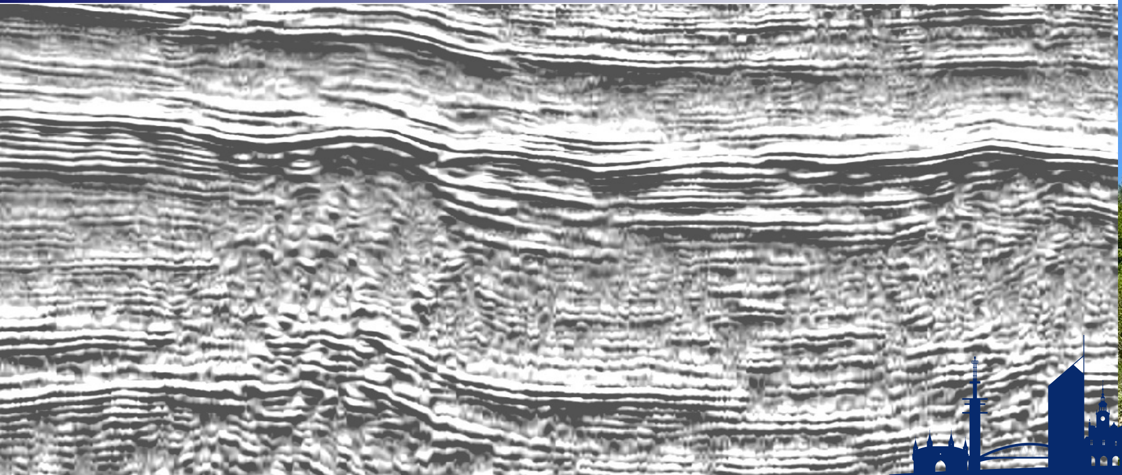
Europe Regional Conference
28-29 May 2024 | Krakow, Poland

Energy Transition:
Is the European Approach Different?

Upper Jurassic Carbonate Depositional System of the Carpathian Foreland – Surface and Subsurface Insight

Monday, 27 May | Krakow, Poland

Pre-conference field trip guidebook



Upper Jurassic Carbonate Depositional System of the Carpathian Foreland – Surface and Subsurface Insight

Field Trip Guide

Monday 27 May 2024

Field Trip Leaders:

Łukasz Słonka[1], Marcin Krajewski[2], Janos Csizmeg[3] and Piotr Krzywiec[1],

[1]*Institute of Geological Sciences, Polish Academy of Sciences (lukasz.slonka@twarda.pan.pl)*

[2]*AGH University of Science and Technology, Kraków (kramar@agh.edu.pl)*

[3]*Ukrgazvydobuvannya, Naftogaz Group*

Table of content

Introduction to the trip

This field trip will be focused on the Upper Jurassic deposits from the southern part of the Polish Basin i.e. Permo-Mesozoic epicontinental basin located in the Carpathian foreland. They have been recognized and described many decades ago within the so-called Polish Jura Chain that stretches from Kraków in the SE towards Częstochowa in the NW (Fig. 1). Since 1970' numerous wells and then seismic data documented these deposits also in the subsurface, within the Nida Trough that was formed due to inversion of the SE segment of the Polish Basin (Fig. 1).

The Permian-Mesozoic Polish Basin belonged to the system of intracontinental basins that developed within the current western and central Europe (Ziegler, 1990; Scheck-Wenderoth et al., 2008; Pharaoh et al., 2010). The dominant feature throughout its history was the Mid-Polish Trough (MPT), a deep axial zone trending NW-SE and flanked to the NE and SW by shallower areas. The regional geometry of the Polish Basin, including the location of the Mid-Polish Trough, was controlled by the NW-SE trending Teisseyre–Tornquist Zone – a key tectonic boundary in Europe located at the transition between the East European Platform Craton and the West European Platform (Dadlez et al., 1995; Dadlez, 1997; Krzywiec et al., 2006; Mazur et al., 2015; Scheck-Wenderoth et al., 2008, Pharaoh et al., 2010; Fig. 1).

