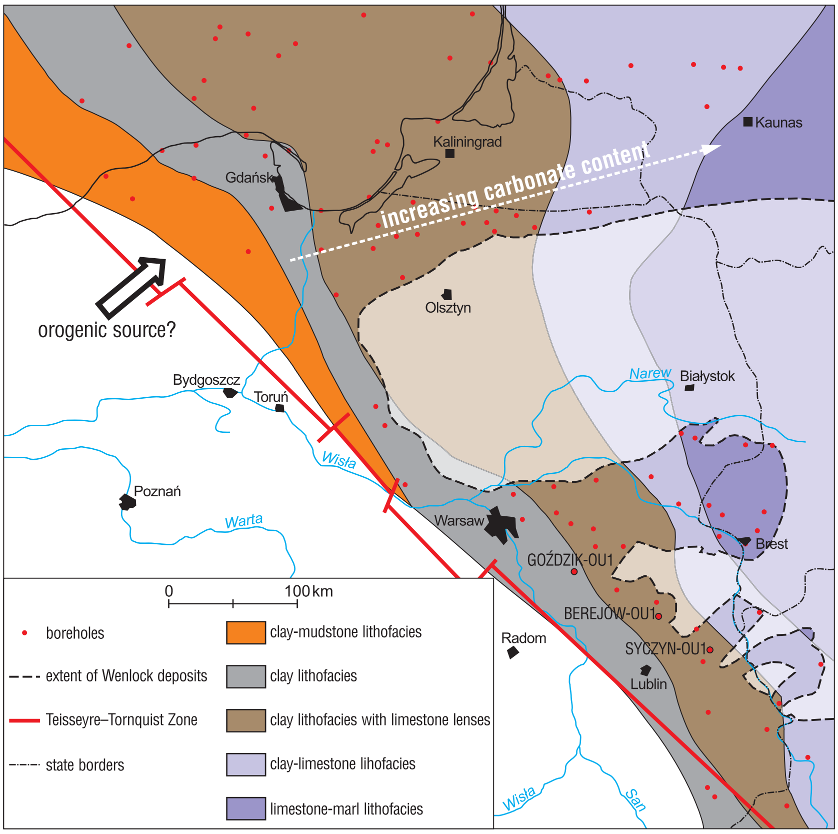

Fig. 2. Wenlock lithofacies belts recognized in the pericratonic shale succession (Modliński et al., 2010 in: Modliński, 2010, modified)

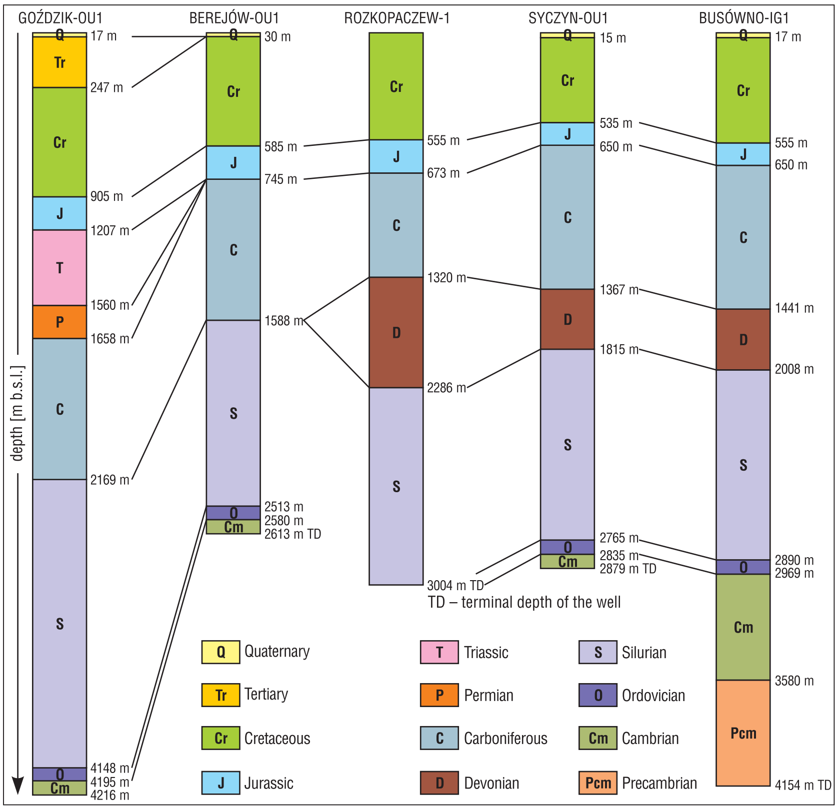

Fig. 3. Stratigraphy of the Berejów-OU1, Syczyn-OU1 and adjacent wells in the Lublin Basin. For location of the wells see Fig. 2

