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Palaeoenvironment and taphonomy of a Late Jurassic (Late Tithonian) Lagerstätte from central Poland

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A rich assemblage of exceptionally preserved marine and terrestrial fossils occurs in fine-grained limestones in the upper part of the Late Tithonian (Middle Volgian) shallowing upward carbonate sequence in Central Poland. The richest horizon, a deposit known locally as the *Corbulomima* horizon, is named after the shallow burrowing suspension feeding bivalve *Corbulomima obscura*, moulds of which occur in densities of up to 500 per square metre on some bedding planes. The fauna in this bed also includes organic and phosphatic remains of a wide range of other creatures including the exuviae of limulids and decapods, disarticulated fish skeletons and rare isolated pterosaur bones and teeth. There are also perfectly preserved dragonfly wings and beetle exoskeletons. The average stable carbon and oxygen isotope values for ostracod shells and fine-grained sediment from this horizon suggest precipitation of the calcium carbonate from warm seawater of normal marine salinity. The carbonate sediments overlying the fossiliferous horizon have been interpreted as nearshore to shoreface facies. These pass abruptly into coarse reworked intraclastic sediments interpreted as possible tsunami or storm surge over-wash deposits. The clasts in this deposit have more positive oxygen isotope values than those in the underlying limestone, which may indicate that they were lithified in a slightly more evaporative, perhaps intertidal, setting. The succession terminates with silicified fine-grained limestones likely to have formed in extremely shallow lagoonal environments. In contrast with the Solnhofen limestones of Lower Tithonian age in south-central Germany the *Corbulomima* horizon is interpreted as a transitional deposit formed in a shallow marine setting by rapid burial with elements of both Konservat- and Konzentrat-Lagerstätte preservation. □ *Konzentrat and Konservat-Lagerstätte, Taphonomy, Palaeoenvironment, Paleogeography, Late Jurassic, Poland.*

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The famous Early Tithonian (Hybonoticeras Zone), Solnhofen limestones in south-central Germany have a unique assemblage of exceptionally well preserved terrestrial and marine invertebrates and vertebrates that provide important insights into Late Jurassic palaeoecology and evolutionary relationships (Allison 1988; Keupp *et al.* 2007). They have been interpreted as Konservat-Lagerstätten deposits formed in a large lagoon, in and around which many of the organisms lived and died.

This paper presents the discovery of a new and very rich fossil assemblage of marine and terrestrial invertebrates and vertebrates from an Late Tithonian (Middle Volgian, Zarajskensis Subzone) carbonate sequence in Central Poland. The aim is to present a preliminary description of the deposits and discuss the general palaeoenvironmental conditions under which both marine (limulids, decapods, fish and sphenodonts) and non-marine (dragonflies, beetles, pterosaurs) fossils occur in the same taphocoenosis. In addition, mechanisms responsible for concentrating the exceptional numbers of bivalve shells, especially *Corbulimima* Vokes 1945 are considered in terms of both palaeoenvironment and sedimentary dynamics.

To date, there have been other known fossil Lagerstätte localities known that would constitute such a close stratigraphical equivalent to the Early Tithonian sediments of Solnhofen area, and additionally represent comparable lithological type (i.e. lithographic limestone or plattenkalk – Munnecke *et al.* 2008). It

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should be emphasized, that the stratigraphical distance between Hybonoticeras Zone and Zaraiskensis Subzone is approximately 2 Ma (Graciansky *et al.* 1998).

Materials and methods

The studied fossils were collected by AK during fieldwork in the Owadów-Brzezinki quarry (lat. 51.374238°, long. 20.136343°) in 2007–2009 and together with BB in 2010–2012. Most invertebrate exoskeletons and vertebrate skeletons are preserved as disarticulated remains. These commonly show a highly variable degree of breakage and/or disaggregation. Articulated examples including limulids and fish occur, but are more rarer. All material collected is housed at the Museum of the Geoscience Friends Association 'Phacops', Łódź (MGFA/O-B 1-11079, (collector AK). Fossils were measured using vernier callipers with an accuracy of 0.01 mm. All macrofossils have been prepared manually at the Museum of Association of Friends of Geosciences, Łódź. Photography was carried out both in Łódź (Museum of Association of Friends of Geosciences) and Warsaw (Institute of Paleobiology, Polish Academy of Science). Photographs were taken using a Canon EOS 400D Digital Camera, and single specimens were coated with ammonium chloride (Fig. 5C). All figures have been subsequently edited with Adobe Photoshop CS3 imaging software. The geochemical analyses were performed on 30 samples: 15 taken from ostracod exoskeletons from the Corbulomima horizon, and 15 from the intraformational breccia (interpreted herein as tsunamite or mega-storm deposit). Samples were analysed for carbon and oxygen isotopes using an automated carbonate reaction device (Kiel IV) connected to a Finnigan Mat Delta Plus mass spectrometer at the Institute of Geological Sciences and the Institute of Paleobiology, Polish Academy of Sciences in Warsaw. Isotope ratios are reported in per mil (‰) in the usual delta notation relative to VPDB scale (defined via NBS 19). External error amounts to less than ±0.08‰. Experiments carried out on each sample replicates showed that the average difference between replicates was less than ±0.15‰ for $\delta^{13}C$ and $\delta^{18}O$. Ostracode shells were extracted following the standard methods used to study this fossil group. In total, five samples of approximately 200 g were prepared mechanically. The material was crushed and boiled in a 5% solution of sodium sulphate (Glauber's salt). The fossiliferous residue was then divided into fractions using sieve grades of 0.1 and 0.3 mm. Subsequently, specimens were extracted using an optical microscope and photographed by scanning electron microscope (SEM). From these it was possible to undertake a detailed taxonomic analysis.

