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KEY ASPECTS OF THE STRATIGRAPHY OF THE UPPER SILESIAN MIDDLE KEUPER, SOUTHERN POLAND

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Abstract: The stratigraphy of the Upper Silesian Keuper, a continental, mudstone-dominated succession is poorly known, although the already renowned, newly discovered veterbrate localities highlight the growing demand for a more precise intra-regional correlation and an appropriate stratigraphic reference framework. A major lithostratigraphic unit, preliminarily proposed for the middle Keuper (i.e., above the Schilfsandstein; Stuttgart Formation in "Stratigraphische Tabelle von Deutschland", 2002) by Szulc and Racki (2015; *Przegląd Geologiczny,* 63: 103–113), is described in detail. The redefined Grabowa Variegated Mudstone-Carbonate Formation, the unit previously based on inaccurately presented information, includes the Upper Gypsum Beds and the Steinmergelkeuper in the traditional scheme from Germany (= Weser and Arnstadt formations). Three members are formally defined: the Ozimek (Mudstone-Evaporite) Member, the Patoka (Marly Mudstone-Sandstone) Member and the Woźniki (Limestone) Member. Two significant bone-bearing horizons (Krasiejów and Lisowice) are placed within the Patoka Mbr. The formation thickness in a composite, regional reference section of the Upper Silesian Keuper, based on the new Woźniki K1 and Patoka 1 well profiles, is approximately 215 m thick. The Grabowa Fm generally correlates with the Norian stage, with the base located in the undefined upper Carnian, and is topped by a major, erosive disconformity and sedimentary sequence boundary, near the Norian-Rhaetian boundary. However, hiatuses in the Silesian middle Keuper succession are located and paired with a cannibalistic type of sand-mud flat deposition, largely controlled by Early Cimmerian movements of tectonic blocks associated with the Kraków–Lubliniec shear zone.

Key words:: Lithostratigraphy, biostratigraphy, disconformities, bone beds, Grabowa Formation, middle Keuper, Upper Silesia.

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INTRODUCTION

The Keuper-type Upper Triassic continental succession of Upper Silesia, mostly in the eastern margin of Upper Silesian Coal Basin, including variegated fine-grained siliciclastics, carbonates and evaporites, still is poorly known in terms of its stratigraphy. This is primarily due to the lack of a formalized lithostratigraphic scheme and the scarcity of fossils (including microfossils) has generated uncertainty with regard to biostratigraphic data (summary in Bilan, 1991; Szulc and Racki, 2015).

Determining the exact age of the Keuper succession in Poland as well as understanding the sedimentary palaeoenvironments are of paramount importance, particularly with regard to the famous discoveries of vertebrate remains in the Opole region (Dzik *et al.*, 2000), supplemented by several localities between Lubliniec and Zawiercie (Dzik *et al.*, 2008; Niedźwiedzki *et al.*, 2014). However, significant controversies exist as to age assignment and interpretation of the associated facies of the bone-bearing sections (Szulc, 2005, 2007b; Dzik and Sulej, 2007; Bodzioch, 2012; Szulc and Racki, 2015). Thus, understanding the Keuper geological and temporal framework is the key to reconstructing the Silesian vertebrate record (Racki, 2010).

This situation creates an urgent need for multidisciplinary research of the poorly-known Upper Triassic strata in Silesia around the whole outcrop belt over a distance of more than 80 km, from Opole to Zawiercie (Figs 1, 2). The major goal of the project "The evolution of terrestrial environments of the Upper Silesian Keuper as biotopes of vertebrates" (N N307 11703; Racki, 2010), funded by the Ministry of Science and Higher Education, was an exhaustive, in-

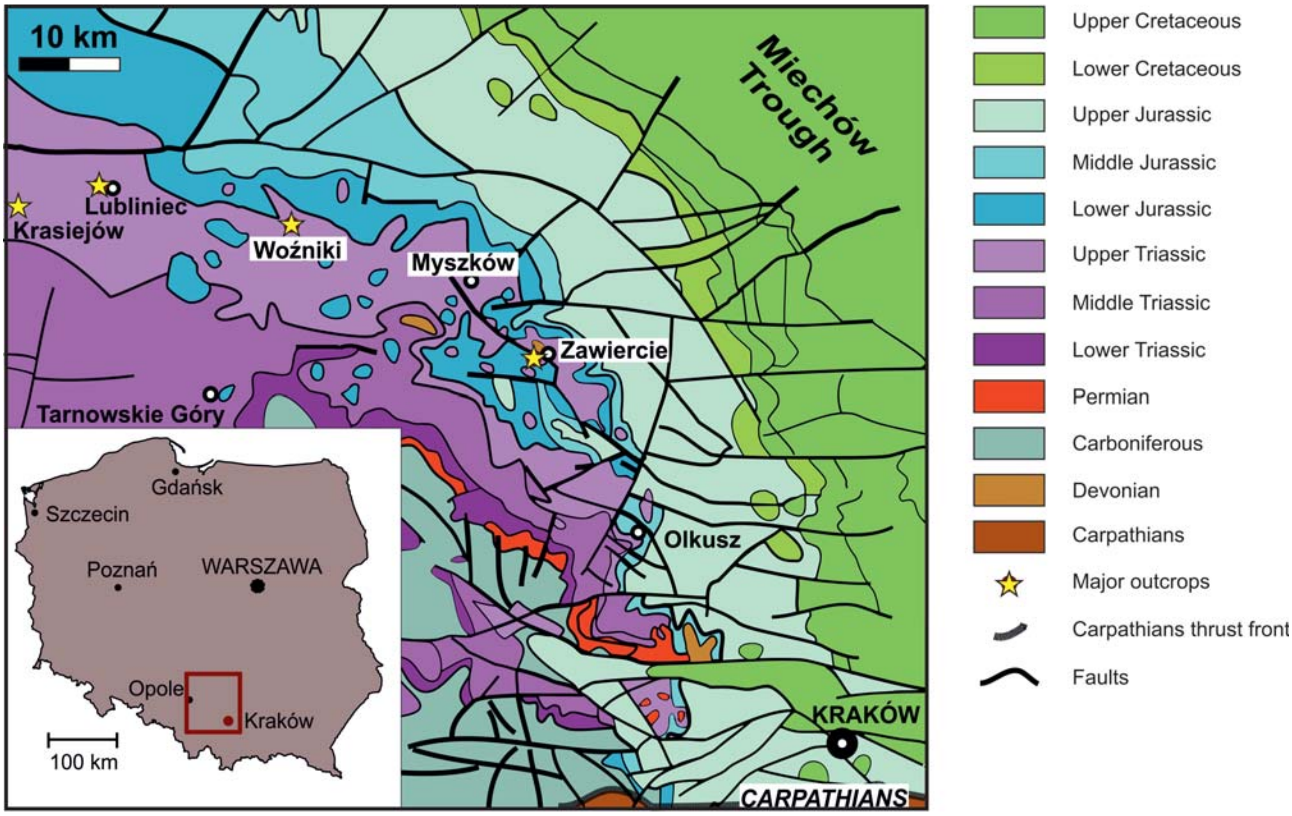


Fig. 1. Geological map of the area studied (after Marks *et al.*, 2006, modified; see Fig. 2 for the location details of the sections studied).

tegrated study of the bone-enriched Keuper interval in terms of stratigraphy, sedimentology, mineralogy and geochemistry. This article complements an introductory proposal of a lithostratigraphic revision in Polish by Szulc and Racki (2015), a stratigraphic setting to an accompanying polemical review of the age, correlation and origin of the Upper Silesian bone beds by Szulc *et al.* (2015), and other papers in this ASGP thematic issue.

Supplementary material is available online at: http://www.ing.pan.pl/Keuper/Bone-bearing_Keuper-1.htm including photographic documentation of drill cores.

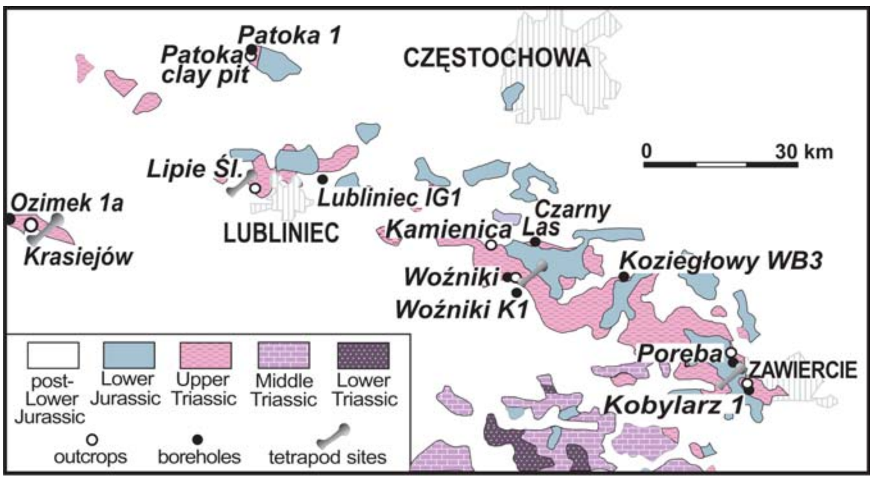


Fig. 2. Simplified geological map (after Bardziński and Chybiorz, 2013) showing the location of the localities studied (outcrops and boreholes) and Triassic to Lower Jurassic surface strata (see the regional geological setting in Fig. 1).

REGIONAL SETTING AND STRATIGRAPHIC ISSUES

The Keuper Group is a predominantly alluvial, fluvial and lacustrine, fine-siliciclastic succession, with subordinate, intercalated evaporites and carbonates (Fig. 3), developed within the Germanic (or Central European) Basin (e.g., Mader, 1997; Reinhardt and Ricken, 2000; Beutler and Nitsch, 2005; Feist-Burkhardt *et al.*, 2008; Bachmann *et al.*, 2010). This low-relief continental basin stretched from western France and Germany to Poland in the east, with an evolving playa system in its vast, central part (Fig. 4). Synsedimentary Early Cimmerian block movements are clearly evidenced by several erosional disconformities and abrupt thickness changes (e.g., Znosko, 1954; Deczkowski and Gajewska, 1977; Deczkowski and Franczyk, 1988; Deczkowski *et al.*, 1997; Bachmann *et al.*, 2010; Beutler *et al.*, 2012). In Poland, these sediments can be observed at the surface in a few outcrops (mostly in

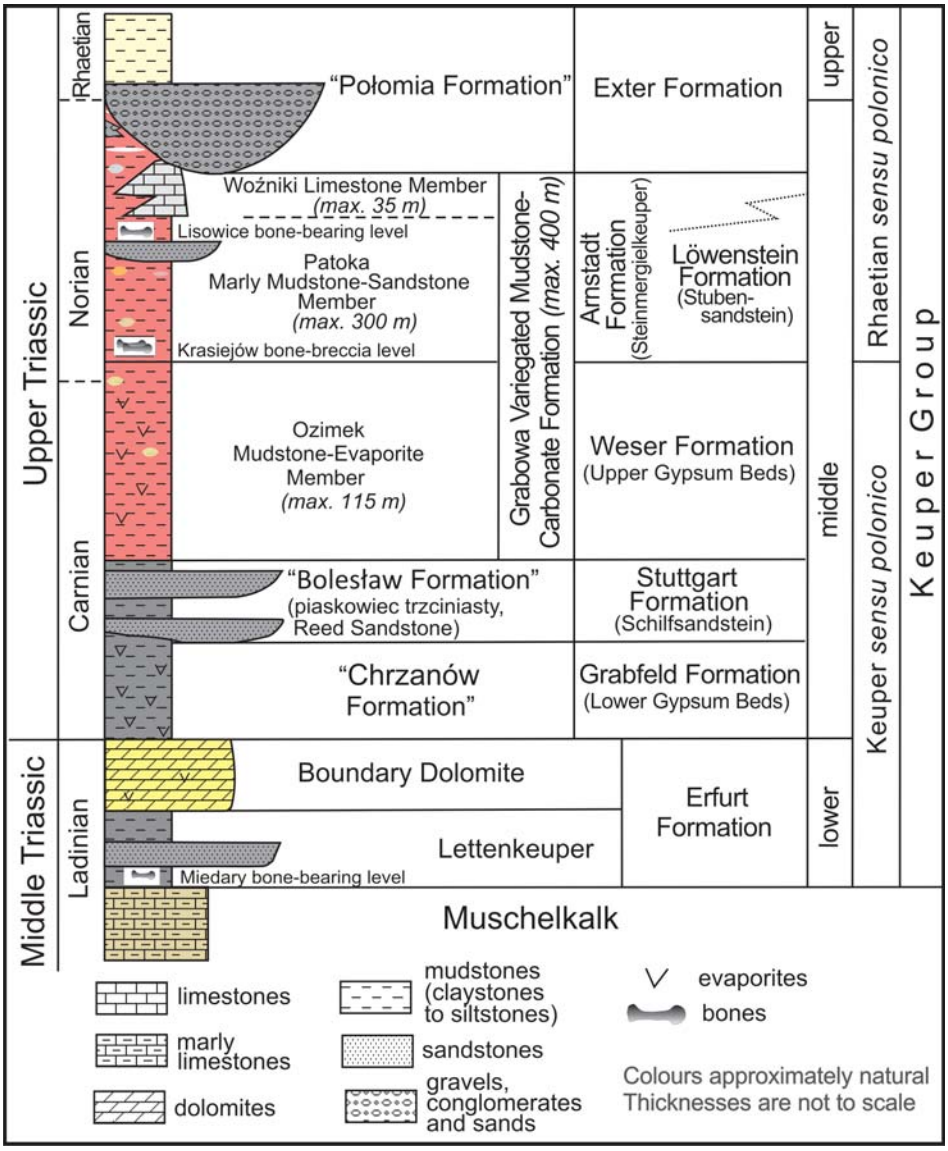


Fig. 3. Schematic section of the Upper Triassic of Upper Silesia, with its partly formal (in upper part) lithostratigraphic subdivision after Szulc and Racki (2015) and a distinct colour evolution from grey to a variegated-spotty succession of the Grabowa Fm (modified, after Jewuła, 2010, fig. 4), with a focus on correlation with the Germanic Basin reference units ("Stratigraphische Tabelle von Deutschland", 2002; Franz, 2008). Informal formations (Chrzanów, Bolesław) based mostly on Becker *et al.* (2008), partly differing from units originally defined by Bilan (1976) and Kotlicki (1995). Note the occurrence of three bone-enriched levels in the Silesian Keuper, but two in the Upper Triassic.

small clay pits; see Nita and Nita, 2014a, b), mainly within the north- eastern margin of the Upper Silesian Coal Basin (Fig. 2) and along the borders of the Holy Cross Mountains. The distribution of the Keuper in Poland, however, is much broader, and this lithofacies has been recognized also in numerous boreholes in central and western Poland [the so-called Polish Basin or (Mid-) Polish Trough; e.g., Gajewska, 1973, 1978, 1988; Deczkowski and Franczyk, 1988; Bachmann *et al.*, 2010; Pieńkowski *et al.*, 2014; Fig. 4].

The Silesian Upper Triassic succession (Fig. 3), in palaeogeographic terms, corresponds to the marginal eastern part of the Germanic Basin (Fig. 4), mostly within the Bohemian Massif provenance domain (e.g., Beutler and Nitsch, 2005; Konieczna *et al.*, 2015), with the exception of the eastern portion (Fig. 5). The source regions were controlled, since the Middle Triassic by Cimmerian uplift movements (Szulc, 2000; Paul *et al.*, 2008). Variegated, fine-grained clastics, and locally evaporites (mostly preserved as pseudomorph gypsum spheroids) and spring carbonates are the most common types of deposit, as the depositional record of ephemeral-lake and fluvial systems, developed under mostly arid to semi-arid climatic conditions with some pluvial interludes (Pieńkowski, 1988; Szulc *et al.*, 2006, 2015; Szulc, 2007a). The Keuper Group is up to 400 m thick in the region and thickens gradually toward the north, where, in the depocentre of the Polish Basin, it attains a thickness of 2,000 m (Deczkowski *et al.*, 1997).

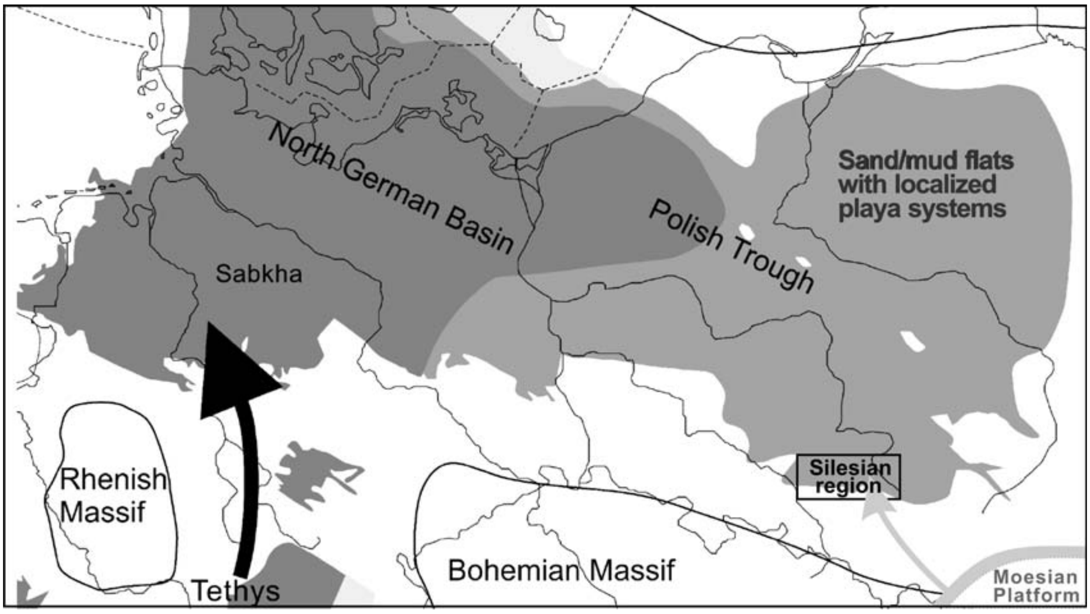


Fig. 4. Palaeogeographic location of Upper Silesia region and present-day distribution and facies map of the Norian (Steinmergelkeuper, modified from Feist-Burkhardt *et al.*, 2008, fig. 13.24B). Solid lines represent the reconstructed eastern Germanic Basin outline, the black arrow indicates the marine ingression from the Tethys Ocean and the grey ones illustrate possible clastic supply from the Moesian terrane (see Fig. 5).