For these shale formations, a deep-downlap model was suggested, in which the phases of fast subsidence due to thrust loading are linked with shale deposition in a deep-water, sediment-starved anoxic basin located in the distal front of siliciclastic shelf-margin clinothems (Ettensohn, 1994; but, see the different view of Smith & Leone, 2010). In this model, the highest concentration of organic matter is restricted to the zones of maximum subsidence where persistent anoxia enhances the preservation of organic carbon irrespectively of the rate of productivity in a near-surface water column (Demaison & Moore, 1980). However, the location of the Silurian shale belt on a presumed foredeep flexure just in front of the craton-margin carbonate shelf suggests a shallower bathymetry than that implied in the deep-downlap model. Recent interpretations assume that the shales were deposited on the outer shelf, which deepened towards the SW to upper bathyal depths (Teller, 1997; Jaworowski, 2000; Modliński et al., 2006; Podhalańska, 2009; Modliński & Podhalańska, 2010). Enrichment of mudrocks in unoxidized organic matter in such shallower settings can result from either an expansion of deep, anoxic water beneath the pycnocline of shallow-water shelf during transgression (the "puddle" model of Wignall, 1991) or near-bottom anoxia caused by high surface productivity alone (Calvert & Pedersen, 1992).

The Berejów-OU1 and Syczyn-OU1 wells, currently under the study, are located slightly updip of the central shale belt in the Lublin Basin (Fig. 2). Llandovery and Wenlock mudrocks that are the main target of the petroleum industry, are dominated by argillaceous, dolomitic and calcareous mudstones, which are very dark gray to gray (N2–N4), seldom black in colour, abounds in graptolites and pyritic nodules/laminae, and show subtle plane-parallel lamination enhanced by carbonate and siliciclastic silt and streaks of organic matter (Fig. 4). The laminated mudstones contain numerous thin intercalations of bioclastic lags, millimetre- to decimetre-thick pyroclastic deposits (tuffs and bentonites), and early-diagenetic calcite concretions. The latter are mostly of a "cannon-ball" type and commonly show thick compaction envelopes (Fig. 5, 6). Beds of graded and laminated siltstones are less common; their thickness and frequency increase in the Ludlow mudstones, which also host single occurrences of rotational slide and slump deposits, up to 4.5 m thick (Fig. 5).

Mudstone facies show numerous signs of current activity. These include (Fig. 6): 1) silt ripple lenses and continuous laminae, both commonly with loaded bases; 2) discontinuous, single grain-thick bioclastic lags, often dominated by crinoid stems; 3) thin, convex-up laminasets resembling the thinnest variety of the so-called micro-hummocky cross-stratification (3D wave ripples), and commonly associated with 4) low-angle erosional surfaces and steep-sided scours

west, at least in the Baltic part of the shale belt (Jaworowski, 2000; Poprawa, 2006). They also imply a bipolar facies gradient and associated bidirectional onlap/downlap stratal termination patterns. Assuming that sedimentation of the Silurian succession took place in the distal foredeep, this would point to the presence of retrogradational and progradational parasequence sets (perhaps with the predominance of the former) in mudstones rimming the carbonate shelf and to the dominance of a normal regression further west. The latter is suggested by the eastward progradation of the turbiditic wedge of the Kociewie Formation. It seems therefore that the main factors controlling stratigraphic architecture of the shale succession are subsidence gradient coupled with a high sediment supply in the rapidly subsiding western part of the foredeep and a strong eustatic component in the creation of accommodation space in the pericratonic part of the basin. On a large scale, this could be manifested by a series of downlapping pinchouts that would ascend generally to the east above the condensed Llandovery–(?)Wenlock section. The testing of this hypothesis may be beyond seismic resolution, but is feasible through detailed stratigraphic correlations on a large set of well data aided by provenance studies.

LITHOFACIES AND DEPOSITIONAL ENVIRONMENT

A genetic link between the deposition of black shales and periods of increased flexural subsidence is archetypal for the early Paleozoic, as demonstrated by the Utica, Marcellus and Barnett shales in the foredeeps of the Taconian, Acadian and Ouachita orogens, respectively (Eoff, 2012).