Geological and palaeontological settings

A small working quarry at Owadów-Brzezinki, in the vicinity of Tomaszów Mazowiecki is the only site in Poland, north of the Carpathian range, where Late Tithonian (Middle Volgian) strata are outcropped (Fig. 1). The whole (~13 m) exposed carbonate sedimentary sequence of the Kcynia Formation has been dated on the basis of monospecific ammonite assemblages of the genus *Zaraiskites* Semenov 1898;. This is a typical representative of the Subboreal Province (Kutek 1994; Kutek & Zeiss 1974, 1997; Rogov & Zakharov 2009) and suggests that the carbonates belong to the Scythicus Zone, containing the uppermost part of the Regularis Subzone and almost all of the Zarajskensis Subzone and Zarajskensis Horizon (Fig. 2). The shallowing carbonate sequence can be divided into three successive units, i.e. I, II and III (directly equivalent to the A, B and C units of Zielińska 2003; but compare with Salamon *et al.* 2006; Figs 1C, 2). The lowermost, unit I, comprises, initially, yellowish thin-bedded marly limestones. These are known to contain abundant assemblages of *Zaraiskites* ex gr. *regularis*, but they are no longer exposed in the quarry. The yellowish marly limestones pass gradually upwards into massive fine-grained limestones (~6.6 m total thickness), with indistinct lamination, but forming a few beds between 40 and 80 cm thick (Figs 1C, 2). They contain numerous specimens of *Zaraiskites zarajskensis* (Michalski 1890) and its various phenotypes, and provide a near continuous series of morphologically differentiated representatives of the species hypodigm (Kin, in prep.; compare Kin 2010, 2011).

The overlying unit (II) is represented by thinnly bedded, fine-grained limestones with occasional distinctive parallel lamination (Figs 1C, 2). A characteristic feature being a mass occurrence of polychaete tubes in a thin horizon described here as a serpulite (Figs 1C, 2; see also Radwańska 2003). Unit II also contains small or medium-sized forms of *Zaraiskites* (i.e. up to 150 mm), but they are not as abundant as in unit I.

The uppermost unit (III) is the most variable in terms of sedimentary structures (Figs 1C, 2), and fossil content, but *Zaraiskites* sp. ($n = 4$, Fig. 3C) becomes rare. The highly fossiliferous *Corbulomima* limestone has a horizon of finely bedded fine-grained limestone at its base. Apart from abundant moulds (up to 500 per square metre) of the opportunistic bivalve *Corbulomima obscura* (Sowerby 1827; Fig. 3A)

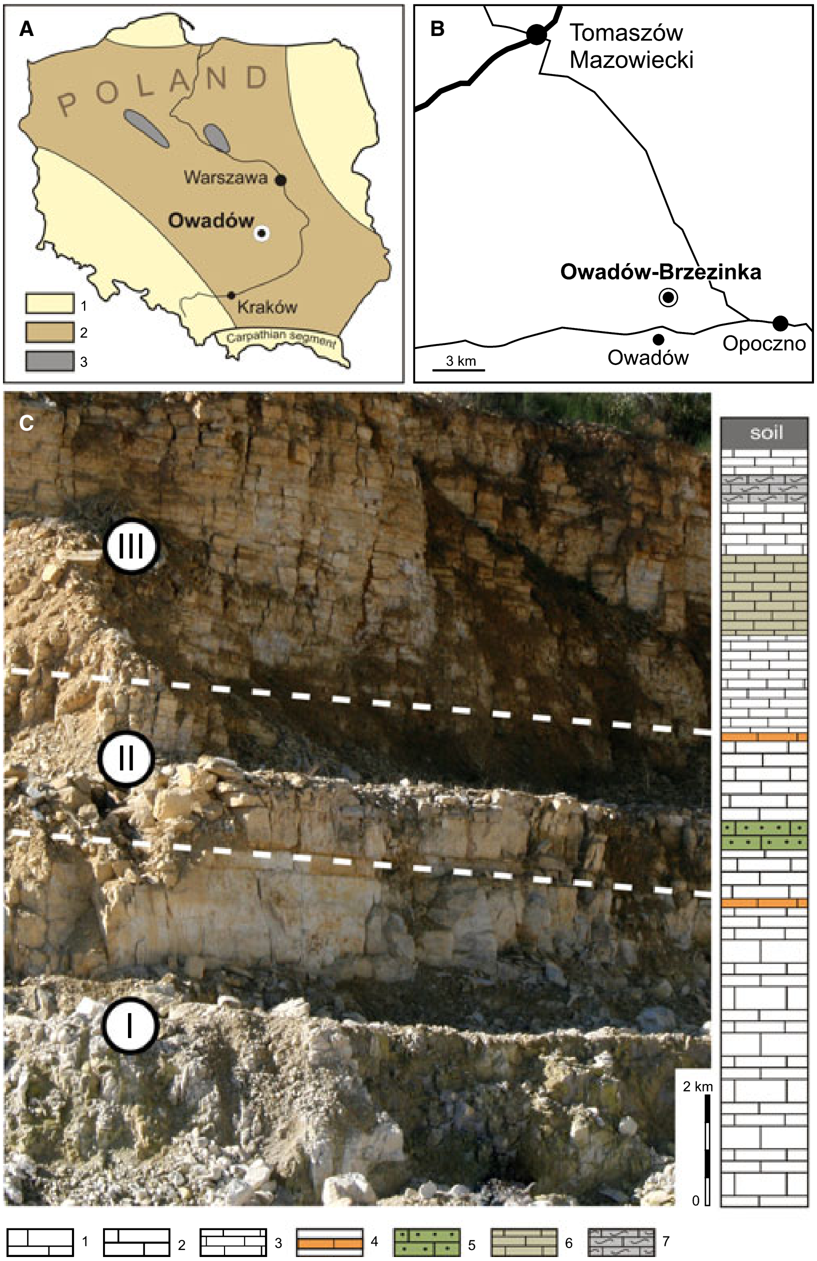

Fig. 1. A, Late Tithonian (= Middle Volgian) palaeofacial map of Poland (after Gaździcka 1998, slightly modified): (1) marine sediments, not studied in detail; (2) shallow water limestones; (3) siliciclastic, fine-grained sediments; OB, Owadów-Brzezinki – site of the studied Late Tithonian (= Middle Volgian sediments). B, road map of Poland showing location of Owadów-Brzezinki quarry: OB, site of quarry. C, image of the quarry at Owadów-Brzezinki showing the successive sedimentary units I–III of the studied Late Tithonian (= Middle Volgian) strata. In the right column are details of the studied profile: (1) thick-bedded limestones of unit I; (2) thin-bedded limestones of unit II; (3) lithographic-type limestones of unit III; (4) boundaries dividing units; (5) serpulite; (6) *Corbulomima* horizon; (7) tsunamite or mega-stormite.

