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HOW MANY UPPER TRIASSIC BONE-BEARING LEVELS ARE THERE IN UPPER SILESIA (SOUTHERN POLAND)? A CRITICAL OVERVIEW OF STRATIGRAPHY AND FACIES

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Abstract: At least three widely separated bone-bearing intervals in the Upper Triassic succession of Upper Silesia, ranging in age from the Carnian to Rhaetian (i.e., in the interval of 25 Ma), are presented in papers by the Warsaw research group, led mainly by Jerzy Dzik and/or Grzegorz Niedźwiedzki. The stratigraphic arguments are reviewed for the vertebrate localities studied so far, in particular for the well-known middle Keuper sites at Krasiejów and Lipie Śląskie, to show that the previously proposed age assignments are still inadequately documented and questionable. This unreliability is exemplified by the evolving stratigraphic correlation of the fragmentary Silesian sections (8–18 m thick) with informal subsurface units from central-western Poland and with the German standard succession, ultimately not corroborated by comparison with the composite reference succession of the Upper Silesian Keuper, including new profiles (ca. 260 m thick) from the Woźniki K1 and Patoka 1 wells. Based on a multidisciplinary stratigraphic study covering consistent litho-, bio-, climato- and chemostratigraphic premises, focused on the regional reference section, two bone-bed levels only are recognized in the Patoka Marly Mudstone-Sandstone Member (= Steinmergelkeuper) of the Grabowa Formation, not very different in age (Classopollis meyeriana Palynozone; probably IVb Subzone): (1) the localized Krasiejów bone breccia level (early Norian in age) in the Opole region, and (2) the far more widely distributed Lisowice bone-bearing level (middle Norian) in a vast alluvial plain (braided to anastomosing river system) during the Eo-Cimmerian tectonic-pluvial episode. As a consequence of the principal uncertainties and controversies in Upper Triassic terrestrial stratigraphy, this is still a somewhat preliminary inference. Typical skeletal concentrations of a combined hydraulic/sedimentologic type, related to fluvial processes, are common in the Upper Silesian Fossil-Lagerstätten, although factors governing preservation are probably important, as well.

Key words: Bone beds, lithostratigraphy, palynostratigraphy, chemostratigraphy, taphonomy, Grabowa Formation, middle Keuper, Upper Silesia.

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INTRODUCTION

The Triassic, as the period between the two great extinctions, was characterized by the substantial reconstruction of continental tetrapod communities (Benton, 2004). After the discovery of very rich bone accumulations in southern Poland at Krasiejów village, near the town of Ozimek, and at Lisowice village (Lipie Śląskie clay pit), near the town of Lubliniec (Dzik *et al.*, 2000, 2008a, 2008b), a new and attractive scientific perspective surprisingly emerged for previously abandoned studies of the Polish Keuper (Racki, 2010; compare Szulc, 2007c). The tetrapod localities have major cognitive importance for the evolution of many important groups of amphibians and reptiles (Dzik *et al.*, 2000, 2008a; Dzik and Sulej, 2007; Sulej and Niedźwiedzki, 2010; Niedźwiedzki, 2012; Niedźwiedzki *et al.*, 2014), and even mammals (Świło *et al.*, 2014). Accordingly, it seems hard to overestimate the importance of the Silesian 'graveyards' with reference to the study of Late Triassic evolutionary patterns, exemplified by the still obscure dawn of di-

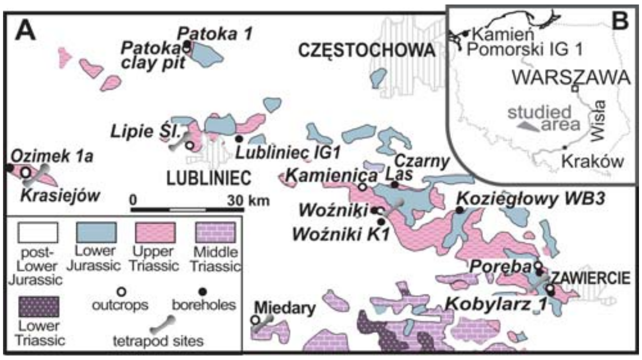


Fig. 1. **A.** Schematic geological map (after Bardziński and Chybiorz, 2013), showing the locations of the localities studied in Upper Silesian region (outcrops and boreholes; for detail see Szulc *et al.*, 2015), and **B.** location of the studied region and the key borehole in Poland.

nosaur development (see Dzik, 2003a; Dzik *et al.*, 2008a; Brusatte *et al.*, 2010; Nesbitt *et al.*, 2010; Irmis, 2011; Niedźwiedzki *et al.*, 2012, 2014; Benton *et al.*, 2014), as well as the supposed biotic turnovers and biodiversity crises, especially at the Carnian-Norian boundary (Benton, 2004; Pieńkowski *et al.*, 2014).

During 15 years of intensive investigation, five vertebrate sites in total have been described across Silesia in the Upper Triassic succession (Fig. 1), supplemented by one basal Keuper, though still Middle Triassic locality (Miedary; Sulej *et al.*, 2011b; Fig. 2). Next, the bone-rich site recently discovered in 2014 in Zawiercie town was reported by Rafał Piechowski (in Malinowska, 2015). Known since Römer's (1867, 1870) papers, these rich fossil assemblages of varied taxonomic composition include both diverse aquatic and terrestrial animals (?mammals, reptiles, amphibians, fishes; also bivalves and other various invertebrates), associated with algae and vascular plants (see Dzik and Sulej, 2007; Sulej *et al.*, 2011a, 2012; Niedźwiedzki *et al.*, 2014; Pieńkowski *et al.*, 2014). The lithostratigraphic assignment, age and, partly, depositional setting of the fossil-bearing deposits were more or less conjectural at most of the sites and quickly became the subject of debate, exemplified by the already famous Krasiejów locality (see summary in Dzik and Sulej, 2007 and Bodzioch, 2012). Thus, the correlation and precise dating of the bone-bearing strata became a key research challenge in investigations of the Silesian Keuper, for example, in the context of evolutionary inferences for the early dinosaurs (Racki, 2010).

This article takes as its focus a critical review of the stratigraphic ideas previously proposed by the authors from the Institute of Paleobiology, Polish Academy of Sciences and Warsaw University, led mainly by Jerzy Dzik and/or Grzegorz Niedźwiedzki. Accordingly, the views presented below are considered to be representative for the Warsaw research group. Furthermore, the authors present herein a new stratigraphic perspective for all of the vertebrate localities, on the basis of integrated lithostratigraphy, biostratigraphy and chemostratigraphy. The data are mostly the results of the study, supported by the grant, "The evolution of terrestrial environments of the Upper Silesian Keuper as biotopes of vertebrates" (N N307 11703; Racki, 2010). A more comprehensive presentation of various geological, sedimentological, geochemical and stratigraphic aspects of the middle Keuper tetrapod localities is given in a regional context by Środoń *et al.* (2014), Szulc and Racki (2015), Szulc *et al.* (2015) and Fijałkowska-Mader *et al.* (2015).

STRATIGRAPHIC AND FACIES BACKGROUND

The Upper Triassic succession of Silesia belongs to the Keuper Group (Fig. 2), and, in palaeogeographic terms, corresponds to the marginal part of the Germanic Basin (e.g., Beutler and Nitsch, 2005; Feist-Burkhardt *et al.*, 2008; Bachmann *et al.*, 2010). Variegated, fine-grained clastics and locally evaporites (mostly gypsum pseudomorphs) and carbonates are the most common deposit type and the records of ephemeral-lake and evolving fluvial systems developed under mostly arid to semi-arid climate conditions with some pluvial interludes (Pieńkowski, 1988; Szulc *et al.*, 2006, 2015; Szulc, 2007a).

The largely monotonous and fossil-poor mudstone-claystone succession, up to 400 m thick in northern Silesia and almost without more distinctive marker horizons, in its facies development differs somewhat from the classical Germanic Keuper, in particular in the occurrence of the palustrine carbonates of the Woźniki Limestone (see Fig. 2), a unique Keuper facies linked to a spring zone of deeply circulating groundwater that surfaces along the Kraków–Lubliniec master fracture (Szulc *et al.*, 2006). Since the 19th century, the mudstone-claystone rocks were in many places in small, local brickyards and thus they crop out in several scattered clay pits. Stratigraphic correlations of the profiles in Upper Silesia are still uncertain because of the paucity of available biostratigraphic data (see review in Bilan, 1991) and the lack of any consistent regional scheme of lithostratigraphy with formally defined units (see Becker *et al.*, 2008). Moreover, the varied palaeotopography of the Silesian Keuper basin, controlled mostly by synsedimentary tectonics, resulted in extreme lateral variability in facies across the basin, which additionally hinders correlation.

To date, some fragmentary successions, less than 20 m thick, have been correlated with traditional or modern units of the Germanic Keuper (after "Stratigraphische Tabelle von Deutschland", STD 2002; Franz, 2008; Menning *et al.*, 2012) and/or with informal lithostratigraphic units in western Poland (Dadlez and Kopik, 1963) or likewise informal local units (e.g., Bilan, 1976). Litho-, allo- and chronostratigraphic aspects of the several units and correlations proposed are frequently mixed together (see Szulc *et al.*, 2015).

An integrated, regional event-stratigraphic approach enables an explanation of the climate-driven and facies-temporal relationships of the bone-bearing deposits and refers them to the revised lithostratigraphic scheme of the middle Keuper (Szulc and Racki, 2015; Szulc *et al.*, 2015). Within the Grabowa Variegated Mudstone-Carbonate Formation (Fig. 2), the Woźniki Limestone Member (hereafter WLM) is formally defined, along with two members that replace traditional Keuper units: the Ozimek Mudstone-Evaporite Member (= the Upper Gypsum Keuper) and the

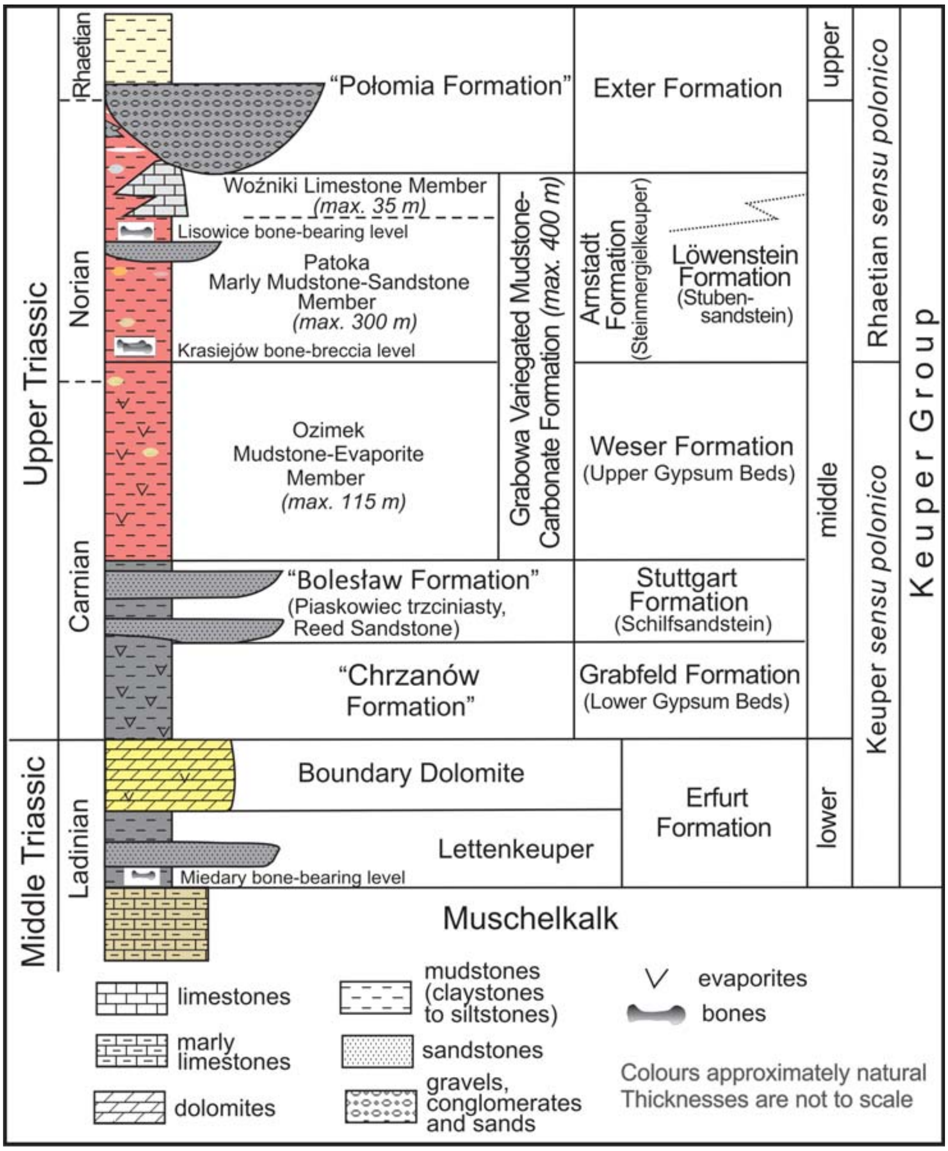


Fig. 2. Schematic section of the Upper Triassic of the Upper Silesia, and its partly formal (in higher part) lithostratigraphic subdivision after Szulc and Racki (2015; changed after Jewuła, 2010, fig. 4), with a focus on correlation with the Germanic Basin reference succession ("Stratigraphische Tabelle von Deutschland" 2002, Franz, 2008); note the occurrence of three bone-enriched levels in the Silesian Keuper, as shown here, but only two Upper Triassic bone beds are defined and discussed in this paper (cf. Szulc and Racki, 2015; Szulc *et al.*, 2015); the Ladinian bone-bed level corresponds to the Miedary Beds of Kotlicki (1974), and the "Miedary sandstone-mudstone member" of Kotlicki (1995; see also Szulc, 2007b; Sulej *et al.*, 2011b).

Patoka Marly Mudstone-Sandstone Member (= the Steinmergelkeuper). The terrestrial vertebrate localities are reviewed below to show their stratigraphic setting in relation to hitherto proposed age designations and to revised or new data collected during the course of this study. Thus, the marginal-marine succession at Miedary (Sulej *et al.*, 2011b) is omitted from the present account.

KRASIEJÓW

The middle Keuper strata in the Ozimek-Krasiejów (formerly Hüttendorf-Krascheow; Fig. 3) area have been known since Römer's (1870) cartographic work and became more accessible since 1905 in the clay pit for local brick production. The excavations eventually intensified between 1974 and 2002, when the mine was included in a cement plant. However, the mass occurrence of vertebrate bones was discovered formally only in 1993 by Robert Niedźwiedzki, although bone-bearing deposits were probably exposed in about 1980 and even were exploited in late 1980s by amateur collectors, such as Krzysztof Spałek (Bodzioch *et al.*, 2010; see the complete case study in R. Niedźwiedzki, 2012, 2015).

Stratigraphic interpretations: the state of debate

As a result of the intensive exploitation bone material and the studies initiated by Jerzy Dzik, the great scientific significance of the Krasiejów 'graveyard' for the study of

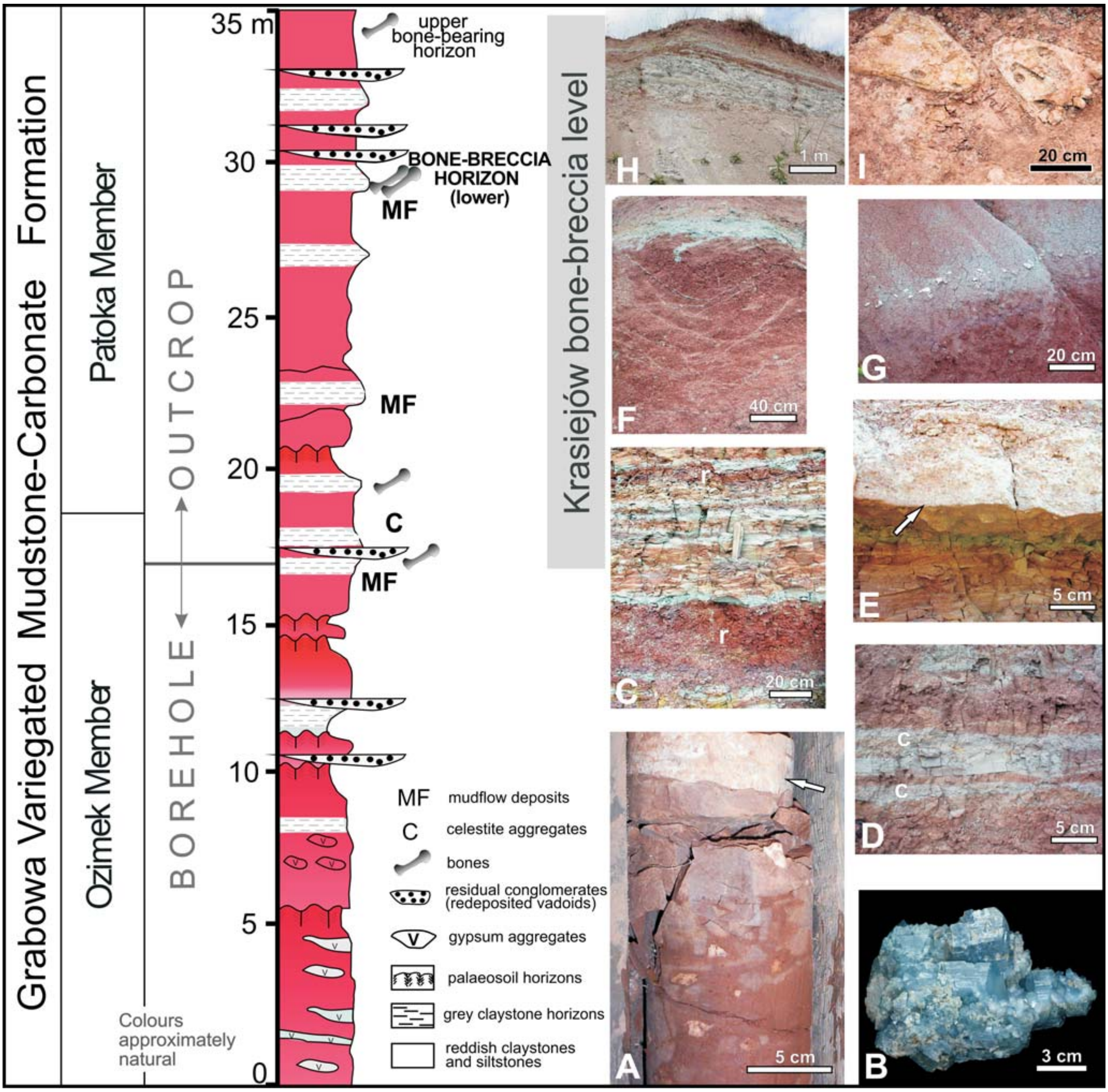


Fig. 3. Simplified lithological column of the Krasiejów succession (after Szulc 2005, fig. 2, modified; see also Bilan, 1975), as the stratotype of the boundary between the Ozimek Mudstone-Evaporite Member with the Patoka Marly Mudstone-Sandstone Member (Szulc and Racki, 2015), and photographs of selected sedimentary features of the Keuper succession in Krasiejów. **A**. Gypsum-bearing (arrowed) red mudstones from Ozimek Mbr. **B**. Celestite crystals from Krasiejów clay pit. Photograph courtesy of Eligiusz Szełęg. **C**. Typical variegated mudstones and claystones of the Patoka Member, composed of alluvial sediments interlayered with regolith horizons (r). **D**. Two layers of reworked palaeosoil grains (c) included in alluvial deposits. **E**. Conglomerates composed of sieved pedogenic nodules. Note the erosive, rounded scour casts at the base (arrowed). **F**. Complex palaeosoil section composed of lower spotty interval, followed by vertisol with slickensides and covered by bluish alluvial sediments. **G**. Carbonate nodular palaeosoil. **H**. Gray fluvial-dominated sediments featuring the upper part of the section in Krasiejów pit. **I**. Metaposaurid skulls from the main bone-bearing horizon. Photographs C and E by Michał Matysik.

Late Triassic terrestrial tetrapods became obvious (e.g., Sues and Fraser, 2010), already after the first publications by Dzik *et al.* (2000) and Dzik (2001, 2003a). The excellently preserved and diverse assemblage, called the *Paleorhinus* fauna, includes numerous, partially articulated skeletons (see summary in Dzik and Sulej, 2007). The presence of the dinosauriform *Silesaurus opolensis* Dzik, 2003, a starting point for the proposal of the new avian-line clade Silesauridae, the closest sister group to dinosaurs, is particularly noteworthy (e.g., Nesbitt *et al.*, 2010; Benton *et al.*, 2014). On the other hand, Bodzioch (2012, p. 33) stressed: "(…) lots of unidentified remains are in collections, numerous problems remain unresolved, and quite a lot of interpretations are controversial (…). Studies of a geological nature mainly revolve around interpretations of the exact age of the bone-bearing deposits, of the sedimentary environment, of diagenesis and of the origin of bone accumulations".

The controversy concerns the age of the bone bearing horizons. In the first papers of the Warsaw group (Dzik *et al.*, 2000; Dzik, 2001, 2003a, 2003b; Sulej, 2002, 2005; but see also Majer and Lubka, 2003), the late Carnian timing of "red-colored middle Keuper marly claystone" was assumed, mainly on the basis of considerations of the vertebrates. This approach allowed a correlation with the standard German Keuper profile of Baden-Württemberg (for the German unit terminology see Fig. 4), even though this is not a very appropriate succession for such a purpose (see the chapter on climatostratigraphy below):

1. The dominant semiaquatic labyrinthodont amphibian *Metoposaurus diagnosticus krasiejowensis* Sulej (= *Metoposaurus krasiejowensis* after Brusatte *et al.*, 2015) is known from the Lehrberg Beds of the middle Weser Formation.

2. Correspondingly, the relatively short-snouted phytosaur *Paleorhinus* from Krasiejów possibly represents "an earlier stage in the evolution of the lineage than the populations from Blasensandstein in Franconia and other known *Paleorhinus* faunas" (Dzik *et al.*, 2000, p. 226) and therefore indicates an equivalent of the lower Bunte Mergel, underlying the Blasensandstein (= a basin margin correlative of the middle Weser Fm in the central basin facies, see Fig. 4).

3. The joint occurrence of *Paleorhinus* and *Metoposaurus* assigns the Krasiejów assemblage to the worldwide and oldest dinosaur-bearing Paleorhinus biochron (Otischalkian land-vertebrate faunal chron, LVF; Lucas, 1998), thought at that time as being dated in a marine context as late Carnian (more exactly, late Julian–early Tuvalian subages; see revised view in Butler *et al.*, 2014).

In terms of the local geology, the tetrapod-bearing calcareous horizon is thought to be about 80 m above the Schilfsandstein (Reed Sandstone) marker, recognized in the Ozimek 1a well (situated 5 km west of Krasiejów; see Kłapciński, 1993), but also about 20 m above the gypsum-bearing unit (after the documented borehole data at this clay pit: Bilan, 1975; Dzik *et al.*, 2000, p. 228). In summary, "based on the position of the Krasiejów fossiliferous horizon in the lithostratigraphic column, it seems to be coeval to the Lehrberg Beds in Germany, which probably terminate the Carnian sedimentary cycle" (Dzik, 2001, p. 625). In the subsurface lithostratigraphic terms of Dadlez and Kopik (1963), the Krasiejów succession was thought to correspond to the Drawno Beds and (in the uppermost part) to the Jarkowo Beds (Dzik *et al.*, 2000, p. 228). Dzik (2001, p. 625) noted a probable correspondence of these highest strata at Krasiejów to the Blasensandstein horizon. Olempska (2004, p. 432) concluded more carefully from the conchostracan correlation with the German succession that this fauna "probably lies within the middle late Carnian time span". However, some authors recently regard all the conchostracan-based dates and correlations as highly conjectural (Becker, 2015; Maron *et al.*, 2015; see below).