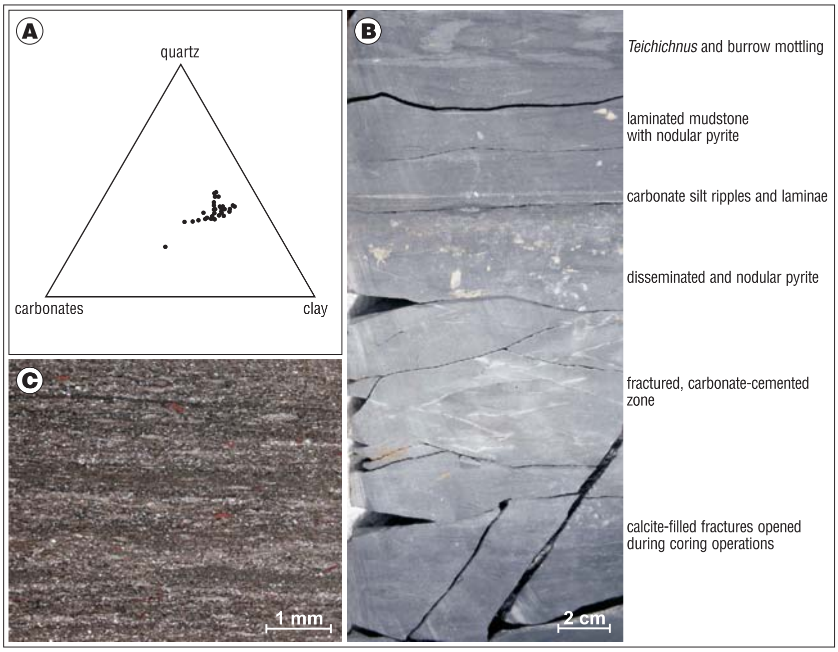

Fig. 4. A – main constituents of Silurian mudrocks in the Syczyn-OU1 well. **B** – close-up view of a Llandovery calcareous mudstone with silt lamination, fine skeletal debris, bioturbation, pyrite nodules, and calcite-cemented fractures opened during coring operations. **C** – microscopic image of a silt-laminated mudstone, showing black stringers and clots of organic matter and numerous oval, silt-filled lenses interpreted as microburrows

similar to gutter casts (see also Lis, 2010). Non-bioturbated and sparsely burrowed sediment commonly alternates on a scale of centimeters to meters. The bioturbation index is low (BI = 0–1); only few centimetre-thick intervals where infaunal activity led to almost complete destruction of primary lamination (B = 4) were observed. Recognizable ichnotaxa are represented by small varieties of *Planolites*, *Chondrites*, *Phycosiphon*, and rare *Teichichnus*.

The sedimentary evidence thus bears the record of suspension fallout accompanied by sporadic action of weak tractive currents, probably generated chiefly by storms. The presence of storm beds in the Baltic Basin was already reported by Jaworowski (2002). The notable absence of coarse-grained storm deposits may, in the present case, may reflect the seafloor bathymetry below the mean storm-wave base, the presence of carbonate buildups at the shelf margin buffering storm sediment supply onto the adjacent muddy bottom, or a narrow grain size range in the material available for storm resuspension. The destruction of water stratification by storms facilitates short-term ventilation of bottom-water and interrupts anoxia (Schieber, 1994). This interpretation is consistent with the impoverished trace-fossil assemblages and their event-like stratigraphic distribution punctuated by non-bioturbated sediment. Therefore, it is likely that the primary productivity and relatively shallow-water, probably seasonal anoxic/dysoxic conditions (Tyson & Pearson, 1991) played significant roles in the accumulation of unoxidized organic matter in the lower Silurian shales. However, the model of a limited circulation may be more pertinent to Rhuddanian shales showing the highest abundance of organic carbon (Podhalańska, 2009).

Thus, the elevated TOC content in the central parts of the Llandovery–Wenlock shale belt may reflect either oxygen minimum in the outer shelf (shallow-water anoxia), or less likely, the deepest part of the flexure (limited circulation). Shallow-water anoxia for organic-rich shales on the distal ramp of a flexural basin implies basinward (here, SW direction) dilution of organic matter (Smith & Leone, 2010) and contradicts the "puddle" model (Wignall, 1991) predicting a basinward increase in organic matter content. The former possibility appears more compatible with the facts published so far. Nevertheless, significant deviations from the NE-SW trend, such as the maximum content of organic carbon in the Podlasie Basin (20%) and its decrease towards the SE in the Lublin Basin (Klimuszko, 2002; Poprawa, 2010) clearly show that alternative solutions should be sought in order to properly and effectively predict the occurrences of areas rich in organic matter on a local scale. These solutions should also take into account the role of intrabasinal factors, such as tectonically controlled basin physiography, which may have been favourable for the development of estuarine bays and axial redistribution of mud.

REGIONAL CORRELATION MARKER (SEISMITE?)

The Ludlow shales in the Lublin Basin are split by a prominent horizon of low gamma-ray event, which occurs ca. 200–250 m above the top of the Ordovician carbonates and is traceable for at least 60 km along the strike (Fig. 7). In the Syczyn-OU-1 well, this event corresponds to a calcite-cemented unit of thinly interlaminated siltstone and mudstone, ca. 4.5 m thick (Fig. 5A), which on a FMI log shows lamination inclined consistently towards 30°SW (Fig. 8A). The unit is enveloped by subtly laminated mudstones with a regional dip of 4° WSW, and neither its base nor its top shows evidence of drag folding that could be attributed to a high-angle fault. The silt laminae in this unit are dissected by normal and reverse subhorizontal synsedimentary faults and show a variety of ptygmatic contortions, diapiric injections, and pseudonodules (Fig. 8B, C), all indicative of a ductile deformation of water-soaked sediment. The unit is interpreted as a rotational slide block formed on a NW-striking paleoslope. In the Berejów-OU1 well, the low gamma-ray excursion corresponds to a similar calcite-cemented, silt-laminated mudstone, which is a part of a homocline dipping 10°WSW (Fig. 8D) and exhibits somewhat different style of hydroplastic deformations. Fragment of a steep, upright fold, 50 cm high, and an antiform sheared off along the axial plane striking NW-WNW, were observed in the drillcore (Fig. 8E, F). These deformations are interpreted as slump structures.