from which the unit takes its name, it contains the remains of dragonflies *Eumorbaeschna* sp. nov. (Fig. 4C), beetles (?*Notocupes* sp.), and marine invertebrates including other bivalves, e.g. *Pleuromya uniformis* (Sowerby 1813) and *Mesosaccella* sp. (Fig. 3A), brachiopods (mainly Terebratulidae sp. indet.), and decapods (*Glyphea* sp., ?*Eryma* sp., ?*Cycleryon* sp., ?*Aeger* sp.). Exuviae of the horseshoe crabs *Limulus* sp. nov. ($n = 9$) and *Crenatolimulus* sp. nov. ($n = 1$), are the first Late Jurassic limulids to be recognized in Poland (Fig. 4A; compare Kin & Żyła 2007). Unit III also contains remains of marine fish (Figs 4B, D, 5B, C), including the elasmobranchs *Notidanus* sp. and *Sphenodus* sp.; the actinopterygians *Caturus* sp., *Lepidotes* sp., *Gyrodus* sp., ?*Coelodus* sp., ?*Macrourogaleus* sp. and ?*Thrissops* sp.); as well as the remains of sphenodonts (Fig. 5A) and isolated bones and a tooth belonging to a pterosaur (Fig. 3B).

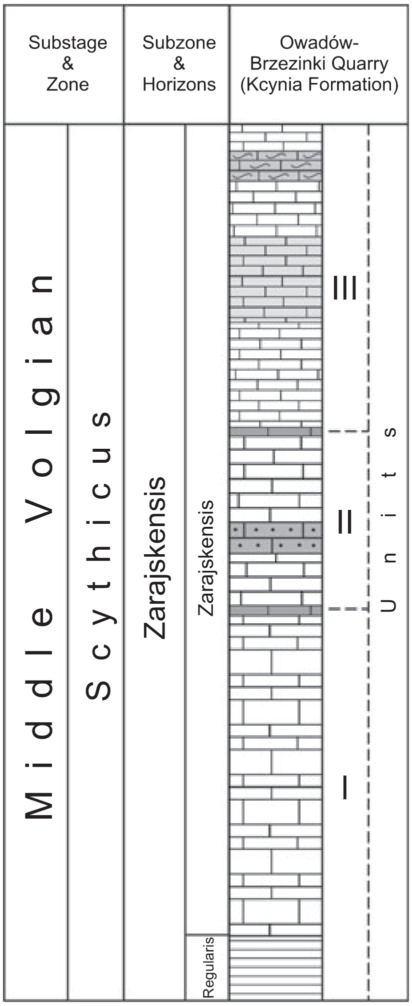

Fig. 2. Stratigraphical position of the sedimentary sequence in the quarry at Owadów-Brzezinki. Explanations of the geological profile (right column) are given in Figure 1C.

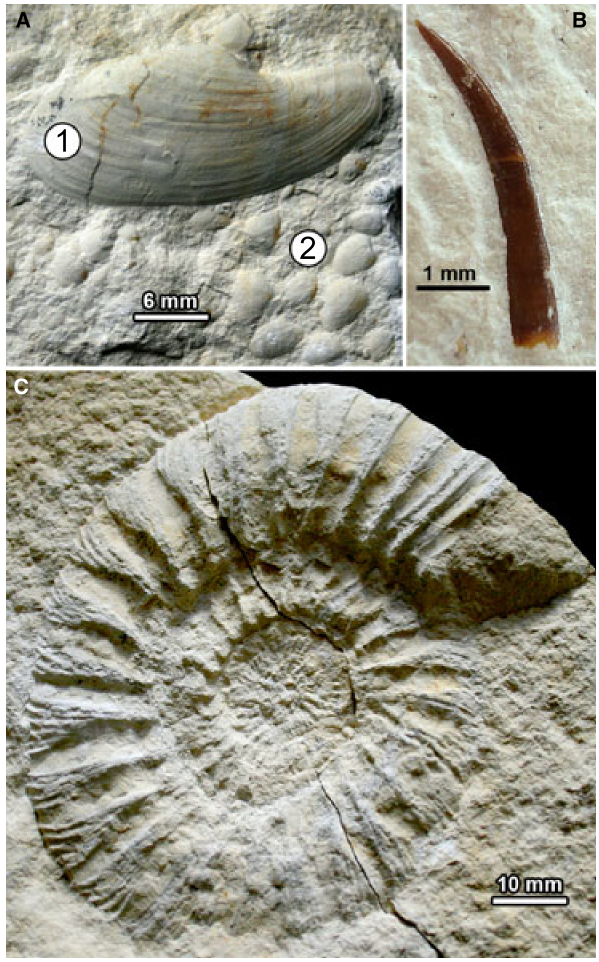

Fig. 3. Macrofossils from the Corbulomima horizon. A, bivalves: *Mesosaccella* sp. (1) and numerous representatives of *Corbulomima obscura* (2). B, indeterminate pterosaur tooth. C, the only example of *Zaraiskites* ex gr. *zaraiskensis* found from the *Corbulomima* horizon.

Preliminary micropalaeontological studies of the *Corbulomima* horizon and carbonate sediments occurring at the top of the studied section (details below) indicate a rather monotonous ostracod assemblage, consisting of forms without ornamentation, including *Klieana* cf. *kujaviana* Bielecka & Sztejn 1966; *Galliaecytheridea* sp.; *Fabanella* sp.; ?*Damonella* sp. and ?*Pachycythereidea* sp. (Fig. 6A–F). No other microfossils were encountered in this horizon. The fossils found in the *Corbulomima* horizon and information about their state of preservation and percentage abundance in the faunal assemblage are summarized in Table 1. The *Corbulomima* horizon passes upwards into thin- to medium-bedded limestones with very rare corbulid bivalves, and almost no other macrofossils (only two partial fish were discovered). These overlying limestones can be divided into: (1) a lowermost thin bedded fine-grained limestone locally dominated by U-shaped burrows of *Glyphichnus* type (Goldring *et al.* 2002; Fig. 7A); (2) a middle, 80 cm-thick, synsedimentary intraclastic breccia (Fig. 7D); and (3) an uppermost unit of thin bedded, fine-grained limestones which has been almost completely silicified (Fig. 7D).