In the abstract of the article only, Dzik *et al.* (2000) noted: "(…) an incomplete skeleton has been found about 8 m below the most fossiliferous horizon, in a calcareous intercalation within red clays comparable with the German Rote Wand". Dzik (2003a, p. 557) indicated a more broad stratigraphic distribution of the bone material, and first clearly distinguished two Fossillagerstätte horizons "of virtually the same geological age" at this locality, where "the upper fossiliferous horizon was identified about 7 m above the lower one during excavations in 2000", and characterized by terrestrial reptiles and capitosauroid amphibians in flood deposits (see also Majer and Lubka, 2003; Dzik and Sulej, 2007; Skawina, 2013).

Szulc (2005, 2007a) presented another approach to the question of the age of the Krasiejów succession, and thus initiated a basic controversy between sedimentologic and facies *versus* palaeontological "schools", as defined by Bodzioch (2012; see also Bodzioch *et al.*, 2010). The author stressed that the succession about 18 m thick was not studied in detail with regard to age and facies, and "the proposed evolutionary inferences (Dzik *et al.*, 2000; Dzik, 2003) could be premature" (Szulc, 2005, p. 161). In the context of dating, Szulc (2005, p. 165) indicated: "Lack of age-diagnostic fossils, including palynomorphs, makes stratigraphic statements uncertain. Nonetheless, the lithostratigraphic framework (which reflects climatostratigraphic constraints) is quite clear and allows one to recognize the gypsum-bearing, lower part of the profile from Krasiejów as the uppermost Upper Gipskeuper (…)". Thus, this section is interpreted as the transition strata from the Weser Fm to the overlying, bone-bearing Steinmergelkeuper (Arnstadt Formation, STD 2002). Furthermore, Szulc (2005, fig. 2) assigned bone-bearing horizons to the Norian stage, as suggested by palynostratigraphic dating of the uppermost Upper Gipskeuper by Orłowska-Zwolińska (1983). A similar viewpoint is presented by Gruszka and Zieliński (2008, fig. 2), who, with reference to Bilan (1975) and Deczkowski *et al.* (1997), pointed out a discrepancy between the palaeontological and lithological premises; they favored at least partial assignment to the Norian stage. Gruszka and Zieliński (2008) advocated also the Steinmergel (= Drawno to Zbąszynek Beds) temporal equivalency, indicated by the lack of sandstone and gypsum intercalations in the profile under debate. Bodzioch and Kowal-Linka (2012) also agreed that the probability of a middle to late Norian age is indicated by the overall facies development.

The age inference of Szulc (2005, 2007a) has been rejected by Dzik and Sulej (2007, pp. 22–23) because of the conchostracan argument alone: "The identity of the rock unit exposed at Krasiejów with the Arnstadt Fm can be immediately dismissed because of the conchostracan evidence. Olempska (2004) identified an abundant conchostracan fauna with *Laxitextella laxitexta* (Jones) in the main fossiliferous horizon of Krasiejów. According to Bachmann and Kozur (2004, p. 49), this species occurs also in Germany in the Coburg Sandstone (Hassberge Formation), immediately above the Lehrberg Beds (Steigerwald Formation). The Coburg Sandstone is correlated with the middle part of the late Carnian (Tuvalian) Weser Fm (formerly Oberer Gipskeuper)". In their extensive review, Dzik and Sulej (2007, p. 3) carefully summarized the situation: "The geological age of the Krasiejów strata can be determined, although with a rather low resolution, based on position of various members of its fauna in their evolutionary lineages. (…). The strata

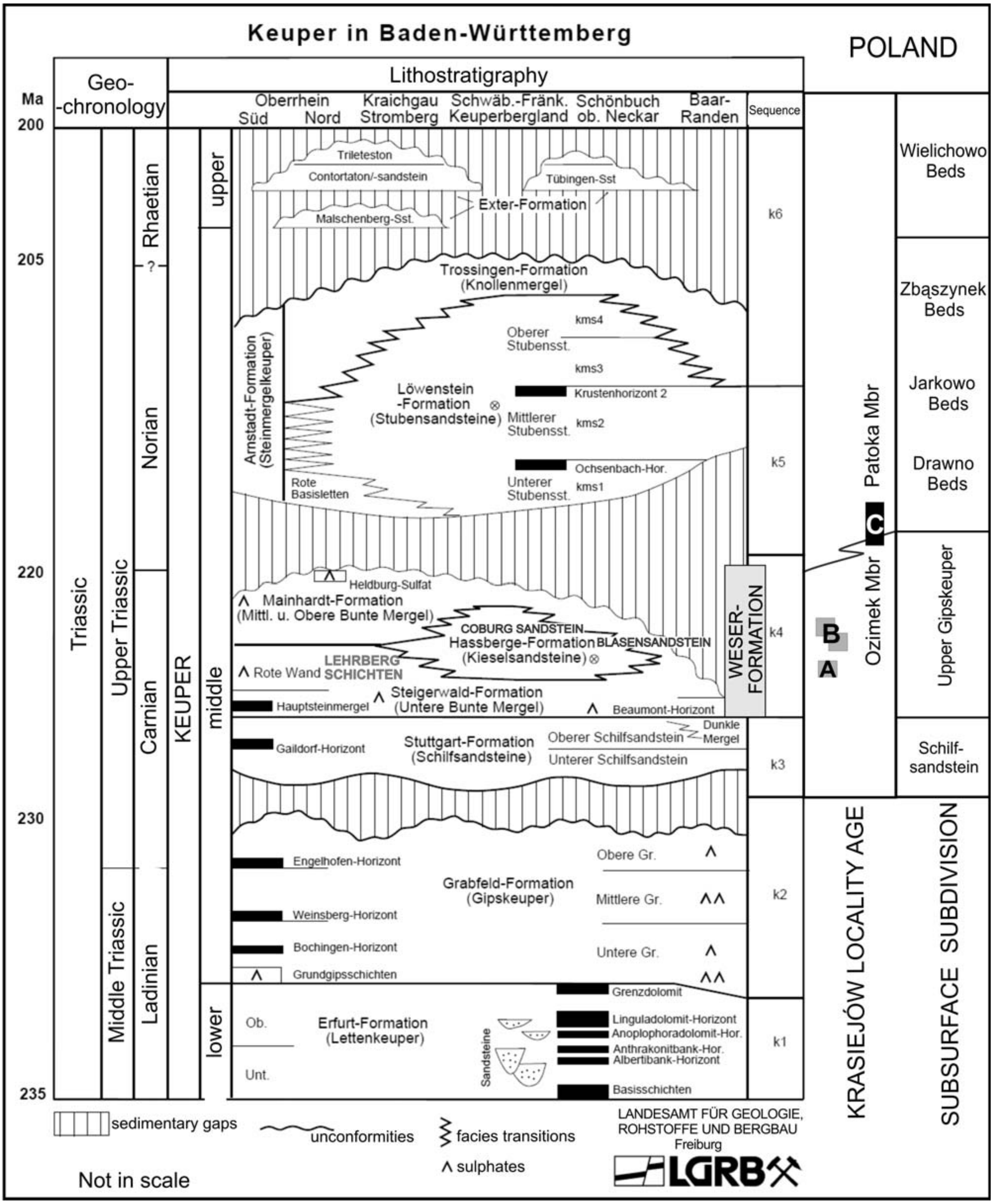


Fig. 4. Three main correlation variants of the Krasiejów clay pit section with the updated reference German Keuper profile (in basin margin facies) of Baden-Württemberg (Nitsch, 2011) and Polish stratigraphic schemes (Dadlez and Kopik, 1963; Becker *et al.*, 2008; Szulc and Racki, 2015): (A) with the Lehrberg Beds (Steigerwald Fm), based on the original vertebrate evidence of Dzik *et al.* (2000), favoured, among others, by the inference from conchostracan dating (Kozur and Weems, 2010); (B) with the Blasensandstein or Coburg Sandstein of the Hassberge Fm, supported by revised vertebrate data (Milner and Schoch, 2004; Butler *et al.*, 2014, fig. 1B) and macrofloral evidence (Pacyna, 2014), respectively; (C) with the Arnstadt Fm, deduced initially from facies development and palynostratigraphic dating (Szulc, 2005, 2007a; cf. also Gruszka and Zieliński, 2008), confirmed by the present, integrative, stratigraphic study (see Fig. 17); the Weser Fm is a lateral equivalent in central basin facies. Note more continuous deposition in Silesia region than assumed in DST 2002 (Szulc *et al.*, 2015), recorded in the transition from the Upper Gipskeuper to Steinmergel facies at Krasiejów (= Ozimek and Patoka mbrs of Grabowa Fm, respectively, Fig. 3; Szulc and Racki, 2015).

seem to correspond with the upper part of the Weser Fm in Germany, believed to be of Late Carnian age".

Despite a somewhat different approach to the same taxonomical questions, including the *Metoposaurus* subspecies, Lucas *et al.* (2007) confirmed the correlation of the Krasiejów tetrapod site with the Lehrberg Beds, but the *Parasuchus* (= *Paleorhinus* of Dzik, 2001) and *Metoposaurus* co-occurrence is seen by Lucas (2010) as key indicators of the middle Carnian (Otischalkian) age. Kozur and Weems (2010, p. 383) formally defined the new conchostracan Laxitextella seegisi Zone, encompassing both the Lehrberg Beds and the Krasiejów succession. Simultaneously Kozur and Weems (2010, p. 383) stressed that Lucas (2010) explained "the contradiction between conchostracan correlations and the land-vertebrate definition of the Otischalkian–Adamanian boundary", because "the famous Krasiejów fauna" is assigned to the succeeding Adamanian Chron LVF (Tuvalian; the Rutiodon Assemblage Zone of Lucas, 1998); the fossiliferous strata were invariably thought to be homotaxial with the German Lehrberg Schichten. This late Carnian interval is defined by the stratigraphic range of the aetosaur *Stagonolepis*, whilst the *Metoposaurus-Parasuchus* association remained a vertebrate indicator of the preceding mid-Carnian LVF in the biochronology scheme of Lucas (2010).

Even though only "believed to be of Late Carnian age" by Dzik and Sulej (2007), this hypothetical age assignment was accepted in a long series of palaeontological studies on tetrapod and invertebrate faunal elements (e.g., Barycka, 2007; Dzik, 2008; Brusatte *et al.*, 2009; Piechowski and Dzik, 2010; Sulej, 2010; Konietzko-Meier *et al.*, 2013; see the reference list in Bodzioch, 2012). Moreover, Dzik and Sulej (2007) and Skawina and Dzik (2011) even assigned a 230 Ma age to this tetrapod graveyard (Dzik, 2003b, assumed 225 Ma). The late Carnian age is also designated by the recent macrofloral correlation of Pacyna (2014), who compared his "Voltzia floral assemblage zone" with the Coburger Sandstone flora.

In the most recent papers on the veterbrate problems (Butler *et al.*, 2014; Piechowski *et al.*, 2014; Antczak, 2016), this age is retained, as well as the lithostratigraphic affiliation to the Drawno Beds (Sulej, 2010; Desojo *et al*, 2013; Skrzycki, 2015). In particular, Butler *et al.* (2014) re-studied the phytosaur taxonomy and phylogeny, as well as the biochronological status of the 'Paleorhinus Biochron', and concluded that the Krasiejów fauna is coeval with the late Carnian Bavarian (Ebrach) assemblage of the Blasensandstein. However, Butler *et al.* (2014, p. 205) noted also "the major differences between the assemblages are the presence of *Ebrachosuchus neukami* and a plagiosaurid temnospondyl at Ebrach (…) and the presence of a 'rauisuchian', *Polonosuchus*, and a silesaurid dinosauromorph, *Silesaurus*, at Krasiejów (…); these differences may represent palaeoenvironmental or sampling biases, particularly given the predominance of aquatic taxa at Ebrach".

Among the palaeontological papers, only Skawina (2013, pp. 70–71) highlights serious difficulties in the interpretation of the age of the Krasiejów fauna. She stated that "precise dating remains a matter of dispute" and it is exclusively "believed to correspond to the Alpine Late Carnian". A possible error in dating ranges from "a rather early part of the Carnian" to "Early Norian", accordingly to the available correlation variants with the German Keuper reference succession. Also Irmis (2011, p. 409 and fig. 2), in the context of the position of *Silesaurus*, stressed that the Carnian age was "based on 'stage of evolution' biostratigraphic arguments, but an early Norian age is equally likely" on the basis of lithostratigraphic correlation.

In fact, the Norian alternative emerged in the light of revised data on the temporal distribution of *Metoposaurus diagnosticus krasiejowensis* in the western Germanic Basin, extended upward to the middle Norian (middle Middle Stubensandstein, Löwenstein Formation) by Milner and Schoch (2004). However, Milner and Schoch (2004) supposed that the proliferation of Silesian subspecies is the temporal equivalent to the Kieselsandstein fauna, whereas the older Lehrberg Beds in fact are characterized by the most primitive chrono-subspecies *M. diagnosticus diagnosticus* Meyer. However, this assertion is rejected by Sulej (2007, pp. 127–128), who has tried to confirm the original correlation of Dzik *et al.* (2000) with the underlying Lehrberg Beds (see Fig. 4), and therefore considered the metaposaurid subspecies as "rather geographical races" (see an updated discussion in Lucas, 2015; compare Brusatte *et al.*, 2015).

In summary, disentangling the correlation dilemma of the Krasiejów succession with the German reference, recent data point to three different hypotheses of correlation (Fig. 4). Both Carnian variants of the Warsaw group are stratigraphically close and may be assigned to the upper Weser Fm (*sensu* Franz, 2008) and late Carnian Tuvalian substage.

Facies and environmental models

In the controversial facies context, Bilan (1975) originally interpreted the Krasiejów mudstone succession as cross-stratified fluvial deposits, succeeded upwards by massive lithologies referable to a brackish (mesohaline) basin. Dzik *et al.* (2000) first considered the fine-grained, organic-rich, dark and uniformly thick bone-bearing deposits as the depositional record of a large lake-deltaic interlude within the cross-bedded fluvial mudstone succession, ascribed to a meandering river. Dzik and Sulej (2007, p. 6) claimed that the profusion of charophyte gyrogonites (Zatoń *et al.*, 2005), bivalves, ostracodes, and articulated fish skeletons is an additional argument for a lacustrine milieu. More generally, this would be a basin-scale event of rising erosional base level in the highstand phase of the Carnian transgressive cycle after the pluvial-type Schilfsandstein sedimentation. Remarkably, Dzik and Sulej (2007, p. 16) noted in addition to the lake community: "The most numerous fossils of land tetrapods have been obtained from the upper fluvial horizon, but virtually all data on coeval flora and invertebrate fauna comes from the basal layer of the lacustrine bed". More advanced studies were not undertaken by the Warsaw group to support this depositional model.

From a strictly sedimentologic viewpoint, Gruszka and Zieliński (2008) described the environment of the Krasiejów succession as "a low-energy anastomosing to meandering silt-bed fluvial system", evolving in a subtropical, seasonally dry but increasingly humid climate. However, "the massive clayey middle unit" was thought to have been deposited in an extensive, long-lived lake basin. Szulc (2005) highlighted the process of bone concentration exclusively in small, ephemeral lakes and ponds in an unstable climatic and tectonic setting. Likewise, Bodzioch and Kowal-Linka (2012) discussed episodic climate-controlled flood events in the origin of the lower (= main) bone bed of the middle unit (i.e., lacustrine interval of Gruszka and Zieliński, 2008). The polemics resulted in changing views on the origin of the fossiliferous deposits and, for example, Konietzko-Meier *et al.* (2013) already wrote about two bone-bearing alluvial horizons (see chapter on taphonomy).

Discussion

As shown above, despite some uncertainties concerning intra-Carnian correlation (Fig. 4), there is no biochronological basis for acceptance of the Norian age of the Krasiejów fossil biota (compare Lucas, 2015). From multidisciplinary viewpoint of the present authors, this conclusion of the Warsaw group is seriously challenged by the following set of data:

1. The reference German succession for the middle Keuper vertebrates is in fact incomplete (Fig. 4), if a great early Norian hiatus is accepted in this part of Germanic Basin. Thus, it is possible that several 'guide' taxa are not strictly limited to the Carnian, but continued into the Norian (see also Lucas, 2015).

2. In strictly lithostratigraphic terms on a regional scale, as noted already by Dzik *et al.* (2000) and stressed by Szulc (2005, 2007a) and Gruszka and Zieliński (2008), the main Krasiejów fossiliferous levels occur above evaporite-bearing deposits. More precisely, in the revised scheme of Szulc and Racki (2015, fig. 7), with reference to the succession from a borehole in the clay pit (Szulc, 2005, fig. 2; cf. also Bilan, 1975), the upper boundary of the Ozimek Mbr, a formal unit replacing the Upper Gypsum Beds, is placed at the top of a celestite-rich horizon, above the gypsum-bearing playa-type strata (see Szulc, 2005, plate 1A–B); this boundary also is placed directly above the oldest bone-bearing strata (Fig. 3). Thus, a straightforward, long-distance correlation of the Krasiejów section with the Weser Fm of SW Germany, omitting closer regions (Brandenburgia, Thuringia and Saxony-Anhalt) is very risky, since there are crucial facies differences between the mid-Keuper in SW Germany and other Germanic basins, including that of Upper Silesia. As a matter of fact, the typical Lehrberg Beds of Baden-Würtemberg, as unquestionably lacustrine carbonate sediments, are completely absent from the Silesian Keuper, as discussed below (see, for instance, the nearby drill sections; Assmann, 1926, 1929; Koeppen, 1997).

3. In the inter-regional context of the Polish Basin, the correlation of the Krasiejów succession with the Drawno Beds and even in part with the Jarkowo Beds, proposed by Dzik *et al.* (2000), remains in distinct contradiction to the accepted late Carnian age of this section and equivalence with the evaporite Weser Fm (as given explicitly by Skrzycki, 2015). The Drawno and Jarkowo Beds in fact overlie the Upper Gypsum Beds, and are obvious correlatives for the Steinmergelkeuper (Arnstadt Fm; cf. Fig. 4). Furthermore, the strongly laterally variable Drawno Beds (as noted already by Dadlez and Kopik, 1963) have been omitted from many correlation schemes since Deczkowski (1977; see Bilan, 1991, fig. 1) and included in the Jarkowo Beds (e.g., Orłowska-Zwolińska, 1985; Becker *et al.*, 2008; Marcinkiewicz *et al.*, 2014; Fijałkowska-Mader, 2015).

4. The correlation of the Krasiejów lacustrine-alluvial deltaic sedimentation with the late Carnian Lehrberg transgression is an original event-stratigraphic concept of Dzik *et al.* (2000), but without comparable examples of such transgression-initiated lacustrine systems in the stratigraphic record (see another lake interpretation in Gruszka and Zieliński, 2008). However, the main obstacle is a sedimentologic flaw in the proposal, because typical lacustrine facies are characterized by fine horizontal lamination, recording depositional rhythmicity, driven by wet/dry seasonality and transient chemocline development, paired with prodelta turbitites, organic-rich muds and carbonate interlayers (see for instance Bohacs *et al.*, 2000; Cohen, 2003; Renaut and Gierlowski-Kordesch, 2010). The diagnostic characteristics are mostly expressed in the Late Triassic basins (see papers in Gierlowski-Kordesch and Kelts, 1994; also e.g., Demico and Gierlowski-Kordesch, 1986, Clemensen *et al.*, 1998, Vollmer *et al.*, 2008), including the adjacent Holy Cross region (lithofacies O of Czapowski and Romanek, 1986). In this context, Dzik and Sulej (2007) explained the massive mudstone structure as an effect of pedogenic homogenization of originally laminated deposits in conditions of profound dry wet seasonality, but this is probably to a limited degree. As a matter of fact, the typical lacustrine deposits encompass a suite of facies from palustrine, through littoral to profundal (controlled by water column stratification) ones. The concept of total pedogenic homogenization of primary lacustrine characteristics, including those from the profundal facies, as assumed by Dzik and Sulej (2007), sounds irrationally even in terms of Walther's Law. Gruszka and Zieliński (2008) thought of this lithologic homogeneity as the primary signature of quiet and stable deposition from settling out of suspension. However, with regard to the massive lacustrine facies, Szulc (2005, p. 165) explained that "the lithological properties of the typical Lehrbergschichten, with the outstanding 2-4 massive, dolomitic lacustrine horizons, differ significantly from those observed in the Krasiejów".

In summary, the Krasiejów section is not composed of typical lacustrine sediments. Instead, the deposits represent a playa flat with small depressions (of gilgai-type topography) forming ephemeral ponds and strongly controlled by wet/dry climatic seasonality (cf. Szulc 2005, 2007a; Bodzioch and Kowal-Linka, 2012; Gruntmejer *et al.*, 2015).

5. The authors of the Warsaw group significantly mentioned (Dzik *et al.*, 2000, pp. 228–229; see also Dzik and Sulej, 2007, p. 22) that the subsurface equivalents above the gypsum-bearing strata of the Krasiejów profile (Drawno and Jarkowo Beds) were palynostratigraphically dated by Orłowska-Zwolińska (1983) as Norian (i.e., Classopolis meyeriana Zone, poorly known ?IVa to lower IVb interval; confirmed in Orłowska-Zwolińska, 1985, Deczkowski *et*

al., 1997; Marcinkiewicz *et a*l., 2014; Fijałkowska-Mader, 2015). Of course, this is inconclusive, owing to a lack of palynological material for direct dating of the succession.

6. The conclusive argument on a regional scale is provided by the mineralogical and chemostratigraphic data of Środoń *et al.* (2014). The Krasiejów profile, despite its mineralogical distinctiveness (occurrence of palygorskite), is placed with certainty in the II "Cr/Ti Chemozone", assigned at least largely to the IVb Palynozone in the regional reference section Patoka 1 (see Szulc *et al.*, 2015).

Thus, the present authors support with the additional evidence the inference of Szulc (2005, 2007a) that the Krasiejów bone-bearing succession represents a mostly Silesian counterpart of the Steinmergel facies (Arnstadt Fm; Patoka Mbr) and therefore its Norian age is reasonably implied. This dating may be partly questioned because the Steinmergel facies occurs also locally in the Carnian Weser Fm, below the main Eo-Cimmerian disconformity (see Nitsch *et al.*, 2005, fig. 1; Feist-Burkhardt *et al.*, 2008, fig. 13.13). The interpretation reveals also the problem of diachroneity of the facies transition between hypersaline playa and alluvial (gypsum-free) facies, known from the western Germanic Basin (Edgar Nitsch, pers. comm., 2015), which is difficult to explain with certainty in the Polish Basin (see Szulc *et al.*, 2015).

However, this principal Eo-Cimmerian hiatus signature, such as a deeply weathered surface and/or an atypically mature soil profile, was not recognized in the Krasiejów–Ozimek area (e.g., Bilan, 1975; Szulc, 2005, 2007a). Only a local scour in a low-energy distributary channel network is documented by Gruszka and Zieliński (2008). The consistent sedimentologic and stratigraphic data contradict the hypothesis of a large-scale middle Keuper unconformity on a regional scale, underlying (or locally also partly overlying?) the Steinmergel-like strata (cf. Szulc and Racki, 2015; Szulc *et al.*, 2015; but see Fig. 5). Moreover, the observed replacement of calcium sulphates (from the Upper Gypsum Beds) by celestite and then by carbonate mineral phases (in Steinmergel deposits) is indicative for of playa brine evolution, formed under changing climatic conditions – from very arid to more humid (Füchtbaeur and Müller, 1977). This, in turn, unequivocally provides evidence of continuing facies changeover, and hence denies the erosive and time gap at between the Upper Gipskeuper and the Steinmergel succession, on subsiding tectonic blocks (in a graben?).