Given the regional extent of the low gamma-ray marker, any purely local origin of its hydroplastic deformation seems highly unlikely. Instead, the evidence suggests a gravitational collapse of the NW-striking submarine slope, possibly triggered by a seismic tremor. An event of

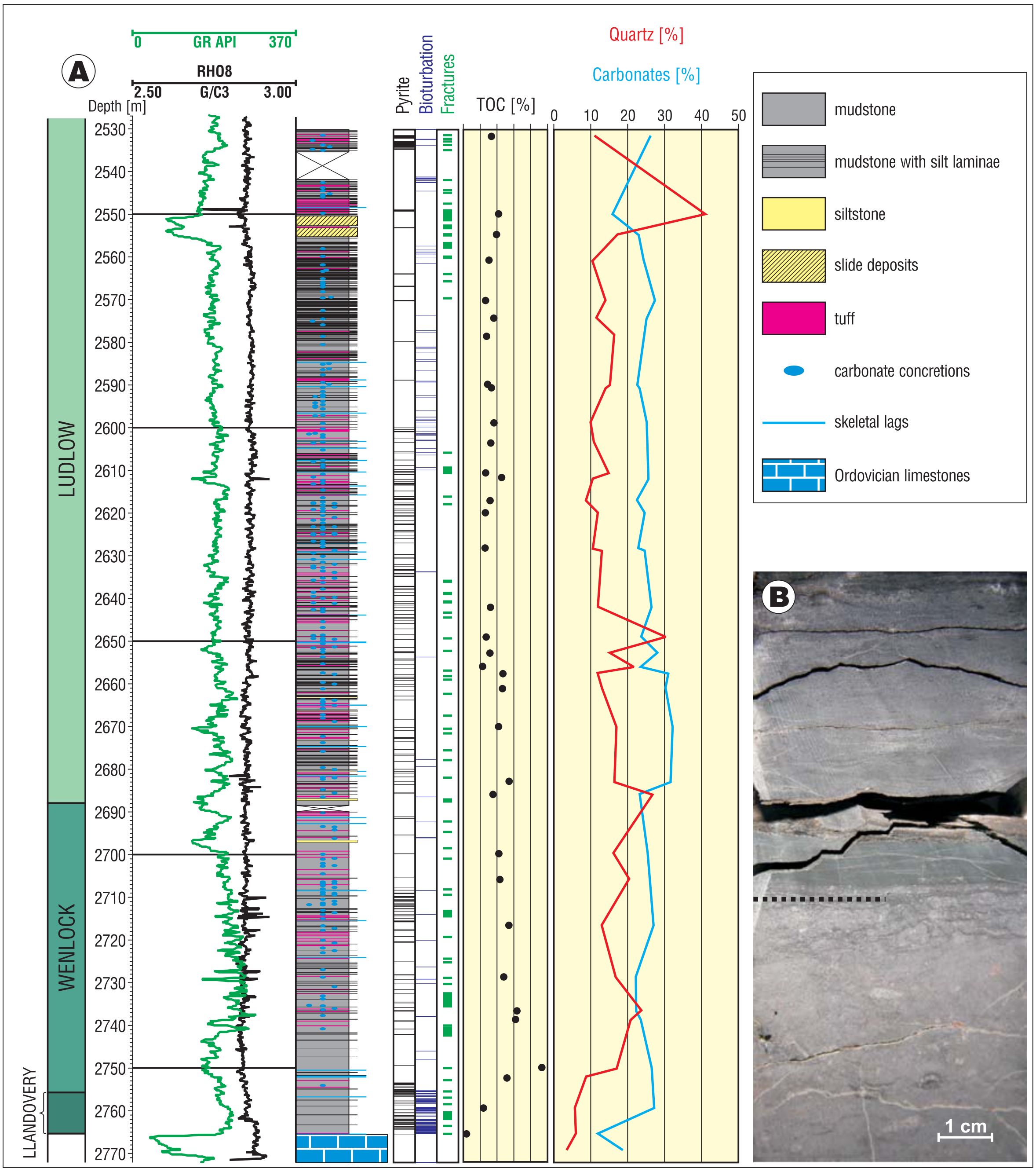

Fig. 5. A – log of the cored section from the Syczyn-OU1 well, showing main lithologies and the distribution of selected sediment properties. **B** – boundary between the Ordovician limestones and the overlying Llandovery shales, which is interpreted as a ravinement surface (dotted line). Horizontal split of the core in the centre of the photograph follows a tuff layer

strong seismic shaking would be consistent with the observed intensity and corrugated nature of ptygmatic deformation (Fig. 8C), knowing that such an intricate style of deformation is not typical for simple slope collapses caused by an increased sediment load. The primary bedding in a rotational slide generally tends to be rotated toward the parental slide scar. This criterion in the present case would then suggest a locally NE- to NNE-dipping paleoslope, opposite to the depositional dip direction of the Llandovery–Wenlock shelf ramp. However, this is just a working hypothesis, because the vergence of slump folds from a larger area is not known. Nevertheless, it is worth considering, because it implies orogenic sourcing for the slope clinoforms (Fig. 9).