Sedimentology, taphonomy and stable isotope geochemistry

The sedimentary sequence is dominated by micritic carbonates with a peloidal texture. Sedimentary structures are absent from both units I and II of the carbonate sequence, probably due to ubiquitous bioturbation in a subtidal setting. In contrast, unit III is quite rich in sedimentary structures and appears to have been deposited in very shallow water. The lowermost fossiliferous *Corbulomima* horizon is capped by fine-grained, thin-bedded (beds of thickness up to

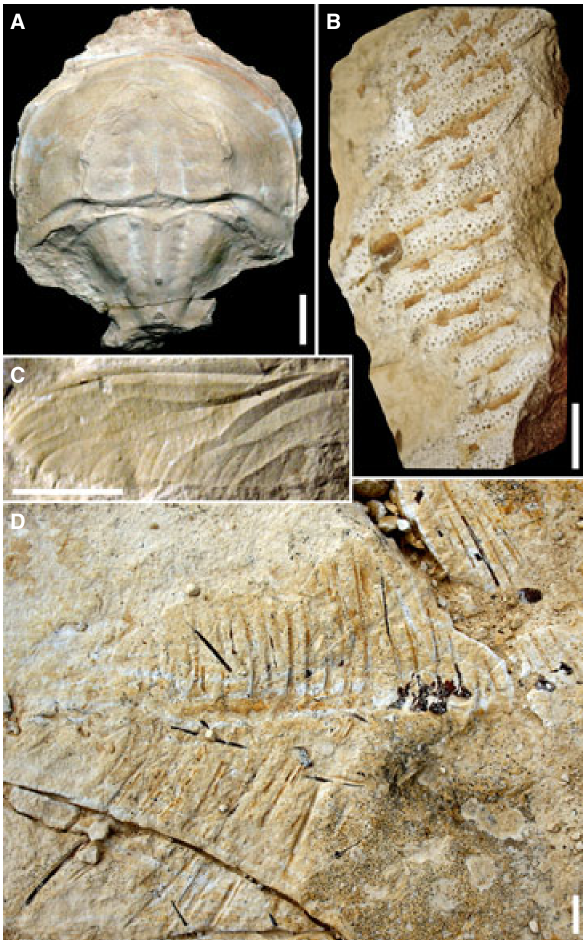

Fig. 4. Representatives of the macrofossil assemblage from the *Corbulomima* horizon of unit III in the Late Tithonian (Middle Volgian) sedimentary sequence at Owadów-Brzezinki. A, nearly complete exuvia of *Crenatolimulus* sp. nov. B, fragmentary preserved pycodontid fish skeleton (tuberculate scales of ?*Coelodus* sp.). C, wing of the dragonfly *Eumorbaeschna* sp. nov. D, partial skeleton of indeterminate pycnodontid fish preserved *in situ*. Scale bar = 10 mm.

10 cm) limestone showing low-angle and parallel stratification. Top surfaces of some of these beds have an appearance of polygonal patches with remains of U-shaped burrows (Fig. 7A). These U-shaped burrows form single systems, never branching networks, with margins characterized by calcareous linings (Fig. 7A). The individual burrows are a few centimetres in diameter (i.e. usually 1–3 cm), and filled with structureless sediment. They are typical of the *Glyphichnus* ichnotaxon described from Cretaceous and Cenozoic deposits by Goldring *et al.* (2002). Individual U-shaped burrows have been truncated, some of the tubes cut-cross each other, some display calcareous linings around the opening and tube termini. All the tubes are filled with coarse-grained sediment lacking internal structure. Low angle cross-stratification as well as parallel lamination within this thin bedded limestone is visible due to the distribution of millimetre-scale spherical peloids, probably of feacal origin. The top surface of this thin-bedded unit has symmetrical wave ripples.

The middle portion of Unit III is distinctive. The base of the lowermost bed drapes directly on the rippled surface, whereas the top shows clear parallel lamination (Fig. 7D). The next 80 cm bed is an intraformational breccia including platy intraclasts of the peloidal micritic sediments, typically 5–7 cm in size, scattered chaotically within the planar-tabular bed (Fig. 7D). The uppermost part consists of a thin layer of more granular (probably also intraclastic) sediment showing parallel lamination (Fig. 7D). Individual clasts of the breccia are made visible by thin seams of clay or organic material (Fig. 6E). The uppermost thin beds of fine-grained limestone of Unit III are almost completely silicified (Fig. 7D).

The taphonomy of the *Corbulomima* horizon and the limestone layer with abundant U-shaped burrows suggest local reworking of the bioclasts and subsequent dissolution of aragonitic shells. The commonest elements of the diverse macrofauna assemblage of the horizon (Table 1) are moulds of the small shallow-burrowing bivalve *Corbulomima*. Articulated bivalve moulds are randomly distributed, locally forming a pavement on bedding surfaces. There are also rare moulds of other molluscs (e.g. gastropods), as well as extremely rare but well preserved brachiopod shells and a quite rich and well preserved assemblage of vertebrate teeth and bones (Figs 3B, 4B–C, 5). Amongst macrofossils showing an exceptional mode of preservations are remains of insects (e.g. wing of the dragonfly - Fig. 4C) and limulines (e.g. appendages). There is no directional sorting or size segregation of the fossils.