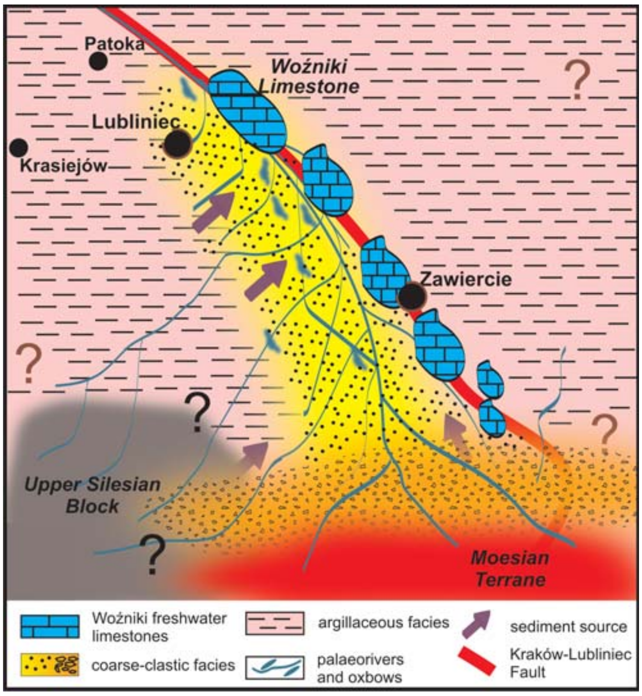


Fig. 5. Schematic representation of mid-Norian palaeogeography and sedimentary palaeoenvironments of the eastern part of Upper Silesia (note: not in scale). Two potential major sources for detritus distributed by fluvial sedimentation are shown by means of arrows: the Moesian terrane (inferred from compositional spectrum of coarse-grained clastics; Mariusz Paszkowski, pers. comm., 2014; cf. Tari *et al.*, 2012) and Upper Silesian Basin. Active faulting, related to the Kraków-Lubliniec sinistral(?) shear zone, promoted a carbonate spring depositional system (Woźniki Mbr; Szulc *et al.*, 2006, 2015), and also primarily controlled the development of hiatuses and unconformities over the uplifted blocks.

In Germany, the Keuper, as an informal lithostratigraphic unit, was subdivided into three parts: lower, middle and upper, whereas in Poland the Keuper was traditionally divided into the lower and upper Keuper only, with the Rhaetian treated as a self-contained unit. These differences were, and still are a source of misunderstanding (see below). However, the Keuper lithostratigraphy is in particular not a very good stratigraphic tool, as it is subjective, and lacks distinctive marker horizons; neither volcanogenic intercalations, nor impact ejecta (Walkden *et al.*, 2002) were discovered in this study. It is impossible to use the lithostratigraphic scheme to correlate Central Poland to the basin's margins, especially in such varied terrigenous environments. Therefore, the selection of an appropriate reference succession for long-distance correlation is of prime importance (see discussion on German equivalents of the Silesian bone-bearing sites in Szulc *et al.*, 2015). The highly active syn-sedimentary tectonics (see Fig. 5) additionally created local depocenteres, where the sedimentary rate was obviously much higher than elsewhere, but also influenced the distribution of erosional disconformities (see Bilan, 1976; Grodzicka-Szymanko, 1978; Deczkowski *et al.*, 1997).

The recognition of lithostratigraphic units in the field or in drill cores is often difficult, mainly owing to the lack of distinctive features and the relatively monotonous lithology. Facies analysis of the studied succession in the Upper Silesia area has shown considerable palaeoenvironmental changes and variation in formation thickness, as expected for terrigenous, fluvial-dominated environments.. Additionally, it is widely accepted that the sedimentary succession of the terrigenous Keuper deposits is diachronous and that sedimentation started in the eastern part of the Germanic Basin, whereas in the west, marine conditions prevailed at that time (Szulc, 2000).

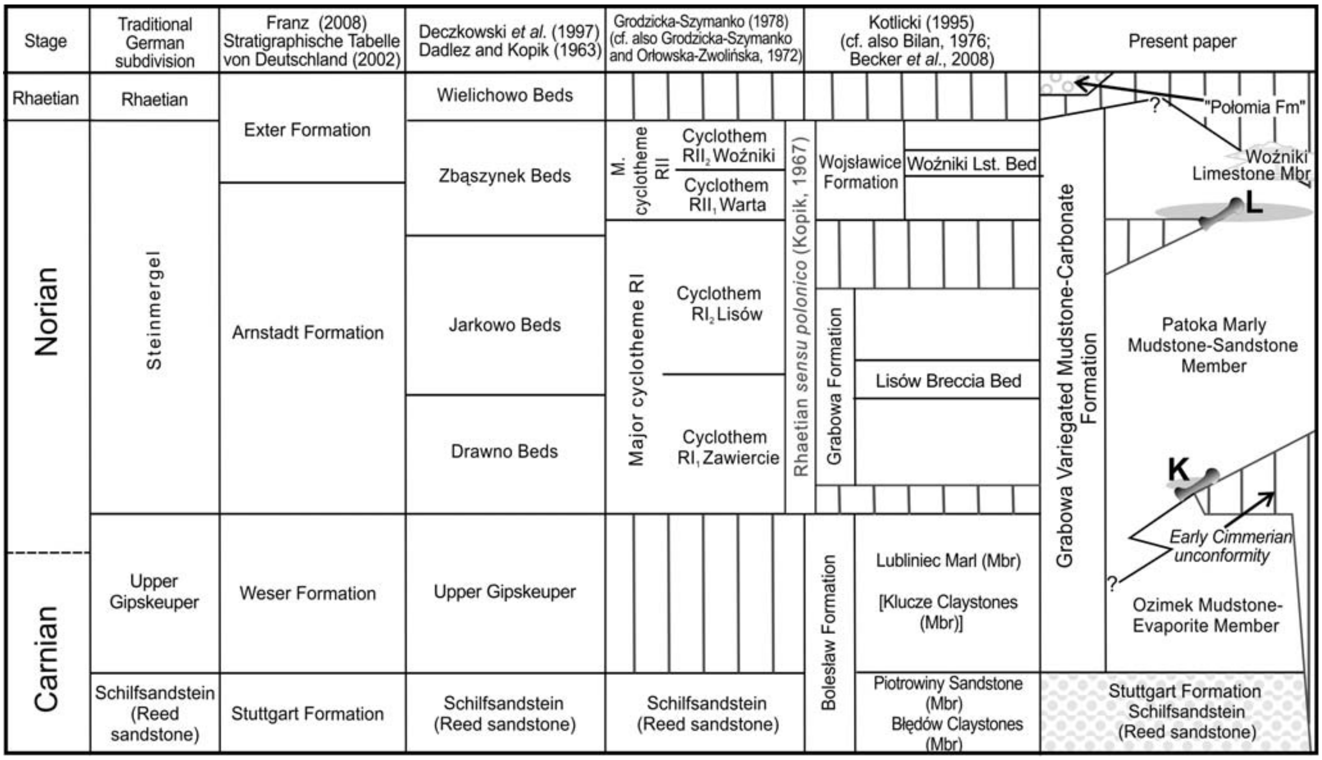


Fig. 6. Overview of selected lithostratigraphic subdivisions of the Upper Triassic succession in the German Basin and Upper Silesia (modified from Szulc and Racki, 2015, fig. 7; see also Senkowiczowa, 1980, table 2); bone-bearing levels: Krasiejów (K) and Lisowice (L) are marked (see Fig. 3).

Another issue in the formal determination of a formation in the area studied is caused by the way geological boundaries are defined. For instance, in the central part of the Polish branch of the Germanic Basin, a thick and distinctive anhydrite bed has been described, which partly defines the boundary between the Upper Gypsum Beds and the Shilfsandstein (Deczkowski *et al.*, 1997). In the more proximal facies, this anhydrite bed pinches out, which makes the distinction of these formations very difficult. The possibly diachronous facies transition from evaporite playa to fluvial-dominated Steinmergel-type deposition remains a complicating argument for the dating of the Krasiejów section (Szulc *et al.*, 2015). The longer persistence of hypersaline regimes in the distal Silesian localities is indicated by chemostratigraphic correlation (Środoń *et al.*, 2014). However, this attractive notion in fact is strongly affected by the disputable lithostratigraphic affiliation of some deposits (see below). The question awaits more extensive supra-regional study.

STATE OF STRATIGRAPHY AD 2015

Over the past one hundred years, geological studies of the Upper Silesian's Keuper successions have been undertaken and many lithostratigraphic schemes have been proposed (Fig. 6). German geologists (Römer, 1862, 1863, 1867, 1870; Assmann, 1926, 1929; among others) established the classical lithostratigrapic subdivisions, which still can be regarded as relevant. After World War II, geological research, focused on stratigraphic aspects, was carried out by Polish geologists, such as Znosko (1954, 1955), Szyperko-Śliwczyńska (1960), Deczkowski (1963, 1977), Grodzicka-Szymanko (1971, 1978), Grodzicka-Szymanko and Orłowska-Zwolińska (1972), Kopik (1973), Kotlicki (1974, 1995), Bilan (1975, 1976, 1991), Orłowska-Zwolińska (1983, 1985), Deczkowski *et al.* (1997) and Szulc (2005, 2007a). Most recently, a new, formal lithostratigraphy of the middle Keuper of Upper Silesia has been proposed by Racki and Szulc (2015; see below).

Lithostratigraphy

Despite several proposals of lithostratigraphic units and supra-regional correlations of the Upper Silesian Keuper (see summary in Fig. 6), the lack of a consistent regional scheme, encompassing formally defined units. is a major hindrance to further progress. Several practical approaches, frequently mixed, as shown in the "Stratigraphic Table of Poland" (Becker *et al.*, 2008; also e.g., Dzik and Sulej, 2007), can be identified:

1. As stressed above, obviously from a historical viewpoint (e.g., Siemiradzki, 1903; Assmann, 1929; Szyperko-Śliwczyńska, 1960), there is an application and thus direct correlation with the standard scheme of the western Germanic Basin, both in traditional (Schilfsandstein, Gipskeuper, Steinmergelkeuper, etc.) and modern formal terms (after "Stratigraphische Tabelle von Deutschland", STD 2002; Franz, 2008; Menning *et al.*, 2012), exemplified recently by the work of Środoń *et al.* (2014).

2. Application of informal subsurface divisions in western-central Poland, proposed in particular by Dadlez and Kopik (1963) and modified by Deczkowski *et al.* (1997), and was practised most recently by Niedźwiedzki *et al.* (2014) and Pieńkowski *et al.* (2014).

3. Diverse informal regional lithostratigraphic units were proposed by Kotlicki (1974), Kotlicki and Kubicz (1974) and Bilan (1976), and also in many cartographic works for the "Detailed Geological Map of Poland 1 : 50 000" (e.g., Haisig *et al.*, 1983; see synoptic table 2 in Kotlicki and Włodek, 1976).

4. There was consideration of the Keuper succession in terms of depositional cyclothems and/or units separated by tectonically-controlled large-scale stratigraphic hiatuses (Grodzicka-Szymanko, 1971, 1978; Grodzicka-Szymanko and Orłowska-Zwolińska, 1972; Becker *et al.*, 2008), that is, as allostratigraphic units (see Racki and Narkiewicz, 2006).

Till now, despite discussion of some variants already by Senkowiczowa (1980), formal units were not defined. That is, even if some basic units, formations, were proposed and described (e.g., "Grabowa Formation", Bilan, 1976; Kotlicki, 1995; "Połomia Formation". Jakubowski, 1977), especially stratotype sections were not indicated (or preserved in drill cores; see Alexandrowicz *et al.*, 1975, and Racki and Narkiewicz, 2006). Thus, many poorly-defined regional informal units are presently used, such as the Chrzanów and Bolesław "formations", the Lisów Beds and the Woźniki Beds (Szulc *et al.*, 2006; Becker *et al.*, 2008). Unfortunately, the most detailed and formal scheme by Kotlicki (1995) has remained unpublished as an archival report.

It seems that in many other cases, the Keuper lithostratigrahic definitions were influenced by palynostratigraphic dating and *vice versa*, that is, circular reasoning was used in a clearly chronostratigraphic context. For example, Dadlez and Kopik (1963) define the ashy, grey and brown-grey colours as the most diagnostic feature of the Rhaetian Wielichowo Beds, distinguishable from other more variegated (red-violet) Keuper units, supplemented by the presence of light kaolinite clays, siderite spherulites and coaly streaks. However, these strict lithostratigraphic criteria are inapplicable to many long-distance correlations, and, for example, the Wielichowo Beds were recently characterized, among other things, as "red-brownish, yellow-greenish, or variegated mudstones" (Pieńkowski *et al.*, 2014, p. 271). In contravention of the rules of the international stratigraphic code, the "beds" were in fact later considered as geological time units, i.e., approximated to the chronostratigraphic category.

In summary, the mixed litho-, allo- and chronostratigraphic aspects of several proposed units and their correlation is still obvious, and, for example, the term Rhaetian is used both as an lithostratigraphic unit (= Rhaetian *sensu polonico*; Kopik, 1967, 1973; Grodzicka-Szymanko, 1978; Bachmann and Beutler, 2007) and as a formal stage.

Biostratigraphy

Stratigraphic relationships of the Keuper profiles within Silesia region are still uncertain because of the paucity of age-diagnostic biostratigraphic data. As reviewed by Bilan (1991; compare e.g., Znosko, 1955; Grodzicka-Szymanko, 1971, and Kotlicki, 1974), micropalaeontogical data with a focus on palynomorphs, charophyte algae and ostracods, are far from sufficient to establish a reliable biozonation; the foraminiferal record is too scarce (and not confirmed in the present study) to provide any inferences about successions. Only some characteristic facies-controlled assemblages may be recognized, but essentially are limited to particular lithostratigraphic units, that is, below the resolution level of a stage. For example, one charophyte zone (Auberbachichara rhaetica) and one ostracod zone (Pulviella silesia) are the approximate equivalent of the Grabowa Formation *sensu* Bilan (1976; see Bilan, 1991, fig. 1).

Palynology appeared to be the most suitable biostratigraphic tool, with similar distributions of palynomorphs known to occur across the Germanic Basin (e.g., Kürschner and Herngreen, 2010). Microspore data are more useful for lower segments of the Silesian Keuper successions, whilst its middle part and poorly defined upper part were assigned by Orłowska-Zwolińska (1983, 1985) to the Corollina (now Classopolis) meyeriana IVb and IVc subzones (see also Deczkowski *et al.*, 1997; Marcinkiewicz *et al.*, 2014). In addition, as stressed by Szulc and Racki (2015) and Szulc *et al.* (2015), this biozonation is inconclusive for more high-resolution dating in its Norian part (compare Cirilli, 2010). Megaspore data are of even lower resolution in this interval (see Marcinkiewicz *et al.*, 2014).

Triassic conchostracans were expected to be a reliable substitute tool to palynology-based inferences in terrestrial stratigraphy (e.g., Kozur and Weems, 2010). Two conchostracan zones are recently identified at the Krasiejów and Lipie Śląskie sites by Kozur and Weems (2010). However, arguments regarding the uncertainty of the zonation were presented by Becker (2015) and Maron *et al.* (2015), especially because of the ambiguous taxonomy and speculative terrestrial-marine correlations, based in fact on single conchostracan successions (see also Kozur *et al.*, 2013).

Among the invertebrate macrofauna, only the bivalve *Unionites posterus* (Deffner and Fraas) (= *Unio kaiperinus* Römer; see Śliwiński, 1964, p. 41) was named as a guide species for the higher Rhaetian strata of Upper Silesia (*sensu polonico*; Bilan, 1976; see also e.g., Dadlez and Kopik, 1963; Grodzicka-Szymanko, 1971; Kopik, 1973; Deczkowski *et al.*, 1997; Bachmann *et al.*, 2010), but Śliwiński (1964, p. 40) reported a "limestone bed with *Unio*" from the lower Keuper. Noteworthy, this species is not confirmed at Silesian localities in the recent study by Skawina and Dzik (2011), who reported only two new common species (see Fig. 15C).

Vertebrate evolutionary/biochronological data, despite enormous current progress, are still conjectural, owing to zoogeographical and taxonomical constraints (Szulc *et al.*, 2015). On a supra-regional scale, the stratigraphic ranges of taxa are still barely known to such a degree that any attempt at a zonal approach to vertebrate biochronology is invariably at the initial stage. Hence, previous dating and correlative inferences for the Silesian vertebrate localities are poorly documented and flawed, and ignored the divergent results of other authors (Szulc *et al.*, 2015; cf. also Lucas, 2015).

In consequence, the timing of the lithostratigraphic boundaries and their relationships to stage boundaries are still mostly vague and conjectural, especially for the Silesian middle Keuper. This is especially notable for its higher part, where palynological data are invariably impoverished or lacking (Orłowska-Zwolińska, 1983, 1985). In fact, these crucial weaknesses have exacerbated significant general uncertainties in the non-marine Upper Triassic chronostratigraphy and geochronology (Ogg, 2012), as summarized by Szulc *et al.* (2015; see also Lucas, 2015).