SIGNIFICANCE OF SEQUENCE STRATIGRAPHY

Given a high surface productivity, the degree of organic carbon dilution in seafloor sediments is controlled primarily by the relationship between relative sea-level oscillations and sediment supply. This relationship can be best rationalized by a sequence stratigraphic approach. Recognition of base-level oscillations is essential for reservoir engineering, because they control geomechanical properties of reservoir mudrocks that are determined by detrital quartz, carbonate, biogenic silica, and pyrite contents (Lash & Engelder, 2011). On the basis of North American examples, Slatt (2011) proposed a generalized sequence-stratigraphic model for unconventional resource shale

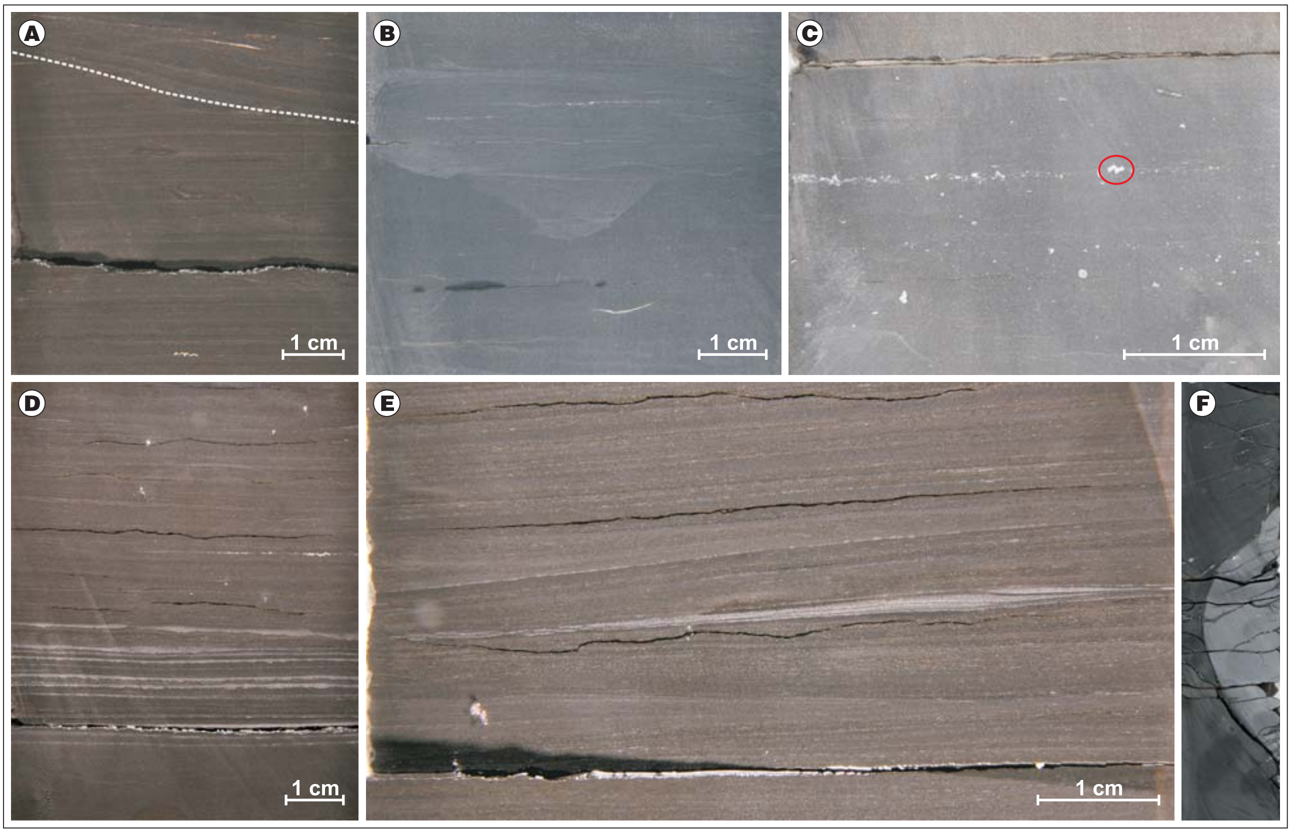

Fig. 6. Sedimentary structures in calcareous mudstones cored in the Syczyn-OU1 well: **A** – inclined erosional surface (dashed line), **B** – steep--sided scour-and-fill interpreted as gutter cast, **C** – skeletal lag showing imbricated crinoid stems (encircled), **D** – silt ripple lenses and plane parallel laminae showing load-casted bases, **E** – section through an erosively based, convex-up laminaset resembling hummocky cross--stratification, **F** – early diagenetic carbonate concretion surrounded by compactionally bent lamination. Width of the illustrated core is 7 cm