Following Permian extension and volcanism, the Polish Basin experienced long-term Mesozoic thermal subsidence, punctuated by three major pulses of accelerated tectonic subsidence: during Late Permian to Early Triassic times, in the Late Jurassic (Oxfordian to Kimmeridgian), and in the early Cenomanian (Dadlez et al., 1995, Stephenson et al., 2003; Krzywiec, 2006).

The Polish Basin was subsequently subjected to the Late Cretaceous to early Paleogene Alpine inversion event that influenced large parts of Europe (Ziegler, 1990; Voigt et al., 2021). During inversion, its axial part, i.e., the Mid-Polish Trough, was uplifted and transformed into the Mid-Polish Anticlinorium, and then deeply eroded (Mazur et al., 2005; Krzywiec, 2002, 2006; Resak et al., 2008; Krzywiec et al., 2009, 2018). The Mid-Polish Anticlinorium is outlined by Lower Cretaceous and older rocks subcropping beneath the mostly flat-lying thin Cenozoic cover (Fig. 1).

Sedimentary infill of the Polish Basin comprises complete Permo-Mesozoic succession (Marek and Pajchlowa, 1997). It starts with the Rotliegend (Cisuralian – lower Lopingian) clastics and Zechstein (upper Lopingian) evaporites and carbonates. Permian is covered by Lower Triassic terrigenous red-beds, Middle Triassic carbonates, Upper Triassic terrigenous and shallow marine clastics with subordinate evaporites, Lower Jurassic mixed terrigenous and marine clastics, Middle Jurassic marine clastics, Upper Jurassic carbonates with subordinate terrigenous clastics and evaporites, Lower Cretaceous marine clastics, and mostly syn-inversion Upper Cretaceous marine carbonates. Post-inversion Cenozoic (Paleogene, Neogene and Quaternary) cover is relatively thin (up 200-300 m), essentially flat-lying and is built mostly of terrigenous clastics locally with brown coal seams (Piwocki 2004; Piwocki et al., 2004; Jarosiński et al., 2009). It was deposited above regional erosional unconformity formed after inversion of the Polish Basin and uplift of the Mid-Polish Anticlinorium (cf. Krzywiec, 2002, 2006b; Krzywiec et al., 2009).