METHODS AND RATIONALE

As a starting point, in addition to the general geological sketch of the Triassic deposits of Upper Silesia (from Zawiercie to Krasiejów, on a scale of 1: 300 000; Fig. 2), more detailed cartographic-geological works were performed in five important Keuper outcrop areas (at an approximate scale of 1: 25 000; Bardziński and Chybiorz, 2013), with a particular focus on the thus far poorly understood border area of Zawiercie and Poręba towns (Szulc *et al.*, 2015). Next to the verified archival cartographic documentation and its photo-interpretive refinement, geophysical field studies in three selected areas were a part of the output of the project. Geophysical measurements with the combined application of geo-electric, electromagnetic and seismic methods, have made it possible to obtain a better understanding of the shallow geological structure to a depth of 50 m. In particular, the use of electric resistance tomography for subsurface imaging showed the geological contrast between the Krasiejów and Lipie Śląskie (an undisturbed succession of horizontally stratified lithosomes) and Zawiercie-Marciszów (displaced by faults; Idziak, 2013; see Szulc *et al.*, 2015, fig. 16).

Within the framework of the grant, two new boreholes, Patoka 1 and Kobylarz 1, were drilled by the company Geofizyka-Toruń for the Institute of Geological Sciences PAS. In June 2012, the first well core, Kobylarz 1, in the western Zawiercie town and with a length of 55 m, was obtained with middle Keuper strata directly below the Woźniki limestone, the regional marker level (Szulc *et al.*, 2006). In the case of the deeper borehole, Patoka 1, at Patoka Brickyard Industries Ltd, this was drilled in August 2012, to a depth of 208 m, of which 192 m is in a relatively diversified Keuper succession, from gravels (including the topmost Połomia-type cyclothem) to blackish claystone sets.

From other shallow boreholes, two well-preserved cores were obtained: Woźniki K1 (90 m in length; recovered for and stored at the University of Silesia in 2008 within the framework of the hydrogeological project of Krystyn Rubin; Rubin and Rubin, 2009) and Koziegłowy WB3 (151 m in length; obtained from the Archive of Geological Samples and Cores of the Polish Geological Institute at Kielniki, near Częstochowa). Both profiles include a long Keuper interval from the Boundary Dolomite at the bottom up to the Woźniki Limestone in the Koziegłowy WB-3 section.

The detailed lithological-sedimentological logging of the well cores by the first co-author was supplemented by reconnaissance work at outcrops, studied earlier by the third co-author in his Master's thesis research (Jewuła, 2010). This introductory work provided an analytical basis for further sampling. Two profiles that are complementary to each other, Woźniki K1 followed in the succession by Patoka 1, are considered to be the regional reference section, about 260 m length. An integrated stratigraphic study began with a formal lithostratigraphic scheme (Szulc and Racki, 2015). The multidisciplinary studies finally made possible a better understanding of the vertical and lateral variability of Upper Triassic mudstone strata, particularly in the crucial context of the bone-enriched levels (Szulc *et al.*, 2015). Extensive biostratigraphic, magnetostratigraphic and especially mineralogical-geochemical (chemostratigraphic) work on these sections are presented by Fijałkowska-Mader *et al.* (2015), Nawrocki *et al.* (2015) and Środoń *et al.* (2014). The significant array of new results is discussed and conceptually finalized in a comprehensive stratigraphy-facies model with a climatostratigraphy orientation in Szulc *et al.* (2015).

OUTCROPS AND BOREHOLES STUDIED

The bone-bearing successions, exposed at a few localities between Opole and Zawiercie (Figs 1b, 2) and presented in several papers (e.g., Dzik *et al.*, 2000, 2008; Sulej *et al.*, 2012; Niedźwiedzki *et al.*, 2014), are reviewed in the updated geological and stratigraphic contexts in the accompanying synoptic article (Szulc *et al.*, 2015). Below only some other key sections are described for the first time in detail (all lithological successions are graphically presented in Fig. 18).

Woźniki area

In addition to the well-known clay-pit succession, where a bone-bearing red to grey mudstone series is exposed (Sulej *et al.*, 2011), the extended succession, ca. 45 m thick, including the Woźniki limestone set (15 m thick), was penetrated by the Woźniki well (Szulc *et al.*, 2006). The limestones crop out in small, abandoned quarries along the nearby Woźniki Swell (Gąsiorowski *et al.*, 1986; Szulc *et al.*, 2006; Nita and Nita, 2014a, b).

A noteworthy borehole was located 2.3 km SE of the clay pit (Rubin and Rubin, 2009). The Woźniki K1 core, 90 m in length, includes a long Keuper interval below the Woźniki limestone, from the Boundary Dolomite at bottom (Fig. 7). All of the traditional German units were distinguished, including the Schilfsandstein (Reed Sandstone), and the stratotype of the bottom of the Grabowa Fm is placed in this profile (Fig. 8B–D). In particular, the red to brown mudstone series of Steinmergel type, ca. 34 m thick, with horizons of carbonate nodules ("Lisów breccia"; see below), dolocretes and regoliths, occurs in the upper part of the section, whilst evaporite nodules and collapse breccias are characteristic features of the underlying spotty-variegated mudstone set (see Szulc and Racki, 2015, fig. 3F; Fig. 8E, F).

Patoka clay pit

This relatively large (800 m × 300 m, up to 25 m depth; Figs 9, 10A), longitudinally elongated excavation is situated at Patoka, a suburb of the village of Panoszów, 15 km

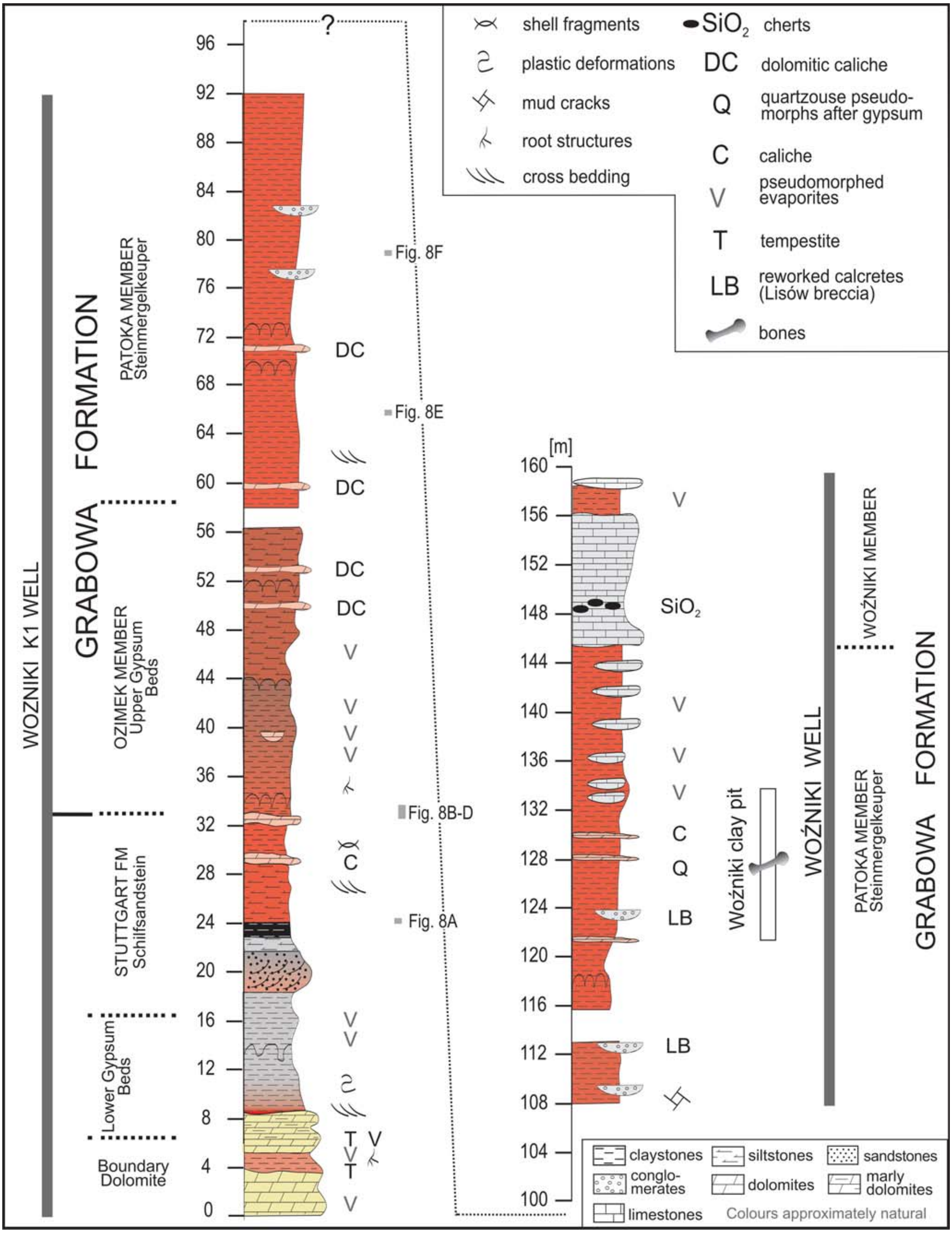


Fig. 7. Composite section of the lower to middle Keuper succession of the Woźniki area (see Figs 2, 8). The Woźniki well section, modified from Szulc *et al.* (2006, fig. 5), with changed position of the gypsum-bearing deposits. For more detail of the clay-pit succession see Sulej *et al.* (2011) and Szulc *et al.* (2015).

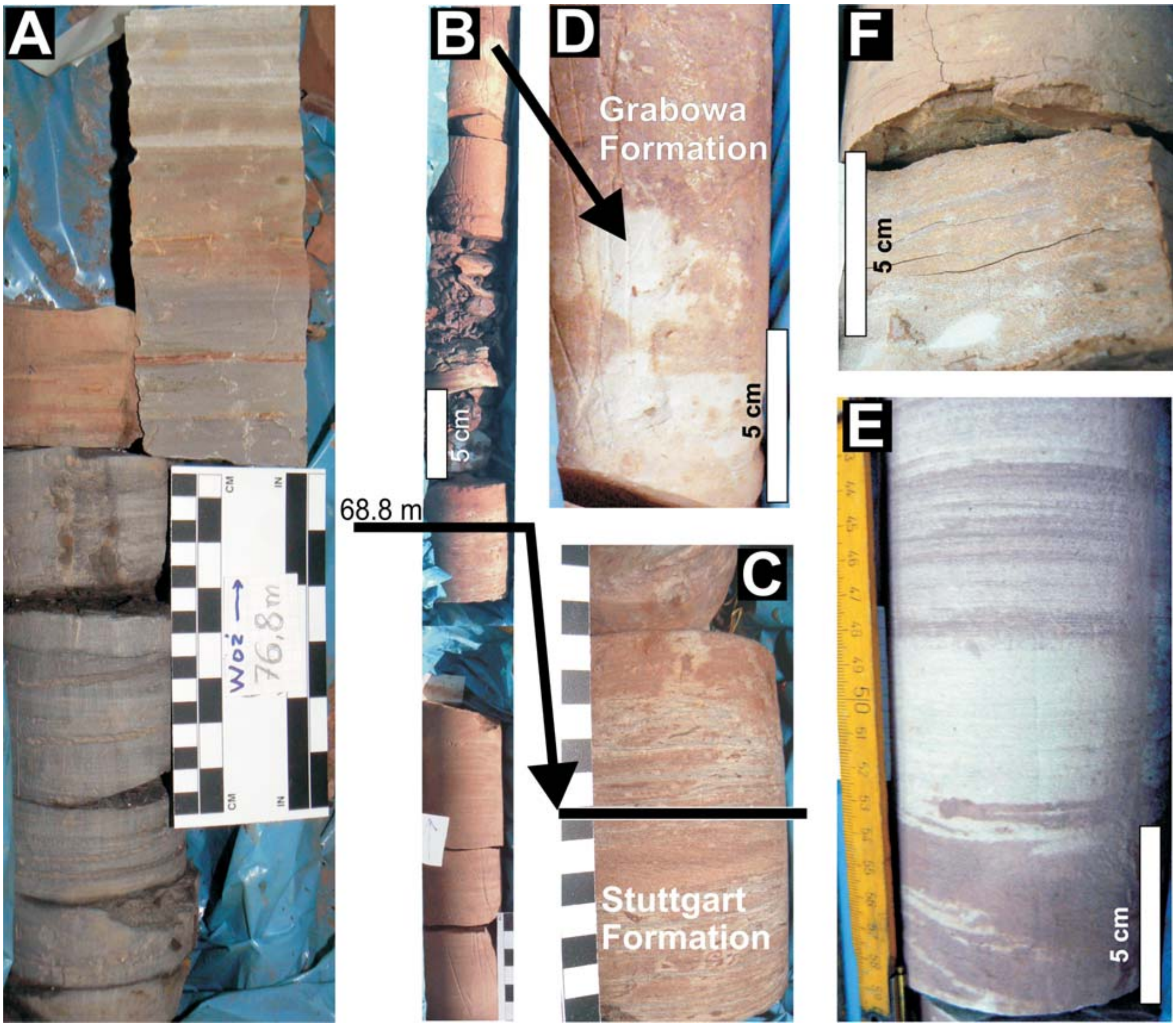


Fig. 8. Transitional interval between the Stuttgart Fm and Grabowa Fm in the section of the Woźniki K1 borehole (Fig. 7), as a stratigraphic setting of the stratotype of the lower boundary of the Grabowa Fm (see Szulc and Racki, 2015, figs 3A–C, F and 5). **A.** Typical plant debris-bearing sandstones of the Schilfsandstein (depth 76.7–76.95 m). **B, C, D.** Overall (B) and close-up views (C, D) of the stratotype of the base of the Grabowa Fm at the top of a red, flaser-bedded silty layer (depth 68.8 m). **E, F.** Variegated mottled mudstones and sandstones of the Patoka Mbr (depth 36.4–36.55 and 23.9–24.0 m, respectively; compare Szulc and Racki, 2015, fig. 3F).

N of the town of Lubliniec. The red clayey middle Keuper deposits have been exploited as a ceramic resource, probably since the 1880s (Wyszomirski and Galos, 2007), and recently for the brickyard of Patoka Industries Ltd.

The uppermost exposed strata, designated the "Woźniki Formation", are shown in contact with sandy-gravelly Liassic deposits (Olewin Beds) in the NE part of the exposure by Haisig *et al.* (1983) on the "Detailed Geological Map of Poland". At present, this part of the pit is mostly covered by post-exploitation rubble and this is where the Patoka 1 borehole is located (Fig. 9).

The Patoka succession is dominated by cherry and red-brownish, but also grey-greenish and variegated illite-kaolinite clays and claystones, with rare intercalations of sandy-gravelly and muddy deposits, mostly in the lower part (see also Wyszomirski and Galos, 2007). Their high quality as ceramic materials is determined by the general near-absence of organic matter (0.1%) and carbonates (0.2–0.4% CaO; but locally to 3%), combined with a high Fe_2O_3 (4.5–11%) and MnO content (Kozydra *et al.*, 1977; Wyszomirski and Galos, 2007). Similar characteristics were reported by Środoń *et al.* (2014) for a higher part of the Patoka 1 core (mineralogical set A of these authors).

Two intervals are particularly characteristic at this outcrop (see Fig. 9), and in fact unique on the regional scale:

– In the northern part of the pit, in a dewatering trench, in the mostly grey-greenish ochreous to red set, occurs a gagate (jet) level with scattered siderite concretions, 20 cm thick (Fig. 10C), succeeded by two more continuous ("massive") siderite horizons in an interval at least 2 m thick (Tomasz Krzykawski, pers. comm., 2014). The large-sized, irregularly-barbed and porous siderite concretions (up to 50 cm) and stem fragments (Fig. 10D) occur in this distinctive unit, at least 2 m thick, in the middle part of the Patoka section.

– The topmost part of the section, several meters thick, exposed in the eastern wall, comprises alternating red to vi-

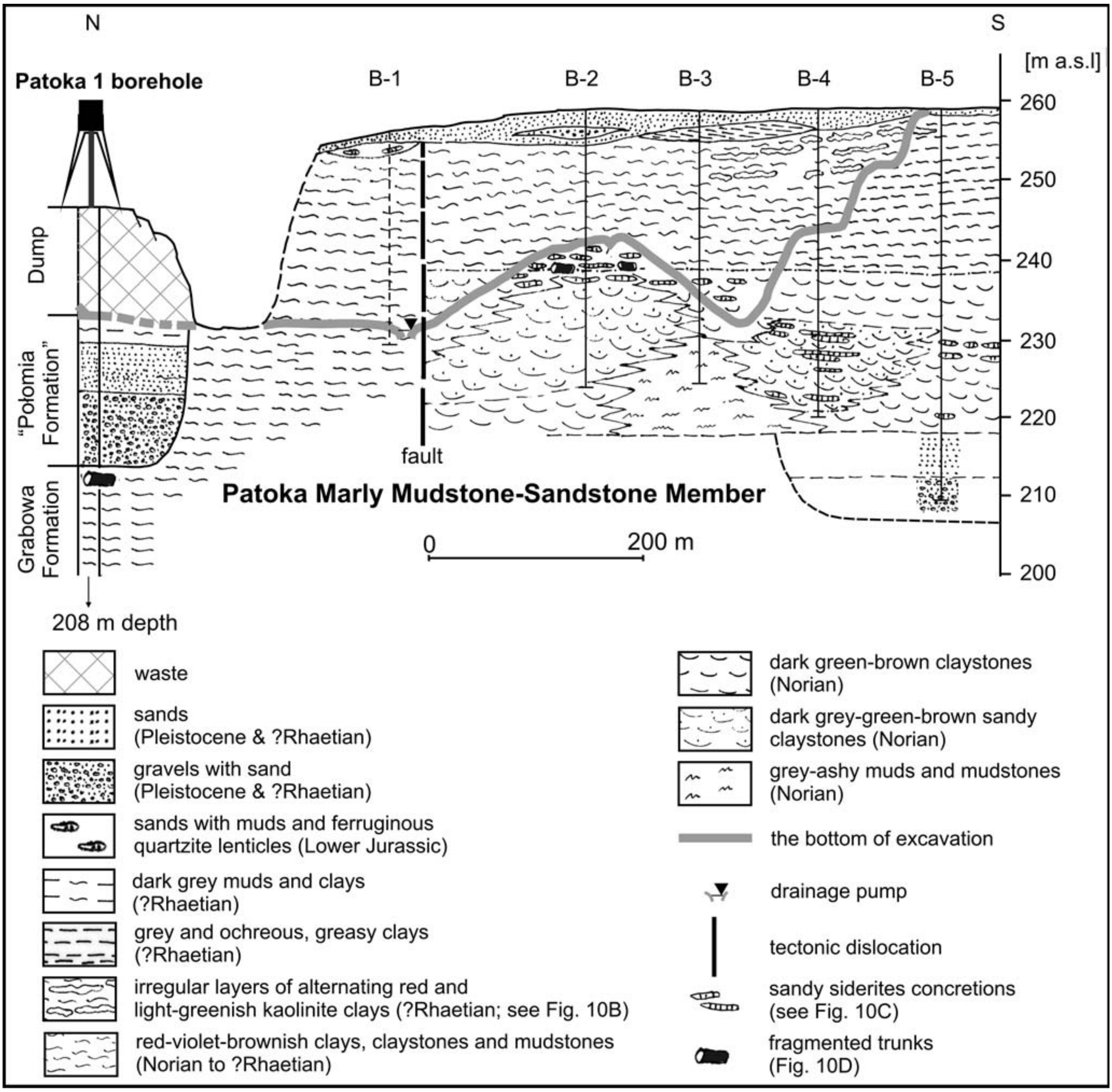


Fig. 9. Geological cross-section of the clay pit of the Patoka Brickyard, based mostly on the Patoka 1 well profile (Fig. 11) and reserve drill holes (B1–B5; after Bardziński and Chybiorz, 2013)

olet and light clays (Fig. 10B). The last interbeds corresponds to kaolinite (Jan Środoń, pers. comm., 2015).