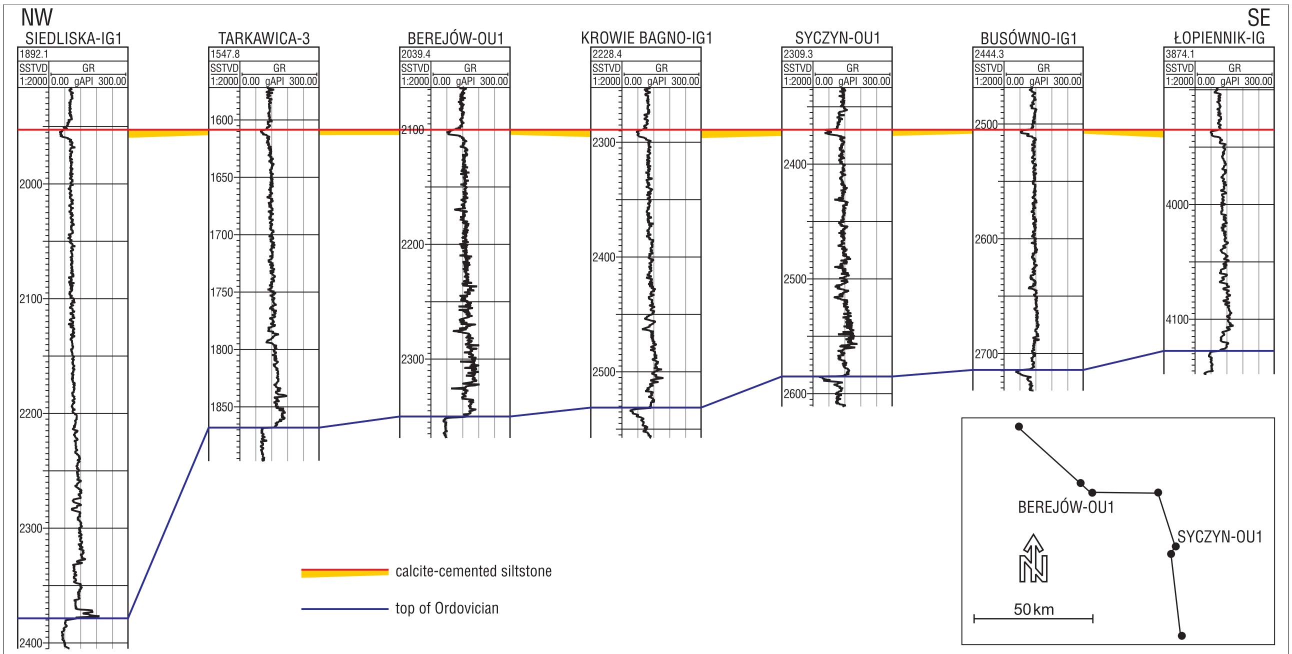

Fig. 7. Well-log correlation showing the conspicuous lateral persistence of low gamma-ray, calcite-cemented siltstone (yellow) throughout much of the Lublin Basin (depth below sea level)

formations. In this model, the shale sequence rests on a regional unconformity often merging with transgressive surface of erosion and commences with a carbon- and clay--rich interval of high gamma-ray response and signs of stratigraphic condensation. This basal interval passes gradationally upwards into siltier and/or more calcareous shales with a lower gamma-ray response. Depending upon biostratigraphic resolution, the upper interval can be divided into higher-order depositional sequences, possibly down to the 4th-order rank.

There seems to be a common consensus that the richest occurrence of organic matter tends to be limited to