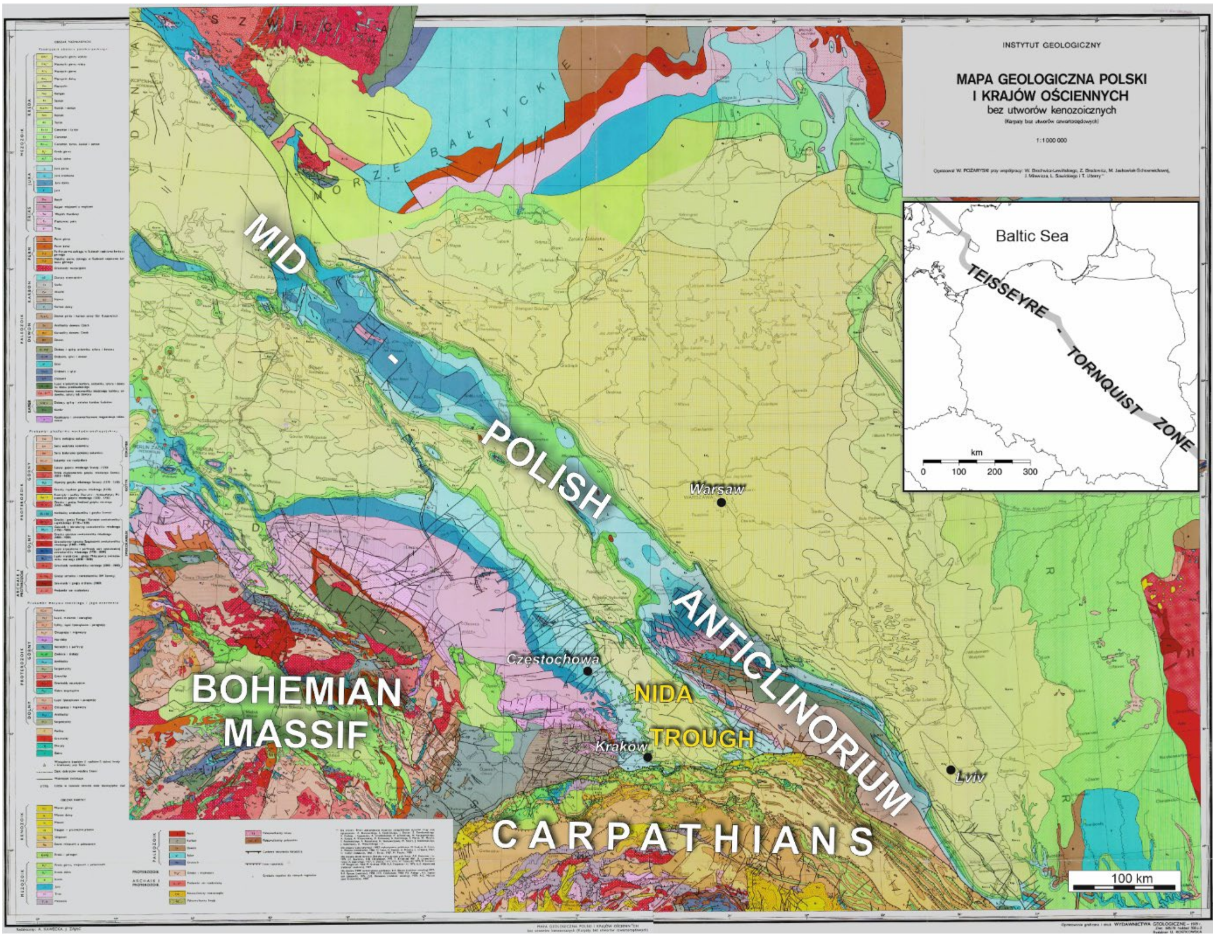


Fig. 1. Geological map of Poland and surrounding countries without Cenozoic (Carpathians without Quaternary) (Pożaryski et al., 1979); green colors: Cretaceous, blue colors: Jurassic, violet colors: Triassic. Location of the Teisseyre-Tornquist Zone after Mazur et al (2015).

The Fieldtrip Route: **Kraków** (Holiday Inn Kraków City Centre) – **Bolechowice** (Stop 1) – **Czajowice** (Stop 2) – **Pieskowa Skała** (view point) – **Kromołowiec** (Stop 3) – **Podzamcze** (Stop 4) – **Kraków** (back to hotel)