Carbon and oxygen stable isotope values for the carbonate sequence have been determined for the sediments in the *Corbulomima* horizon and the intraformational breccia. The average $\delta^{13}C$ values for the ostracod shells and their fine-grained carbonate in-fills vary around $-1‰$ VPDB, whereas the average $\delta^{18}O$ values are around $-3‰$ VPDB. The $\delta^{13}C$ values for all studied clasts from the intra-formational breccia lie within a narrow range between 1 and 1.2‰ VPDB, whereas the $\delta^{18}O$ values lie between -1 and $-3.2‰$ VPDB.

Discussion

In general, the sedimentary and palaeontological evidence from units I and II records a change from an offshore to nearshore, perhaps lagoonal or coastal, setting. The low energy environment must then have been disturbed under extreme dynamic conditions, to

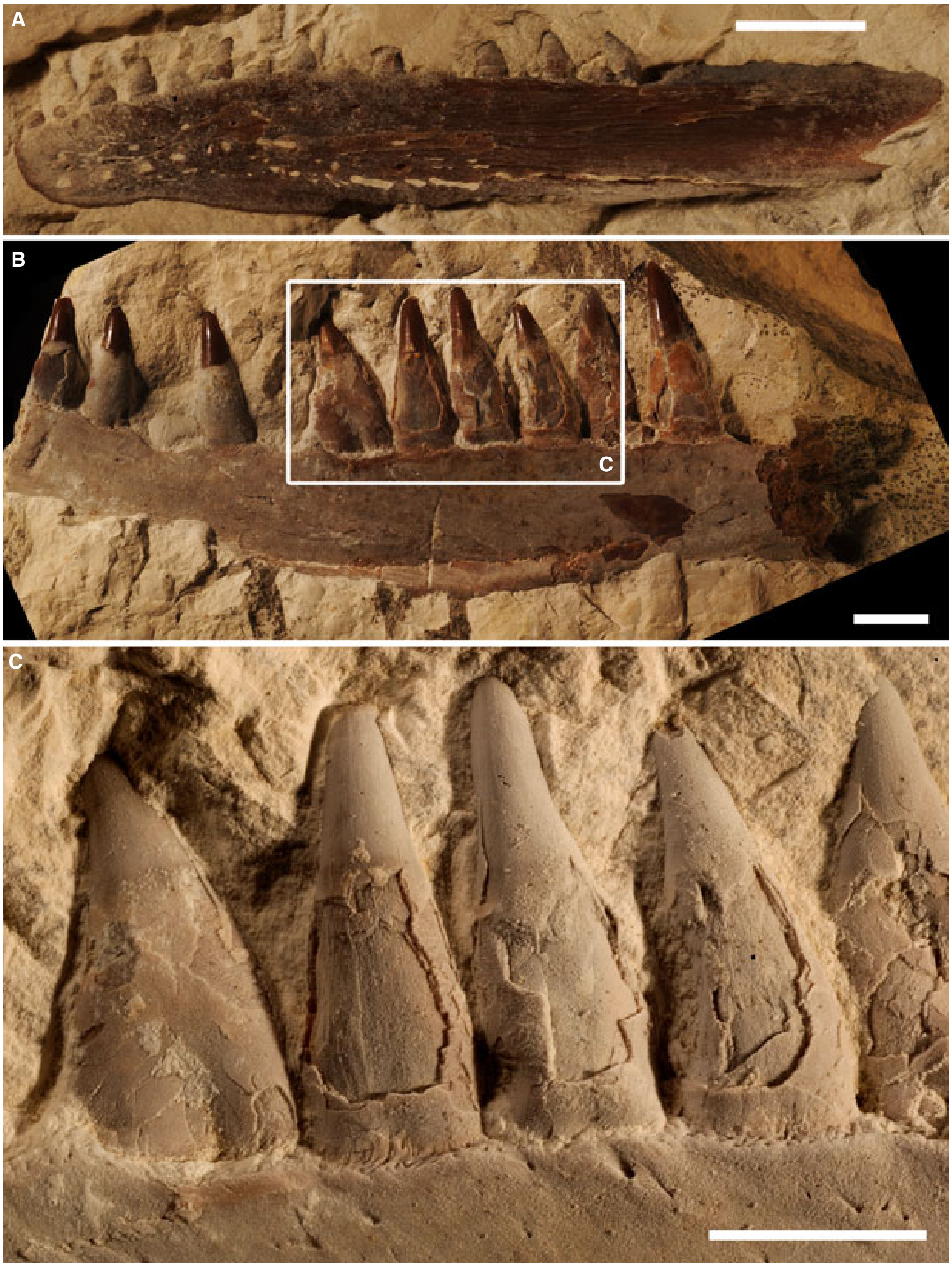

Fig. 5. Examples of vertebrates from the *Corbulomima* horizon. A, mandible of aquatic sphenodontian *Pleurosaurus* ex gr. *goldfussi*. B, nearly complete dentary bone of actinopterygian fish *Caturus* sp. C, details of same specimen, showing teeth of the mid dentary in detail. Scale bar = 10 mm.

form the intraformational breccia. This chaotic unit is a single ‘event-horizon’, it’s thickness locally varying from 30 to 80 cm. Based on the information presented here, it possibly represents a tsunami or storm surge deposit (Morton *et al.* 2007). There has been much discussion about the recognition of tsunami deposits in the sedimentary record (Dawson & Stewart 2007). In the case of the Owadów-Brzezinki deposit, diagenetic processes leading to sediment cementation and lithification have obliterated some of the key depositional evidence, however, some distinctive internal sedimentary structures have survived. These include sheet-like packets and intercalations of parallel laminated coarser sediment (Bathurst 1975; Morton *et al.* 2007; see also Bourgeois 2009). The very constant $\delta^{13}C$ values suggest normal oxic marine conditions prevailed but the rather more variable $\delta^{18}O$ values for the individual clasts of the breccia, might