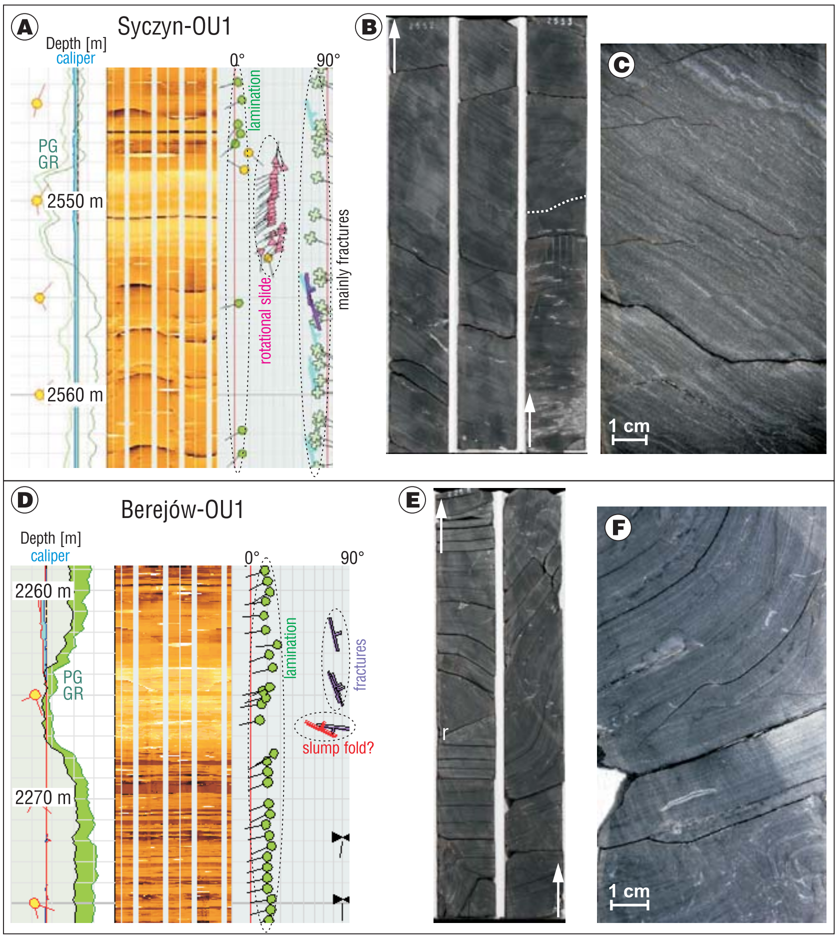

Fig. 8. FMI images, orientation of planar structures (**A**, **D**), and soft sediment deformations (**B**, **C**, **E**, **F**) encountered in the calcite-cemented siltstone forming a regional correlation marker in the Lublin Basin wells (see Fig. 7). **B** – rotational packet based by a non-planar glide(?) surface (dotted line). Arrows show the younging direction. Thickness of the section is 1.5 m. **C** – close-up view of the rotational packet, showing corrugated and liquefied silt laminae and numerous antithetic soft-sediment faults. **E** – large, upright to overturned slump fold overlain by the oppositely verging antiform that is dissected by a reverse fault (r) showing liquefied laminae in the footwall. Thickness of the section is 1 m. **F** – close-up view of the inferred slump fold, showing the contorted and liquefied silt laminae in the right lowermost part of Fig. 8E

a condensed interval associated with the maximum marine flooding (Loutit et al., 1988) and the sediment interval deposited just after the turnaround to regression, when the rate of relative sea-level rise begins to slow (e.g. Curiale et al., 1992). This sedimentation timing corresponds to the late transgressive and early highstand systems tracts, although the entire transgressive systems tract may be carbon-prone in the basinward reaches of a shelf ramp subject to fast transgression (Wignall, 1991; Bohacs, 1998). As a first approximation, therefore, the lateral tracing of the maximum flooding surfaces of major transgressive events appears to offer the best perspective for a prediction of carbon-rich source rocks in shaly successions.

Ten 3rd-order depositional sequences have been identified in the Silurian of the eastern part of the Baltic Basin (Lazauskiene et al., 2003). However, similar division for the pericratonic shale succession in Poland has barely begun (Jaworowski, 2000, 2002; Modliński & Podhalańska, 2010). Throughout much of its regional extent, the succession rests on a drowned unconformity and hiatus (Hirnantian–early Llandovery) that separates Ashgill carbonates, marls or local quartzose wackes from the overlying condensed section of Llandovery graptolitic black shales and passes westwards into a correlative conformity. The unconformity is interpreted to reflect a eustatic regression forced by the Hirnantian glaciations in Gondwana and followed by a rapid post-glacial onlap during the Early Silurian global warming and anoxia (Modliński et al., 2006; Podhalańska, 2009; Modliński & Podhalańska, 2010). According to Lazauskiene et al. (2003), the Llandovery transgression coincided with the initiation of flexural bending. In the Syczyn-OU1 and Berejów-OU1 wells, this unconformity separates the Ordovician limestones showing no signs of subaerial exposure from upper(?) Llandovery, dark gray, laminated and locally bioturbated calcareous mudstones. The unconformity is lined with small limestone clasts (Fig. 5B) and it is interpreted as a transgressive ravinement surface. In the Goździk-OU1 well (Garwolin area), the O/S boundary interval, 4.5 m thick, contains intercalations of diamictic mudrocks with dispersed sand, granules and small pebbles deposited probably from a floating ice (Kędzior et al., 2013; cf. Modliński, 1982). Cyclic variations in the frequency of silt intercalations, carbonate and clay contents and bioturbation intensity provide clues for parasequence identification. In particular, layers showing early-diagenetic carbonate concretions correspond to periods of stratigraphic condensation and some may contain flooding surfaces. Two major flooding surfaces with elevated TOC values are recognizable in the upper(?) Llandovery and Wenlock sediments. The abundant graptolites and occurrence of tephra layers offer a good possibility for tying up the key correlation surfaces into the existing biostratigraphic and the calibrating correlation scheme against a geochronological framework (work in progress).

RESERVOIR PROPERTIES

The two studied wells from the Lublin Basin have penetrated a homoclinal bed stack dipping consistently at 3°WSW (Syczyn-OU-1) to 9°W (Berejów-OU-1) and showing no deformation except for fractured intervals and minor faults. The breakout elongation in these vertical wells indicates the maximum horizontal stress in N-S (7–187°) direction, in agreement with regional stress-field data (Heidbach et al., 2008). Numerous single fractures and fracture zones were recognized in cores and measured in FMI logs. These are mainly steep (ca. 70°) fractures with sub-millimetre apertures, calcite-cemented and seldom