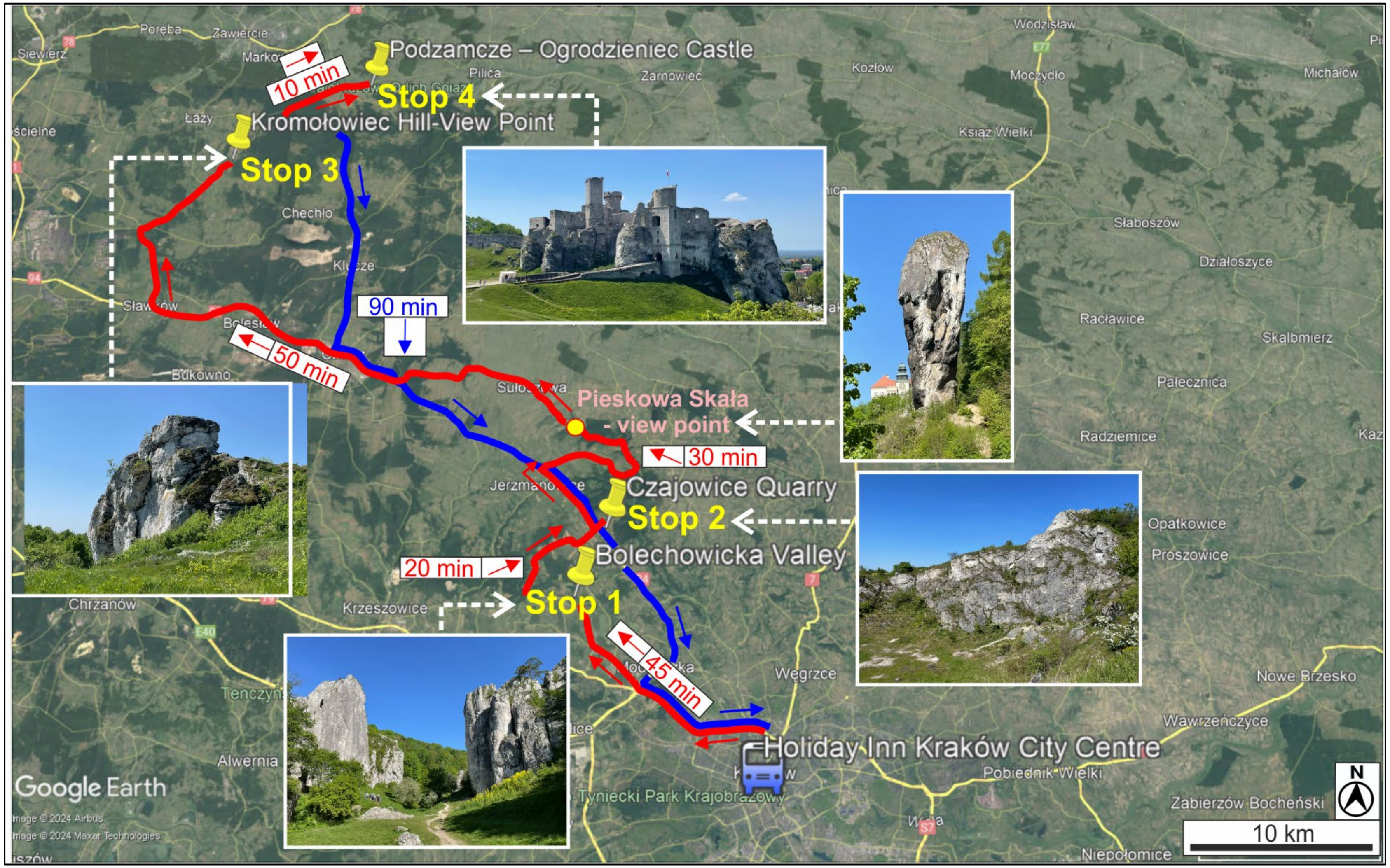


Fig. 2. The Fieldtrip location/road map superimposed on a satellite image (map data by *Google Earth*) showing the stops with estimated travel times between them (red colored). The return route is marked in blue

Fieldtrip itinerary

Time	Stops
7:45	Meet at Holiday Inn, Kraków City Center (hotel parking lot)
7:45 – 8:00	Boarding the bus
8:00	Departure from Hotel
8:45	Arrival to Bolechowice
	Stop 1: Bolechowice Valley
10:00	Departure to Czajowice
10:20	Arrival to Czajowice
	Stop 2: Czajowice Quarry
11:20	Departure to Kromołowiec
11:50 – 12:00	Pieskowa Skała-view point
12:50	Arrival to Kromołowiec
12:50 – 13:20	Field Lunch
	Stop 3: Kromołowiec Hill-view point
13:50	Departure to Podzamcze
14:00	Arrival to Podzamcze
	Stop 4: Podzamcze – Ogrodzieniec Castle
15:15	Departure to Kraków
17:00	Arrival to Kraków (Holiday Inn, Kraków City Center)

Upper Jurassic Carbonate Depositional System of the Carpathian Foreland based on example of Kraków-Częstochowa Upland: Introduction

The trip route (Fig. 2) is located in the southern (Stop 1 and Stop 2) and central (Stop 3 and Stop 4) part of Kraków-Częstochowa Upland (abbreviated - KCU; Fig. 3). KCU, also named the "Polish Jura", represent the classic and best area in southern Poland for field observations of the Upper Jurassic carbonate depositional system of the Carpathian Foreland.