Patoka 1 borehole

The Patoka 1 drill core encompasses a succession of multicolored and lithologically diversified Keuper deposit types, 192 m thick (Fig. 11). Its top interval corresponds to the Połomia gravels, grading upward to sands and kaolinite clays. Similar fining-up cyclothems, with partly cross-laminated, grey, sandy to gravelly sets at the base (Fig. 12C), characterize the remaining part of the Patoka 1 section. Dark to black, clayey intervals, with plant debris in places, determine the upper parts of the cycles in the lower part of the profile. Post-evaporite collapse breccias at the depth interval 201.2–201.9 m (see Szulc and Racki, 2015, fig. 3D, E) are indicative of tentative assignment to the atypically developed Upper Gypsum Beds (as presented in Środoń *et al.*, 2014, fig. 17), but this lithostratigraphic interpretation is abandoned in the present account. Intervening spotted-variegated mudstone complexes are characterized by debris-flow deposits and numerous reworked vadoid horizons of the Lisów breccia, up to 0.5 m thick (see Szulc, 2005, Jewuła, 2010; Fig. 12D).

Strongly weathered mudstone sediments were recognized repeatedly in the Patoka 1 section, in particular at depths 175.4 m (0.6 m thick; Fig. 12D), 73.0–76.7 m and 35.0 m (directly below the Połomia gravels). The latter interval also in-

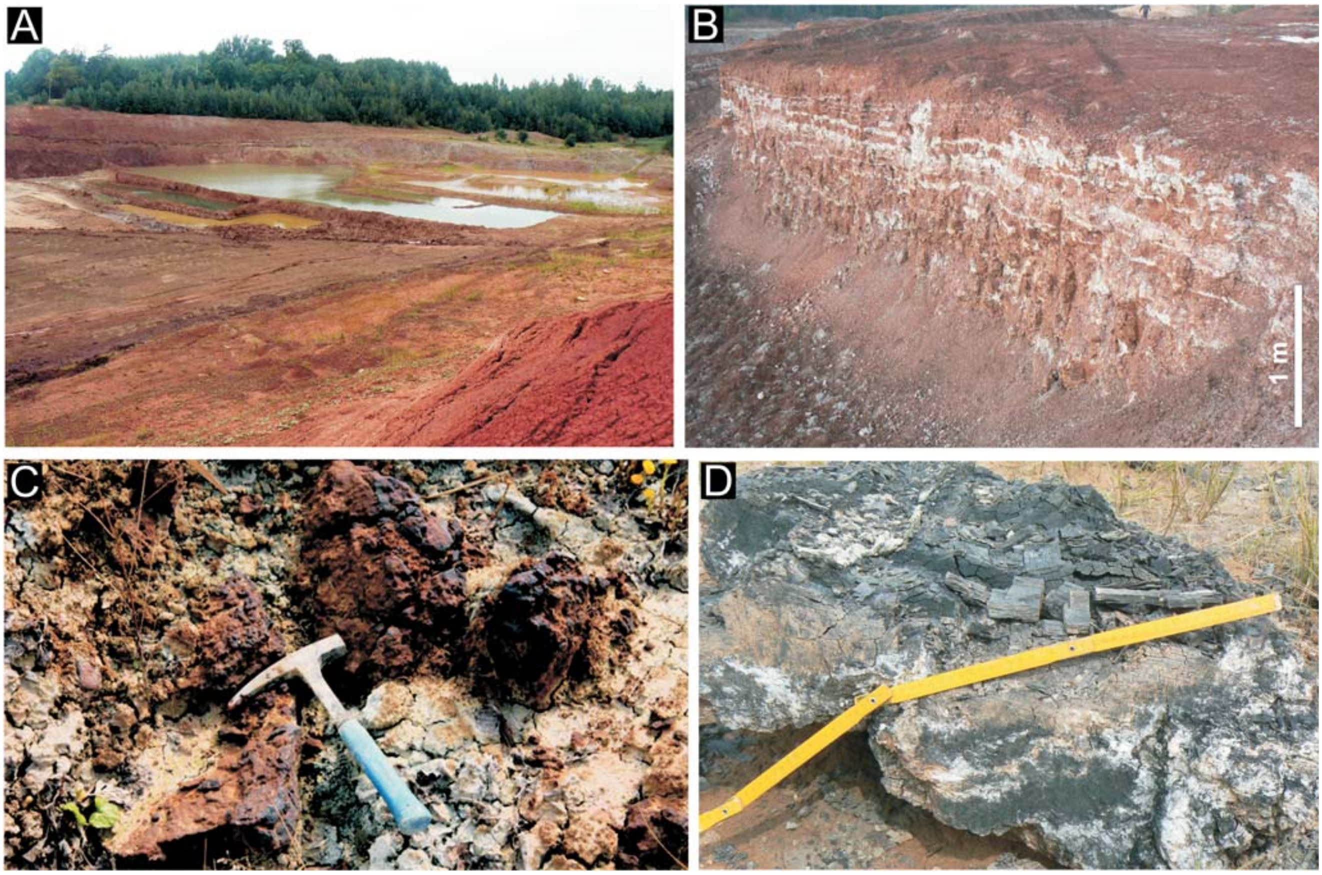


Fig. 10. Distinguishing characteristics of the uppermost Patoka Mbr in the pit of the Patoka Brickyard (see Szulc and Racki, 2015, fig. 4D, E). **A.** An overall view of the SE part of the excavation, with dominantly red-brownish Norian to ?Rhaetian transitional series. **B.** Uppermost Norian -?Rhaetian red beds in the topmost part of the profile with remarkable light-coloured kaolinite intercalations. **C. D.** Upper siderite concretionary level (C), and coalified and locally pyritized large stem fragment (D; *Agathoxylon keuperianum* in Philippe *et al.*, 2015) in the middle, grey-greenish part of the section (see Fig. 9). Courtesy of W. Bardziński (A, B, D) and T. Krzykawski (C).

cludes coalified tree trunks (37.0 m), whereas bone material is found in intraclastic sands at 119.3–119.7 m (Fig. 12C).

Kobylarz 1 borehole

The borehole was drilled 250 m east of the former exposure in an excavated niche, under a city dump on Kobylarz Hill, in the western part of the town of Zawiercie (Szulc *et al.*, 2006, fig. 5). This core, with a length of 55 m, includes a monotonous, multicolored, mostly red or grey mudstone series (Fig. 13), capped by the Woźniki limestone that is poorly exposed in an adjacent road cut.

Numerous regolith and debris-flow levels are particularly representative, paired with vertisoils and carbonate-nodular intercalations. Fining-upward, light grey, conglomerate to claystone cyclothems (5.70–10.15 m interval), with floral debris and a thin oncoidal-coquina layer, are other distinctive features (see Fig. 12A, B).

FORMAL LITHOSTRATIGRAPHIC SCHEME

Four formal and two informal lithostratigraphic units of the middle Keuper are proposed (cf. Szulc and Racki, 2015), which is a prerequisite for the stratigraphic interpretation of the tetrapod localities (Szulc *et al.*, 2015): the Grabowa Formation is defined in detail below, as are its three members in stratigraphic order: the Ozimek Member, the Patoka Member and the Woźniki Member (Figs 3, 6).

In the revised sense, this unit of variegated mudstones and carbonates, based on the Grabowa Formation, previously inaccurately defined by Bilan (1976; Fig. 14; cf. Deczkowski *et al.*, 1997, p. 190), is for the most part relatively easy to distinguish in geological cartography on the basis of macroscopic criteria. Its boundaries are defined by the transition to grey mudstone-sandstone unit of the Schilfsandstein (the Stuttgart Formation; Figs 8A–D) at the base and a large-scale, erosional unconformity below coarse-grained siliciclastics at the top. However, it should be pointed out that, owing to considerable lateral and vertical variation, the assignment of fragmentary profiles (e.g., dominated by sandstones) is not possible without knowing the greater part of the Keuper succession.

Grabowa Variegated Mudstone-Carbonate Formation

In the name of the formation, the quantitatively dominant fine-grained siliciclastics are referred generally as "mudstone" ("detrital fine-grained sediments, all those com-

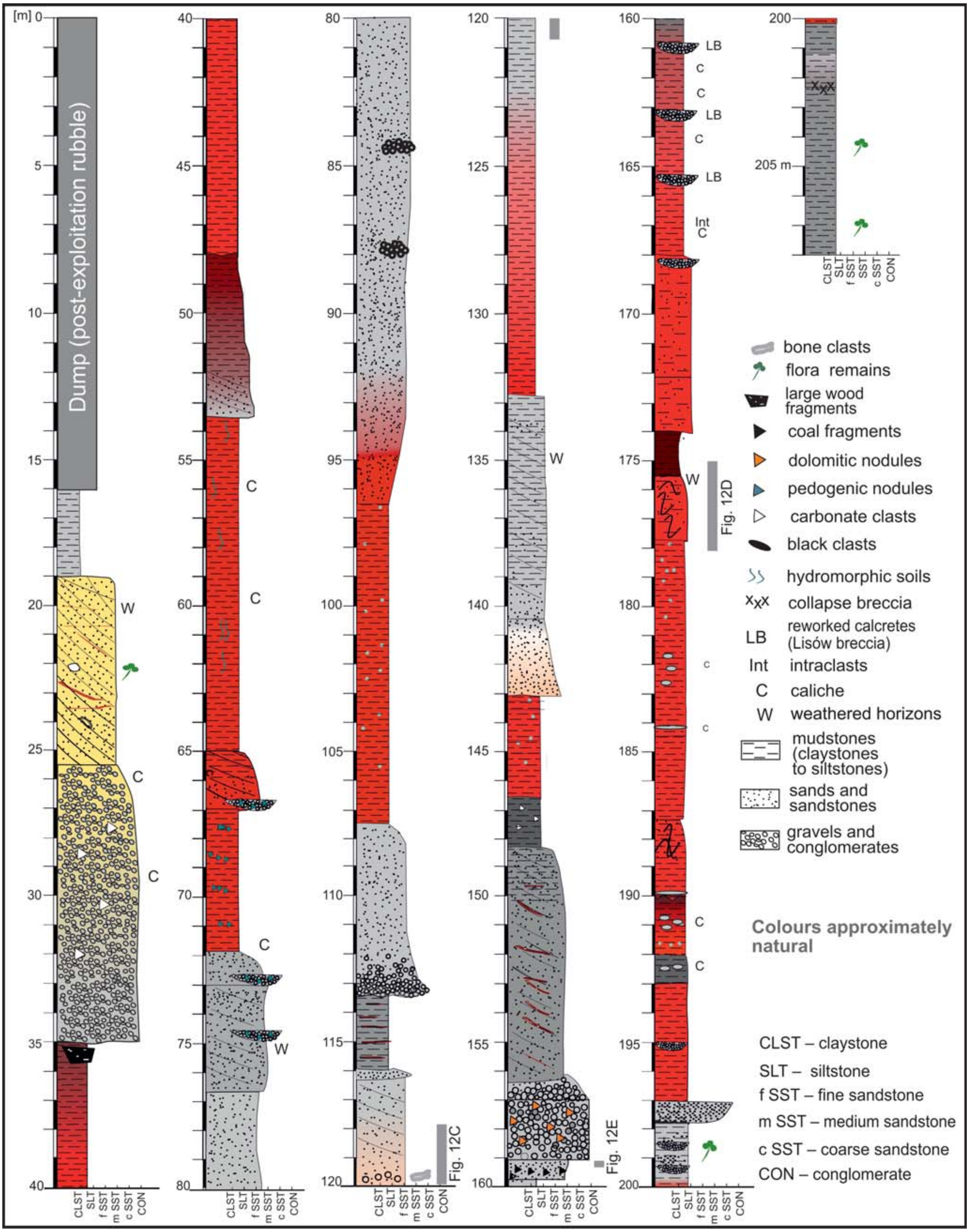


Fig. 11. Lithological section of the middle to upper Keuper succession in the Patoka 1 drill core (see Fig. 12C–E).

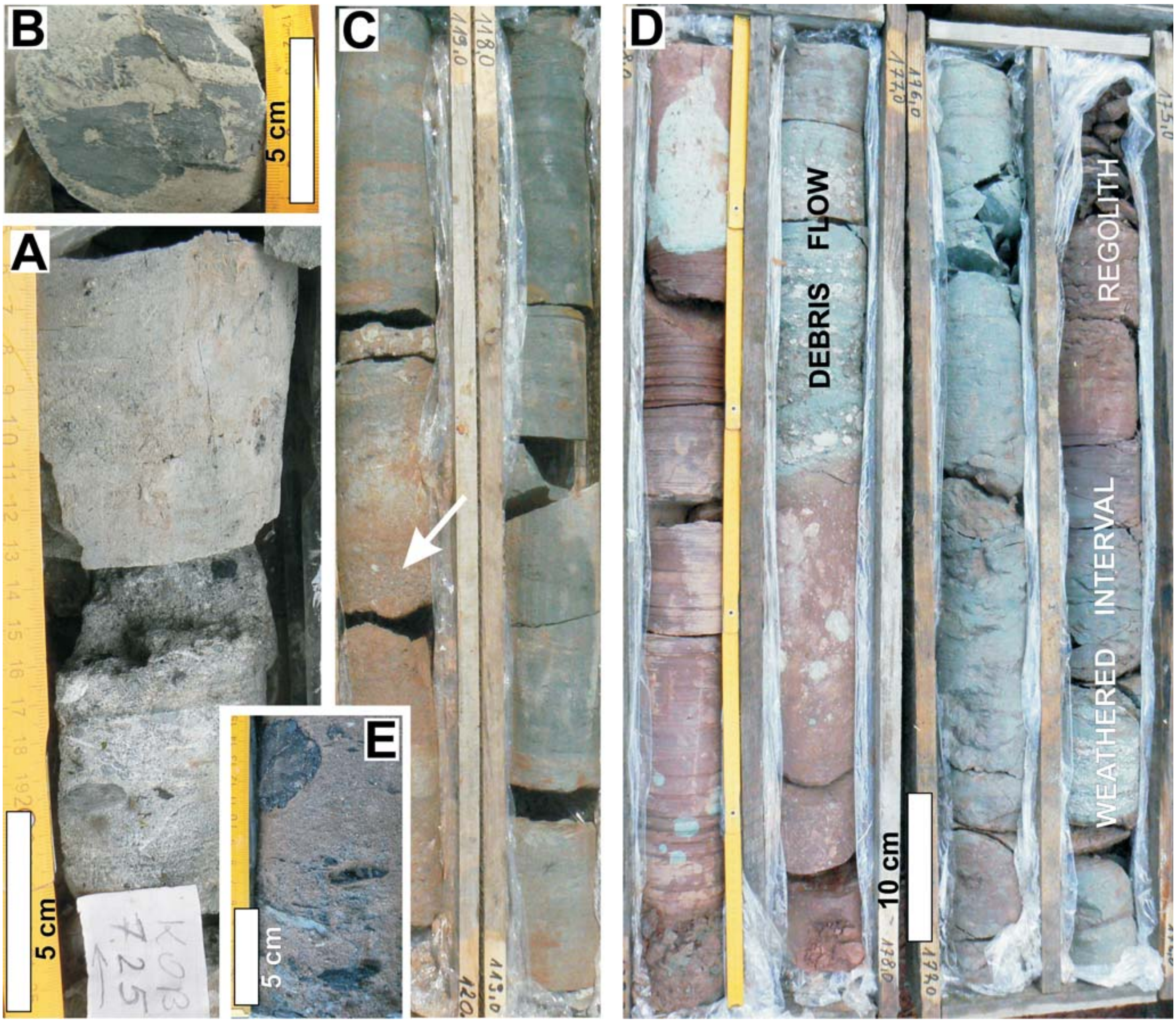


Fig. 12. Selected characteristics of the Patoka Mbr, from the Kobylarz 1 (A, B) and Patoka 1 boreholes (C–E). **A, B.** Oncoidal-bivalve limestone (A), underlying grey mudstones with plant debris (B), typical of the Lisowice level (depth 7.05–7.25 m; see Fig. 16E). **C.** Sandstones containing grey mudstone intraclasts and coarse-grained bone debris (arrow). Sandstones grade upward into dark laminated mudstones, assumed to be a possible equivalent of the Lisowice level (depth 118–120.5 m; see also the correlation variant C3 in Fig. 18). **D.** Multi-coloured mudstones with caliche horizon followed by debris-flow deposit, comprising reworked caliche nodules (depth 175.0–178.0 m). **E.** Sandstones with clasts of Carboniferous coal (depth 159.0–159.2 m).

posed of 50 percent or more of particles smaller than 62 micrometers"; after Potter *et al.*, 2005, p. 1).