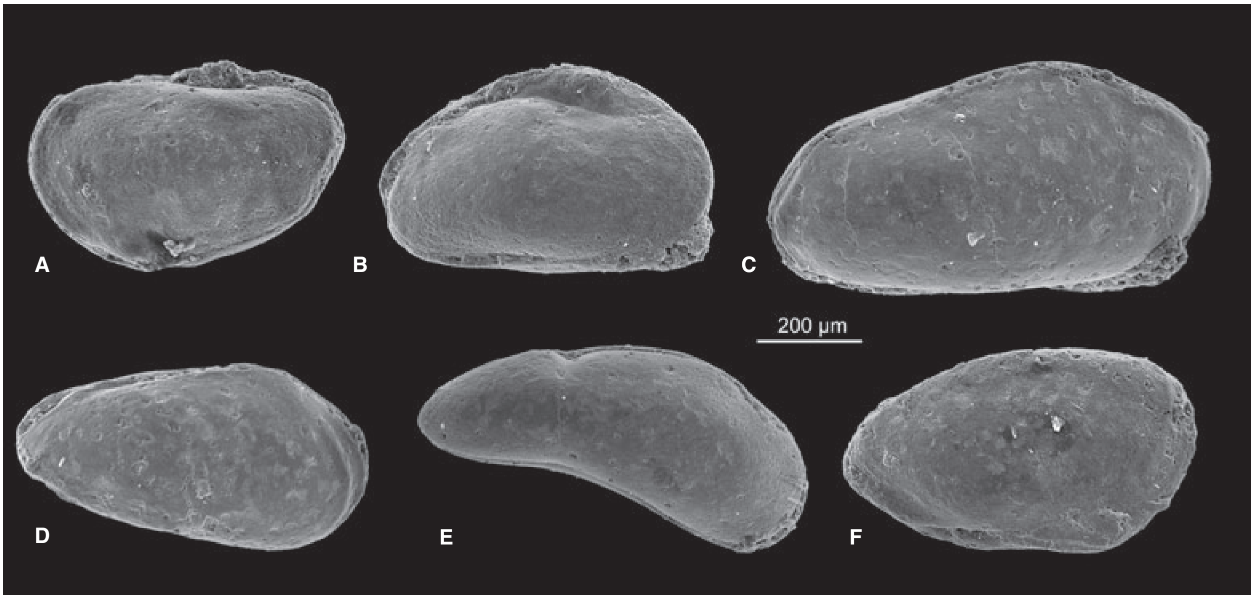

Fig. 6. Ostracods from the *Corbulomima* horizon (unit III) of the Late Tithonian (= Middle Volgian) sedimentery sequence at Owadów-Brzezinki. A, *Galliaecytheridea* sp. B, *Fabanella* sp. C and D, *Klieana* cf. *kujaviana* Bielecka & Sztejn 1966. E, ?*Damonella* sp. F, ?*Pachycythereidea* sp.

Table 1. Fossils identified in the *Corbulomima* horizon (unit III) at Owadów-Brzezinki quarry. A, percentage presence of particular fossils (n = 10 000 specimens) in the *Corbulomima* horizon faunal assemblage. B, mode of fossil preservation: m = internal and/or external moulds, c = calcite remains, p = phosphatic remains, p/c = phosphatic and calcite remains, m/c = moulds dominate but some calcitic remains also occurred.

Category of fossils	Faunal assemblage occurring in the Corbulomima horizon (Owadow-Brzezinki quarry)	A [%]	B
Microfossils – Ostracoda	*Klieana* cf. *kujaviana* Bielecka & Sztejn 1966; *Galliaecytheridea* sp.; *Fabanella* sp.; ?*Damonella* sp.; ?*Pachycythereidea* sp.	–	c
Bivalvia	*Corbulomima obscura* (Sowerby 1827); *Pleuromya uniformis* (Sowerby 1813); *Mesosaccella* sp.	97	m
Ammonoidea	*Zaraiskites* ex gr. *Zarajskensis*	0.04	m
Brachiopda	Terebratulidae sp. indet.	0.02	c
Decapoda	*Glyphea* sp.; ?*Eryma* sp.; ?*Cycleryon* sp.; ?*Aeger* sp.	0.2	m
Limulida	*Limulus* sp. nov. (Kin, in prep.); *Crenatolimulus* sp. (Kin *et al.*, in prep.)	0.1	m
Odonata	*Eumorbaeschna* sp. nov. (Bechly & Kin, in prep.)	0.01	m
Coleoptera	?*Notocupes* sp.	0.02	m
Elasmobranchii	*Notidanus* sp.; *Sphenodus* sp.	0.24	p
Actinopterygii	*Caturus* sp.; *Lepidotes* sp.; *Gyrodus* sp., ?*Coelodus* sp.; ?*Macrourogaleus* sp. and ?*Thrissops* sp.	2.3	p/c
Sphenodontia	*Pleurosaurus* ex gr. *goldfussi*	0.01	p/c
Pterosauria	Indeterminate pterosaur remains (tooth and bones)	0.03	p/c
Other macrofossils	e.g. gastropods; serpulids *etc.*	0.03	m/c

suggest that some of the clasts were at least partially lithified in a slightly more evaporitic beach or tidal flat environment before being ripped up to form the deposit.

Tsunamites have been documented in deep water sedimentary sequences from the Middle (Brookfield *et al.* 2006) and Late Jurassic (Dypvik *et al.* 2004) and some coarse-grained sediments of the 'Purbeckian' facies in northern France (Deconnick *et al.* 2000). If the interpretation above is correct, the deposit from Owadów-Brzezinki is likely the first Mesozoic tsunami deposit analysed in details and recognized in a relatively low energy tidal flat environment. It is not clear what might have generated the sudden event in the shallow epicontinental sea, but palaeogeographic reconstruction for the Kimmeridgian-Tithonian demonstrates the close proximity of the rapidly subsiding Middle Polish Trough (Stampili *et al.* 2001). It is tentatively suggested therefore that tectonic activity on the margins of the basin (Fig. 8), may have caused local submarine earthquakes.