On the other hand, the early Norian age of the Krasiejów succession implies a longer-lasting, restricted playa flat in the eastern peripheral part of Germanic Basin during the late Carnian-early Norian regression, paired with the Eo-Cimmerian remodelling of basin topography. This combination of events resulted in a profound within-basin biogeographical differentiation that finally led to a misleading long-distance biostratigraphic correlation, as noted by Sulej (2007) for *Metoposaurus* populations affected by the preceding Carnian (Schilfsandstein) fall in sea level. The stratigraphic interpretation of the present authors implies that these amphibians in the Krasiejów area belong to the last survivors, which is in agreement with the model of Milner and Schoch (2004).

LIPIE ŚLĄSKIE

The clay pit in Lipie Śląskie, at Lisowice village, near Lubliniec, was active, with some interruption, since 1928, and has been known in the literature since 1980 (Fuglewicz and Śnieżek, 1980). The bone material was discovered and initially exploited by the Warsaw research group in 2006, after notification from the amateur mineral collectors, Piotr Menducki and Robert Borzęcki. The first reports, already with an assignment of Rhaetian age, were published two years later (Dzik *et al.*, 2008a, 2008b; Niedźwiedzki and Sulej, 2008). Almost concurrently, this excavation section, extended by two shallow boreholes, was studied by Szulc *et al.* (2006), who assumed a Norian age for the exposed strata, which were dated palynostratigraphically.

The Rhaetian age and alleged atypical nature of the biota

The stratigraphy of the Lipie Śląskie section, located 25 km E of Krasiejów, in fact was established firmly in the first papers. Dzik *et al.* (2008b, p. 733) described the succession (Fig. 5) as: "Bone bearing greenish, reddish, and grey fluvial mudstones and siltstones, interbedded with cross or horizontally stratified greywacke sandstones (the whole stratigraphic section is aproximately 12 meters thick) (…)". Well-preserved Rhaetian vertebrate remains were found "in a lenticular body of grey mudstone and claystone", partly within limestone concretions.

Unfortunately, the most detailed data are presented in a popular-science article in Polish, without individual citations of references (Dzik *et al.*, 2008b). Even if no decisive stage assignment was proposed in this paper, the Rhaetian temporal affinities were strongly favoured on the basis of floral (conifers, twigs, seed-ferns, isoëtaleans) and faunal (conchostracans, dinosaur trace fossils) evidence. Dzik *et al.* (2008a, p. 734) considered the macrofloral and palynological, but also conchostracan data as indicative of a Rhaetian age for this site. This age is accepted (e.g., Gorzelak *et al.*, 2010; Skawina and Dzik, 2011), and strengthened even recently by the macrofloral study of Pacyna (2014). However, the age of the Lipie Śląskie locality subsequently also was defined more widely, between the undivided "late Norian–early Rhaetian" (Niedźwiedzki *et al.*, 2011; Sulej and Niedźwiedzki, 2010; Sulej *et al.*, 2011a; see also e.g., Bajdek *et al.*, 2014; Świło *et al.*, 2014) and "latest Norian and early (possible also younger) Rhaetian" (Pieńkowski *et al.*, 2014, p. 269; see Fig. 5 for this stratigraphic interpretation).

A significant controversy concerns the age of the oddly composed assemblage of vertebrate fauna, a mixture of typically Triassic ('conservative') and advanced, Jurassic types. Also well-preserved floral constituents are likewise surprisingly diverse (cf. also Pacyna, 2014). Dzik *et al.* (2008a) claimed that the discovery of large theropod dinosaurs (3 m in length) expands their fossil record from the Early–Middle Jurassic into the Triassic. However, the predatory archosaur was described by Niedźwiedzki *et al.* (2012) as a new species, *Smok wawelski*, being "a mosaic of primitive archosaur, crocodile-line archosaur, and dinosaur characters" (Niedźwiedzki *et al.*, 2012: 275; see "large

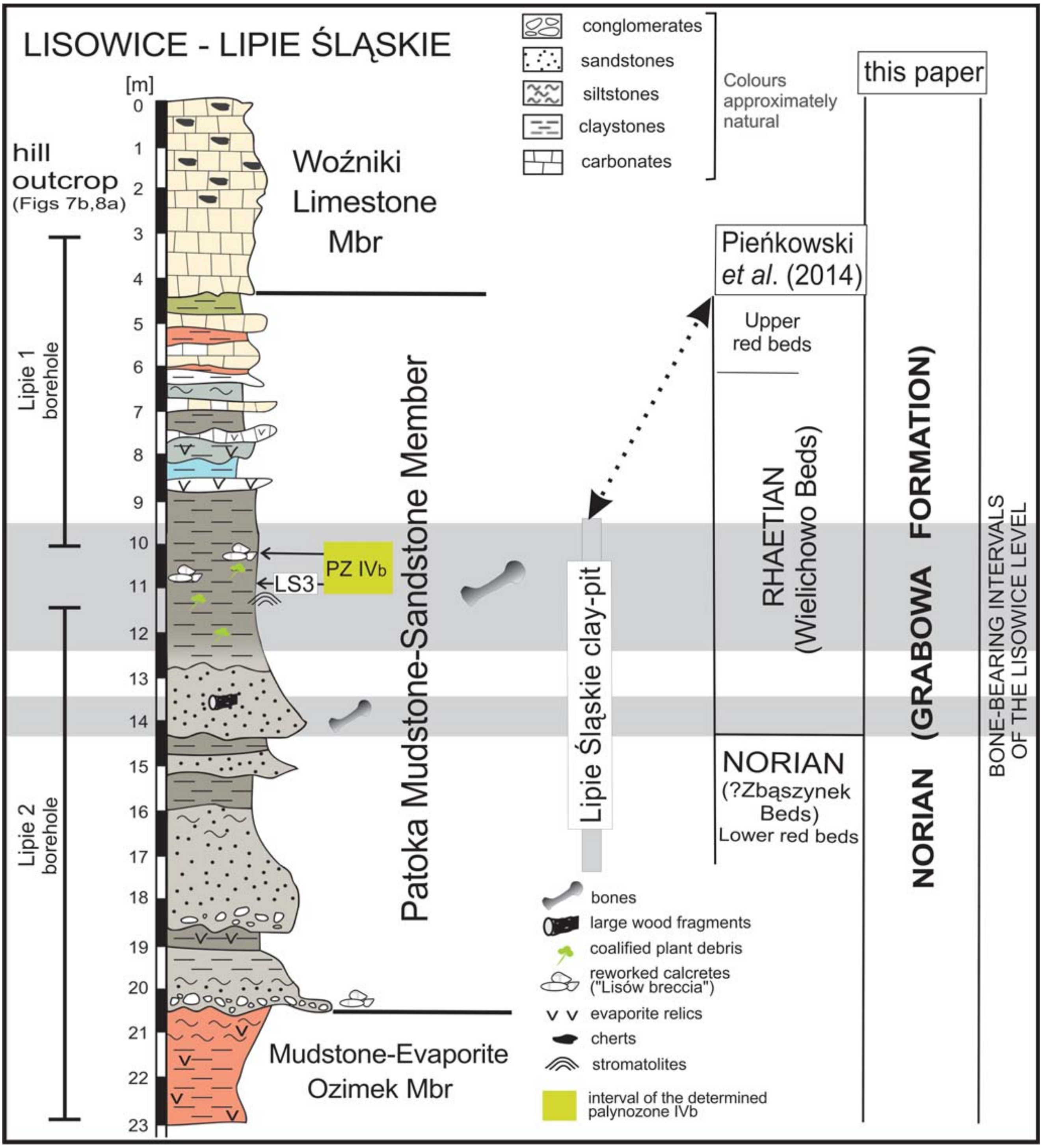


Fig. 5. Lithological succession of the clay pit at Lipie Śląskie and nearby boreholes (cf. Szulc *et al.*, 2006, fig. 5), with marked revised lithostratigraphy (formal units after Szulc and Racki, 2015 and Szulc *et al.*, 2015), bone- and macroflora-bearing intervals (partly after Pieńkowski *et al.*, 2014, fig. 4) and palynologically dated level (PZ IVb; Fijałkowska-Mader *et al.*, 2015; LS3 – sample studied by Anna Fijałkowska-Mader, see Fig. 6). Stratigraphic correlations of Pieńkowski *et al.* (2014, fig. 4) are presented for comparison; note an erroneously estimated thickness of the Lipie Śląskie section (12 m instead 8 m; marked by arrow) by the authors of the Warsaw group since paper of Dzik *et al.* (2008a), as well as misinterpreted red beds as primary depositional units (see Fig. 9); true red beds occur in the Lipie 2 well below an erosional surface.

predatory dinosaur" in Pieńkowski *et al.*, 2014; Zatoń *et al.*, 2015). Lastly, the importance of the site was reinforced by the discovery of a mammal-like tooth (Świło *et al.*, 2014).

All biostratigraphic data from Lipie Śląskie and supposed correlations are still not documented in systematic studies and even largely not illustrated, as exemplified by

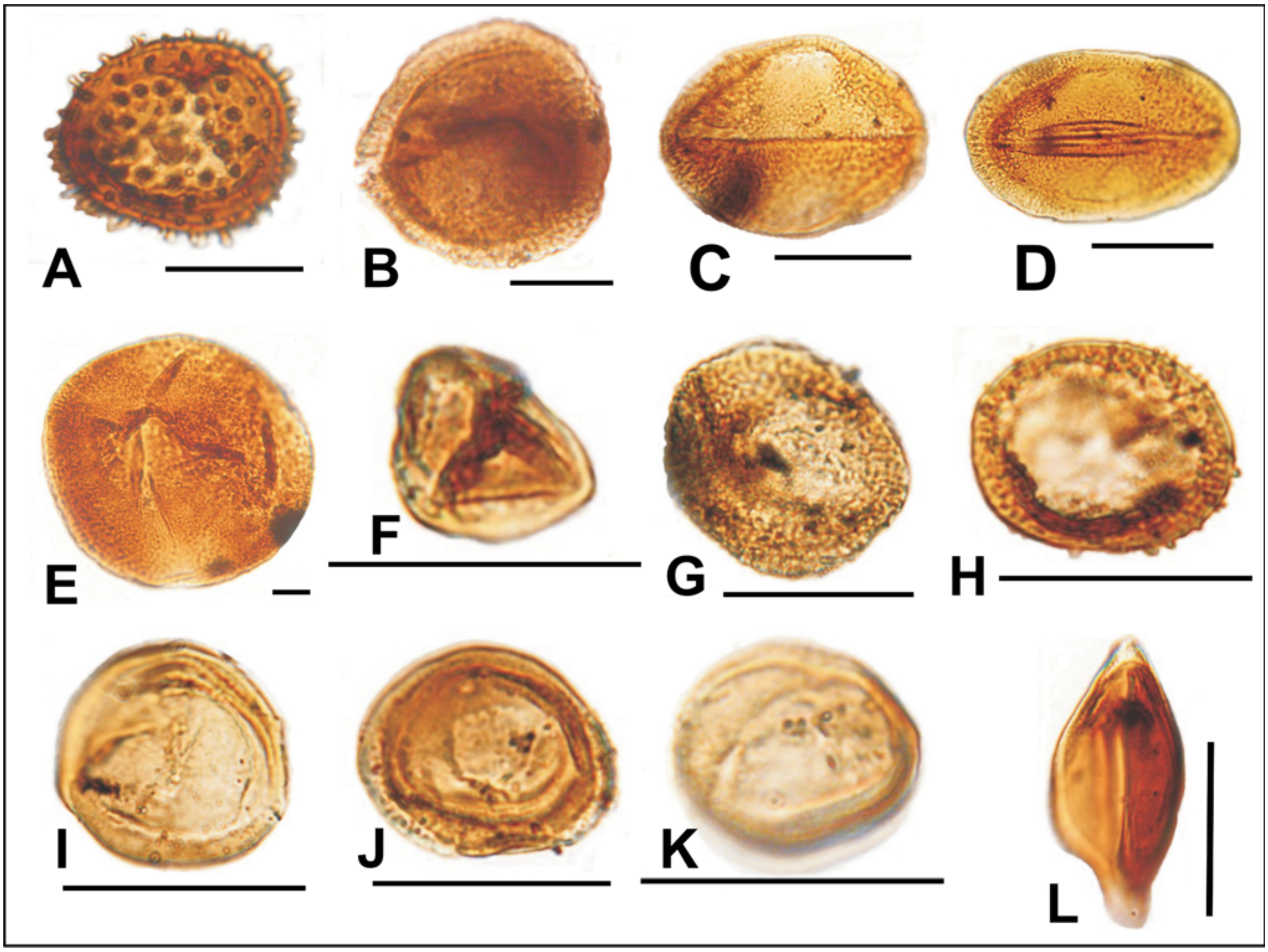


Fig. 6. Miospores from the Lipie Śląskie clay-pit (courtesy of Anna Fijałkowska-Mader). For the location of sample LS3 see Fig. 5. Scale 30 µm. **A**. *Anapiculatisporites telephorus* (Pautsch) Klaus. **B**. *Enzonalasporites vigens* Leschik. **C**. *Ovalipollis* cf. *rarus* Klaus. **D**. *O. ovalis* Krutzsch. **E**. *Brachysaccus neomundanus* (Leschik) Mädler. **F**. *Duplicisporites granulatus* Leschik. **G**. *Praecirculina granifer* (Leschik) Klaus. **H**. *Granuloperculatipollis rudis* Venktachala et Góczán. **I**, **J**. *Classopollis meyeriana* (Klaus) Venktachala et Góczán. **K**. *Geopollis zwolinskae* (Lund) Brenner. **L**. *Monosulcites* sp.

the key palynological data of the Warsaw group. The Subzone IVb of the Classopollis meyeriana Zone and possibly higher ones (IVc to V, *sensu* Orłowska-Zwolińska,1983) were quoted by Dzik *et al.* (2008a) from the succession, although the first one, determined earlier by the experienced palynologist Carmen Heunisch in Szulc *et al.* (2006) and by Staneczko (2007), is clearly limited to the Norian (see below). The dating was revised recently by Pieńkowski *et al.* (2014), who quoted only the Rhaetian IVc and V zones. The palynological studies were supplemented recently by Anna Fijałkowska-Mader and Subzone IV was recognized finally in the organic-rich fossiliferous level (Figs 5, 6; see Fijałkowska-Mader *et al.*, 2015). Therefore, there is no obvious palynostratigraphic evidence for the correlation of the Lisowice bone-bearing horizon with the higher Rhaetian biozones.

The first, strongest arguments for the presence of Rhaetian strata at the Lipie Śląskie pit are derived from macrofloral evidence, including the ‘guide’ Rhaetian seed-fern *Lepidopteris ottonis* (Goeppert) Schimper and the conifer *Stachyotaxus septentrionalis* (Agardh) Nath, both quoted by Pieńkowski *et al.* (2014) and Świło *et al.* (2014), though only the presence of *L. ottonis* was confirmed by Pacyna (2014). Twigs and associated seed scales, described only as “similar to *Stachyotaxus*”, were illustrated by Dzik *et al.* (2008b, pp. 8–9; compare Dzik *et al.*, 2008a) and most probably represent another genus (*Elatocladus*; Pacyna 2014, p. 17).

The second “flag” index Rhaetian species was identified as isolated cuticles merely as cf. [*sic*!] *Lepidopteris ottonis* (Staneczko 2007), or as “very similar to *Lepidopteris ottonis*” (Zatoń *et al.*, 2015, fig. 17), so the occurrence of the species is in fact not demonstrated at Lipie Śląskie (Zuzanna Wawrzyniak, pers. comm., 2015). Furthermore, the possible Norian occurrences of *L. ottonis* in Poland are summarized (i.e., in the Steinmergelkeuper, IVb Subzone) in a recent botanical study by Pacyna (2014, p. 11),: “Because the cuticular differences between *Lepidopteris* species from the Upper Triassic of Europe cannot be compared at present, the question of extending the Lepidopteris ottonis Zone to the Norian on the basis of isolated cuticle fragments cannot be settled. The Norian specimens of *Lepidopteris* may belong to a species undescribed as yet. The inter- and intraspecific

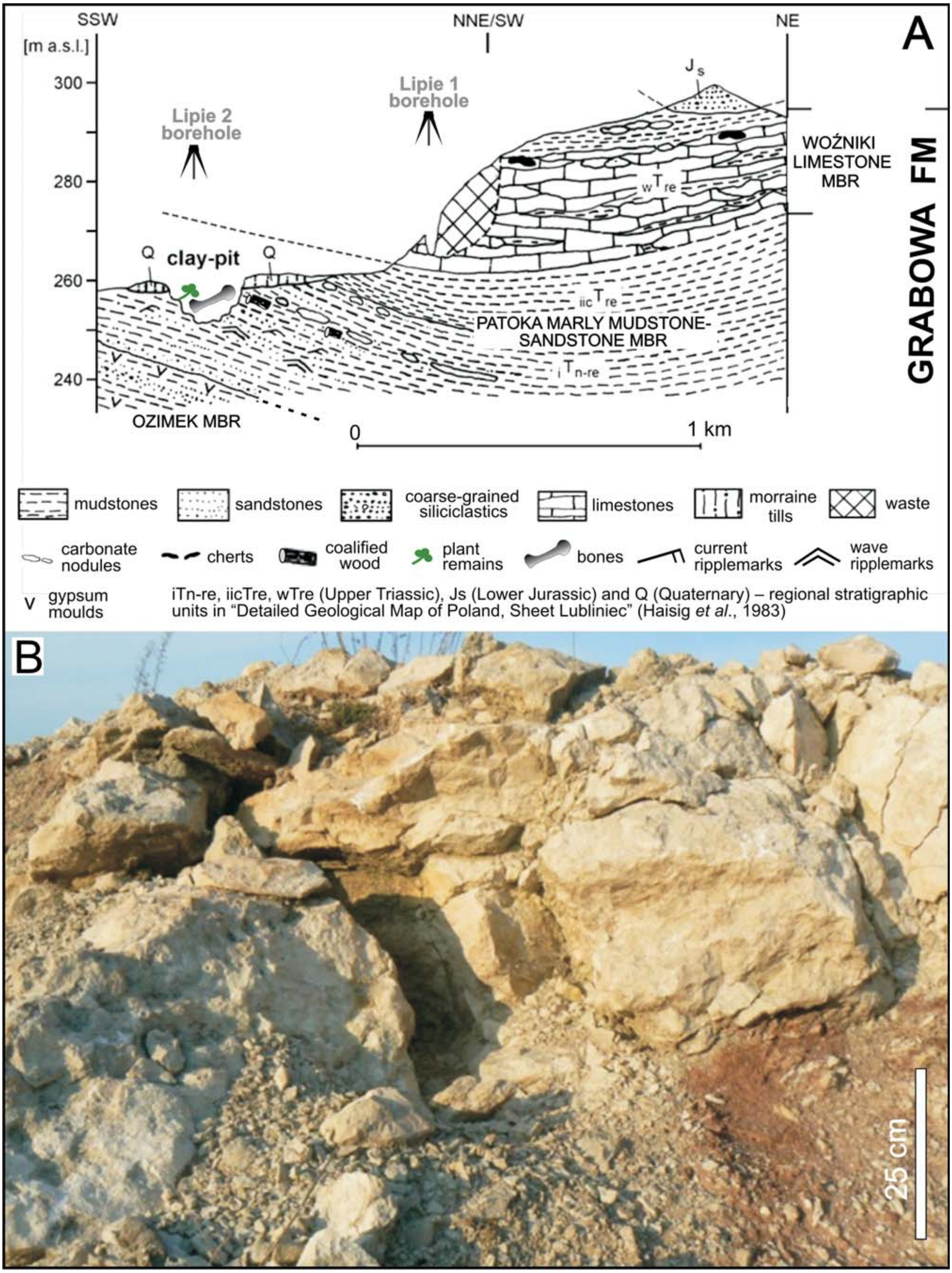


Fig. 7. Schematic geological section across outcrops in the Lisowice - Lipie Śląskie area (**A**; from Bardziński and Chybiorz, 2013), and the Woźniki Limestone Mbr above the brown mudstones, mostly covered by a rubbish dump, as recently visible (November 2014) in an inactive quarry on the Lisowice Hill, situated some 400 m N of the pit (**B**; see Figs 5 and 8, compare Szulc *et al.*, 2006, fig. 8B; see also Gąsiorowski *et al.*, 1986; courtesy of Waldemar Bardziński).

variation of the cuticle in *Lepidopteris* is very poorly known" (see also Marcinkiewicz and Orłowska-Zwolińska, 1994, table 1).

In contrast to the Krasiejów site, however, the evolutionary vertebrate arguments were never used. Foreign authors referred to the amazing Lipie Śląskie findings in different ways. Lucas (2010, p. 465) remarked: "Dzik *et al.* (2008a) recently reported a Triassic dicynodont from Poland in strata they deemed Rhaetian based on palaeobotany", but does not try to compare this fauna with his LVF chrons. Kozur and Weems (2010, p. 386) noted: "a Norian (or possibly Rhaetian) dicynodont recently has been reported from Poland". Irmis (2011, p. 398) quoted "the unexpected co-occurrence of dicynodont synapsids and dinosaurs in the latest Triassic", whilst Brusatte *et al.* (2010, p. 81 and table 1) indicated an unnamed and scarcely described large theropod dinosaur from Lipie Śląskie as "?Norian-Rhaetian" or "?Rhaetian" in age, but highlighted the fact that "Triassic theropods of the same general size of the new Polish material are already known (*Gojirasaurus, Liliensternus*)". In fact, both genera are reported from the Norian of Germany and New Mexico (Brusatte *et al.*, 2010, table 1).

Geological and facies setting

Noteworthy, the lithostratigraphic assignment of the bone-bearing level evolved upward from the Jarkowo and Zbąszynek Beds (Staneczko, 2007) to the Zbąszynek Beds (cf. Niedźwiedzki *et al.*, 2014), the uppermost Zbąszynek to lower Wielichowo Beds (Świło *et al.*, 2014), and lastly to the lower Wielichowo Beds by Pieńkowski *et al.* (2014; Fig. 5). In a local stratigraphic context, a correlation with the interval 18.5–42.0 m of the nearby Lubliniec IG1 borehole (quoted as "Lesieniec IG 1") and with the Krasiejów section was offered by Dzik *et al.* (2008a, 2008b). These correlations are rather speculative, as the middle Keuper deposits from Lubliniec IG1 were described merely as "crumby samples – marly claystones, spotty, variegated" (Siewniak-Madej, 1982, pp. 3–4), and referred to the uppermost "Lisów Beds", 83.5 m thick, 60 m above the Upper Gypsum Keuper (= Weser Fm). Likewise, the relationship to the Krasiejów succession (even ca. 150 m above the playa-type strata – Dzik *et al.*, 2008b, p. 7) is difficult to accept, because Szulc *et al.* (2006, fig. 5) already documented the occurrence of the evaporite-bearing deposits in the Lipie 2 borehole, just a few metres below the exposed strata and below the erosional disconformity (Fig. 5).