Definition: A thick succession of variegated mudstone to claystone deposits, reaching up to ca. 400 m, mostly with a carbonate admixture (marls), and – particularly in the upper part – with frequent light coloured limestones and calcareous breccias. Cyclically arranged sandstones and coarse-grained siliciclastic intercalations are a subordinate component of the formation.

Origin of name: From the village of Grabowa, located ca. 15 km NW of the town of Olkusz.

Previous nomenclature: The unit was originally described by Bilan (1976) as the "Grabowa Formation" in the Olkusz–Chrzanów region, thought of as including diverse lithologies of the lower Rhaetian (see Fig. 14). However, in the proposed revision it is a unit of much wider extent, as it also includes the underlying "Klucze Claystone Member" of the "Bolesław Fm", as well as the following "higher Rhaetian deposits" within the scheme of this author. In an unpublished proposal by Kotlicki (1995), its equivalents encompass the "Lubliniec Marl Member" (= Upper Gypsum Beds) of the "Boleslaw Fm" and the two succeeding formations, the "Grabowa" and "Wojslawice" formations (Fig. 6).

On a regional scale, this Upper Triassic succession was described, among others, as the Rhaetian RI-RII cyclothems (Zawiercie, Lisów, Warta and Woźniki; Grodzicka-Szymanko, 1978; see also Grodzicka-Szymanko, 1971; Grodzicka-Szymanko and Orłowska-Zwolińska, 1972; Deczkowski *et al.*, 1997), the red deposits association (Pień-

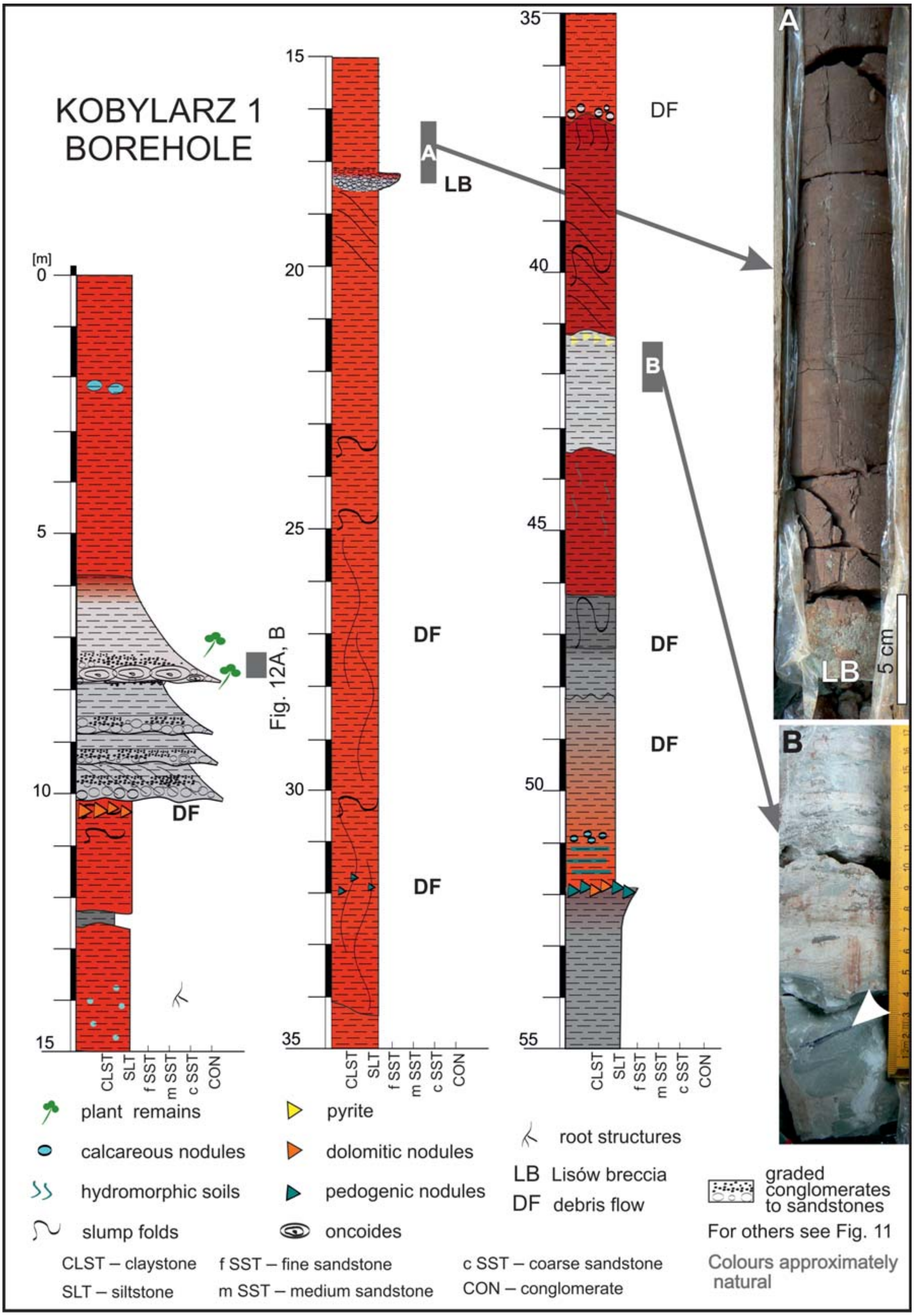


Fig. 13. Lithological section of the middle Keuper succession in the Kobylarz 1 drill core (see Fig. 12A, B). **A.** Isolated bone (arrowed) in grey marly mudstone interval (depth 41.2–42.2 m). **B.** Reworked vadoids (LB) in brownish mudstone (depth 16.2–17.3 m).

kowski, 1988) and the Woźniki limestone assemblage (Szulc *et al.*, 2006). The term "Grabowa Formation" last was used as a unit of the middle Keuper for the entire region of Silesia (Becker *et al.*, 2008; also as "Grabow Fm", Franz, 2008), and interpreted as a facies equivalent of the Steinmergelkeuper (= Arnstadt Formation) of the German Keuper (Szulc, 2007a; Figs 3, 6).

Stratotype group: The type area of the Grabowa Fm is located between Olkusz and Lubliniec, but only small fragments of the succession occur in a few exposures (Woźniki, Lipie Śląskie, Patoka; see Szulc *et al.*, 2015). The complete unit profile is in the combined Woźniki K1 and Patoka 1 well sections as the regional reference succession, supplemented largely with the Koziegłowy WB-3 section. The unit top is everywhere of an erosional nature, and there is no possibility of another stratotype selection for this boundary (cf. Pieńkowski, 1988).

Description: Thick and highly variable laterally, a succession of variegated and mottled claystone-siltstone deposits, plastic to shaly, mostly red to pinkish with green, grey and yellow irregular specks, and composed of numerous mudstone-carbonate cycles. The formation is distinguished by a monotonous clay fraction, significantly dominated by illite (see mineralogical and geochemical characteristics in Środon *et al.*, 2014; also e.g., Serafin-Radlicz, 1971; Śnieżek, 1986). The calcite content ranges between 5 and 15% (with the most significant exception of the totally decalcified uppermost portion; Środoń *et al.*, 2014, table 1; see also Znosko, 1955, and Deczkowski, 1963). Horizontal lamination and other sedimentary structures are recognizable. Calcrete horizons and vertisols, regolith layers up to several m thick, and variously disturbed laminations (a record of mudflows and other types of gravitational movements; see Bilan, 1975, 1976; Szulc, 2005, 2007a; Szulc *et al.*, 2006; Jewuła, 2010) are very characteristic, as well. Numerous lensoidal sandstones and poorly-sorted conglomerates (fig. 4A, B in Szulc and Racki, 2015; petrographic data in Jakubowski, 1977) form largely irregular, simple cycles (Pieńkowski, 1988; Jewuła, 2010; Pieńkowski *et al.*, 2014).

An important component in the upper part of the formation are carbonates that are common in some sections: the micritic Woźniki Limestone Member (WLM; Szulc *et al.*, 2006), and also microbial carbonates. A characteristic, but subordinate and not everywhere recognizable lithologic type in the formation is evaporite pseudomorphs, mostly gypsum. They are distinctive for the lower part (= equivalent of the Upper Gypsum Beds), but occur also locally in the higher units (for example, at Patoka), and especially frequently in the Woźniki Limestone.

A common component of the formation is conglomeratic limestone deposits, known as the Lisów breccia (e.g., Roemer, 1870; Znosko, 1954; Śliwiński, 1964; Maliszewska, 1972; Bilan, 1976). These sediments, reach a thickness of a few to tens of centimeters (up to 3 m; Bilan, 1976, p. 45; Haisig *et al.*, 1983). According to Szulc (2005, 2007a), these discontinuous conglomerate horizons are composed of rewashed and redeposited soil nodules (vadoids).

Light grey and dark to black mudstone-sandstone, up to 20 m thick, are in the middle part of formation (in the Patoka 1 section, Szulc *et al.*, 2015) and this is a particularly fossil-rich interval, abounding in plant debris, coaly streaks, and even large tree trunks and bivalve shells (Poręba, Marciszów, Patoka; Bilan, 1976; Sulej *et al.*, 2012; Pieńkowski *et al.*, 2014; Szulc and Racki, 2015, fig. 4A–C; Figs 12A, B, 15, 16). The Lisowice bone-bearing level consists mainly of this lithologic type (Szulc *et al.*, 2006; Szulc, 2007a; Dzik *et al.*, 2008). However, with the exception of the bone-enriched intervals (see below), the formation is mostly impoverished in fossils (see summary in Bilan, 1976, 1991).

In the highest part of the succession are also frequent siderite concretions (Grodzicka-Szymanko and Orłowska-Zwolińska, 1972; Pieńkowski, 1988), found only at Patoka. Grodzicka-Szymanko (1978) reported a lower level of siderite, in and below the WLM, but probably for the most part of secondary origin (Grodzicka-Szymanko, 1963, 1971).

Thickness: From a few meters in the east to at least 175 m in a north-westerly direction, for example, at Patoka (cf. Śliwiński, 1964; Grodzicka-Szymanko and Orłowska-Zwolińska, 1972; Bilan, 1976; Grodzicka-Szymanko, 1978; Pieńkowski, 1988). By aggregating information about equivalent units, distinguished by Kotlicki (1995), in the most northern parts (Kluczbork area), the thickness of the Grabowa Fm exceeds 400 m.

Lower boundary: The base of the formation is placed within the variegated, mostly brown-reddish mudstone deposits and this is the first appearance of the usually pseudomorphed gypsum, and/or the disappearance of sandstone layers (cf. Bilan, 1976; Siewniak-Madej, 1982a; Kłapciński, 1993; Szulc, 2005). It is a record of gradually changing siliciclastic sedimentation, from fluvial to a chemical type (hypersaline playa type; Szulc, 2005, 2007a). The Woźniki K1 well section is named as the stratotype of this boundary (Szulc and Racki, 2015, fig. 3; Fig. 8). In eastern areas, the variegated mudstones directly overlie the Middle Triassic carbonates in some sections (Fig. 14).

Upper boundary: The Grabowa Fm top corresponds to the bottom of the quartz conglomerate/gravel succession, containing also sandstones and siltstone-clayey deposits with greenish-white kaolinite clays in higher layers (thought to be Rhaetian to Liassic in age; Znosko, 1955; Unrug and Calikowski, 1960; Mossoczy, 1961; Deczkowski, 1963; Górzyński and Pomykała, 1964; Górzyński, 1972; Grodzicka-Szymanko and Orłowska-Zwolińska, 1972; Śnieżek, 1986; Pieńkowski, 1988; Szulc *et al.*, 2006) that are the so-called Połomia Formation of Jakubowski (1977); the stratotype is located in the Patoka 1 borehole. Diverse mudstone (-conglomeratic?) successions between the Woźniki Limestone Mbr and the Połomia gravels were reported by Mossoczy (1961), Grodzicka-Szymanko (1963, 1978) and Gąsiorowski *et al.* (1986; see also Pieńkowski, 1988). A continuous record of sedimentation presumably occurs farther to the north, where the Triassic–Jurassic boundary is located in the mudstone-sandy succession (Pieńkowski, 1988).

Age: Palynostratigraphic dating clearly indicates a Norian age for the greater part of the formation (C. meyeriana IVb Subzone), with the exception of its lower interval (see below). The presence of the succeeding C. meyeriana IVc Subzone in the presumably Rhaetian, kaolinite-rich segment is not evidenced in the Patoka sections (Fijałkowska-Mader *et al.*, 2015).

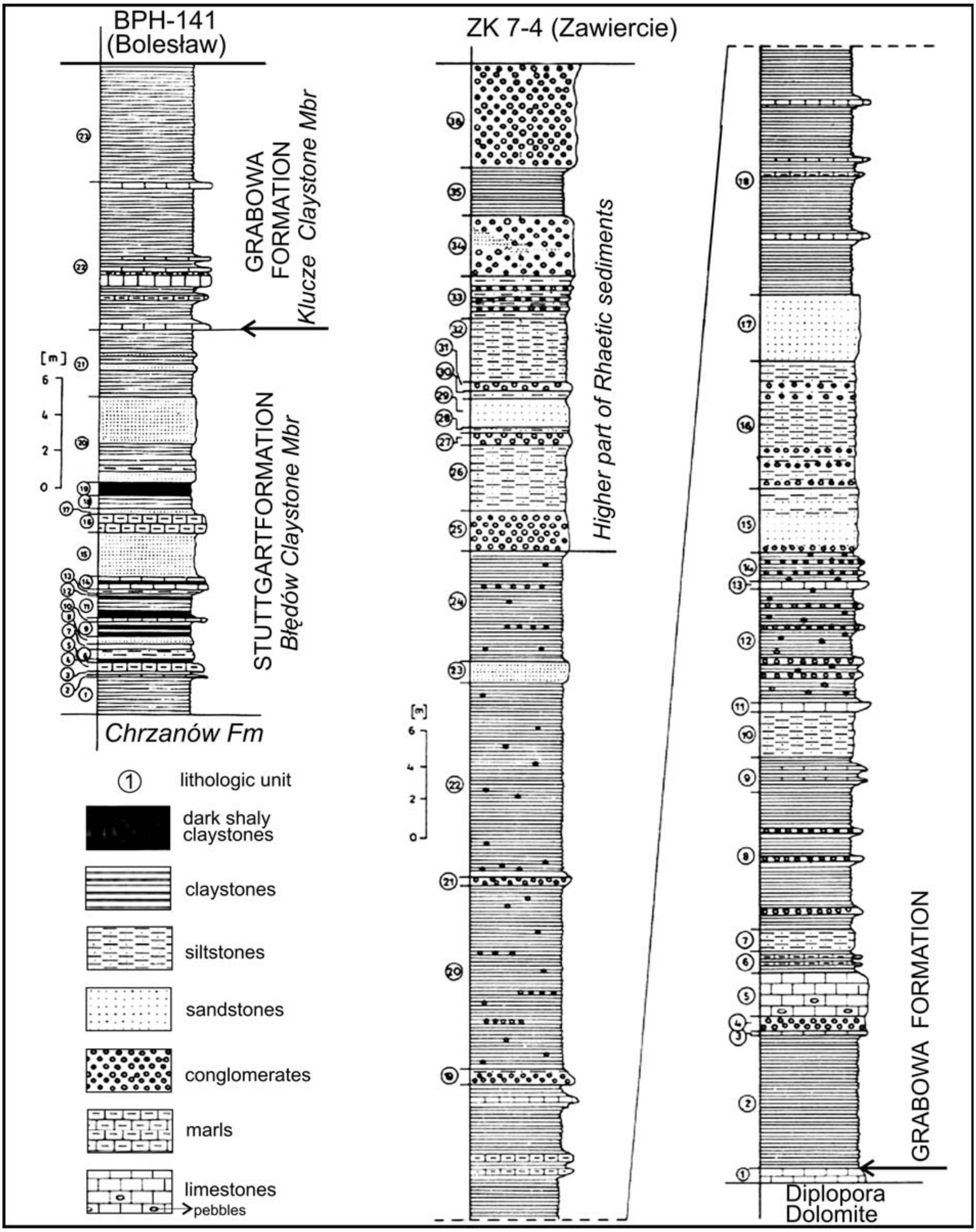


Fig. 14. Lithological section of two typical middle Keuper successions from the Zawiercie-Olkusz region, as a starting point to an original proposition of the Grabowa Formation by Bilan (1976, copied figs 6 and 14, with arrowed bottom of the redefined formation; other original units italicized). Note that an explanation of the lithological logs was not given in Bilan's (1976) publication and only the numbered units were described.

Geographic range: Northeastern periphery of Upper Silesian Coal Basin (around the towns of Olkusz, Zawiercie, Siewierz) towards the towns of Lubliniec and Opole to the west, and the Częstochowa region to the north.