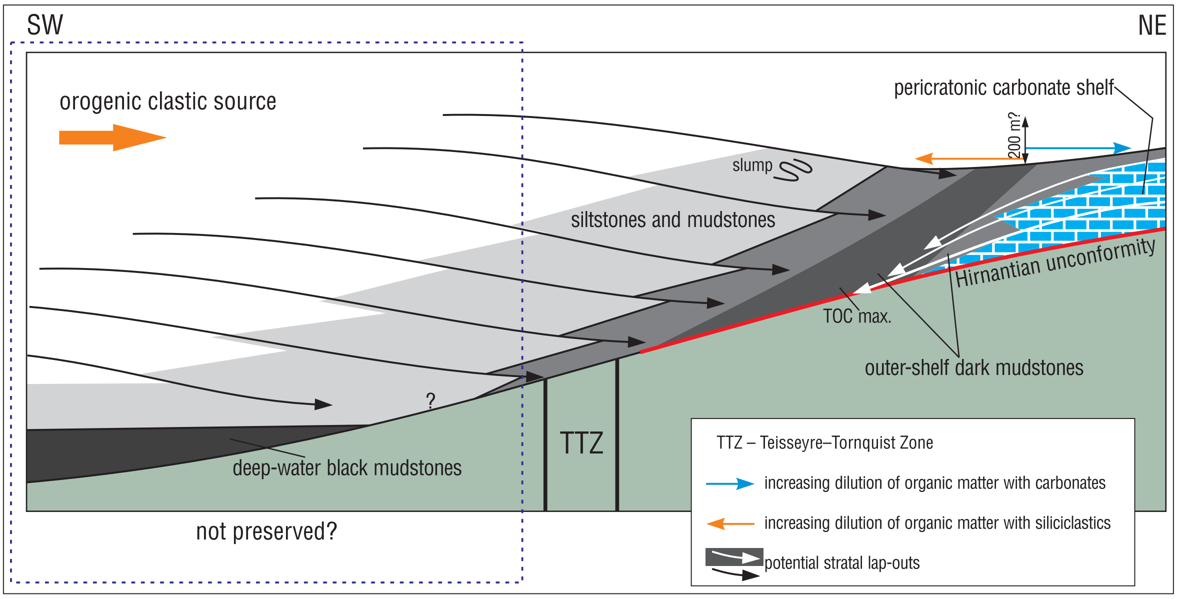

Fig. 9. Simplified depositional-stratigraphic model for Llandovery–lower Ludlow shales

open. They show a remarkable consistency in strike, which is NW-SE in the Syczyn-OU-1 well, but predominantly NE-SW and subordinately NW-SE in the Berejów-OU-1 well.

The Silurian shales show an effective porosity of up to 4.7%, permeability of up to 240 nD, and TOC content of up to 3.5%. Even though these values may seem to be on the low side, some stratigraphic intervals fulfil the economic pay criteria, which – together with the abundant signs of gas during drilling – warrant a production test with lateral wells. It is worth mentioning that even if the TOC values are relatively low, significant gas flow can be achieved provided that the reservoir rocks are within the dry gas window and under a thick overburden, as exemplified by gas production from the Haynesville Formation (Spain & Anderson, 2010; R. Miller – personal comm. 2013).

The observed frequent occurrences of carbonate cements (calcite 1–13%, dolomite 1–17%) increase the overall reservoir brittleness. Calcite is also the dominant component of early diagenetic concretions, which are densely distributed throughout the cored sections and appear to form barriers for the natural fractures observed there. The influence of these concretions surrounded by compactionally bent strata on the mechanical anisotropy and quality of the reservoir needs to be understood for proper well completion designs (cf. Suarez-Rivera, 2011). In both wells, the dominant basin-parallel ENE or NE dipping steep fractures have high shear stress and low effective normal stress load today, favourable for fluid transmissibility. Simulations of horizontal deviations suggest that a NE or SW direction is most advantageous for extensive artificial fracturing in this area (Ruehlicke & Hansen, 2012).

SUMMARY

Although the geology of the pericratonic Silurian shale succession in Poland appears well-constrained, it is still insufficient for a proper evaluation of its source-rock potential and a successful development of this emerging shale gas play. We believe that a further fundamental research should principally focus on: 1) the determination of the role of cratonic versus orogenic sources for the fine-grained siliciclastic material and the importance of advective transport for the redistribution of mud, 2) the identification of depositional and diagenetic factors controlling the trends in organic carbon distribution on regional and local scales, and 3) subdivision of the Silurian succession in terms of high-resolution sequence stratigraphy, because relative base-level oscillations have a major impact on the organic matter concentration and many other properties of the reservoir shale.

A preliminary stratigraphic model proposed here that needs critical testing assumes the deposition of the Llandovery–Ludlow mudrocks in the outer part of a pericratonic shelf ramp that was gradually downlapped from the west by gently inclined silty clinoforms fed from an orogenic source (Fig. 9). A less likely alternative is a basinal, "layer-cake" sheet showing a large-scale onlap towards the east. Deposition took place in relatively shallow-water anoxic/dysoxic conditions that were periodically interrupted by oxygenated storm currents halting the near-bottom anoxia. Clinoform toes in the youngest bundles occurred probably at depths not much exceeding the wave base of extreme storms (200 m?). The maximum TOC abundance seems to occur in the distal part of the ramp far beyond the clinoform toes, and organic matter is gradually diluted away from this area by carbonate (to the NE) and siliciclastic (to the SW) material. The preliminary data from the boreholes drilled by Orlen Upstream in the Lublin Basin indicate that the Llandovery–Wenlock shales show moderate to good reservoir properties, which warrant production tests in horizontal wells.

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