On the other hand, the clastic deposits occurring in the Lisowice area pass gradually up-section into relatively pure limestone of crenogenic and palustrine origin, with abundant evaporite pseudomorphs (WLM, as redefined by Szulc and Racki, 2015; Figs 7, 8). Therefore, the key lithostratigraphic argument concerning the stratigraphy of the Lipie Śląskie section is its position below the WLM (Figs 5, 7), a marker unit in local stratigraphy (Szulc *et al.*, 2015).

Dzik *et al.* (2008b) established the superposition of the allegedly Rhaetian fossiliferous strata at the pit and the WLM in Lisowice, but they consequently assigned a latest Rhaetian age to the WLM. The palaeobotanical argument of Dzik *et al.* (2008b), the presence of the fern *Clathropteris*, presently is rejected by Pacyna (2014), who accepted the Norian dating of the Woźniki Limestone (as the Brachyphyllum Floral Assemblage Zone, with *Clathropteris*). On the other hand, Pacyna (2014) supported the Rhaetian age (i.e., the Lepidopteris ottonis Zone) of the Lipie Śląskie succession, which, if true, would imply a reversal of the stratigraphic succession (it would place the Norian above the Rhaetian!) in the area.

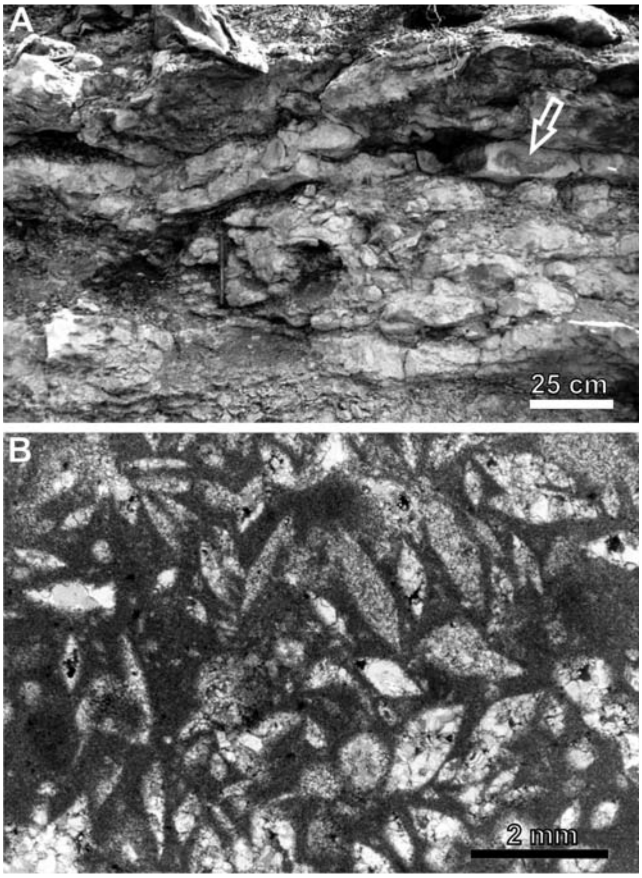


Fig. 8. Woźniki limestones at Lipie Śląskie, with post-evaporitic cherts (**A**; arrowed), photo taken in 1996 (compare Fig. 7B); and gypsum pseudomorphs preserved in these cherts (**B**; thin section).

As stressed above, the authors of the Warsaw group overlooked the data from Szulc *et al.* (2006), where the Norian IVb subzone was identified at Lipie Śląskie, and also the Norian age assigned to the Woźniki Limestone (but see Zatoń *et al.*, 2015). Pieńkowski *et al.* (2014) suggested an alternative: the lateral relationship between the Lipie Śląskie succession and Woźniki Limestone. However, these authors misinterpreted some dozen-cm-thick carbonate concretions from the clay pit as "Woźniki Limestone Beds", while this unit was clearly defined by Szulc *et al.* (2006) as a carbonate body of crenogenic, palustrine, and pedogenic origin, several metres thick. Therefore, such thin and discontinuous limestone occurrences are excluded from the WLM definition in Szulc and Racki (2015; only continuous layers above 0.5 m thick are included). The true Woźniki Limestone crops out in a small, inactive quarry nearby (Figs 7, 8A), where it reaches above 5 metres in thickness (see Fig. 5).

Fig. 9. Apparent "redbeds" from the Lipie Śląskie section. **A**. Lateral pinching of red colour (left side of the section; arrowed) in the "Lower red bed" of Pieńkowski *et al.* (2014). **B**. Complex strike-slip fault surfaces covered with a red Fe oxide patina. **C**, **D**. Details from Fig. 9B. **E**. Topmost part of the section cropping out in the clay pit. **F**. Secondary reddening (arrowed) of the primary grey sediments from the "Upper red beds" of Pieńkowski *et al.* (2014).

In the same paper, Pieńkowski *et al.* (2014, figs 4, 5) misinterpreted two "red intervals" visible in the Lipie Śląskie excavation: one at the bottom (called "Lower red beds") and another in the topmost part of the section ("Upper red beds") as primary redbeds. In fact, the reddish colour is of secondary origin, since the red colour pinches out laterally (Fig. 9A). Due to a significant contribution of organic matter and dispersed pyrite, the original colour of the entire section cropping out in the clay pit is grey or even black. During postdepositional weathering (during the Triassic or even later) the Fe sulphides underwent oxidation and Fe oxides were transported downsection by meteoric waters, percolating along a distinctive fault zone (see Fig. 9B–F). This interpretation invalidates the conclusion regarding these "red" horizons as evidence of a semi-arid climate during deposition and correlation with the originally red Wielichowo Beds (Pieńkowski *et al.*, 2014). True redbed sediments have been penetrated by the Lipie 2 drillhole, some 5 m deeper (Fig. 5).

From a more refined sedimentological perspective, the occurrence of gypsum pseudomorphs (Fig. 7B) within the "Upper red beds" and WLM (see Szulc *et al.*, 2006), and reworked vadoids in the same stratigraphic position (= Lisów Breccia "Beds" of Pieńkowski *et al.*, 2014), indicate arid/semiarid climatic conditions (Szulc *et al*., 2006). This is another strong argument against assigning the Lipie Śląskie succession to the permanently wet Rhaetian stage (see below), even though Pieńkowski *et al.* (2014, p. 283 and fig. 5) tried to explain this apparent facies anomaly in a humid setting by an age correlation with the late Rhaetian climate reversal.

WOŹNIKI

The locality belongs to the historically oldest area around the town of Woźniki, where vertebrate remains (teeth, scales) of fishes and reptiles were known already to Römer (1867, 1870). The pit was active for the production of bricks since 1920 and mining ended in the 1960s (Sulej *et al.*, 2011a).

Stratigraphic interpretation

This excavation has been exploited palaeontologically since 2007 by Tomasz Sulej and his collaborators. This research resulted in the discovery of a dicynodont-archosaur assemblage (including silesaurids?), both as bone material and tracks (Sulej *et al.*, 2011a). The authors presented the section of about 10.5-m-thick red and grey mudstones (fig. 1A therein), with carbonate (hard oolite-like grainstones) and sandstone layers and intercalations (Fig. 10). The two fossil-bearing intervals in the eastern wall are located about 3 m (the main source of bone material) and 10 m above its bottom, assumed to be late Carnian in age. Sulej *et al.* (2011a, p. 261) gave the following summary in their abstract: "The Woźniki vertebrate assemblage is similar to that of Lisowice-Lipie Śląskie (…), in the presence of dicynodonts, shark spines, plagiosaurs and a cyclotosaur, but conchostracans and bivalves are similar to those from the Krasiejów site (late Carnian)".

Discussion

Sulej *et al.* (2011a, pp. 261–262), in fact, correctly noted two essential stratigraphic attributes of the Woźniki section: (1) a similar middle Keuper succession was presented by Grodzicka-Szymanko and Orłowska-Zwolińska (1972, fig. 2) from the CW 62 well located at Woźniki, and the mid–late Norian age for this originally "Rhaetian" well section is designated with reference to Szulc *et al.* (2006), and, more significantly, (2) "the fossiliferous strata at Woźniki grade upwards conformably into the crenogenic–lacustrine deposits of the Woźniki (…) considered to be of Norian age (Szulc *et al.*, 2006)". The authors did not refer to the far more similar succession in the Woźniki borehole, 45 m thick, documented by Szulc *et al.* (2006, fig. 4). The data altogether are sufficient to reject the surprising biochronological inference of Sulej *et al.* (2011a) that this succession is coeval with the late Carnian Krasiejów profile, especially since the conchostracan and bivalve basis for this correlation is poorly documented and only the conchostracan *Laxitextella* cf. *laxitexta* is illustrated. In fact, the Krasiejów succession equivalent occurs about 60 m below the Woźniki clay-pit succession, as indicated by the data from nearby Woźniki K1 and Koziegłowy WB3 wells (cf. Szulc *et al.*, 2015, fig. 7).

PORĘBA

This excavation near the abandoned municipal waste dump, located near the western limit of the town of Poręba (Fig. 11), was known to the Silesian geological community since April 2008 (Krystyn Rubin, pers. comm., 2010; Fig. 12). This small dig was explored for bone material after the discovery of the fossiliferous strata by Tomasz Sulej in September 2008 (Urbański, 2012).

Stratigraphic interpretation

The Poręba site is described in papers of Sulej *et al.* (2012) and Niedźwiedzki *et al.* (2014) as a source of exceptionally rich and diverse vertebrate fauna from two dissimilar habitats (terrestrial and aquatic). This locality is particularly significant for the study of dinosaur clade origins because basal dinosauriforms and theropod dinosaurs co-occur at the site, along with an "armored" reptile group, the aetosaurs (Desojo *et al.*, 2013), and large temnospondyl amphibians. Plentiful specimens of turtles are especially characteristic, as well as the abundance of coalified plants, including a woody stem, 14 m long (see also Kubik *et al.*, 2015), described as the conifer *Agathoxylon keuperianum* (Unger) Philippe by Philippe *et al.* (2015). The overall well-preserved bone material was collected from four intervals grouped in lower part of the allegedly 11 m thick succession, mostly from "yellowish carbonatic conglomerates (…) and grey fluvial carbonatic, organic-rich mudstones and claystones with rare bones (mainly fish remains)" (Niedźwiedzki *et al.*, 2014, p. 1122, see also Figs 13I, 14).

According to the Warsaw group, the dominantly grey marly-mudstone strata exposed at Poręba, interbedded with horizontally stratified yellowish or reddish sandstones and

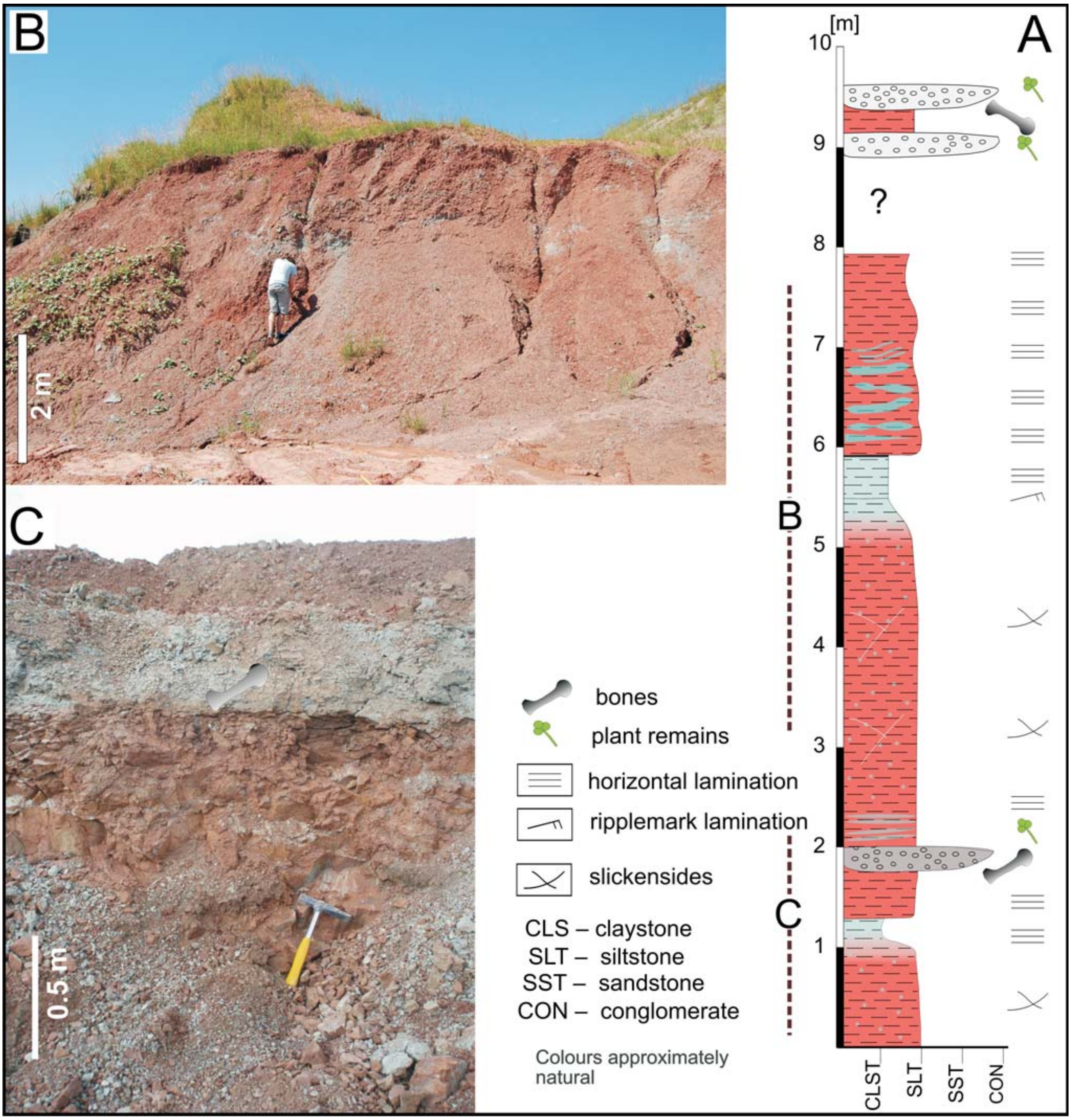


Fig. 10. Composite section (**A**) and field photographs (**B**, **C**) of the Woźniki clay pit succession. Stratigraphic position of bone-bearing horizons of the Lisowice level are approximated from Sulej *et al.* (2011a, fig. 1A).

"Lisów Breccia" carbonates (Figs 12, 13), are assigned to the Zbąszynek Beds and Woźniki Limestones *sensu* Szulc *et al.* (2006), correlative with the Steinmergelkeuper (= the upper Arnstadt Fm and lowermost Exter Fm). The stratigraphic position is evidenced by the palynological material, identified by Anna Fijałkowska-Mader (in Niedźwiedzki *et al.*, 2014) as typical for the mid–late Norian IVb Subzone of the C. meyeriana Zone.

Discussion

In the opinion of the present authors, this middle Keuper locality is correctly dated, although without any attempt to correlate it with the nearby coeval sections, dated as the same IVb Subzone, namely with partly condensed strata from the Poręba well and the Zawiercie outcrop (Szulc *et al.*, 2006, fig. 5). In the local scale, this bone-bearing profile belongs to the broad transition interval between the Patoka Mbr and the Woźniki Limestone Mbr that is widely distributed in the area.

ZAWIERCIE-MARCISZÓW

The lithological section of this new vertebrate locality (Fig. 11), interpreted as coeval with the Lipie Śląskie bone-rich succession (Fig. 14), was presented by Szulc *et al.* (2006), as a result of observations in 2000 by Joachim Szulc in an excavated niche under a new city dump. However, the bone material was first identified by Grzegorz Racki in May 2009 in the pile of Keuper deposits (Fig. 15), mined from the dump niche (now totally filled). The niche profile was extended by the Kobylarz 1 borehole, drilled in 2012, about 250 m east of the former exposure (Figs 11, 14).

Stratigraphic interpretation

The stratigraphic position of the bone-bearing interval was clearly determined by two observations: (1) the bone-bearing strata occur just below the Woźniki Limestone cover, sparsely outcropping in the Kobylarz hill top (Fig. 11), and are associated with microbial, coquinoid and lime conglomeratic layers (Racki, 2010, figs 1, 2; Szulc *et al.*, 2015, fig. 15C–E), and (2) palynostratigraphic dating of the strata as the IVb Subzone (Heunisch in Szulc *et al.*, 2006; see also Sadlok and Wawrzyniak, 2013). As in the nearby Poręba site, located 1.7 km NW, differently preserved, partly reworked bone material is found in rare conglomeratic layers (Fig. 15B, C), whilst isolated and well-preserved remains occur in grey marly mudstones and claystones with carbonate concretions (see Racki, 2010, fig. 1; Fig. 15D). Large dicynodonts and predatory archosaurs of the genus *Smok* are especially distinct elements identified in the collected, not very rich bone material (Budziszewska-Karwowska *et al.*, 2010; Niedźwiedzki and Budziszewska-Karwowska, 2015), supplemented by a tetrapod track assemblage (Sadlok and Wawrzyniak, 2013) and partly charcoaled plant material (Kubik *et al.*, 2015; Philippe *et al.*, 2015; Szulc *et al.*, 2015, fig. 15B).

Fig. 11. Localization of the tetrapod localities near municipal waste dumps and the borehole Kobylarz 1 in the Zawiercie-Poręba boundary area on a Google Earth satellite photograph.

A quite different stratigraphic concept, presented lastly by Niedźwiedzki *et al.* (2014, p. 1122), is therefore astonishing, especially in that the previous data are not discussed by these authors. The Warsaw group suggests that the Marciszów site lies about 20–30 m above the Norian Poręba

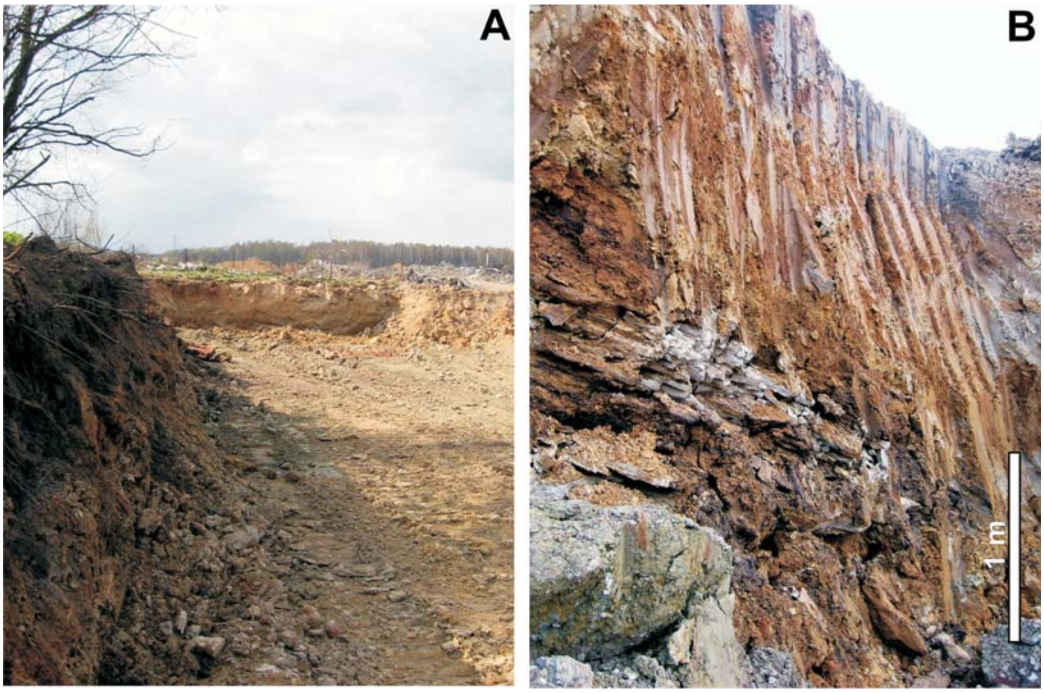
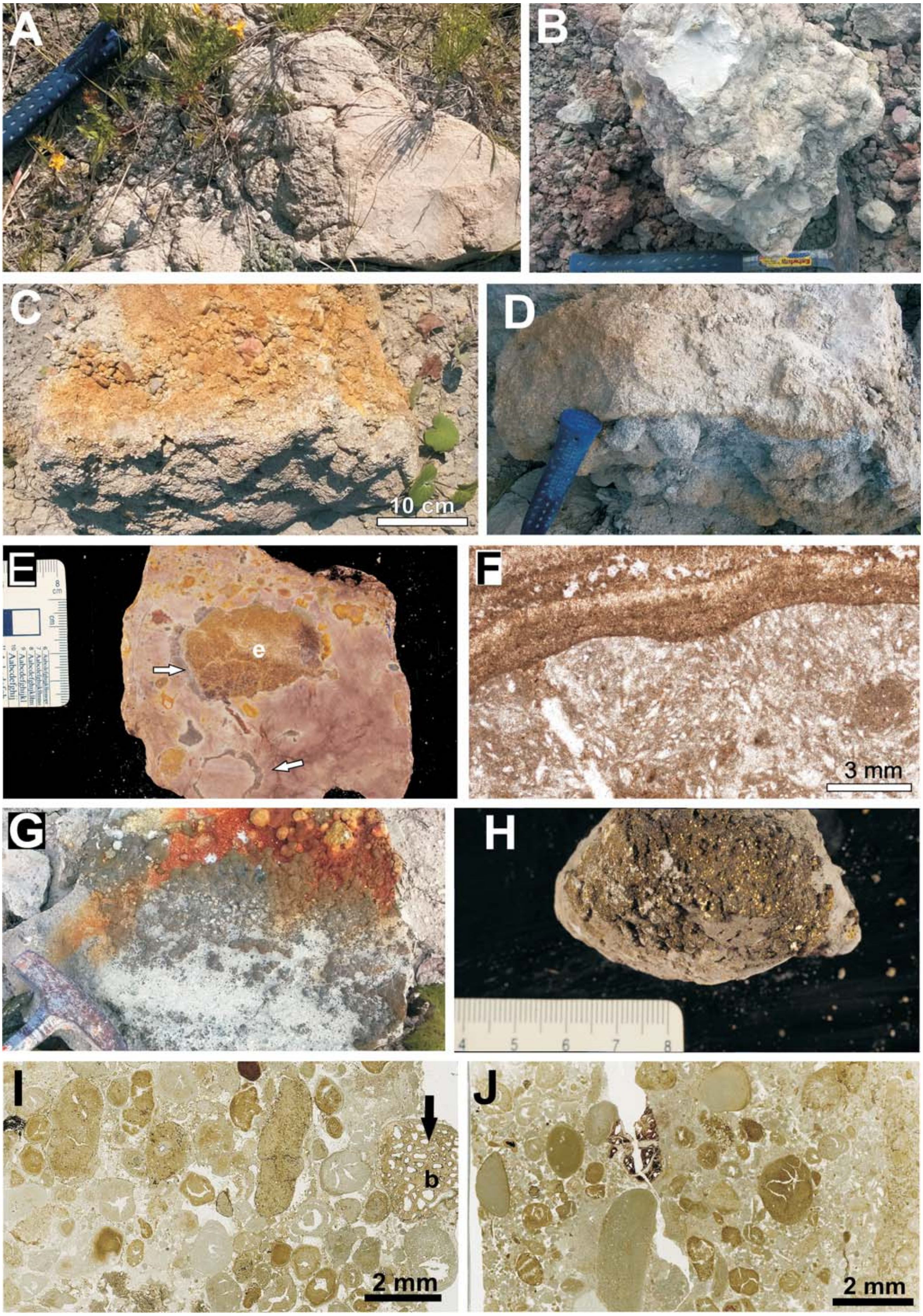


Fig. 12. Photographs of the Poręba locality, taken in April 2008. **A**. View of the western part of fresh excavation, adjacent to the inactive municipal dump (see Fig. 11). **B**. Newly exposed horizontally laminated conglomeratic to sandstone layer in a mudstone series in the southern wall, in the upper part of the section. Courtesy of Krystyn Rubin.