Remarks: The Grabowa Fm is characterized by major facies variation, both vertically and laterally (see Grodzicka-Szymanko and Orłowska-Zwolińska, 1972, fig. 2; Śliwiński, 1964). The presence of stratigraphic hiatuses, com-

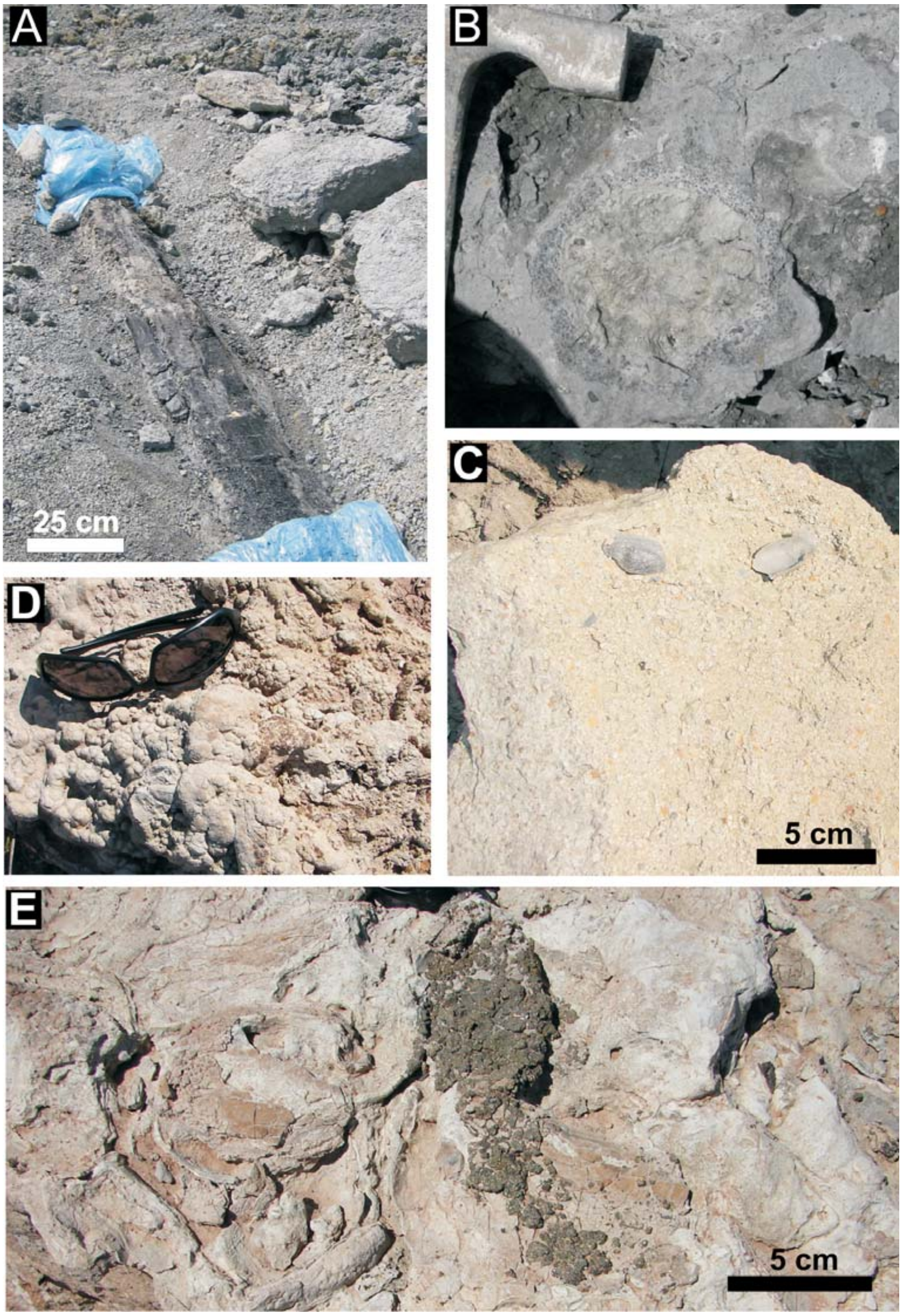


Fig. 15. Lithofacies characteristics of the Patoka Mbr, with the Lisowice bone-bearing level, at the Poręba (A) and Zawiercie-Marciszów (B–E) localities (see Szulc *et al.*, 2015). **A.** Large 14 m length conifer(?) tree trunk in dark grey mudstones (compare Sulej *et al.*, 2012, fig. 2A–B) and calcareous conglomerates. **B.** Cross-section of smaller tree stem. **C.** Fine-grained limestone conglomerate of Lisów breccia type, with mussel valves of *Tihkia(?) silesiaca* Skawina and Dzik (see Skawina and Dzik, 2011, fig. 10C, D). **D.** Stromatolites (see Racki, 2010, fig. 3). **E.** Weathered bivalve-oncolite limestone, with pyritic encrustations (see Racki, 2010, fig. 2, and Fig. 16 for microfacies). Courtesy of W. Bardziński (A), E. Budziszewska-Karwowska (B and M. Racka (C–E).

bined with rhythmically alternating fluvial deposition and pedogenesis processes (see facies description in Szulc *et al.*, 2006; cf. also Bilan, 1976; Pieńkowski, 1988; Deczkowski *et al.*, 1997; Jewuła, 2010), is a common feature, too.

Ozimek Mudstone-Evaporite Member

Definition: Variegated, but mostly red and marly mudstones with common pseudomorphed gypsum aggregates and a subordinate contribution of carbonates and sandstones.

Origin of name: From the town of Ozimek near Opole.

Previous nomenclature: The unit was described previously as the Upper Gypsum Beds (or Series), Red Keuper (Kotlicki and Kubicz, 1974), “marl member from Lubliniec” of the “Bolesław Fm” (Kotlicki, 1995), “Lubliniec Formation” or Lubliniec Beds (Kotlicki and Włodek, 1976; Siewniak-Madej, 1982a; b; Haisig *et al.*, 1983), or the Zawiercie cyclothem (Grodzicka-Szymanko, 1978). This interval was only partially cored in the Lubliniec IG 1 reference well, proposed by Kotlicki (1995; see Siewniak-Madej, 1982a, b). Therefore, the Ozimek–Krasiejów area is preferred as the type area, especially because of the single exposure of the top of this member and several borehole profiles documenting this unit with well-preserved evaporites in the Opole region (Bilan, 1975; Kłapciński, 1993; Szulc, 2005).

Stratotype group: The succession occurs only in borehole profiles: at Ozimek Ia (Kłapciński, 1993, p. 83–84), Krasiejów (Bilan, 1975; Szulc, 2005), and at Woźniki K1 and Koziegłowy WB3, whereas its upper part is present in several shallow boreholes in the Lubliniec–Zawiercie area presented in Szulc *et al.* (2006). The upper boundary stratotype is located at the bottom of the clay pit at Krasiejów, at the top of the celestite-bearing level (Szulc, 2005). The proposed type section of the lower boundary is at Woźniki K1 (Fig. 8).

Description: Brick-red to cherryish and brown marly mudstones displaying celadone to green spots and streaks, mostly in the upper part. A carbonate admixture, manifested as marls and dolomitic intercalations, and sandy laminae and layers up to 0.5 m thick, are other characteristic features. Common fabrics are regoliths up to 3 m thick, caliche and vertisol soils, combined with the carbonate Lisów breccia horizons, and rare, conglomeratic debris flows.

Diagnostic constituents of the member are evaporites, mainly as scattered crystals, aggregates (nodules) and incrustations of gypsum, and oblique veins of fibrous gypsum (often present as pseudomorphs and/or dissolution breccias; Szulc and Racki, 2015, fig. 3E, F). Occasionally, anhydrite and celestite containing barite intergrowths also are present (Krasiejów, Szulc, 2005; Bzowska *et al.*, 2004; Bzowska and Racka, 2006).

For further details, see Bilan (1975, 1976), Grodzicka-Szymanko and Orłowska-Zwolińska (1972), Kotlicki (1995) and Szulc (2005, 2007a).

Thickness: From ca. 100–115 m in the northern part (Kotlicki, 1995) to 56 m in the Koziegłowy WB3 succession, to a total disappearance toward the east (Bilan, 1976).

Lower boundary: The Ozimek Mbr base corresponds to the lower boundary of the Grabowa Fm.

Upper boundary: The upper boundary of the member is determined by the disappearance of evaporites, mostly pseudomorphed gypsum (Szulc *et al.*, 2006), clearly visible in the succession at Krasiejów (Bilan, 1975; Szulc, 2005, 2007a; Bzowska and Racka 2006), and the appearance of the carbonate rock debris and clay rollers or the lowest conglomerate-carbonate parting (Olkusz-Chrzanów region; Bilan, 1976). In a few sections (e.g., at Lipie Śląskie; Szulc *et al.*, 2015, fig. 5), this basal contact is marked by a distinct erosional disconformity (see also Bilan, 1976; Kotlicki, 1995).

In the opinion of Kotlicki (1995, p. 138), the boundary (= the top of marl from Lubliniec of this author) is usually “poorly readable”, located “within the similar clayey sediments of red color, even if sometimes only underlined the surface of erosional unconformity and the substrate weathering”. A similar observation was presented by Bilan (1976, pp. 44-45), even if this lithostratigraphic boundary was interpreted at the time as an equivalent of the diastrophically controlled Keuper-Rhaetian boundary (see e.g., Grodzicka-Szymanko, 1971).

Age: The Ozimek Mbr is characterized by a paucity of fossils (only charophytes and rare ostracods; Bilan, 1976, 1991). Palynostratigraphic dating (Subzone IVa) was thought to indicate an early Norian age, only of the upper part of the Ozimek Mbr (Orłowska-Zwolińska 1983, 1985), but this stage assignment is somewhat uncertain (see below).

Geographic range: Kraków-Częstochowa Upland and Upper Silesia, from the vicinity of Olkusz up to the cities of Częstochowa and Opole.

Remarks: Some authors (e.g., Grodzicka-Szymanko, 1971, 1978; Grodzicka-Szymanko and Orłowska-Zwolińska, 1972) envisioned the complete lack of equivalents of the Upper Gypsum Keuper in Upper Silesia (compare Gajewska, 1978), but in fact it must be included in the Zawiercie cyclothem of these authors. Remarkably, these authors assumed the absence of calcium sulphate as a conclusive criterion (see also Bilan, 1976, p. 17), but the lack of recognition by them in this interval of an ubiquitous post-depositional calcification of sulphates invalidates their claim. On the other hand, this diagenetic bias at the same time somewhat reduces the value of evaporite occurrence as a lithostratigraphic criterion. This macroscopic ambiguity (diagenetically obscured *vs.* primarily absent evaporite record), resulted also in an alleged substantial diachronism of the top of the Ozimek Mbr, as indicated by the chemostratigraphic correlations of the profiles under study (Środoń *et al.*, 2014, p. 590); in fact, the lower part of the Patoka 1 well section (depths below 160 m) was re-assigned in the present account from the Ozimek Mbr to the Patoka Mbr.

The member is a record of evaporative playa sedimentation and its upper boundary corresponds to the change from siliciclastic-chemical playa-type deposition to the fluvial systems, dominated by mud-sand flats with highly effective pedogenic processes (Szulc, 2007a).

Patoka Marly Mudstone-Sandstone Member

Definition: A thick set (up to ca. 300 m) of variegated (“mottled”), mostly red to brownish marly massive mudstones, with numerous horizons of limestone-claystone conglomerates (reworked pedogenic nodules), associated with sandstones. Rare coarser-grained siliciclastics build lensoidal bodies.

Origin of name: From the village of Patoka near Panoszów, N of the town of Lubliniec.

Previous nomenclature: The unit corresponds to the diverse thick siliciclastic series forming the middle to upper segments of the Grabowa Fm. In this sense, it strictly follows the original definition of the Grabowa Formation by Bilan (1976; Fig. 14), as well as the Steinmergelkeuper in German literature and the Rhaetian *sensu polonico* (Kopik, 1967; Bachmann and Beutler, 2007). Due to the absence of gypsum-bearing deposits in "Klucze Mbr" in the vicinity of Olkusz, assumed by Bilan (1976), this unit is added to the Patoka Mbr.

In addition, the Poręba Mbr also includes – partially or completely – most of the uppermost Upper Triassic succession, well known in the literature as the Gorzów Beds (Znosko, 1955; Mossoczy, 1961; Deczkowski, 1963), Lisów Beds or "Lisów Formation" (Kotlicki and Włodek, 1976; Kotlicki and Kubicz, 1974; Siewniak-Madej, 1982a, b; Haisig *et al.*, 1983), Woźniki Beds or "Woźniki Formation" (Kotlicki and Włodek, 1976; Haisig *et al.*, 1983), Woźniki Cyclothem (RIIb; Grodzicka-Szymanko, 1978) or the "Wojsławice Formation" (Kotlicki, 1995). These authors largely assumed that the highest Keuper series lies discordantly on the Grabowa Fm *sensu* Bilan (1976) and Kotlicki (1995; see discussion below).

Stratotype group: The type area is situated in the active mine of the Patoka brickyard and the Patoka 1 well. The top of the member frequently corresponds to the erosional top of this formation, although the stratotype of this boundary is placed in the sedimentary continuum to the WLM in the Cynków well succession (Szulc *et al.*, 2006; see Szulc and Racki, 2015, fig. 6B). The near-bottom part of the Patoka Mbr is exposed at the Krasiejów pit.

Description: Typically multicolored marly mudstones, largely red to brown with greenish spots and streaks, frequently affected by shrinkage-crack structures. Both plastic to fissile deformations are common. Primary sedimentary structures include parallel and ripple-drift cross-lamination, however, due to common pedogenic processes they are replaced by massive fabrics and mottlings. The palaeosoils ranged from incipient, regolithic type to more mature varieties of aridisoils and semiarid cambisoils-vertisoils (*sensu* Retallack, 2001; see Jewuła, 2010). The pedogenic horizons forming nodular and friable mudstones reach 1 m in thickness and display well-developed root systems or slickensides deformations. The common carbonate soils are developed within the weathered mudstones either as nodules or as coated grains (vadoids). In addition, numerous coarse-grained limestone-claystone intercalations of reworked pedogenic nodules (the Lisów breccia) frequently are associated with debris-flow fabrics. The fining-upward calcrete-soil rhythmicity, from vadoidal conglomerate to laminated and finally to friable massive pedogenic mudstones, was described by Jewuła (2010) as Association (Cm, Mrh, Mm; massive conglomerate, laminated horizontally or ripple-marked mudstones, massive mudstones).

Subordinate, but common lithologies include plane-bedded, cross-bedded, and rippled, fine-grained, grey to yellowish sandstone sets, partly arkosic, with cross-lamination or horizontal lamination, up to 4 m thick, and – rarely – with gravelly lenticular packages, arranged in fining-upward cycles (up to 20 m thick). Carbonate content is strongly reduced in the upper part (Środoń *et al.*, 2014), whereas thin limestone layers and lenticles are distinctively frequent only directly below the WLM.

As stressed above, the co-occurrence of siderite concretions, pyritized wood trunks and light-grey kaolinite matrix are a unique lithological assemblage, known only from the topmost part exposed at Patoka.

The member contains both bone-bearing levels, described in detail by Szulc *et al.* (2015a; see below); the intervals are the most fossiliferous in the formation, marked by plant remains (*Voltzia* and *Lepidopteris ottonis* floral assemblages, Pacyna, 2014; Philippe *et al.*, 2015), and charophyte, bivalve, ostracod and conchostracan associations (see Dzik and Sulej, 2007; Skawina and Dzik, 2011; Sulej *et al.*, 2011, 2012; Skawina, 2013; see Fig. 17). For the widespread Lisowice level in the middle Patoka Mbr, green and celadone clay-marly sets, associated with dark-coloured, macroflora-rich and coaly horizons, and microbial limestones, are particular guide characteristics (Figs 12B, 15, 16).

Additional descriptions are given by Bilan (1975, 1976), Grodzicka-Szymanko (1978), Kotlicki (1995), Szulc *et al.* (2006, fluvial and pedogenic facies, 2015), Gruszka and Zieliński (2008) and Jewuła (2010).

Thickness: From a dozen meters (and locally less) in the eastern area and some borehole sections near Zawiercie and Woźniki (e.g., Poręba and Cynków; Szulc *et al.*, 2006) to 125 m in a westerly direction and ca. 300 m toward the N (see the regional reference profile below).

Lower boundary: The base of the Patoka Mbr defines the top of Ozimek Mbr, in some places along an erosive and weathered surface (= major Eo-Cimmerian disconformity; STG 2002). In the neighborhood of Olkusz, this boundary defines the bottom of the entire Grabowa Fm (= the base of the Klucze Mbr *sensu* Bilan, 1976; Fig. 14).

Upper boundary: The top of the member corresponds to the erosional upper boundary of the whole formation or to the first occurrence of massive limestone layers with a thickness more than 0.5 m (= the bottom of Woźniki Limestone Mbr; cf. Gąsiorowski and Piekarska, 1977).

Age: Palynostratigraphic dating points to an exclusively Norian age of the member (IV b Subzone; Fijałkowska-Mader *et al.*, 2015), but a transition to the Rhaetian, at least in some sections, is probable in the light of Orłowska-Zwolińska's (1983) data (see below).