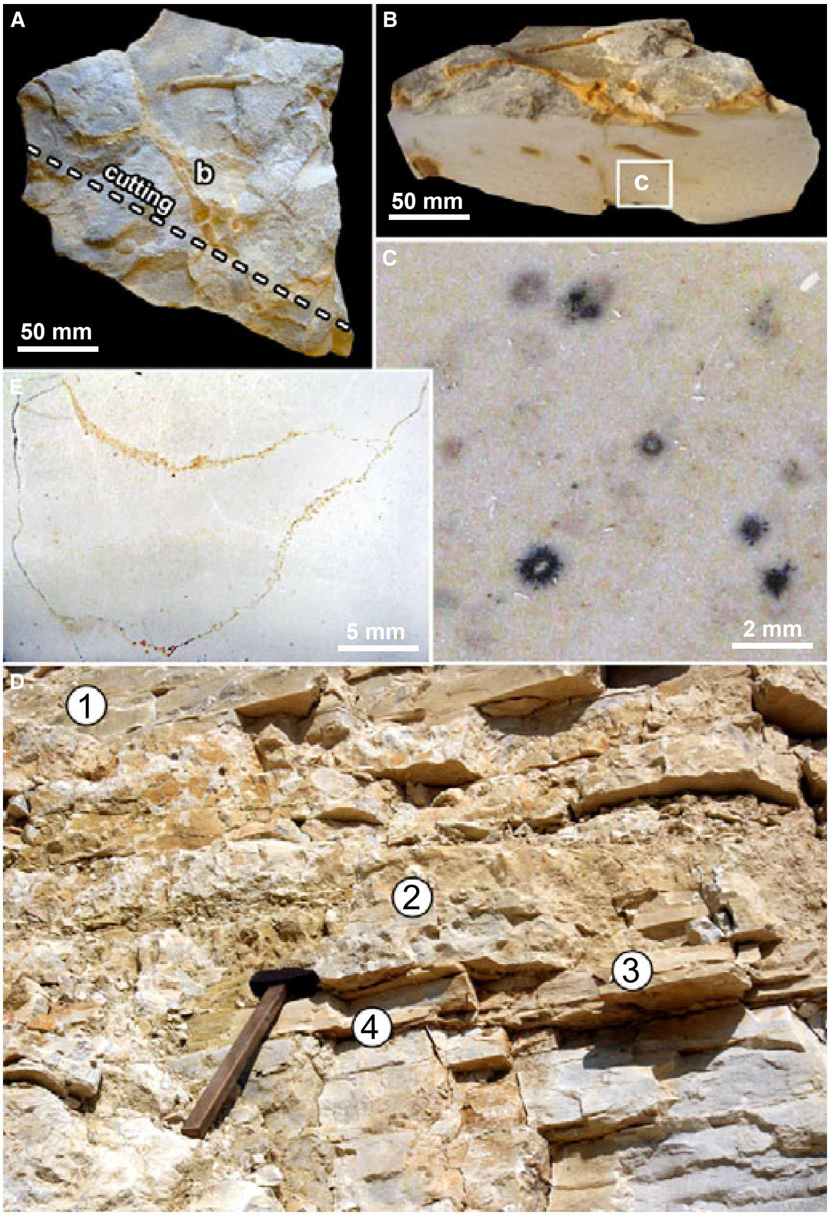

Fig. 7. A, limestone bed from unit III showing an assemblage of U-shaped burrows; notice lining around a visible part of the *Glyphichnus* burrow. B, elongate and oval crosssections of burrows visible in a cut surface. C, weak halos around the burrow margins and differentiated burrow-fill sediments. D, part of the sedimentary succession showing internal characteristics represented by the overwash deposits: (1) silicified limestones at the top of the unit III; (2) tsunamite or mega-stormite; (3) boundary between tsunamite or mega-stormite and lithographic limestone; (4) uppermost part of lithographic limestones with horizon of U-shaped burrows. E, polished surface of one of the beds belonging to the tsunamite or mega-stormite; (note clasts picked out by insipient ?stylolite seams).

Taphonomic evidence from the macrofossil assemblage of the fossiliferous *Corbulomima* horizon (Figs 1C, 2; Table 1) shows that the unit is dominantly a Konzentrat-Lagerstätten but with elements of local conservation of delicate fauna (Seilacher 1970). The overall diversity of the macrofossils and composition of the fossil assemblage show similarities to the well-known macrofossil assemblage from the world famous Konservat-Lagerstätten of Solnhofen (Bavaria, Germany), (Allison 1988; Barthel *et al.* 1990; Keupp *et al.* 2007). In contrast with Solnhofen, however, soft tissue preservation is extremely rare in the sequence and is restricted to tougher arthropod cuticular material. We suggest rapid, shallow, initial burial within oxic bottom sediments. There is no direct evidence of water stagnation, evaporation, or thermohaline stratification as is the case in the Solnhofen Formation (Keupp 1977; Keupp *et al.* 2007). The shelly fossils suggest that salinities might have been variable and there is a suggestion that the ostracod assemblage