A
B
C
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D
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3 mm
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H
4
5
6
7
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I
b
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Fig. 13. Setting of the most typical facies and microfacies characteristics from sections at Poręba (A, C, E, G, I) and Marciszów (B, D, F, H, J), to show a strict resemblance of the Lisowice bone-bearing level in the both localities (see also Szulc *et al.*, 2015, fig. 16). **A, B**. Massive pedogenic nodules. **C, D**. Conglomerates composed of poorly sorted, sieved pedogenic nodules (= "Lisów breccia" of Niedźwiedzki *et al.*, 2014; see Fig, 14). Note the erosive rounded scour casts at their base. **E, F.** Oncoidal coating developed around lithoclasts, E – polished slab, (e – pseudomorphed gypsum concretion with microbial envelope – arrows), F – thin section; note densely packed small crystals of gypsum, now pseudomorphed. **G, H**. Heavily sulphide encrusted oncoids. **I, J.** Thin-section photographs from finer-grained conglomerates, composed of typical small pedogenic grains; bone fragment (b) is arrowed.

◄

section "according to field observations and local correlations", and consequently should be attributed "to the latest Norian–early Rhaetian faunal assemblage including dicynodonts and archosaurs from the Lisowice locality". The Zawiercie area is noticeably affected by fault tectonics in the Triassic strata (Fig. 16), as evidenced also by recent geophysical study (Idziak, 2013), and any simple correlation of the surficial sections is therefore very risky.

Considering the facies and microfacies characteristics of the main sediment types occurring in the both nearby-situated both outcrops (Marciszow and Poręba), they are uniform (Figs 13, 14). The dominant redbed facies abounds in evaporites (recently preserved as carbonate pseudomorphs), while the conglomerates are mostly composed of reworked pedogenic nodules, and form a the bases of fining-up sedimentary rhythms. The nodules are sometimes coated with cyanobacterial envelopes, suggesting episodic and short wetting events. This all strongly suggests that the both sites encompass sediments of the same age.

CHEMOSTRATIGRAPHY AND MINERAL INDICATORS

This approach to the correlation of the Silesian Keuper profiles was elaborated in detail by Środoń *et al.* (2014),

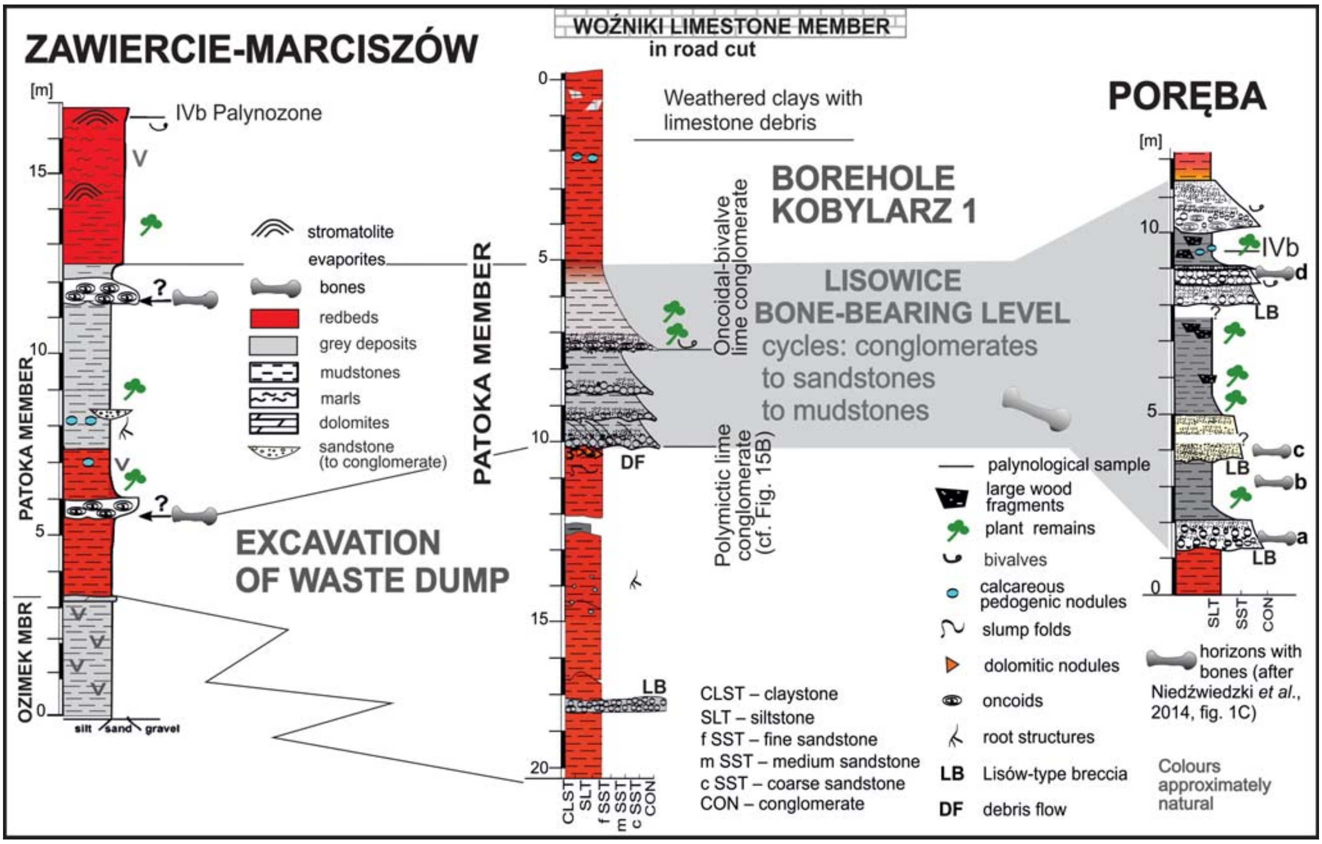

Fig. 14. The lithological section of the Zawiercie-Marciszów site (see Figs 11 and 16), as exposed in the municipal dump excavation in 2000 (reproduced from Budziszewska-Karwowska *et al.*, 2010, fig. 2, based on Szulc *et al.*, 2006, fig. 5; modified) and in the Kobylarz 1 well (Szulc *et al.*, 2015) and at the Poręba site (based on Niedźwiedzki *et al.*, 2014, fig. 1C and observations of the present authors). Arrows indicate alleged bone-rich horizons of the hypothetically-defined Lisowice level, suspected as a source for material exploited since 2009 in the adjacent mound of the Keuper deposits derived from the dig (see Figs 11, 15, 16).

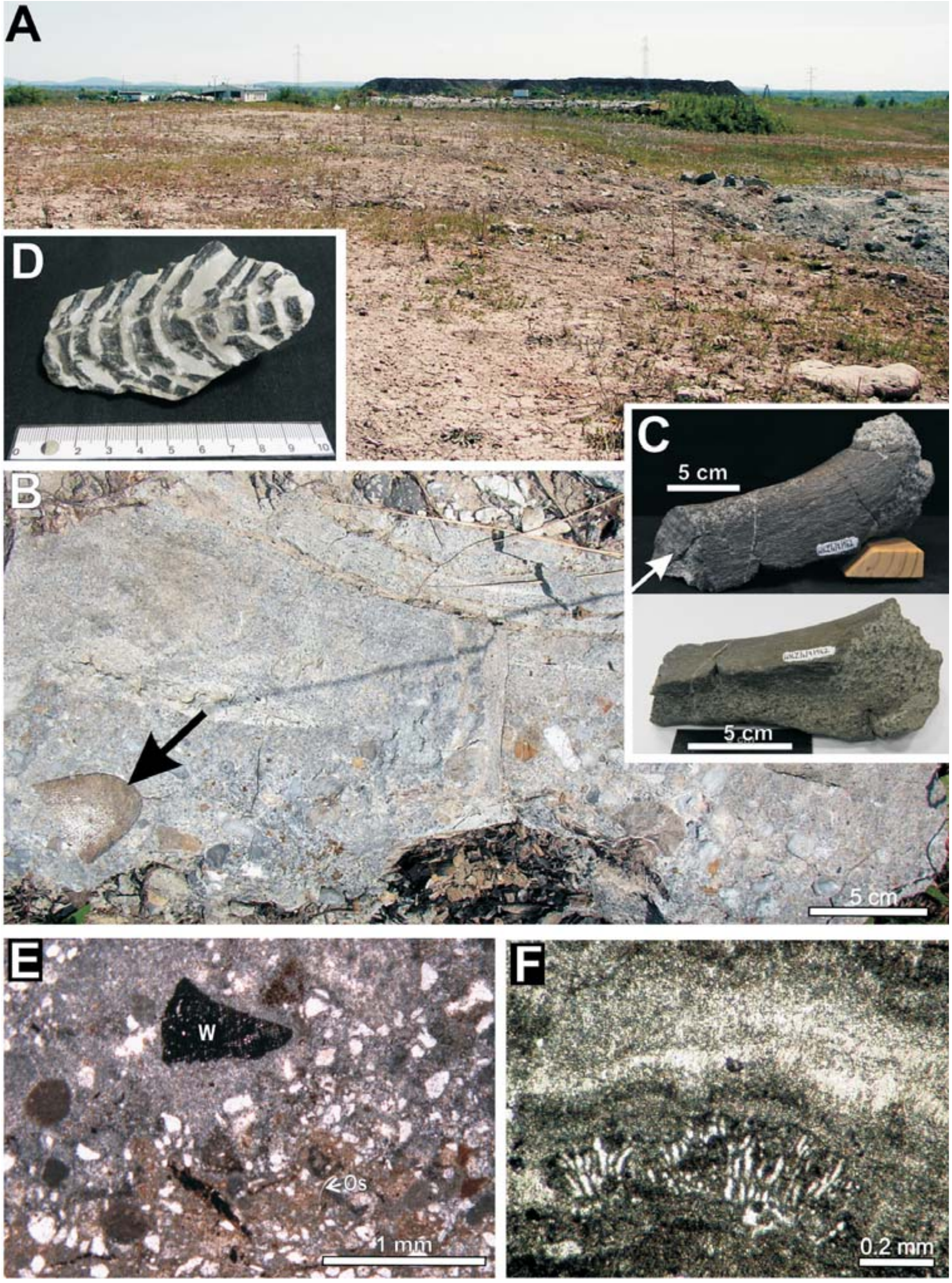

Fig. 15. Field (A, B), palaeontological (C, D) and microfacies (E, F) aspects of the Keuper deposits stored in the mound near municipal dump dig at Zawiercie-Marciszów (see Figs 11, 14; for further detail see in Szulc *et al.*, 2015, figs 16, 17). **A** .View southward from the muddy top of the waste pile, with visible abandoned, overgrown, and modern waste municipal dumps (see Fig. 11). **B, C**. Block of graded polymictic lime conglomerate (with dolomite clasts) in the heap, with visible bone cross section (arrowed in B, see also Racki, 2010, fig. 2B), and the recovered fragment of cracked, probably dicynodont long bone in two views (**C**). **D**. An articulated tetrapod tail in limestone concretion (coll. Waldemar Bardziński). **E**. Micritic-sandy microfacies of the coquina-oncoidal lime comglomerate, to show co-occurrence of coalified wood debris (W) and disarticulated ostracodes (Os, arrowed). **F**. Finely-laminated calcareous microbial envelope on large unionid shell, to show the zone with vertically oriented, fine tubular structures, corresponding to cyanobacterial colonies, in the stromatolite-like deposit. Photographs taken by Maria Racka in May 2009 (A, B) and courtesy of Ewa Budziszewska-Karwowska (C, D) and Józef Kaźmierczak (F).

who studied the profiles from the Krasiejów and Lipie Śląskie pits and the Woźniki K1, Patoka, Koziegłowy WB3 and Kobylarz cores, encompassing the entire Silesian Keuper profile. This composite succession includes the bottom of the Rhaetian, identified as the "Połomia formation" at Patoka (this timing is tentatively palynostratigraphically supported at the Kamienica gravel mine section, Fijałkowska-Mader, 2015a). They found two geochemical indices: Cr/Ti and Cr/Nb, which are the proxies for the ratio of basic/acidic source rocks, to decrease systematically in all longer profiles, thus offering a basis for the chemostratigraphic correlation (Środoń *et al.*, 2014, fig. 19). Four zones were

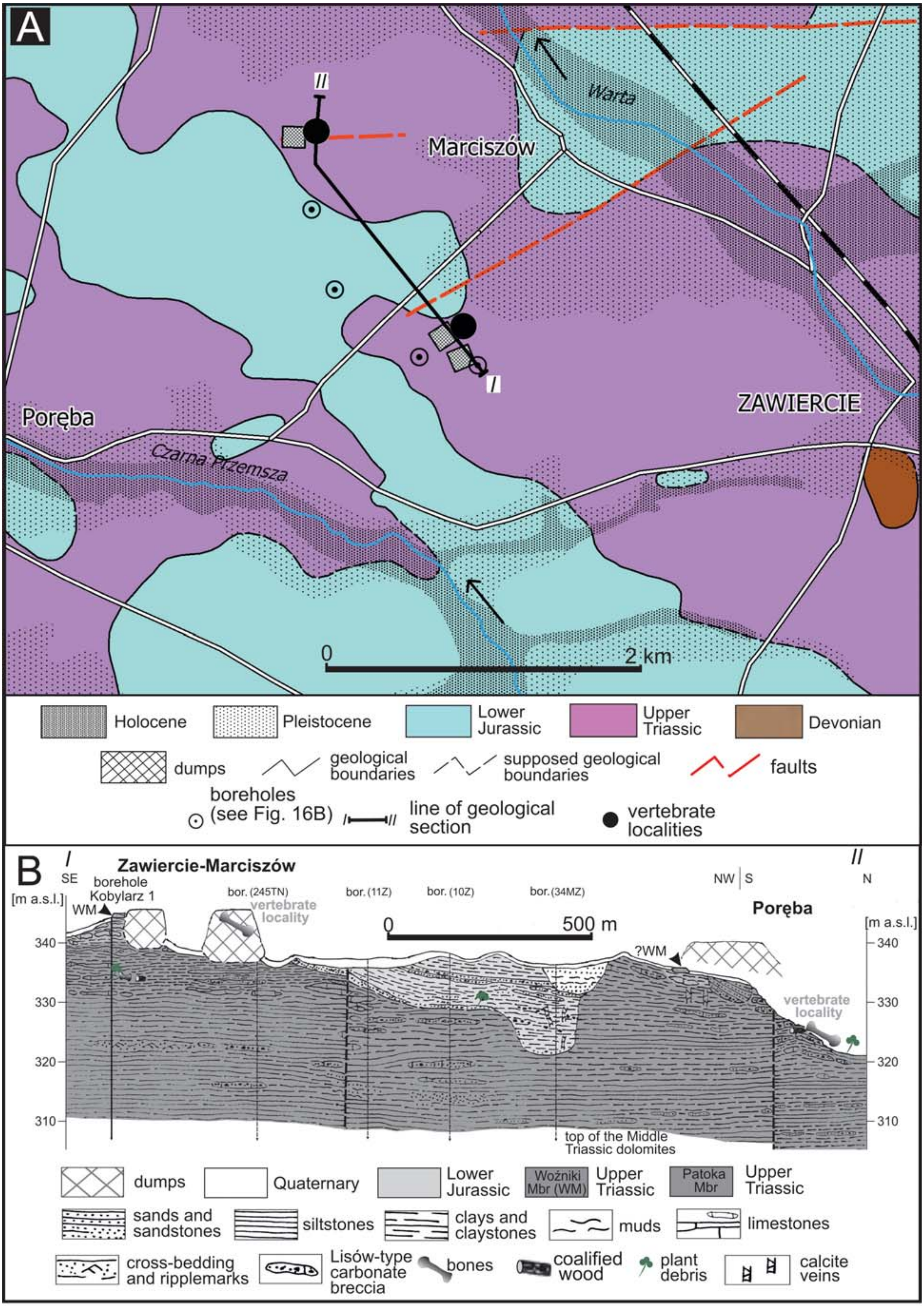

Fig. 16. Geological sketch (**A**) and cross-section (**B**) of the borderland between Zawiercie and Por臋ba towns (after Bardzi艅ski and Chybiorz, 2013, cf. Kotlicki, 1966; see Fig. 11), to show stratigraphic setting of the Por臋ba and Zawiercie-Marcisz贸w vertebrate sites.

Table 1

Zonation of the Silesian Keuper based on two geochemical indices. The average values are given in the table

Average values of Cr/Ti						
	Patoka	Woźniki	Koziegłowy	Kobylarz	Lipie	Krasiejów
Zone I	80					
Zone II	104	95	108	93	94	90
Zone III		123	128	131		
Zone IV		156	151			
Average values of Cr/Nb						
	Patoka	Woźniki	Koziegłowy	Kobylarz	Lipie	Krasiejów
Zone I	3.6					
Zone II	4.7	4.9	5.4	5.1	4.6	4.7
Zone III		7.5	7.3	7.5		
Zone IV		7.6	7.7			

specified, Zone I occurs only at the top of the Patoka profile and zone IV only at the bottom of Woźniki and Koziegłowy. Zone II is present in all profiles, and both the Krasiejów and Lipie Śląskie pits belong to this zone. The zonation demonstrated in fig. 19 of Środoń *et al.* (2014) becomes even more evident, when the average values for particular zones are calculated (Table 1).

The chemostratigraphic zonation is well correlated with lithostratigraphy. Zone I corresponds to the Rhaetian (Połomia gravels) and upper Steinmergelkeuper (Patoka Mbr), zone II to the Steinmergelkeuper and/or uppermost Upper Gipskeuper (= lower Patoka Mbr), zone III to the Upper Gipskeuper and Schilfsandstein and zone IV to the Schilfsandstein and Lower Gipskeuper.

The quantitative mineral data of Środoń *et al.* (2014) support the distinction between the Rhaetian and the underlying Keuper strata, based on lithostratigraphy: the Rhaetian rocks contain particularly abundant kaolinite and are free of carbonates. By this criterion, all the studied samples, except for the "Połomia Fm" in the Patoka 1 well (and probably the kaolinite-rich uppermost part of Patoka clay-pit section; Szulc *et al.*, 2015), have to be classified as older than Rhaetian.

There is no reason to speculate that the chemostratigraphic zonation may be diachronic in such a small fragment of one sedimentary basin. If it is not, then it can be calibrated, on the basis of available biostratigraphic data. Unfortunately, these are scarce (see Fijałkowska-Mader *et al.*, 2015). The bottom of the chemostratigraphic zone I at Patoka and zone II at Lipie Śląskie were identified as the middle-late Norian Palynozone IVb and the upper part of chemostratigraphic zone IV at Woźniki as the late Carnian biozones II and III (cf. Fig. 17). The vertical extensions of these biozones are not known, being limited in these profiles to their unoxidized sections. Thus, the chemostratigraphic zone II, containing both the Krasiejów and Lisowice bone horizons, is – on the basis of this approach – most broadly dated as late Carnian to late Norian (see below), but definitely not Rhaetian (compare the magnetostratigraphic inferences in Nawrocki *et al.*, 2015).

SUMMARY OF INTEGRATED STRATIGRAPHIC INTERPRETATION

From the papers by the Warsaw group reviewed above, it may be concluded that three widely separated bone-bearing intervals are present in the Upper Triassic Silesian succession, ranging in age from the Carnian to Rhaetian. Because the intra-regional stratigraphic relationships of the bone beds were never discussed in detail, the exact temporal equivalency of the Krasiejów and Woźniki sections, as well as the Zawiercie and Lipie Śląskie sections, is rather questionable, and the presence of more than three bone-rich intervals would be worth considering. From a geographical viewpoint, the Norian (Poręba-type) fossil assemblage of the Warsaw group is known from one locality only, while the other two are reported as having potentially wide distribution in a regional scale.

Lithostratigraphic aspect

The present authors define two informal units, bone-enriched levels, as the entire stratigraphic interval containing bone material, even if the vertebrate-fossil-rich horizons are interlayers only in thick, (almost) barren deposits (cf. Szulc and Racki, 2015). Pieńkowski *et al.* (2014, p. 272) showed that the main fossiliferous interval at Lipie Śląskie "(…) has four discrete bone-bearing beds, separated by bone-barren mudstone-siltstone levels with numerous plant remains and casts of bivalve shells". At Poręba, four fossiliferous horizons were also distinguished (Fig. 14), while at least three such intervals occur at Krasiejów (Dzik and Sulej, 2007, p. 7; Gruszka and Zieliński, 2008; compare Fig. 3).

The proposed levels have distinctly different lithostratigraphic settings, and the lower one represents largely equivalents of the Steinmergelkeuper at Krasiejów, including also in its basal part a transition to the Upper Gypsum Beds (recorded in the disappearance of the barite-bearing celestines; see Szulc, 2005; Bzowska and Racka, 2006), that is, the broad passage between the Ozimek and Patoka Mbrs. This relatively thick unit (17 m; Bodzioch and Kowal-Linka, 2012, fig. 2; Fig. 3) also is characterized by a high density of bone material accumulation, coupled with the relative lateral continuity of the main Fossillagerstätte deposit (= lower horizon of Dzik, 2003; middle unit of Gruszka and Zieliński, 2008), and therefore the term "Krasiejów bone-breccia level" is coined. On the other hand, comparable fossil-rich deposits are totally absent from the apparently continuous well successions (Woźniki K1, Koziegłowy WB3). Therefore, their distribution is demonstrated to be limited to the western Silesia region. Its restriction to the Opole region might be partly controlled by the topographic rejuvenation of the basin and intraformational erosion following the Eo-Cimmerian movements in the Carnian-Norian transition.