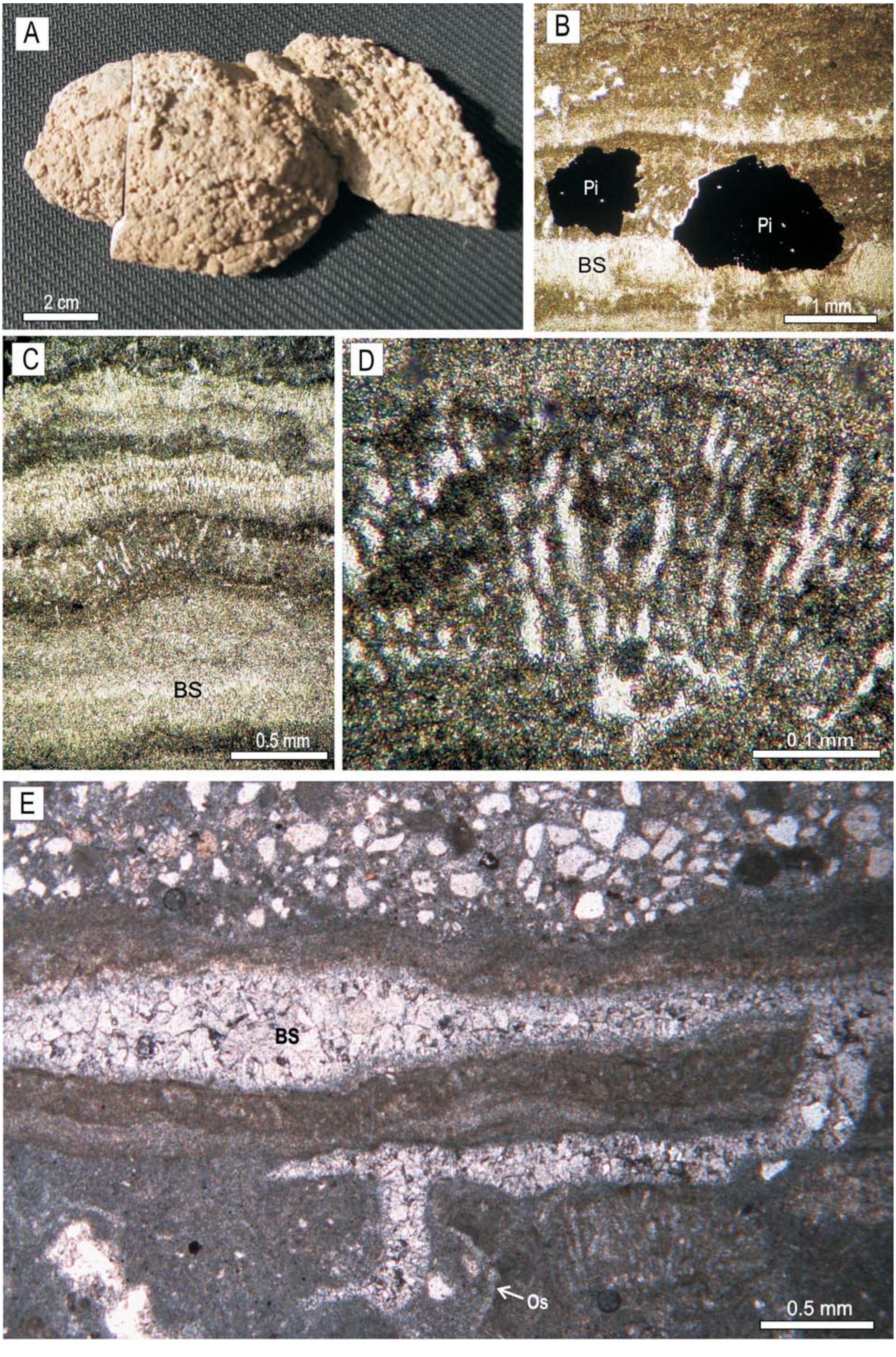
Geographic range: Kraków-Częstochowa Upland and Upper Silesia, from the vicinity of Olkusz to at least Lubliniec and Opole (Krasiejów; Ozimek Ia well).

Remarks: In many well profiles, especially in the more northern localities, there are doubts as to the lithostratigraphic assignment of the mainly mudstone terminal-Keuper successions (Kotlicki, 1995, pp. 155–156), also in the context of possible continuity in sedimentation across the Triassic-Jurassic boundary. Thus, for example, the characteristically kaolinite-enriched and siderite-bearing part of the profile (exposed only at the Patoka clay pit; Fig. 10) could be designated in the future as a separate member.

Woźniki Limestone Member

Definition: A complex of light coloured, poorly bedded limestones, composed of homogeneous micritic limestones and travertines, supplemented by gypsum-rich and cherty intervals. Sheet cracks, calcrete crusts, teepee and karstic fabrics are common features. Variegated mudstones occur as a subordinate component.

Origin of name: From the small town of Woźniki near Częstochowa.


A
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1 mm
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BS
0.5 mm
D
0.1 mm
E
BS
Os
0.5 mm

Fig. 16. Oncolites developed on large unionid bivalve shells of the Lisowice bone-bearing level from Zawiercie-Marciszów (see Figs 12A and 15E; see Szulc *et al.*, 2015). **A.** Two mussels with thick (ca. 2 cm thick), calcareous microbial envelope. **B–E.** Thin-section photographs, showing the locally cracked microbial layers developed on dissolved aragonitic shell material (BS). Note cyanobacterial fabrics forming the oncoids (C, D), diagenetic pyrite crystals drown within the microbial coating (B), and an admixture of sandy fraction (upper part) and isolated ostracod valves (Os; E). Courtesy of Józef Kaźmierczak (A–D).

Previous nomenclature: The unit was described as "Kalkstein von Woischnik" by Römer (1862, p. 650, 1867), and previously by Carnall (1846) as "Kalkstein des Lublinitzer Kreises". Other names include the Woźniki Beds or the "Woźniki Formation" (Kotlicki, 1974; Kotlicki and Włodek, 1976; Haisig *et al.*, 1983), and the Woźniki Cyclothem (IIb; Grodzicka-Szymanko, 1978; see also Piotrowski and Piotrowska, 2004), being in fact composite units comprising also higher parts of the Patoka Mbr.

Stratotype group: The area of typical development is a region between Poręba and Lubliniec, but in outcrops (Woźniki, Cynków) only parts of the member succession are present, e.g., with a historical stratotype at Sobolowa Hill, Woźniki (see localities in Gąsiorowski *et al.*, 1986, Szulc *et al.*, 2006, Nita and Nita, 2014a, b). Larger fragments of the Woźniki Limestone section can be seen in the cores of the reference boreholes: Cynków, Woźniki and Koziegłowy WB-3. The upper erosional boundary in the latter profile corresponds to the formation top. The Cynków section was selected as the stratotype of the member base (see Szulc and Racki, 2015, fig. 6B).

Description: Light coloured limestones, typically arranged in two packages divided by variegated mudstones (up to 5 m thick), reach 40 m in total thickness. The original limestone fabrics, including evaporite relics, are especially well preserved in cherty horizons, reaching 4 m in thickness (see Gąsiorowski and Piekarska, 1977; Gąsiorowski *et al.*, 1986; Szulc *et al.*, 2006). In general, the non-carbonate admixture in the Woźniki Limestone is below 5% (clay minerals up to 3%; Szulc *et al.*, 2006).

The dominant sediments (wetland palustrine facies, Szulc *et al.*, 2006) are massive and/or indistinctly stratified, white (to creamy), micritic limestones and rarely marls. Intraformational breccias, sheet cracks, calcrete crusts and teepee fabrics, rootlets and karst horizons are common features. In microfacies terms, the homogeneous micritic limestones display microgranular and clotted texture, similar to the automicritic, peloidal muds (cf. also Piekarska, 1984).

The subordinate member component is attributed to travertines (spring facies of Szulc *et al.*, 2006), developed as either highly porous, pure limestones, composed of thin calcitic rafts and calcified detritus of vascular plants, or as pisoids (up to 1 cm in size), interlayered with stromatolites, composed of dendritic shrubs or of filamentous fabrics. Finely laminated peloidal limestones are present as well in the microbialite association.

Surficial karst features comprise the different-sized cavities and voids, and sinkholes up to 1 m in depth. Two types of calcisoils, up to and 0.5 m in thickness, developed upon the limestone massif, as demonstrated by glaebules, circumgranular and septarian cracks, cutans, and root fabrics. In addition, the palustrine limestones below the siliciclastic sets are commonly dolomitized, as deep as 5 m, in the form of yellow, vuggy levels ("cellular dolomites").

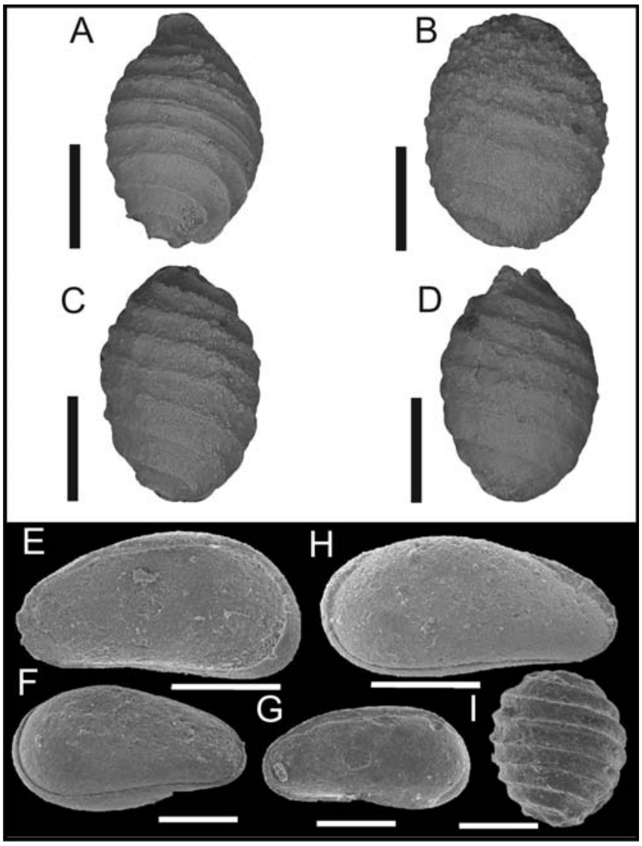

Fig. 17. Typical association of charophyte algae (A–D, I) and ostracods (E–G) from the Norian Grabowa Fm (Olempska *et al.*, 2012). **A.** *Stellatochara*. **B, I.** *Porochara*. **C.** *Stenochara*. **D.** *Stomochara*. **E, F, G.** *Suchonella* sp. **H.** *Darwinula oblonga* (Römer). Woźniki K1 well, depth 30.5 m (A–D), Patoka 1 well, depth 176.1 m (E–G); Woźniki K1 well, depth 18.5 m (I). Scale 200 μm.

Among fossils, plant debris is most widely distributed, in particular, in travertines (cf. *Brachyphyllum* assemblage of Pacyna, 2014), where also sporadic bivalve and gastropod shells, bones and locally abundant charophyte gyrogonites, ostracods and conchostracans occur (Grodzicka-Szymanko, 1971, plates 2, 4; Gąsiorowski *et al.*, 1986; Szulc *et al.*, 2006).

Thickness: From at least 35 m in the area of Woźniki–Cynków (see Szulc *et al.*, 2006, fig. 4; 40 m after Gąsiorowski and Piekarska, 1977, and Słowakiewicz, 2003) to the occurrences in the form of limestone debris within the Patoka Mbr in the vicinity of Olkusz (Bilan, 1976) and in the Czarny Las well and to a complete pinchout (see also Gąsiorowski *et al.*, 1986, Pieńkowski, 1988).

Lower boundary: Designates the top of the Patoka Mbr.

Upper boundary: The top of the typically developed Woźniki Mbr corresponds to the upper erosional boundary of the Grabowa Fm.

Age: Palynostratigraphic dating clearly indicates a middle Norian age of the Woźniki Limestone (Subzone IVb; Szulc *et al.*, 2006; Fijałkowska-Mader *et al.*, 2015; see also Pacyna, 2014).

Geographic range: Kraków-Częstochowa Upland and Upper Silesia, from the vicinity of Olkusz (Stare Gliny quarry) to Lubliniec (Lipie Śląskie), along the Kraków–Lubliniec dislocation zone, forming mostly a chain range (up to 366 m a.s.l.), called the Woźniki Swell (Garb Woźnicki; see Nita and Nita, 2014a, b). The unit is presumably discontinuous laterally.

Remarks: The formal status of the traditional unit of the Woźniki limestone as a member is in line with the proposal of Senkowiczowa (1980). The crenogenic lithology in the Germanic Basin was a unique record of thermal-spring deposition, a concept proposed by Dżułyński (in Bogacz *et al.*, 1970; see Słowakiewicz, 2003).

Informal bone-bed levels

Two bone-enriched levels were informally distinguished by Szulc *et al.* (2015) as "the entire stratigraphic interval containing bone material, even if vertebrate fossil-rich horizons are interlayers only in thick (almost) barren deposits". In fact, from two to four fossiliferous intervals occur in particular localities, and the main bone-rich layer set at Lipie Śląskie was internally subdivided into four bone-bed horizons by Pieńkowski *et al.* (2014).

The **Krasiejów bone-breccia level** represents largely equivalents of the lowermost Steinmergelkeuper (= Patoka Mbr) at Krasiejów, but including also the broad transitional interval between the Ozimek and Patoka Mbrs. This unit is distinguished by an anomalously high density of hard-part accumulation (true bone-breccia), the relative lateral continuity of the main horizon, and its limited geographic extent in western Silesia.

The **Lisowice bone-bearing level** comprises the remaining bone-bed sites (i.e., at Lipie Śląskie, Woźniki and Poręba-Zawiercie border area; Fig. 2) from the transitional strata between the Patoka and Woźniki Mbrs, extending from Lubliniec probably to the southern vicinity of the city of Zawiercie (see Bilan, 1976). Diagnostic characteristics include "greyish-seledine" to locally blackish mudstone intervals, with abundant coalified plant debris (even a coal parting at Lipie Śląskie), thin and discontinuous microbial carbonates (stromatolites and oncolites), supplemented by dispersed to coquinoid-type occurrences of disarticulated bivalves, including a large-sized variety at Zawiercie-Marciszów (Szulc *et al.*, 2006, figs 6G, 7G; Racki, 2010, figs 2, 3; Szulc and Racki, 2015, fig. 4C; see Figs 12A, B, 15, 16). The thickness of the bone-bearing strata, marked mostly by fining-upward cyclicity typical of the evolving depositional regime of braided rivers (Jewuła, 2010), is unexpectedly constant, at least in exposed parts of the succession, between 5 and 10 m (see further discussion in Szulc *et al.*, 2015).

REMARKS ON BIOSTRATIGRAPHY AND AGE INFERENCES

Micropalaeontological research, carried out within the framework of the project, on the cores of the Woźniki K1, Kobylarz 1 and Patoka 1 wells (Olempska *et al.*, 2012), provided only scarce and for the most part poorly preserved material from the Patoka Mbr, of no biostratigraphic value (contrary to earlier suggestions of Bilan, 1991). As expected, they revealed the co-occurrence of charophyte algae (gyrogonites) and ostracod carapaces (Fig. 17), only in 12 of the 61 processed samples from selected, potentially fossil-rich unoxidized gray and dark mudstone lithologies. Foraminiferans and conchostracans were notably absent in the samples. The Patoka succession is particularly fossil-impoverished (merely 10% positive samples).

The ostracod association includes three common species of the podocopid genus *Darwinula* [*D. oblonga* (Römer), *D.* sp. 1 i *D.* sp. 2], supplemented by one undetermined species of *Suchonella*. Charophytes are represented by the genera *Stellatochara*, *Porochara*, *Stellatochara*, *Stenochara*, and *Stomochara* (= *Auerbachichara* of Bilan, 1991). This fossil microbiota, known also from Krasiejów and Lipie Śląskie (Zatoń *et al.*, 2005; Olempska, 2011), may be considered as typical for shallow, richly vegetated freshwater basins of the Grabowa Fm (see Bilan, 1976, 1991). The assemblages are overall less diverse that these reported from more eastern localities, for example owing to the absence of the zonal index ostracod *Pulviella silesia* (Styk), as well as from Krasiejów (Bilan, 1991; Olempska, 2001). On the other hand, the absence of palaeoecological marine indicators (foraminiferans; see Grodzicka-Szymanko, 1971, fig. 3) suggests strongly an exclusively continental nature of the succession of the Grabowa Fm (without a record of Norian marine ingressions; cf. also Feist-Burkhardt *et al.*, 2008).

The palynological analysis performed in the framework of the grant (see Fijałkowska-Mader *et al.*, 2015) was based on 59 samples from three borehole profiles, but the recovered palynomorph material allowed only limited palynostratigraphic dating of the Woźniki K1 and Patoka 1 profiles. More than 50% of the samples were in fact negative, and conclusions also were hampered by the poor preservation of the palynomorphs and the presence of numerous, redeposited specimens, possibly even from Silurian and Devonian strata. Microspore assemblages from the Patoka Mbr and in particular from the Lisowice bone-bearing level represented the middle-late Norian C. meyeriana b Subzone, as evidenced in the depth interval 134.6–153.1 m of the Patoka 1 section, whilst in its lowermost part (199.0 m) only the undivided C. meyeriana Zone was identifiable. In addition, the same IVb Subzone was recognized or confirmed only by Fijałkowska-Mader *et al.* (2015), mostly in previously undescribed material quoted by Szulc *et al.*, (2006), from the Patoka clay pit (the lower part of the section), the Lipie Śląskie clay pit (see Szulc *et al.*, 2015, fig. 5), the Zawiercie-Marciszów outcrop (compare Sadlok and Wawrzyniak, 2013), the Poręba outcrop (see Niedźwiedzki *et al.*, 2014), and the Poręba and Czarny Las boreholes. Altogether, the data strongly indicate that the Norian IVb Subzone encompasses the greater part of Patoka Mbr, at least 120 m thick in the composite oftline Patoka section (Fig. 18), but probably without the lowest and topmost parts of this member.

Age of the Grabowa Fm base

Because of the absence of fossils in the sections of the Ozimek Mbr studied, the age assignment for the base of the formation in fact is related to dating of the Krasiejów bonebreccia level, constrained by the lack of palynological material in the succession (for an extensive discussion see Szulc *et al.*, 2015). The assumed subsurface equivalents directly above the gypsum-bearing strata (Drawno and Jarkowo Beds) were dated palynostratigraphically by Orłowska-Zwolińska (1983) as lowermost Norian (i.e., a poorly recognized lower segment of the Classopolis meyeriana Zone, ?IVa to the lower IVb interval; confirmed in Orłowska-Zwolińska, 1985; Deczkowski *et al.*, 1997; Marcinkiewicz *et al.*, 2014; Fijałkowska-Mader *et al.*, 2015). This date remains conjectural, owing to barren intervals and uncertain temporal relationships between the IVa Subzone and the Carnian–Norian boundary. The assignment of the base of the Grabowa Fm to an undetermined upper Carnian interval was established, however, by combined chemostratigraphic and palynostratigraphic data (see Fig. 18).