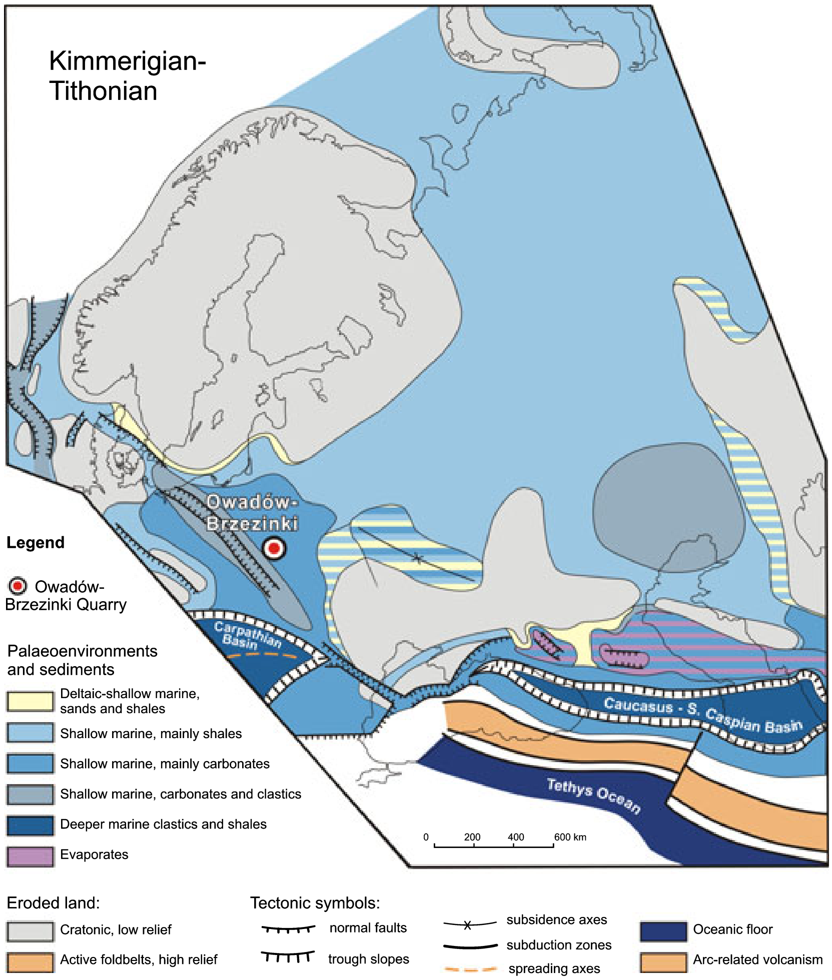

Fig. 8. Palaeogeographical map (after Stampili *et al.* 2001) showing position of the Owadów-Brzezinki quarry on the margin of the Middle Polish Trough.

(Bielecka & Sztejn 1966), and dominance of corbulid bivalves might even indicate brackish or schizohaline environments. However, recent work suggests that the simple presence of autochthonous bivalves such as *Corbulomima obscura* is not environmentally diagnostic. The dominance of these bivalves, however, might be quite significant as they were shallow burrowing suspension feeders reliant on an abundant food supply. Assuming the Middle Polish Trough formed a seaway connected with the Norwegian-Greenland Seaway (Langrock *et al.* 2003) and Tethyan Ocean in the south, then oceanic currents would have brought a lot of particulate organic matter into the shallow water areas. These would have supported local phytoplankton blooms, and in turn, the abundant zooplankton essential to feed the bivalve population. The corbulids themselves seem to have been easy prey for other marine invertebrates, and may have attracted other organisms to the site. Such higher predators would have included the limulids and decapods, as well as the durophagous vertebrates including the various fish and marine sphenodonts found in the deposit. We have not found, so far, the remains of larger marine predators (e.g., ichthyosaurs; plesiosaurs; crocodiles). However, rare large bones (e.g. vertebrae) have been discovered in the lower part of the succession (unit I, B.A. Matyja, personal communication, June 2003).

Just how abundant the population of *Corbulomima obscura* might have been can be estimated from observations of recent large tidal flats inhabited by dominant shallow burrowing suspension feeding bivalves. For example, the number of empty, sometimes disarticulated, shells of *Lyocyma fluctuosa* found in bottom sediments of a Spitsbergen tidal flat represent approximately 1–2% of the living specimens which can occur in densities of up to 12 000 per square metre (Różycki & Gruszczyński 1992). By analogy the moulds after *Corbulomima obscura* on the bedding surfaces within the Corbulomima horizon can be more than 500 per square metre, so a living assemblage could, perhaps, embrace several thousand (up to about 20 000) specimens per square metre.

The total lack of preservation of the shell material of *Corbulomima* and other bivalves suggests very early diagenetic dissolution of aragonite. This could have been caused by the oxidation of organic matter by dissolved oxygen within the pore waters during initial burial. The average $\delta^{13}C$ values for the ostracod shells and fine-grained carbonate filling these shells, in the *Corbulomima* horizon of −1‰ VPDB, suggest incorporation of negligible quantities of carbon sourced from organic matter (−25 per mil). The decay of organic matter could, however, have created relatively low pH conditions, to cause the dissolution of the calcium carbonate shells without incorporation of that carbon in the carbonate sediments. The average $\delta^{18}O$ values oscillating around −3‰ VPDB is perfectly compatible with precipitation of carbonate in warm shallow marine waters (Hudson 1977).

Further evidence for the extremely shallow sedimentary environments in which *Corbulomima* bloomed is provided by the erosional truncation of U-shaped burrows and calcareous linings around some of these burrows. Whilst the truncations suggest erosion, most likely by waves within nearshore to foreshore environments, the linings might suggest protection of the burrow openings against infill by shifting sand.

Conclusions

Preliminary studies of the Late Tithonian (Middle Volgian) sedimentary sequence from Central Poland have led us to the general conclusion that rare occurrences of almost complete preserved organisms (e.g. limulid and fish) within the highly fossiliferous shelly Corbulomima horizon makes this horizon a transitional facies between *Konzentrat* and *Konservat-Lagerstätten*. This is in contrast with the Early Tithonian limestones from Solnhofen, which are classic examples of *Konservat-Lagerstätten* facies. There are some similarities between the deposits. Firstly, a similar range of macrofauna has been identified in both localities; secondly, both fossiliferous horizons are succeeded by rapidly deposited sediments possibly created by submarine earthquakes. In the Solnhofen Limestone the Krummenlage beds are interpreted as submarine slumps (Krumbeck 1928), while the Late Tithonian 'Polish Solnhofen' described here has shallow water deposits interpreted as a possible tsunami deposit.

The major difference between the sites is their palaeogeographical context. In the case of Solnhofen, the sediments were deposited in the relatively deep lethal lagoon, where the seafloor was dominated by microbial mats (compare Keupp *et al.* 2007). In contrast, the epicontinental sea at Owadów-Brzezinki was extremely shallow and the bottom sediment was composed of peloidal micrites. The inferred existence of a large nearshore zone or tidal flat system in the Polish part of the subboreal epicratonic sea, illustrates that the rifting Middle Polish Trough shallowed markedly towards its margins. The rift zone could have acted as a seaway providing a supply of nutrients to the adjacent carbonate shoals, and building up a trophic web from phytoplankton to zooplankton which would have fed the corbulid bivalves, their predators the limulids, decapods, fish marine sphenodonts and in turn the opportunistic airborne insects and pterosaurs.

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