All other bone-bearing strata (i.e., Lipie Śląskie, Woźniki, Poręba-Zawiercie; Fig. 1B) are associated with the transitional interval between the Patoka and Woźniki Mbrs, and this superposition is directly observed in the areas around the localities (Figs 5, 7, 14), with the exception of Poręba. However, several distinct lithologies at this site are clearly correlative with the Lisowice level of the nearby

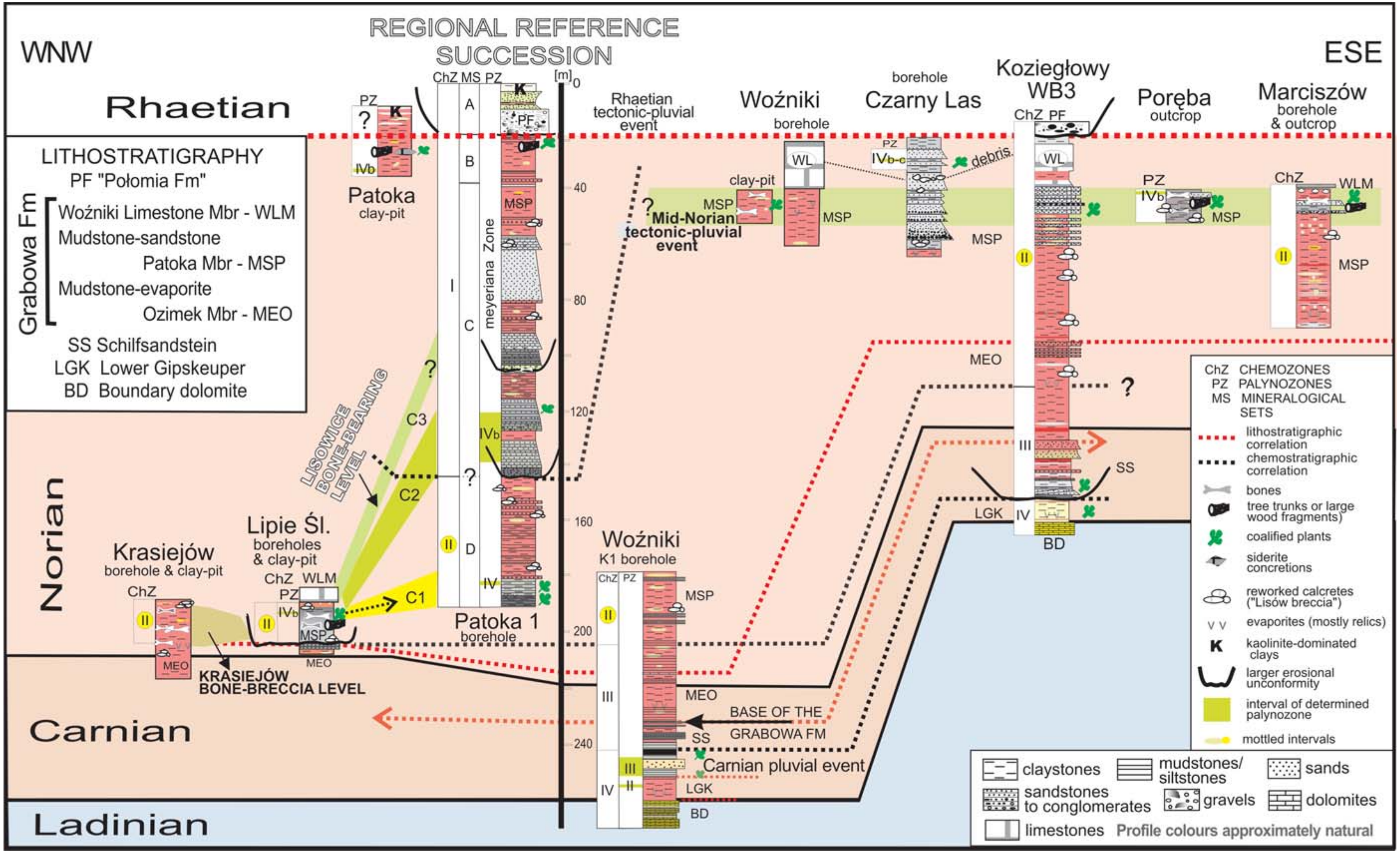

Fig. 17. Integrated stratigraphic correlation of the vertebrate localities with the reference composite Keuper section for Upper Silesia, comprising boreholes and outcrops at Patoka 1 and Woźniki K1 (see the description of the successions in Szulc *et al.*, 2006, 2015), with combined use of lithostratigraphic (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) data. Note three variants of the correlation of the Lisowice level from Lipie Śląskie section, forming a graded fluvial cycle (Fig. 3), with similar deposits at Patoka 1: with its bottom part indicated by chemostratigraphic indices (C1), and with slightly higher intervals of the lower Chemozone 1, marked by localized palynomorph preservation/acme (?) in lacustrine palynofacies (C2), and discovery of bone material (C3). Three main climatic and/or tectonic events are marked as well, including the mid-Norian fluvial-tectonic episode corresponding to the Lisowice level, hypothetically only placed in the borehole sections.

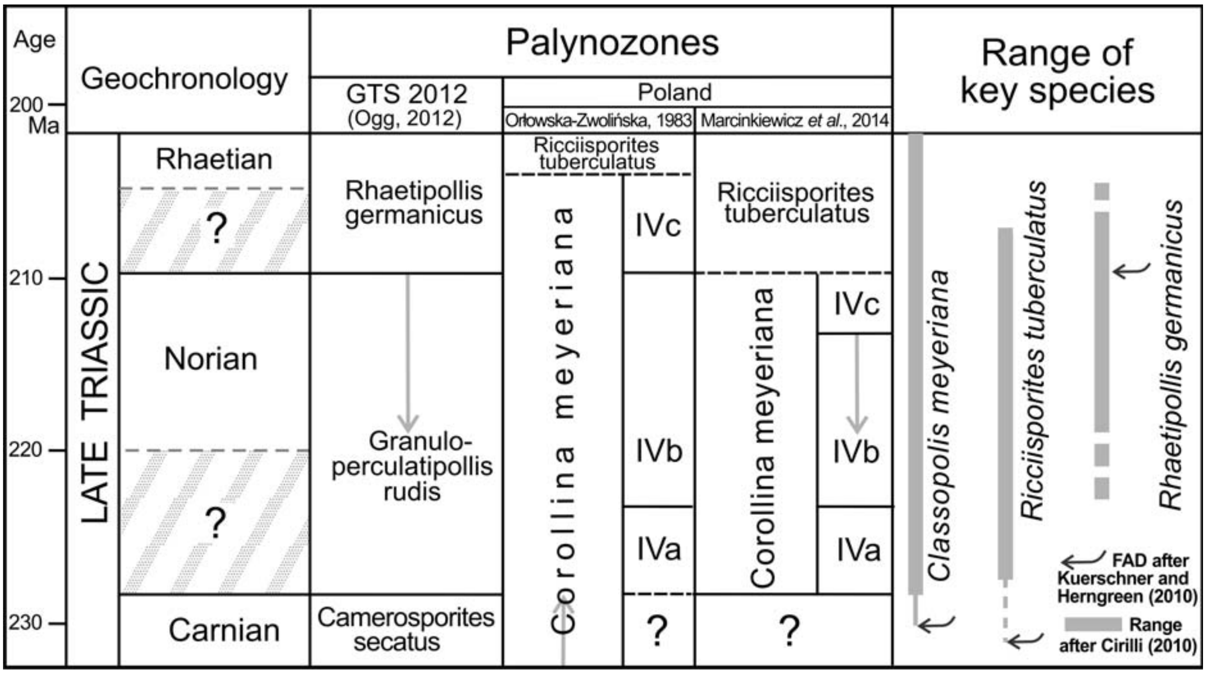

Fig. 18. Diagram showing the range of uncertainty in timing of the Upper Triassic stages (after Ogg, 2012, figs 25.6 and 25.7; compare Lucas *et al.*, 2012) and the range of the possible correlation error for these boundaries with global palynozones (according to Kürschner and Herngreen, 2010; adopted by Ogg, 2012, fig. 25.7, in "Geological Time Scale 2012"; GTS 2012) and the original and updated Polish palynozones (see also Fijałkowska-Mader *et al.*, 2015); arrows show the strikingly different positions of the palynozone boundaries on the basis of index species ranges in Cirilli (2010, fig. 2), against the first appearance datum (FAD) of these species in Kürschner and Herngreen (2010, fig. 3; see also Barth and Kozur, 2011).

Marciszów site (see also Fig. 16B). In general, the occurrence of a thin (less than 0.5 m) and discontinuous horizon of microbial carbonates (oncoids, stromatolites) is a distinguishing feature of the greyish to locally black mudstone intervals, rich in coalified plants (note a coal parting at Lipie Śląskie) and even tree trunks many meters long (Lipie Śląskie – Szulc, 2007a; Poręba – Sulej *et al.*, 2012), as well as shelly bivalve material (especially at Marciszów; Racki, 2010, fig. 3; see also Szulc *et al.*, 2015, figs 15, 16). It is noteworthy that some 15 years ago, in a small outcrop at Brudzowice village (some 13 km west from Poręba outcrop), no longer in existence, a direct contact was visible between the oncoid- and bone-bearing conglomerates with the overlying, 3-m-thick carbonates of the Woźniki Limestone. The thickness of the so delineated Lisowice bone-bearing complex is surprisingly constant, at least in the exposed successions, namely between 5 and 10 m.

In light of the descriptions of the borehole sections by Bilan (1976, pp. 49–54), more broadly defined Lisowice level probably continues at least 10 km southward from Zawiercie, as gray-seledine mudstones with limestone-clayey conglomerate sets and sandstone partings, containing macroflora detritus and lignite fragments, up to a dozen cm at two or three levels (up to 5.1 m thick), and mussels (see also Kotlicki, 1995 for account of his "Wojsławice Formation"). The thickness of this characteristic bottom part of the "higher Rhaetian" unit of Bilan (1976) is probably about 20 m in two wells, but the macroflora- and coal-bearing interval is about 17.6 m and 13.7 m thick, respectively. Also, in the Koziegłowy WB 3 well section, a 14-m-thick grey marly set, underlying the Woźniki Limestone, comprises cross-stratified sandstones and conglomerate-oncolitic layers with macroflora debris. Therefore, a slight diachronism of the bone accumulations is predicted in the laterally variable environments, characterizing the mid-Norian tectonic-pluvial interval (see below).

Grey to blackish, sandstone-conglomerate to claystone graded cyclic deposits, up to 20 m thick, in places with abundant plant debris, occur in the lower part of the succession of the Patoka borehole (Szulc and Racki, 2015, figs 3D, 4B), and allow the establishment of the equivalence of the 6-m-thick fluvial cycle in the Lipie Śląskie section with this part of the mudstone-sandstone Patoka Mbr in the regional reference section of the present authors (see Fig. 17). On a more refined scale, three fining-up cycles may be taken into consideration, but only the oldest one (C1), incomplete at the bottom of the drill core, is supported by chemostratigraphic correlation, whilst the real bone material occurs about 80 m higher (C3). Thus, this attempt is a resolution that is far from conclusive.

Age of vertebrate localities

The dating of the Krasiejów bone breccia is somewhat uncertain, owing to the conjectural temporal relationships between a lower segment of the Classopolis meyeriana Zone (i.e., its IVa Subzone) and the Carnian-Norian boundary (see e.g., Orłowska-Zwolińska, 1985; Marcinkiewicz and Orłowska-Zwolińska, 1994; Deczkowski *et al.*, 1997; Kürschner and Herngreen, 2010; Heunisch and Nitsch, 2011; Marcinkiewicz *et al.*, 2014; Fijałkowska-Mader, 2015), complicated by barren intervals below and above this subzone in the scheme of Orłowska-Zwolińska (1983). The initial assignment of the upper part of Upper Gypsum Beds (more exactly, grey claystones with anhydrites) and the IVa Subzone to the Carnian-Norian stage transition by Orłowska-Zwolińska (1983, tables 14, 15), narrowed by Orłowska-Zwolińska (1985, table 1) to the Norian, was confirmed by Cirilli (2010, fig. 2), because the index species first appears exactly at the Carnian-Norian boundary (Fig. 19). On the other hand, the Drawno Beds (later included in the Jarkowo Beds), a supposed subsurface equivalent of the Krasiejów level (Dzik *et al.*, 2000), are assigned to the basal IVb Subzone by Deczkowski *et al.* (1997). The Norian age of the Jarkowo Beds as well as the entire Patoka Mbr, is reasonably shown (see Fijałkowska-Mader *et al.*, 2015), and supported also by mineralogical and chemostratigraphic proxies (Fig. 17; Środoń *et al.*, 2014), viewed in the well-known Late Triassic climatostratigraphic context (see below).

The Lisowice bone-bearing level is therefore located between 100 m and at least 180 m below the probable Rhaetian deposits in the regional reference section, marked by light kaolinite clays and siderite-concretionary horizons (see Fig. 17; Szulc and Racki, 2015, fig. 4D, E; Szulc *et al.*, 2015, fig. 10). Thus, the Lisowice bone beds, as well as the overlying WLM (Szulc *et al.*, 2006), are considered to be a middle Norian interval, corresponding to the lower part of the very lengthy IVb Subzone, because the three sites studied are assigned to this subzone (see Fijałkowska-Mader *et al.*, 2015). This conclusion agrees well with the Norian dating of the WLM by macroflora by Pacyna (2014). Independent support is provided by the chemostratigraphic assignment of the WLM in the Koziegłowy WB3 well section to zone II by Środoń *et al.* (2014; see Fig. 17). It is also noteworthy that in a core from a well drilled some 27 km E from Lisowice (Czarny Las), sands and conglomerates with clasts of eroded WLM were dated (Fijałkowska-Mader *et al.*, 2015) by means of palynomorphs as Subzone IVb, which indicates the Norian age of the WLM.

In summary, in place of three widely separated bone-bearing intervals in terms of stratigraphy in the Upper Triassic Silesian succession, in an interval of about 25 Ma, the authors propose a far narrower two-step temporal distribution. The bone-rich strata are assigned a Norian age, with a range of less than 10 Ma (Fig. 19), but owing to the uncertainties and controversies in Upper Triassic terrestrial stratigraphy (see below), this is still a somewhat preliminary inference. This interpretation is indirectly supported by the conclusion of Sulej *et al.* (2011a), who have correlated the amphibian-dominated Krasiejów fauna with the dicynodont-archosaur assemblage from Woźniki. Of course, variability in local habitat and/or taphonomical factors during the deposition of the Lisowice level is clearly recorded in the sections under study and for example the turtle-dominated community at Poręba (Niedźwiedzki *et al.*, 2014) is strongly distinguished by such a wide representation of freshwater reptilian biota (see the coeval diversity data from Germany in Milner and Schoch, 2004). Consequently, a paradox of the peculiar vertebrate fauna at Lipie Śląskie (it looks so surprisingly young, if it is Rhaetian) is largely lost and the mid-Norian assemblage fits the global distribution data much better (Lucas, 2015).

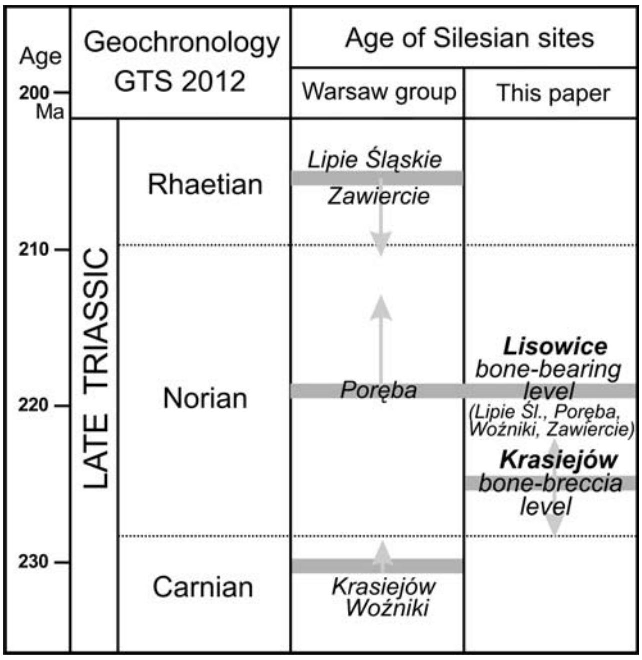

Fig. 19. Diagram showing the important differences in stratigraphic distribution of bone-bearing deposits in the Silesian Upper Triassic proposed by the authors of the Warsaw group (230 Ma for Krasiejów; Dzik and Sulej, 2007; 205 Ma for Lipie Śląskie; Skawina and Dzik, 2011) and in the present paper. Uncertainty in ages of the Upper Triassic stages (taken from, Ogg 2012; see Fig. 18) is marked as dotted boundary lines, as well as an extent of dating ambiguity for particular bone-bearing units (light grey arrows), shown by the both research groups.

Climatostratigraphic context of the Keuper succession in Germany and in Upper Silesia

The general lithostratigraphic pattern of the Upper Triassic in the Germanic Basin reflects long-term climatic fluctuations between dry and humid intervals. The dry periods are represented by the Carnian evaporitic Lower and Upper Gypsum Beds, while the main humid intervals are indicated by the fluvial Schilfsandstein for the Carnian and the Rhaetian clastics for the uppermost Triassic. Because of the supraregional nature of the climatic changes, the general climatostratigraphic framework of the Keuper may be reliably correlated with the better dated Upper Triassic of the Tethys domain (Szulc, 2007a). This correlation is confirmed also by preliminary magnetostratigraphic studies (see Nawrocki *et al.*, 2015).

With regard to the internal framework of the Steinmergelkeuper (Arnstadt Fm) from the closest German regions, namely from Thuringia (Dockter, 1995), Lower Saxony (Arp *et al.*, 2005), Saxony Anhalt and Brandenburgia (Beutler, 2008) a conspicuous tripartite facies development becomes an obvious feature of this succession. The Arnstadt Fm is composed of the so-called Lower Red (or Variegated) Series, the Middle Grey Series and the Upper Red

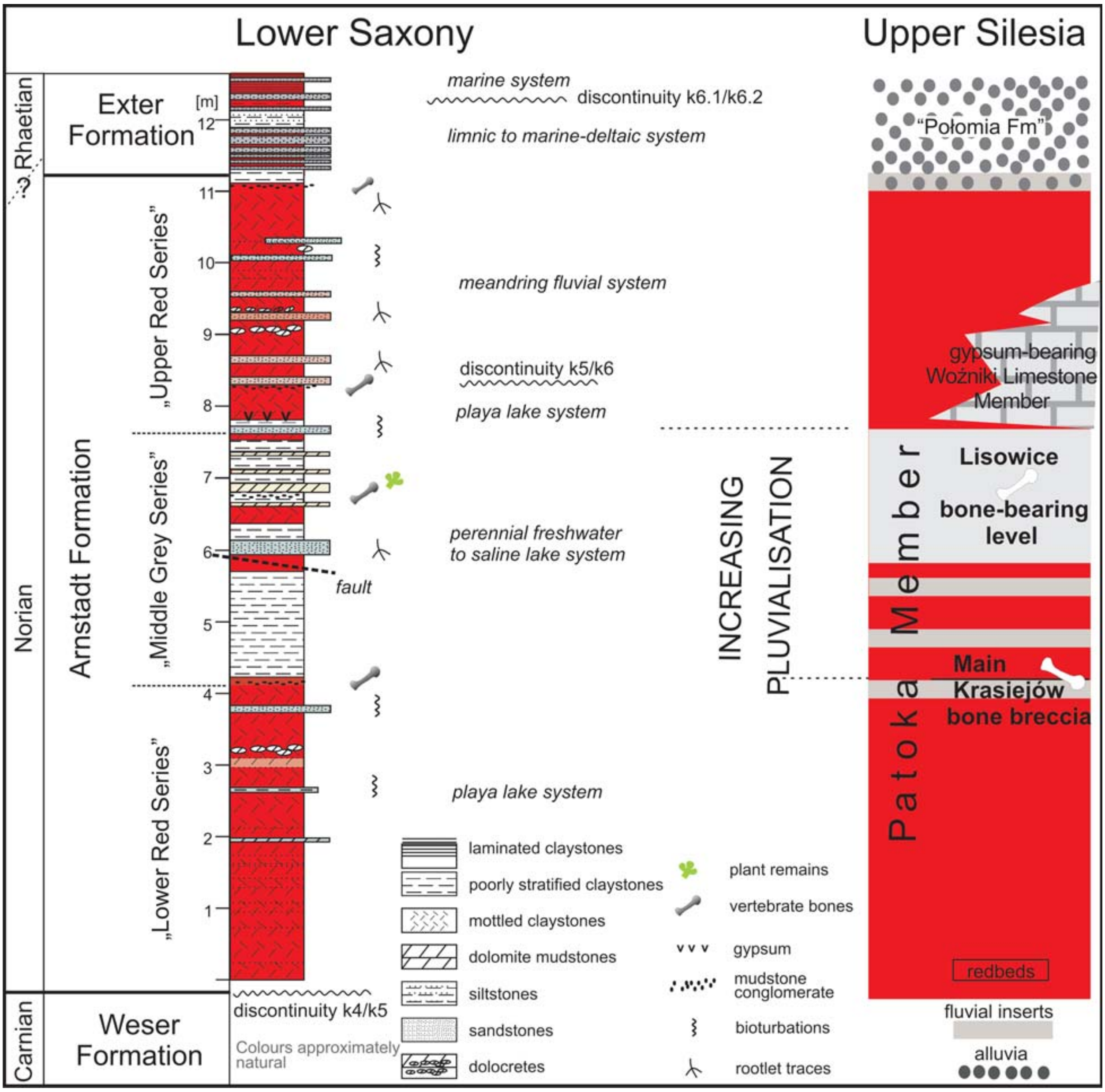

Fig. 20. Stratigraphic correlation of Upper Silesian vertebrate-bearing levels with an appropriate German middle Keuper reference succession in Lower Saxony (after Arp *et al.*, 2005, fig. 2). Note that only major Krasiejów bone-rich horizons are shown (see Fig. 3).

(Variegated) Series. The tripartite subdivision reflects longer climatic fluctuation (several Ma for each) and reflects gradual climate pluvialisation, reaching its maximum in the Middle Grey Series (as evidenced by the increased contribution of alluvial sediments, rich in plant and bone debris), replaced then by the next, drier interval of the Upper Red Series. However, the latter is richer in alluvia than the Lower Red Series. The climatically-driven tripartite subdivision is evident and unequivocal also in the more marginal facies (Löwenstein Fm) (see overview by Franz, 2008).

When the Upper Silesian Patoka Mbr is compared to its German counterparts, the tripartite subdivision is also apparent (Fig. 20). In the Krasiejów borehole, the redbed interval lying between the last gypsum-bearing horizon and the bone breccia reasonably could be correlated with the Lower Red Series in Germany. The section encompassing all the bone beds is the time and facies equivalent of the Middle Grey Series and reflects gradual climate pluvialisation that reached its climax around the time of formation of the Lisowice bone-bearing complex (see below). The next aridisation trend is recorded in the reddening of the clastic deposits and the sedimentation of the evaporite-bearing carbonates of the Woźniki Limestone that postdates the grey alluvial sediments and that is equivalent to the Upper Red Series.

In summary, the Steinmergel succession in southern Poland (in Upper Silesia in particular) displays a similar succession of lithofacies to its equivalents in the eastern regions of Germany. It is also noteworthy that the most abundant bone breccias in the well exposed and extensively studied (for more than 100 years) German Keuper are found within the Middle Grey Series or its equivalents (Seegis, 2005), that is in the middle Norian. It disapproves the age assumptions discussed above that were presented by the Warsaw group for the Silesian Fossillagerstätte.

VAGUENESS OF THE TERRESTRIAL NORIAN STAGE

As shown in Fig. 18, any attempt to clarify the absolute age of Upper Triassic sections is strongly influenced by the controversy concerning the ages of the stage boundaries, including the disputed intervals of many millions of years (Ogg, 2012). For example, the age of the Lipie Śląskie succession was identified as "Rhaetian; about 205 Ma old" by Skawina and Dzik (2011, p. 864). This conclusion certainly is correct only for "the long-Rhaetian option" (i.e., with the Rhaetian age lasting above 8 Ma, beginning from 209.5 Ma), given tentatively for the "Geological Time Scale 2012" (GTS 2012) by Ogg (2012). More recently, Wotzlaw *et al.* (2014) estimated the age of the lower boundary of this stage as 205.5 ± 0.39 Ma and the short duration of the Rhaetian as 4.14 ± 0.39 Ma; similar data are given by Maron *et al.* (2015) as: 205.7 Ma and 4.4 Ma, respectively. Another major uncertainty is associated with the selection of global stratotype sections for the Upper Triassic stage boundaries in marine settings, still under discussion (see the Carnian–Norian boundary candidate in Canada; Onoue *et al.*, 2016), and conjectural marine-terrestrial correlations (see e.g., Lucas *et al.*, 2012; Maron *et al.*, 2015; Tanner and Lucas, 2015). The correlation of the Silesian bone-bearing level with the global stratigraphic points will be a serious challenge,

This ambiguity especially concerns terrestrial successions because of the weaknesses of the present palynozonal schemes, particularly with regard to the Norian dates, because of the transitional nature of successive floras (Cirilli, 2010). As well, Kürschner and Herngreen (2010, p. 267) stressed: "The Norian is, at about 15 million years, the longest Triassic stage, but the pollen and spore assemblages are insufficiently known due to the scattered nature of the palynomorph record". The Polish scheme of Orłowska-Zwolińska (1983) is based generally on acme zones, but even in the Polish Basin, Pieńkowski *et al.* (2014, p. 279) indicated a dissimilarity between the "Rhaetian" palynofloras from Lipie Śląskie and Kamień Pomorski. Potentially reliable range zones of Kürschner and Herngreen (2010), implemented in the "Geological Time Scale 2012", are still characterized by unawareness of the details of these ranges (Fig. 18), exacerbated by "discrepancies in the taxonomy of sporomorphs" (Cirilli, 2010, p. 305; compare Lucas, 2015). Not surprisingly, Becker and Nawrocki (2014), using magnetostratigraphic correlation, showed a substantial diachronism of the macrospore-based palynozones in the Lower Triassic.