Age of the Grabowa Fm top

Accurate dating of the large-scale erosional contact (= a major Cimmerian sequence boundary in Pieńkowski, 2004; see also Pieńkowski *et al.*, 2014) between the Grabowa Fm (mostly WLM) and the coarse-clastic “Połomia Fm” remains conjectural. This surface is believed to correspond approximately to the Norian-Rhaetian boundary (or placed in the Rhaetian stage). The data from the Patoka pit, such as the occurrence of light kaolinite partings and associated siderite- and macroflora-rich interbeds (Fig. 10B–D), strongly indicated the transition to the Rhaetian stage, but this was not supported directly by the impoverished palynostratigraphic data in this section (Fijałkowska-Mader *et al.*, 2015).

Remarkably, the C. meyeriana c Subzone, considered by some authors to be Rhaetian in age (see discussion in Szulc *et al.*, 2015), was reported by Orłowska-Zwolińska (1983) from the terminal Keuper subsurface sections of Upper Silesia. The IVc Subzone in fact recently was documented on a preliminary basis in the Połomia gravels at the Kamienica gravel mine (see Nita and Nita, 2014a, figs 8, 9) by Fijałkowska-Mader (2015).

THE REGIONAL COMPOSITE REFERENCE SUCCESSION AND CORRELATION

With reference to the palynostratigraphic tool, the Norian age of the Grabowa Fm is well documented for the greater part of the monotonous, variegated mudstone succession (Fijałkowska-Mader *et al.*, 2015). On a regional scale, however, the present authors could only roughly correlate the several fragmentary Patoka Mbr successions at the outcrops (including Lipie Śląskie; see Szulc *et al.*, 2015) and boreholes with the long cored section of the Patoka 1 well (Fig. 18).

Magnetostratigraphic data from the well sections under study, in magnetic polarity terms, are similarly useful for correlations that are only approximate. However, the mostly normal-polarity signature, recognized especially in the 97.0–173.0 m depth interval of the Patoka 1 core, probably corresponds in part to the Norian magnetozones NRn2 and NRn3, evidenced also in the Patoka Mbr of the uppermost part of the Woźniki K1 succession (Nawrocki *et al.*, 2015). This conclusion, due to the discontinuous magnetic signature at Patoka, agrees overall with erratically available palynostratigraphic dates, but this tentative correlation would be refined conclusively by geochemical analysis of the mudstone series.

One of the main goals of the grant proposal was to apply chemostratigraphy to resolve at least some problems of Keuper stratigraphy, in the hope that climate (but also tectonics) controlled the systematic change in the terrigenous source during more than 35 Ma and can be used to provide a stratigraphic interpretation of isolated outcrops, more reliable than that, at present, provided by vague terrestrial bio- and magnetostratigraphy. Clay sediments represent a final product of terrestrial weathering processes and therefore may record related climatic trends, well known in the Keuper (Szulc, 2007a; Feist-Burkhardt *et al.*, 2008; Szulc *et al.*, 2015). In fact, the evidence for correlation using variations in elemental composition and mineral data, is the most conclusive.

Środoń *et al.* (2014) comprehensively analysed claystone samples from the Lisowice level localities and highlighted a similarity with the Krasiejów section because: “they are low in quartz and kaolinite and high in carbonates and 2:1 minerals. Also the expandability of illite-smectite is similarly high” (Środoń *et al*., 2014. p. 577). With reference to the Lisowice level, a very high dominance of illite in the clay fraction is particularly characteristic, mostly composed of illite-smectite (79%). The features are overall typical for the monotonous, illite-dominated mudstone succession of the Grabowa Formation, deposited mostly over a vast alluvial floodplain in semidry, monsoon-affected climate regimes (Szulc, 2007a; Feist-Burkhardt *et al.*, 2008).

The extended profile of the Patoka borehole (192 m; Fig. 11) was regarded by Środoń *et al.* (2014) as the reference section, supplemented downward by the Woźniki K1 succession (90 m thick; Fig. 7), where four mineral sets and four ‘chemozones’ were reliably distinguished. In lithostratigraphic terms, the exact correlation of both sections is somewhat conjectural, as the top of the Woźniki K1 section and the bottom of the Patoka 1 section are assigned to the same Patoka Mbr. A partial overlap of both sections is assumed, as indicated especially by palaeomagnetic data, even if the supposedly equivalent portions of the successions show a contrast in terms of lithology (red in Woźniki K1 and grey to black at Patoka 1). The present authors are

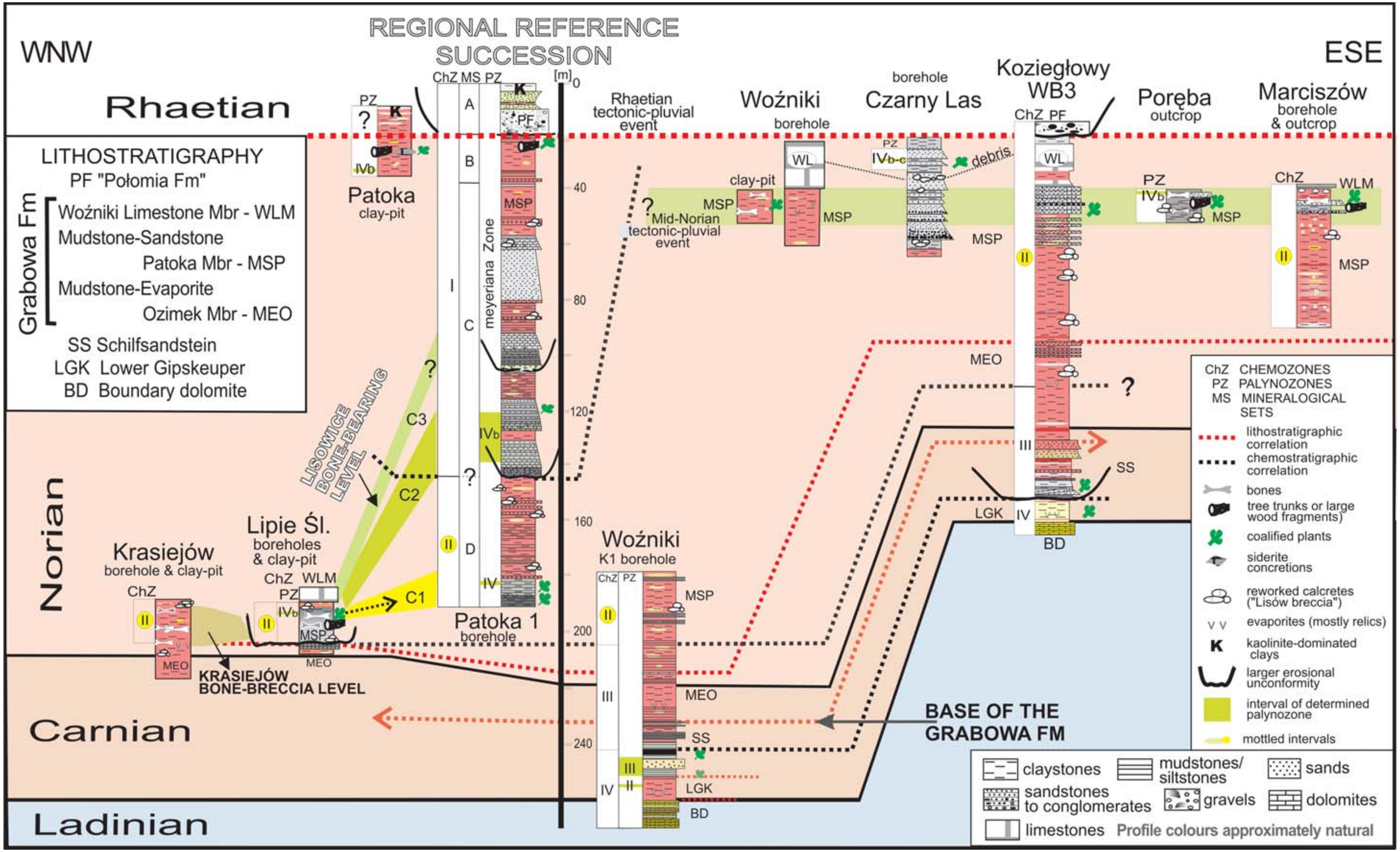

Fig. 18. Integrated stratigraphic correlation of localities and boreholes studied with the reference composite Keuper section of Upper Silesia, comprising profiles at the Patoka 1 and Woźniki K1 wells, with the combined use of lithostratigraphic (Szulc and Racki, 2015), palynostratigraphic (Fijałkowska-Mader *et al.*, 2015; palynozone numbers after Orłowska-Zwolińska, 1983) and comprehensive mineralogical and chemostratigraphic (Środoń *et al.*, 2014) premises. Note three alternative variants (C1-C3) of the correlation of the key Lipie Śląskie section with the Patoka borehole succession, discussed in Szulc *et al.* (2015).

guided by the auxiliary Woźniki borehole section of Szulc *et al.* (2006; see Fig. 7) and by the Koziegłowy WB3 well profile, where the stratigraphic position of the WLM in the upper part of the II Cr/Ti Chemozone of Środoń *et al.* (2014) was established. Therefore, the chemostratigraphic correlation of the Lisowice level in all localities with Chemozone II is a starting point in the regional stratigraphic scheme. Importantly, these integrated chemostratigraphic and mineralogic proxies confirm a generally close stratigraphic position of both bone-bed levels, that is, in the same Chemozone II (Fig. 18; Szulc *et al.*, 2015).

The total thickness of the composite regional reference succession is approximated as 260 m, from the Boundary Dolomite to the mostly gravelly "Połomia Fm" (Fig. 18). Even if several erosional hiatuses were influenced by river fining-up cycles, with the most significant at the base of the Połomia gravels, and weathered horizons reduced the continuity of the section, its relative completeness remains undoubted on a regional scale. The bottom part is placed in the early Carnian, as proved by the palynological content (Fijałkowska-Mader *et al.*, 2015). Because the key middle-late Norian IVb Subzone at Patoka (including the excavation) is very thick (at least 120 m, possibly even 190 m), the biocorrelation value is limited, but conclusive for a mid-Norian age of the Lisowice bone-bearing level that is placed with certainty in its lower part. In summary, the Carnian to early Rhaetian age is acknowledged for the regional standard of the Upper Silesian Keuper, strengthened recently by the Rhaetian age of "Połomia Fm" (Fijałkowska-Mader, 2015).

THE QUESTION OF HIATUSES AND UNCONFORMITIES

Extensive hiatuses at the large-scale sequence boundaries in the Upper Triassic are assumed in the Germanic Basin and were recently accepted in STD 2002 (Nitsch *et al.*, 2005; Menning *et al.*, 2012). Some Polish authors adopted this view, as shown in the "Stratigraphic Table of Poland" (Becker *et al.*, 2008; compare e.g., Grodzicka-Szymanko and Orlowska-Zwolińska, 1972; Bilan, 1976; Kotlicki, 1995, Deczkowski *et al.*, 1997; Pieńkowski, 2004; Fig. 6). As explained by Edgar Nitsch (pers. comm., 2015), for the example of the Lipie Śląskie section, the average sedimentation rate is less than 2 mm/ka in this stratigraphic record; therefore, "depositional activity of all depositional events documented will hardly sum up to millions of years. So, where is the time?" Thus, for Norian successions, large-scale discontinuities, embracing at least 5 Ma, are assumed to characterize their basal and terminal parts ("Stratigraphische Tabelle von Deutschland", 2002; Nitsch *et al.*, 2005; Becker *et al.*, 2008). Nitsch et al. (2005, p. 225) concluded that at most half of the time interval is represented in the stratigraphic record of the Keuper Group.

However, the question of such profound basin-wide gaps framing the Norian stage is certainly controversial, even in Germany (see dissimilar views in e.g., Franz, 2008, and Kozur and Weems, 2010). For example, Kozur *et al.* (2013, p. 328) claimed: "Within the central basin facies, the gradual change of the conchostracan faunas from the uppermost Weser Formation (Heldburg Gypsum Member) to the overlying basal Arnstadt Formation indicates that no significant time gap is represented there by the Early Cimmerian Main Discordance between the two formations".

The observations of the authors in the Upper Silesian sections also do not confirm this viewpoint with evidence of a deeply weathered surface, highly mature palaeosoils and thick, residual clayey debris. Even if hiatuses indeed embrace locally an interval from the WLM downward to the Muschelkalk at the base (e.g., Górzyński and Pomykała, 1964; Bilan, 1976; Szulc, 2007a; compare Gajewska, 1978, table 3), overlooking of the Upper Gypsum Keuper in the Silesian succession by some authors (see above) artificially exaggerated the question of discontinuity in their stratigraphic schemes (see Fig. 6). The best proof is manifested in some serious trouble over the definition of the lithostratigraphic boundary between the Ozimek and Patoka Mbrs, near the Carnian–Norian boundary, in fact corresponding with the "Altkimmerische Hauptdiskordanz" distinguished in STD 2002, as highlighted previously by Bilan (1976) and Kotlicki (1995; see above), and evident in the drill cores studied. Of course, this supra-regional tectonic episode is traceable in the Silesian Keuper, but only conclusively in some successions.

Otherwise, a mid-Norian event of tectonically induced topographic rejuvenation (corresponding to the major Rhaetian cyclothem boundary *sensu* Grodzicka-Szymanko and Orlowska-Zwolińska, 1972; cf. Bilan, 1976, Kotlicki, 1995), resulted in the intensive remodeling of fluvial systems and intraformational erosion. This episode is recognized in the tectonic-pluvial interval controlling the depositional regimes of the Lisowice bone-bearing level (see discussion in Szulc *et al.*, 2015), combined with block movements and geothermal activity along the Kraków–Lubliniec fault zone that eventually led to deposition of the Woźniki limestone (Szulc *et al.*, 2006; Fig. 5).

Among the successions of the Grabowa Fm studied, only the Patoka pit and maybe the Czarny Las borehole represent a possible continuous transition across the Norian–Rhaetian boundary (Fig. 18). All other sections are marked by an erosive contact at the top with coarse-grained clastics ("Połomia Fm"), typically sheltered by the resistant Woźniki Limestone Mbr (exemplified by the Koziegłowy WB3 section) or encompass the debris of this marker layer (Czarny Las, Fig. 18; see also Grodzicka-Szymanko and Orlowska-Zwolińska, 1972, Bilan, 1976, Pieńkowski, 1988). Thus, only this supra-regional erosional surface corresponds with certainty to a significant non-depositional hiatus, locally including even the Rhaetian to Sinemurian interval (see depositional sequence I of Pieńkowski, 2004; also e.g., Głowacki and Senkowiczowa, 1969; Deczkowski and Gajewska, 1977; Gajewska, 1978; Deczkowski and Franczyk, 1988; Dadlez, 1989).

As indicated by Grodzicka-Szymanko (1978), the various thicknesses of the 'Rhaetian' (= Grabowa Fm) are laterally confined to narrow zones, and differential block movements are indicated by the post-WLM interval as a green clay blanket, occurring on parts of a karstified massif (see also an example of abrupt lateral facies change in Szulc *et al.*, 2015, fig. 14). Consequently, the present authors assume that most of the absent time is represented in two types of geological record. The first is related to the numerous soil horizons (of various types) occurring in the Patoka Mbr succession. The other is the ensuing phenomenon of the multiple, short, and localized, but effective erosion and redeposition events, following catastrophic runoffs, typical of a semiarid climate. This cannibalistic mode of (re)sedimentation is particularly well exemplified by the reworked and sieved pedogenic grains, forming specific conglomerate horizons (Lisów breccia-type).

The more effective gaps are limited to the sections situated closer to the main fault structure in the region, that is, to the Kraków-Lubliniec shear zone. In this fault-bounded area, the erosion process was augmented by block tectonism that led to the frequent exposure of the older Triassic and Palaeozoic substratum (see Śliwiński, 1964, Bilan, 1975, 1976; Szulc, 2005). The phenomenon is well developed in the palynological record (Fijałkowska-Mader *et al.*, 2015), the composition of the lithoclasts (with Devonian microfossils Haisig *et al.*, 1983; Carboniferous coal clasts in the Patoka 1 succession; Fig. 12E), and the diagenetic features of the bone material (Bodzioch and Kowal-Linka, 2012).

In summary, instead of spectacular depositional breaks, lasting for millions of years, the present authors propose the cumulative temporal effect of numerous, superimposed minor and irregular erosion and starvation episodes as the main cause of the total time gap evident in the Upper Silesian Keuper succession. The Rhaetian (and younger) Jurassic Cimmerian tectonic-erosional intervals under humid-climate settings are the only significant exception (Znosko, 1955; Szulc, 2007a; Brański, 2014; Pieńkowski *et al.*, 2014; Szulc *et al.*, 2015; see a similar situation, e.g., in the Arctic region of Norway, Paterson *et al.*, 2016; also Bachmann *et al.*, 2010, fig. 9.1).

CONCLUSIONS

1. The redefined Grabowa Formation, a major lithostratigraphic unit, formally proposed by Szulc and Racki (2015) for the middle Keuper (i.e., above the Schilfsandstein or Stuttgart Formation), includes the Upper Gypsum Beds and Steinmergelkeuper of the traditional scheme in Germany (= Weser and Arnstadt formations). This important unit is completely subdivided into three members: the Ozimek (mudstone-evaporite) Member, the Patoka (Marly Mudstone-Sandstone) Member and the Woźniki (Limestone) Member.

2. Two significant Norian bone-bearing horizons (Krasiejów and Lisowice) are placed within the Patoka Mbr, and the latter represents a record of a mid-Norian pluvial-tectonic event (Szulc *et al.*, 2015).

3. The Grabowa Fm generally correlates with the Norian stage, with the base located in the undefined upper Carnian, and is topped by a major erosive disconformity, believed to be located near the Norian-Rhaetian boundary. Both boundaries are dated with some uncertainty, however, also because of the overall biostratigraphic weaknesses of the definition of the Norian stage in continental settings.

4. Discontinuities in the Silesian middle Keuper succession were localized and controlled by Early Cimmerian tectonic block movements within the Kraków–Lubliniec fault zone, with the exception of a large-scale erosional episode recorded near the base of the Rhaetian stage, combined with a climatic turning point toward humid conditions, as an effect of plate-tectonic reorganisation in the Western Tethys domain.

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