As shown above, a careful taxonomic study of the Silesian floras and comparative foreign collections is still needed urgently (compare Pacyna, 2014). In general, megafossil plant genera are more useful in Upper Triassic biostratigraphy than mostly endemic species (see discussion in Lucas, 2013; compare Kelber, 2005).

The Triassic conchostracan-based zonation is hoped to be a consistent alternative tool of palynostratigraphy (Kozur and Weems, 2010). Arguments as to the vagueness of the Early Triassic zonation were presented by Becker (2015), and include (1) an uncertain conchostracan taxonomy, jointly with the index species, (2) unreliable palynostratigraphic dating of the zones, augmented by (3) speculative terrestrial-marine correlations and consequently, chronostratigraphic inferences that also are biased, because they are determined exclusively from marine-based stage boundaries. The last fundamental inadequacy of the Late Triassic zonal scheme of Kozur and Weems (2010) was recently exposed by Maron *et al.* (2015, p. 973): "(…) conchostracans from the Weser Fm of the Germanic Basin are assigned an early Tuvalian age (late Carnian) because the Weser Fm is considered correlative with the Dolomie de Beaumont of France, which contains marine bivalves considered to be of such age (Lucas *et al.*, 2012). As a further example, the conchostracan fauna from the Coburg Sandstein of the Germanic Basin is considered late Carnian, seemingly because it lies immediately below the beginning of a sporomorph association considered to be late Tuvalian". This reservation is significant also for the dating of the Krasiejów fauna, in the context of the Polish-German correlations (Fig. 4).

As to the possible lower Rhaetian dating through the use of conchostracans, Gregoriusella polonica Zone was identified at Lipie Śląskie (as the type locality), but it is confirmed elsewhere in the Tarnow (Mecklenburg) borehole "in the basal few meters of the Exter Formation" (Kozur and Weems, 2010, p. 360). As noted by Edgar Nitsch (pers. comm., 2015): "The facies boundary from Arnstadt Fm ("Steinmergelkeuper", variegated) to Exter Fm ("Rätkeuper", grey) is diachronous, however, and ranges regionally from Sevatian (formerly taken as part of the "Rhaetian") to Rhaetian *sensu stricto*. The "basal few meters" in the Schwerin–Rostock area are probably Sevatian in age. The species could possibly appear already in the Norian (as pointed out by Kozur himself in Kozur and Weems, 2010, p. 388), and its range still has to be assessed" (see also the Lower Saxonian occurrence in Barth and Kozur, 2011).

Considering the latest Triassic (= Apachean) non-marine tetrapod biochronology, Lucas (2010, p. 473) indicated: "The Apachean is the most difficult Triassic LVF [land-vertebrate faunachron] to correlate globally. This almost certainly reflects a provincialization of the global tetrapod fauna near the end of the Triassic. Some of the apparent endemism of Apachean land-vertebrate assemblages may also be due to facies, sampling and taphonomical biases". In fact, this experienced author even does not try to correlate the Lipie Śląskie fauna with any of his two Norian-Rhaetian chrones (see an explanation in Lucas, 2015). Dzik *et al.* (2008b, p. 19) expressed a similar opinion: "Replacements of one faunas to others in single geological profiles are merely a record of local environmental shifts but not of global evolutionary changes. The particular species have changed their areas of distribution, moving not uncommonly to hard-to-identify refugee in remote regions of the world". This warning also surely applies to the Krasiejów fauna, as well as to Silesian land floras (see discussion in Lucas, 2013). The biogeographical differences between the western and eastern parts of the Germanic Basin, determined by “the unique nature” of the Silesian faunas, are mentioned by some authors (e.g., Sulej *et al.*, 2011a; Butler *et al.*, 2014). Sulej and Niedźwiedzki (2010, p. 113) only concluded cautiously in this context: “the fossil record of tetrapod succession in the Late Triassic was strongly controlled by ecological factors and biased by uneven representation of particular environments”.

As recapitulated by Edgar Nitsch (pers. comm, 2015): “Biostratigraphy of the Keuper has always been a kind of a quiz game that has lost the answer cards (…) Up to now, all groups have their limitations: macrophytes have typically too broad age ranges to be very helpful, acme palynozones are prone to show some bias from ecology, vertebrates include some uncertainties due to endemism at low taxonomic levels, and the conchostracan zonation scheme is yet too new to have overcome its teething completely”. In another extreme perspective, Cesar Schultz (pers. comm., 2015) indicated in the context of the paper by Lucas (2015): “I consider valid the (biostratigraphic) correlation between the paleofaunas present in Polish bone beds with Lucas’ LVFs, but I do not consider that the assignment of a Carnian and/or Norian Age (according to the Standard Global Chronostratigraphic Scale) for Polish bone beds be conclusive in the absence of absolute dating for the latter”.

BONE CONCENTRATION PROCESSES AND TETRAPOD HABITATS

Genetic aspects of the bone beds, as well their sedimentary settings, were discussed mostly for the reference Krasiejów site, but no exhaustive taphonomical study was undertaken. Dzik *et al.* (2000, pp. 228–229) mentioned the possible current transport of carapaces and/or predator and scavenger activity in an allegedly calm and oxygen-deficient lake milieu, but concluded: “This “graveyard” was not the catastrophic nature and differentiation of size does not correspond to the distribution in the living population there”. River-induced alkalinity of the lake environment was predicted in the carbonate-rich drainage area. This hydrochemical setting would be expected to have neutralized humic acids, resulting from the bacterial decomposition of organic matter, and led to the conservation of apatite and carbonate hardparts (also Dzik, 2003b), in addition to diminished scavenging, predation and bioturbation in a hypoxic habitat.

A more-or-less opposite model of depositional events emerges from sedimentological studies (see review in Bodzioch and Kowal-Linka, 2012). Szulc (2005) first proposed a sheet-flood fan model for the main bone-bed level (see below). In the opinion of Dzik and Sulej (2007, p. 6), this interpretation is in conflict with the “presence of several such strictly horizontal intercalations at various levels within the approximately one meter thick fossiliferous unit”, combined with “the common occurrence of thin horizontal concretionary layers with unionid bivalves having their valves closed”. Thus, “a local *Metoposaurus–Paleorhinus* biota with a suite of fish and invertebrate fauna and algal flora” is advocated for the vast lacustrine marly claystone level (Dzik and Sulej, 2007, p. 7). In the words of Sulej (2007, pp. 32–33), the bone bed was formed as follows: “The *Metoposaurus* specimens from the lower horizon were deposited probably on the bottom of a lake as partially decayed cadavers. This is suggested by the common association of skulls with mandibles and bones of the pectoral girdle. Winnowing was frequent and many disarticulated bones occur in lenticular intercalations of calcareous grainstone. The clavicles usually occur with their convex side down, indicating deposition from suspension. Closed shells of unionid bivalves co occur, which probably died from suffocation under the load of dysaerobic mud” (cf. also Skawina, 2013). On the other hand, an actually allochthonous terrestrial *Aetosaurus-Silesaurus* assemblage occurs in an upper fluvial fossiliferous level at Krasiejów, “1 m thick and 15 m wide lens of red clay within fluvial cross-laminated deposits” (Dzik and Sulej, 2007, p. 7).

According to Gruszka and Zieliński (2008), the lowermost Krasiejów bone-bearing horizon corresponds to the basal layer of the graded channel succession, whereas the highest interval is located in the massive mudstone, overlying the channel cycle set. The main bone-breccia level lies within dark brown, massive, lacustrine claystones, capping the vertisol, but more detailed genetic explanation is not provided. Thus, two channel-hosted, bone-bearing levels were interpreted by Gruszka and Zieliński (2008) as a hardpart burial record in moist niches of low-energy alluvial plains under seasonally dry conditions, such as flood basins, abandoned channels and residual ponds. The seasonal aridity in a dry to semi-dry climate was also stressed earlier by Szulc (2005; see also Bilan, 1975), who linked the bone accumulation with ephemeral lakes and ponds. In a tectonically mobile regime paired with catastrophic runoffs, the accumulated skeletal parts were easily replaced through debris-flow mass movements. Szulc (2005, p. 164) claimed that “the bone-bearing bed is a typical high-viscosity debris flow deposit, encompassing a relatively narrow sheet of replaced bone-bearing mudstones”. This fluctuating climatic setting was further confirmed by a histological study of the bone pattern of growth of metoposaurids (e.g., Konietzko-Meier *et al.*, 2013; Konietzko-Meier and Klein, 2013).

Bodzioch and Kowal-Linka (2012) also emphasized a trigger role for episodic climate-controlled catastrophic events in the origin of the main bone breccia. The palaeohistological, mineralogical and geochemical study of diagenetic overprint, based on mineral types of infills and calcite cement and the chemical composition of bone, conclusively indicates crucial differences between the early diagenetic histories and the initial fossilization of aquatic and terrestrial vertebrate bone material. Bodzioch and Kowal-Linka (2012) deduced the following three-step order pf events for bone-breccia formation: (1) an episode of rapid deposition, indicated by the erosional base directly above the vertisol massive deposits and ecologically mixed (aquatic-terrestrial) fossil assemblage, whereas (2) the *in situ* burial of bivalve populations points to the subsequent development of a transient, shallow pond, that (3) quickly evaporated finally during a waterless interval. Consequently, the skeletal remains were certainly reworked post-mortem and transported from different habitats of the alluvial plain toward an ephemeral, shallow depression in the course of high-energy flooding after periodic catastrophic rainfall. Extreme-weather calamity events in seasonally rainy conditions undoubtedly influenced the rapid tetrapod mortality and mode of fossilization. Therefore, this concentration Lagerstätten (Konzentrat-Lagerstätten *sensu* Seilacher, 1970) is certainly not promoted by an exceptional catastrophic mass-mortality burial event of a single living community (obrution scenario of Seilacher *et al.*, 1985), as stressed by Dzik *et al.* (2000). Recurrent resedimentation phenomena and related cannibalism of muddy deposits already were indicated by Bilan (1975) for the Krasiejów succession (see also e.g., Bilan, 1976; Dzik *et al.*, 2000; Szulc *et al.*, 2006).

Genetic aspects of the Krasiejów bone-breccia

As reviewed in depth by Rogers and Kidwell (2007), bone beds can be grouped genetically in terms of either biogenic or physical (hydraulic or sedimentologic) control processes, although more complex taphonomical histories are frequent. Considering these agents, the mixed formative scenario is evidenced conclusively by Bodzioch and Kowal-Linka (2012; see also Gruntmejer *et al.*, 2015), owing to differentiated taphonomic pathways of jointly fossilized, skeletal parts. Therefore, the spectacular bone-breccia level at Krasiejów represents a complex case. In fact, all Upper Silesian bone-enriched intervals seem to correspond to physical vertebrate skeletal concentrations of a common mixed hydraulic/sedimentologic type (see diversity of alike Cretaceous examples in Wood *et al.*, 1988; Ryan *et al.*, 2001; Bell and Campione, 2014 and Botfalvai *et al.*, 2015; also review in Behrensmeyer, 2007).

In the case of the main Krasiejów bone-breccia level, the efficient cumulative action of water transport and trapping mechanisms in a laterally extensive depression seems to be more important than sedimentation/erosion ratio (= the flood/drowning causal category of Behrensmeyer, 2007) to an extraordinary degree. However, Bodzioch and Kowal-Linka (2012) have shown an initial role for the re-concentration of rich preexisting bone sources from the adjacent alluvial domain, characterized by a reduced sedimentation rate or even episodic sediment starvation, and the gradual, passive accumulation of the tetrapod remains (attritional mode; Behrensmeyer, 2007, p. 87). Nevertheless, signatures of abrasion, weathering and predation are rare. When combined with the abundance of partially articulated skeletons, this indicates short-distance post-mortem transport and quick burial. The taphonomic circumstances led Dzik and Sulej (2007) to the final conclusion that the "lake-dwelling *Metoposaurus–Paleorhinus* biota" is of a local and – implicitly – of dominantly autochthonous nature. However, as stressed by Lucas *et al.* (2010; cf. also Brusatte *et al.*, 2015), the Krasiejów bone breccia is different from most metoposaurid bone beds that are nearly monotaxial and certainly monodominant, and interpreted as a mass-death record of breeding populations. Therefore, a combination of three factors should be considered:

1. Large density and fertility of living tetrapod populations, even if not exactly coexistent (i.e., a time-averaging factor). Certainly many thousands of individuals were killed by the disastrous flooding, but this was a uniquely cumulative effect of many small precursor water bodies along the floodplain, and not a single large-scale lacustrine source (as claimed by the Warsaw group).

2. Syndepositional and early diagenetic augmentation of fossilization potential and restriction of destructive processes, primarily owing to the high pH and low Eh conditions (a conservation aspect *sensu* Seilacher, 1967; Dzik *et al.*, 2000; Dzik, 2003b; Dzik and Sulej, 2007; Bodzioch, 2015; see below).

3. Probable participation of a very rapid burial process, manifested in extraordinary sediment discharge, such as the high-viscosity debris flows, proposed by Szulc (2005). As shown by Rogers (2005), exceptionally intensive rainfalls in the Late Cretaceous of Madagascar were recorded in episodes of catastrophic sediment-laden subaerial flow, paired with the amazing vertebrate burial of many articulated specimens in the resultant, massive, muddy deposits (see also Britt *et al.*, 2009 and Flaig *et al.*, 2014). In the case of not very prolonged transport (Bodzioch and Kowal-Linka, 2012, p. 35), the assembled hardpart accumulation still could be ecologically coherent and within-habitat time averaged only (i.e., parautochthonous). On the other hand, this paradox could have been enhanced by the truly autochthonous nature of some biotic elements (not only bivalves) in the relict aquatic basin (in the event scenario of Bodzioch and Kowal-Linka, 2012).

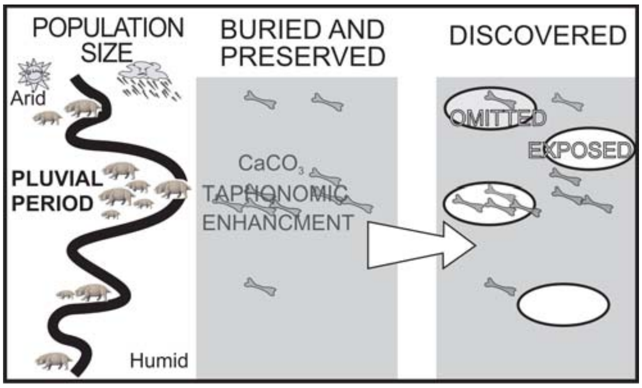

Fig. 21. Diagrammatic scheme of general factors leading to the Upper Silesian bone concentrations in the Norian Patoka Mbr. Tetrapod populations, controlled by pronounced climatic fluctuations, were preserved preferentially in an acme time during the most prolonged wet period, combined with suitable fluvial depositional/burial and diagenetic settings, and are partly recovered in random outcrops today.

Bone beds of the Lisowice level

The multitaxic and largely low-density vertebrate accumulations in the higher parts of Patoka Mbr are overall comparable to subordinate tetrapod occurrences at Krasiejów, strongly dominated by the hardparts of scattered terrestrial species (with the exception of Poręba) for deposits varying in extent. The sedimentary context of the Lisowice-type tetrapod occurrences is more conjectural, however. Typical for the Steinmergel facies, short-term climatic rhythmicity records noticeable dry-wet seasonality in a monsoon-like or trade-wind-influenced system (Reinhardt and Ricken, 2000; Szulc *et al.*, 2006; Bodzioch and Kowal-Linka, 2012; see the discussion of orbital controls in Vollmer *et al.*, 2008). Vast, extremely flat, muddy lowlands in wet periods and the consequent floral acme offered many niches for a diverse fauna, while the habitable localities contracted to the environs of water sources during arid intervals (Fig. 21). The muddy deposits were periodically pedogenically modified in the Late Triassic climatic setting (e.g., Sarkar, 1988; Therrien and Fastovsky, 2000; Szulc, 2005). Vertebrate remains, when subaerially exposed to weathering and abrasion, were progressively destroyed, particularly as a result of these soil processes (e.g., organic acidification, varying oxidation states in wet/dry seasons). Thus, the accumulated hardparts did not survive the prolonged degradation process (Dzik and Sulej, 2007, p. 7), especially in periods of sediment starvation. A genetic link between hardpart concentrations and discontinuity surfaces is not observed in Keuper successions (a typical case for the fossil record; Rogers and Kidwell, 2000). On the other hand, even bone lags are reported from greenish- and bluish-gray palaeosoil horizons in variegated muddy floodplain facies (Eocene Willwood Formation of Wyoming; Bown and Kraus, 1981; see Upper Triassic example in Therrien and Fastovsky, 2000).

The skeletons also were exposed to intensive scavenging and cracking by large archosaur (?dinosaur) carnivores prior to burial, as evidenced at Marciszów (Budziszewska-Karwowska *et al.*, 2010). At Lipie Śląskie, about 12% of the dicynodont bones exhibit tooth bite or pathological traces that clearly manifest a significant scale of predator-prey interactions in that time (Niedźwiedzki *et al.*, 2011; see also Pieńkowski *et al.*, 2014).

The more-or-less biased death assemblages, derived from within-habitat sources, were episodically winnowed, transported and finally concentrated in sediment traps during recurrent overbank inundations on different scales, although extreme rainfalls resulted in major flood catastrophes and mass mortality, as envisioned above for the Krasiejów bone breccia. The muddy sediments of the Patoka Mbr were extensively eroded, reworked and redeposited (Bilan, 1975, 1976; Szulc *et al.*, 2006, 2015) and the significant transformation of river-stream systems was therefore a frequent phenomenon. In consequence, the bone material could escape (near)surface degradation, and when rapidly buried in flood or mudflow sediments, could be found only in the wet intervals with more intensive fluvial activity (Szulc *et al.*, 2006, p. 149; see Fig. 20). Obviously, at least partly permineralized ("prefossilized") specimens, preserved to different degrees, were assembled, as shown for vertebrate signatures from similar low-gradient river systems by Mukherjee and Ray (2012) in the Upper Triassic Tiki Formation of India, and, for example, by Botfalvai *et al.* (2015) in an Upper Cretaceous Iharkút vertebrate assemblage (Hungary). The skeletal material and the carcasses of animals were redistributed downstream and two efficient trapping mechanisms are known: in-channel blockades (e.g., tree trunks) and rapid falls in hydraulic competence, usually at sinuous channel bends (Aslan and Behrensmeyer, 1996; Rogers and Kidwell 2007, p. 24).

Therefore, the channel-hosted bone beds include precursor material from a variety of floodplain settings. Behrensmeyer (1988) distinguished between Lagerstätten concentrated by active drainage (channel-lag assemblages) and those that accumulated in an inactive channel (channel-fill assemblages). The lag variety occurs in coarse-grained lithologies, deposited at the erosional base of a channel succession, and contains – in extreme cases – allochthonous, destroyed and mostly unidentifiable bone pebbles that experienced several cycles of reworking. The fill mode is associated with fine-grained to mixed facies of channels, essentially abandoned by flow and the resultant Lagerstätten may include even complete skeletons.

A channel-lag assemblage is clearly evidenced in the lowermost fossil level at Krasiejów (Gruszka and Zieliński, 2008) and in the lower horizon at Lipie Śląskie (Pieńkowski *et al.*, 2014; see Fig. 5). This category also may be applied tentatively to the occurrences of differently preserved hardparts in the carbonate (partly reworked vadoids, Lisów breccia-type) or polymictic conglomeratic deposits at Poręba (horizons a, c and d, Niedźwiedzki *et al.*, 2014; Fig. 14) and Zawiercie (Racki, 2010, fig. 1B). Less clear is the interpretation of the fossil-bearing grey grainstones with "ooid-like structures", also comparable to the "Lisów breccias", in the Woźniki Lagerstätte (Sulej *et al.*, 2011a; Fig. 10), as well as a bone occurrence in the gravelly sands of the Patoka 1 borehole section (depth 119.7 m). In particular, the Poręba locality is distinguished by numerous, highly eroded fragments of turtle carapace or plastron in coarse-grained lithologies, and the mixing of elements from aquatic and terrestrial habitats is evident in "a high-energy fluvial system" (Sulej *et al.*, 2012, p. 1039). However, a residual hydraulic lag of highly abraded, durable elements was not observed at the sites, although actualistic analysis does not show a simple association between mechanical reworking effects and the length of transport before burial (Aslan and Behrensmeyer, 1996).

The uppermost Krasiejów Lagerstätte corresponds to the channel-fill assemblages, located in the massive mudstone cap of the channel-fill cycle (Gruszka and Zieliński, 2008), where the mostly transported *Aetosaurus-Silesaurus* assemblage is evidenced, but characterized by the high articulation of many specimens (Dzik, 2003a; Dzik and Sulej, 2007; Piechowski *et al.*, 2014). The authors assume a similar taphonomical category for the rich assemblage of terrestrial tetrapod remains from the main dark organic-rich mudstone level at Lipie Śląskie (Fig. 5), and also for the fish-dominated assemblage at Poręba, collected as well-preserved, isolated bones in the organic-rich horizon b of Niedźwiedzki *et al.* (2014; Fig. 13). However, even in this setting a post-mortem mixing was significant, as implied by the diagenetic pattern for dicynodont bones at Lipie Śląskie by Bodzioch *et al.* (2015). In fact, the palustrine facies of residual ponds, mires and marshes frequently may develop in the abandoned channels and this would be an effective attritional trap for well-preserved skeletal material (Dzik *et al*, 2008a, 2008b; Niedźwiedzki *et al.*, 2012). However, a distinction between the channel-fill and floodplain succession is equivocal without more detailed spatial documentation of particular lithosomes in the river facies architecture. Floodplain muds can also provide rarer, but well-preserved, even partly articulated bone material, as noted for the

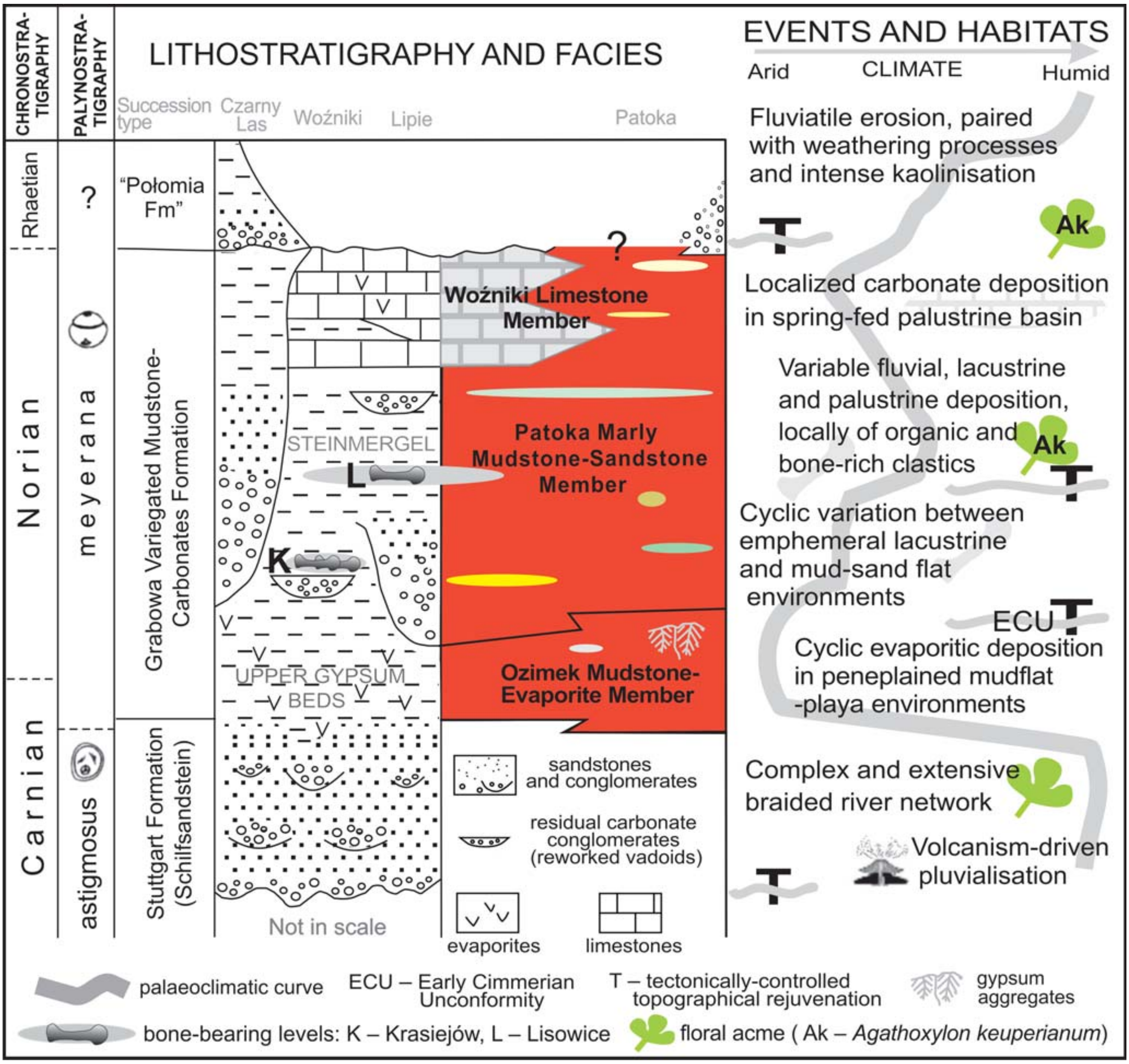

Fig. 22. Stratigraphy-facies and climatostratigraphy schema of the middle and upper Keuper of Upper Silesia, to show overall stratigraphic position and relationships of bone- and flora-rich horizons (with reference to four generalized succession types, see Fig. 17 and Szulc *et al.*, 2015; modified after Szulc and Racki, 2015, fig. 9); palyzonation scheme after Orłowska-Zwolińska (1983; see Fijałkowska-Mader *et al.*, 2015).

Krasiejów succession by Dzik and Sulej (2007, p. 7). The vertebrate hardparts seem to be associated with marly mudstones and/or limestone concretions, as well known at Krasiejów and Lipie Śląskie (Dzik *et al.*, 2000, 2008a), but also at Marciszów (Racki, 2010, fig. 1A; Fig. 15D) and in the Kobylarz 1 well core (?mudflow recorded in grey mudstones; depth 41.0 m; Szulc *et al.*, 2015, fig. 13).

Interestingly, Behrensmeyer (1988) stressed that the laterally migrating river would be expected to form channel-lag bone beds, in contrast to avulsion-dominated, braided to anastomosing networks. This general deduction is not substantiated in the Krasiejów succession, where, for example, the fill concentration mode is noted only in the meandering river stage of Gruszka and Zieliński (2008). The Lisowice-level bone beds were probably deposited mostly in multiple channel belts by a mostly low-gradient river system (see below). In Behrensmeyer's (1988) model, attritional channel-fill assemblages should be more frequently generated in abandoned channels by analogy to Carboniferous bone beds, associated with sapropels (Behrensmeyer, 2007, p. 89).

The mid-Norian pluvial prelude and tectonic-fluvial event

The Lisowice bone-rich level is thought to have resulted from a combination of several factors (Figs 21, 22): (1) a more prolonged interval of climatic pluvialization, a prelude to the Rhaetian humid climate (Feist-Burkhardt *et*

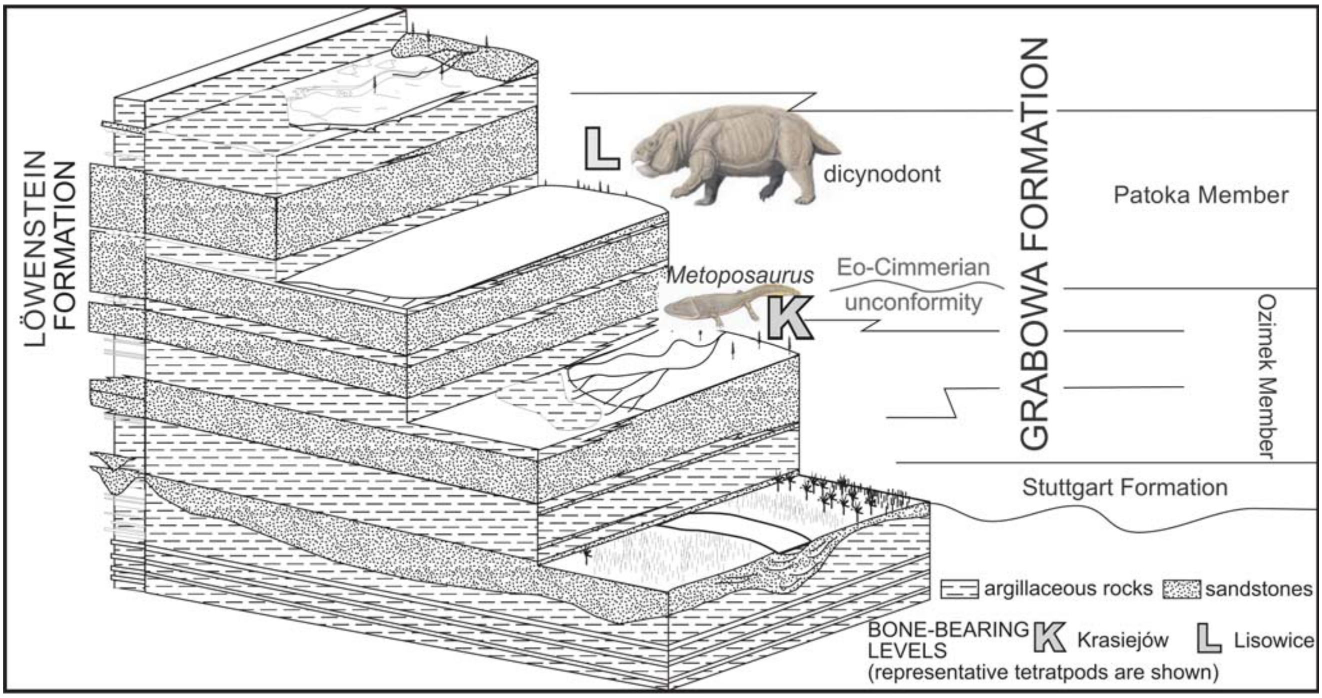

Fig. 23. Sketch diagram of environmental evolution and main facies distribution of the southern German Keuper (from Kelber and Nitsch, 2005, fig. 2), with reference to the Silesian lithostratigraphy scheme and stratigraphic context of bone-rich levels. Tetrapod reconstructions are after Dmitry Bogdanov (https://pl.wikipedia.org/wiki/Dicynodonty#/media/File:Dicynodont_from_PolandDB.jpg; https://upload.wikimedia.org/wikipedia/commons/6/6b/Metoposaurus_diagnosticus_kraselovi_1DB.jpg).

al., 2008; Fijałkowska-Mader, 2015b), that resulted in (2) a floral acme, as a trophic basis for (3) more abundant and diverse vertebrate life. Additional circumstances were influenced significantly by (4) tectonic rejuvenation of sedimentary basin topography, manifested probably in block movements indicated by very variable, but localized hiatuses (e.g., Bilan, 1976). In effect (5), a braided to anastomosing river network developed (= mid-Norian tectonic-pluvial event; Figs 17, 22), as indicated by the rarity of sheet sandstones and lateral accretion surfaces. This early Cimmerian event (see Szulc *et al.*, 2015) was probably controlled by the overall uplift of source areas and subsequent progradation of alluvial fans in the environments of extensive muddy-sandy flats. In fact, a more extensive drainage system, evolving with progressive peneplenisation toward multiple channel belts (see e.g., Makaske, 2001), promoted not only more diverse moist niches within the gently undulating mud flats, but also strengthened exhumation, burial and preservation potential in the proximal Keuper facies (see below).

All the factors record rather ordinary ecological and geological circumstances in the mid-Norian pluvial/tectonic-fluvial interval, but (6) an additional taphonomical enhancement of early fossilization processes was probable both in the organic-rich swamp muds or overbank conglomeratic deposits (Fig. 21). As manifested by a frequent link of bone occurrences with carbonate concretions or marlstone layers, an occurrence of calcium-rich interstitial fluids, stimulating also common microbial lime precipitation, indeed might have been crucial. This hydrochemical factor was controlled mostly by the karstification of uplifted Muschelkalk blocks and/or caliche soil degradation (cf. Lisów breccia levels; see the above quoted concept of Dzik *et al.*, 2000). More likely for most sites of the Lisowice level, the burial places were fed by an extensive, fault-bounded spring system in its initial phase, just before the common palustrine deposition of the Woźniki Limestone (an implication of the model of Szulc *et al.*, 2006). Microbial films and induced carbonate precipitation, recorded in common oncolites and stromatolites (see Szulc *et al.*, 2015, fig. 16; Fig. 15F), might be an efficient protective agent (see Seilacher *et al.*, 1985; Seilacher, 2008). An additional, possible source of calcium and bicarbonate ions was a bacterially induced, early diagenetic alteration of 'fresh' bone material (with soft tissues), especially in that calcite is the main mineral in bone voids at Krasiejów and Lipie Śląskie (Bodzioch, 2015; Bodzioch *et al.*, 2015).

Vertebrate ecosystems

The lithofacies succession of the Upper Triassic of the Germanic Basin almost perfectly reflects climatic fluctuations overwhelming the Western Tethys domain during Carnian–Rhaetian time (Feist-Burkhardt *et al.*, 2008). Certainly, the fundamental climatic turnover in the Late Triassic, which took place at about the Norian-Rhaetian boundary, consisted of a shift from dry/semi-dry to permanently wet climatic conditions, partly volcanically induced and of an extreme greenhouse type, which culminated during the end-Triassic ecological catastrophe (Feist-Burkhardt *et al.*, 2008; Preto *et al.*, 2010; Pieńkowski *et al.*, 2014; Fijałkowska-Mader, 2015b), recorded in floral shift (see below). This turnover is recorded as the replacement of a lithofacies

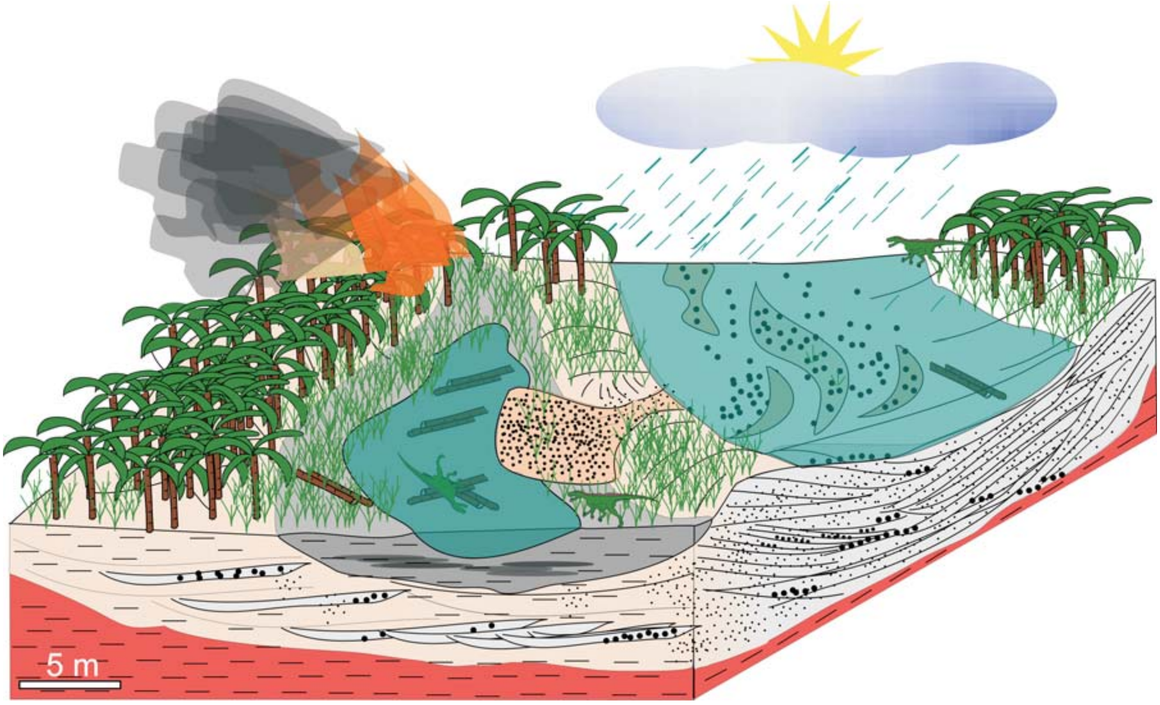

Fig. 24. Environmental model for the Lipie Śląskie tetrapod locality (after Jewuła, 2010, fig. 22); forest fires are shown after Marynowski and Simoneit (2009).

of dry conditions (redbeds including local evaporites) by wet, pluvial kaolinite-enriched lithofacies, including fluvial and perennial, lacustrine deposits. As highlighted above, tetrapod population sizes were certainly controlled by the climatic fluctuations and they thrived mostly during the wetter periods and related vegetation growth in wetland habitats (Figs 21–23).

The likely local nature of the Krasiejów-type biotope in western Upper Silesia suggests the development of extensive wetlands inside meandering to anastomosing rivers, flowing from the rather degraded Variscan massif of the Sudetes, situated several dozen kilometres to the southwest (cf. Dzik *et al.*, 2000; Dzik, 2003b; Gruszka and Zieliński, 2008; Bodzioch and Kowal-Linka, 2012). The Sudety Land (*sensu* Pieńkowski *et al.*, 2014) provenance was evidenced recently by the geochemical signatures of bulk mudstone samples (Konieczna *et al.*, 2015). As supposed by Edgar Nitsch (pers. comm., 2015), the vertebrate acme might have recorded “a kind of ‘mid-Tuvalian pluvial event’ that happened in the Bohemian Massif (and neighboring Sudety Massif) and propagated alluvial (gypsum-free) facies to related basin-marginal setting”. An increasing humidity in fact is evidenced by the sedimentological attributes of the Krasiejów succession (Gruszka and Zieliński, 2008). Vast, probably conifer-dominated forests, with ferns and bennettitaleans (*Voltzia* flora of Pacyna, 2014), and a plethora of different-sized freshwater basins occupied by charophyte algae (Zatoń *et al.*, 2005), were a prerequisite factor for the rich fauna flourishing in the river catchment draining Sudety Land. In particular, metaposaurid amphibians richly populated the ponds and small open lakes. The ubiquitous amphibians and the semi-aquatic crocodile-like parasuchids occupied the highest level in the food pyramid of the ecosystems (compare Mukherjee and Ray, 2012).

The Lisowice level records an important wet interval in the mid-Norian, but also an overall facies-tectonic remodelling. Therefore, variable alluvial to palustrine environments probably characterized this pluvial interval (channels, muddy floodplains, marshy ponds to small lakes etc.; Szulc, 2007a). Pieńkowski *et al.* (2014, p. 272) categorized the fossiliferous facies of Lipie Śląskie as: “(…) a mosaic of alluvial-plain environments swamps with ephemeral ponds and laterally shifting river channels” (see Fig. 24).

In palynofacies terms, lacustrine (or more accurately, stagnant water) (Poręba, Lipie Śląskie), floodplain (Kobylarz 1) and floodplain or lacustrine to playa (Patoka 1) habitats are recognizable (Fijałkowska-Mader *et al.*, 2015). In the palynomorph spectra, the increasing Norian climatic humidity toward the “late Norian pluvial event” is detectable by an expansion of hygrophytic elements (lycopsids and equisetales) within the eurytopic xerophytic biota dominated by cheirolepidacean conifers (Fijałkowska-Mader, 2015b; see also Orłowska-Zwolińska, 1983; Fijałkowska-Mader *et al.*, 2015; compare *Brachyphyllum* and *Lepidopteris* floras of Pacyna, 2014). This conclusion is supported by anatomical characters of the conifer wood of *Agathoxylon keuperianum* from Zawiercie area (Philippe *et al.*, 2015). Thus, Fijałkowska-Mader (2015b) characterized these enviromments as: “Moist to wet in land floodplain was occupied by lycopsids and equisetales. Dry uplands were covered with conifer forests consisting mainly of cedars. Cheirolepidacean formed bushfields along river banks and lagoon coastal zones (...)”. A facies transition from carbonate to fine siliciclastic depositional regimes along the Tethys shelf might have been, at least in part, a signature of this same climatic shift (Berra *et al.*, 2010; see also Preto lain *et al.*, 2010). Floral turnover took place in far more humid settings in the Rhaetian, when pteridophyte vegetation definitely outnumbered conifer forests (Orłowska-Zwolińska, 1983, p. 65; see also Krupnik *et al.*, 2014; Fijałkowska-Mader, 2015b). The wet and warm conditions also are recorded in the thriving nature of the *Agathoxylon keuperianum* trees (found at Patoka; Philippe *et al.*, 2015).

In the spatially heterogeneous ecosystem, diverse reptilian-dominated land communities thrived, with unusually large, herbivorous dicynodonts and the giant top predator, the archosaur *Smok wawelski*, in a most spectacular role in a rather complex trophic array (see Pieńkowski *et al.*, 2014, fig. 9; Zatoń *et al.*, 2015). In the Poręba assemblage, the top carnivores include also medium-to-large-bodied dinosaurs (Niedźwiedzki *et al.*, 2014). When compared with the Krasiejów biota, aquatic life seems to have been impoverished, restricted largely to fishes and local populations of turtles and amphibians. However, a strong taphonomical bias, evident in the more-or-less reworked assemblages, precludes the possibility of further consideration.

As already highlighted, the bone-bearing grey fluvial deposits of the Lisowice level, when analyzed in terms of the general climatically-controlled lithofacies succession of the Central European Keuper, appear to be most likely the time and facies equivalent of the middle Norian, Middle Grey Series and Middle Löwenstein Fm from Thuringia and Brandenburgia (cf. Franz, 2008; see also Milner and Schoch, 2004, Schoch and Wild, 1999, Seegis, 2005 and Sues and Fraser 2010, pp. 89–95; Fig. 23). As noted by Milner and Schoch (2004), these different Germanic facies contain dissimilar reptilian faunas, characterized by plagiosaurs, capitosaurs, crocodylomorphs, and dinosaurs, while metoposaurid amphibians were an infrequent component of the phytosaur-turtle assemblage. So, one can only assume a similar differentiation of Upper Silesian tetrapod communities.

The fluvial-erosive events, discussed above, correlate very well with similar episodes, identified in other peripheral zones of the Central Europe Basin, represented in Germany by the coarser-clastic Löwenstein Formation and the similar KĺgerÖd Formation in Denmark and Sweden (Franz, 2008). It is also noteworthy that the greatest and the most important localities of the bone breccia of the Upper Triassic in Central Europe are associated with proximal Keuper facies (e.g., Löwenstein Fm, Schoch and Wild, 1999; Seegis, 2005). The marginal basin zones were the most rich in water, and, therefore, there were the most favorable niches for tretrapod communities on land. Intense fluvial processes (including disastrous floods) facilitated the rapid burial of organic remains that allowed the formation of the many Upper Silesian bone beds.

CONCLUSIONS

1. On the basis of a multidisciplinary stratigraphic study of the complete composite section of the Silesian Upper Triassic, the authors have concluded that three widely separated bone-enriched intervals, ranging in age from the Carnian to Rhaetian, assumed in papers of the Warsaw research group, should not be accepted, as their datings and correlative inferences are poorly documented, flawed and ignore the results of other studies.

2. On the basis of a generally consistent compilation of litho-, bio-, climato- and chemostratigraphic premises (Fig. 17), the present authors propose two Norian bone-bearing levels, in a time interval less than 10 Ma (Fig. 19). Both levels noticeably correlate with the lower part of *C. meyeriana* Palynozone (likely mostly with the same IVb Subzone) and the same II Cr/Ti Chemozone. The authors stress the imprecise character of this dating, due to the vagueness of Late Triassic bio- and chronostratigraphy in terrestrial settings, and admit to a feasible amount of information noise. Their conclusion, however, is well grounded in terms of Ockham's razor.

3. The Krasiejów succession is placed in the lower part of the Grabowa Fm, including in its basal part a transition from the evaporate-bearing Ozimek Mbr to the Patoka Mbr (= equivalents of transitional beds between the Upper Gypsum Keuper and Steinmergelkeuper). The Krasiejów bone-breccia level, limited to the Opole region, represents most probably the early Norian interval. Of course, the authors cannot preclude the possibility that future correlation of the critical profile with an approved global stratotype for the Carnian–Norian boundary will lead to its re-location in the late Carnian.

4. The more widely distributed Lisowice bone-bearing level (also the Woźniki and Poręba-Zawiercie sites) corresponds to the mid-Norian middle part of the Grabowa Fm (= lower part of Patoka Mbr), and records a niche mosaic in an extensive alluvial plain (braided to anastomosing river system) during the Eo-Cimmerian tectonic-pluvial episode recorded in the entire Germanic Basin.

5. The revised locality timing highlights the very ambiguous problem of the evolutionary uniqueness of the Silesian biotas, jointly with the mostly lost refugium status of the 'Rhaetian' Lipie Śląskie fauna, and eliminated a surprising contrast between the Rhaetian vertebrate assemblages, rich in Silesia and very poor in Germany (see Schoch and Wild, 1999; Seegis, 2005; Sues and Fraser, 2010). A Norian age for the Lisowice assemblage fits the global distribution pattern much better (cf. Lucas 2015). On the other hand, this characteristic now may be assigned in part to the Krasiejów assemblage, at least to the dominating amphibians, but this fossil record probably is affected by a basal Norian hiatus (the main Eo-Cimmerian disconformity).

6. The Upper Silesian bone beds correspond largely to typical skeletal concentrations of combined hydraulic/sedimentologic type and of fluvial origin. The taphonomic enhancement of preservation by hydrochemical (alkalinity) and/or microbially- or bacterially-induced (synsedimentary or diagenetic) carbonate precipitation can be assumed as well. Thus, a mixed concentration/conservation nature of the Fossilagerstätten is considered on a preliminary basis in several cases, but in particular for the main breccia level at Krasiejów, probably distinguished by a variety of obrution mechanisms, such as viscous mudflow.

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