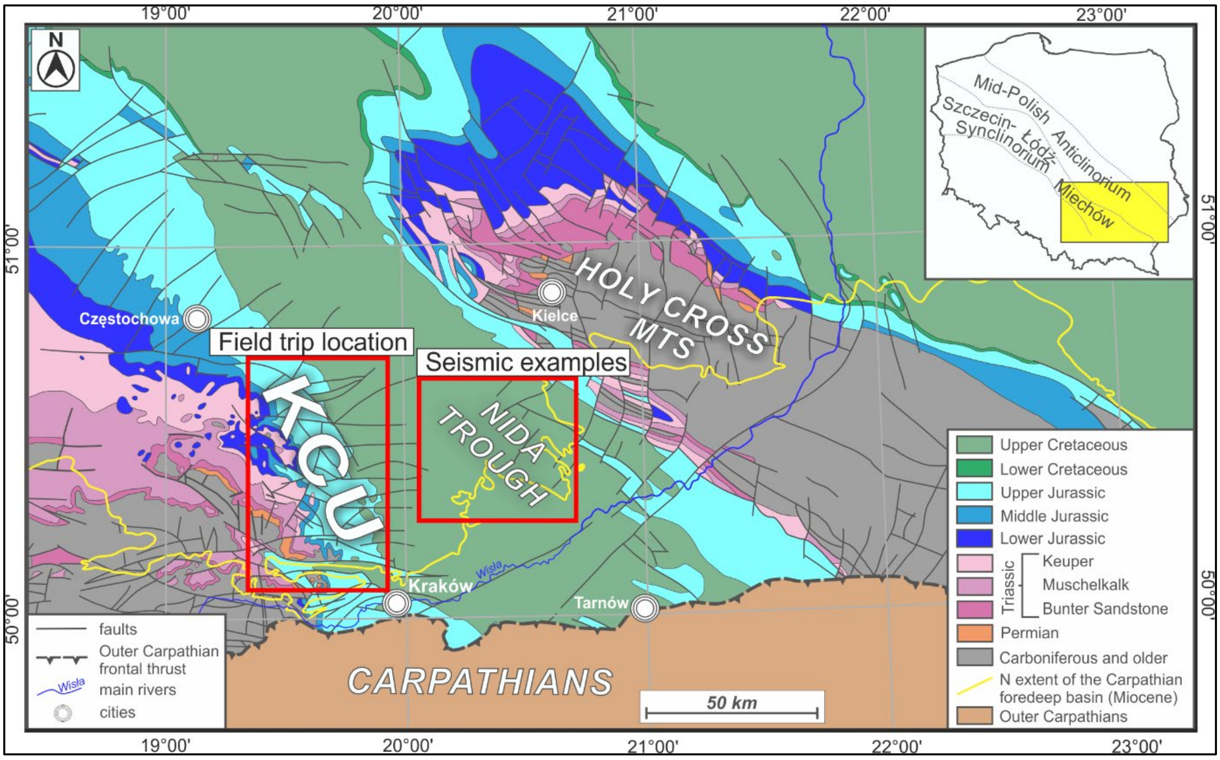


Fig. 3. Geological map of southeastern Poland without Cenozoic (Słonka and Krzywiec, 2020b; after Dadlez et al., 2000, simplified; northern extend of the Carpatian Foredeep basin after Żytko et al., 1988). Red rectangles show: (1) the localization of the Field Trip and (2) the location of subsurface examples from the seismic interpretation study in the Nida Trough (Słonka and Krzywiec, 2020a, b). KCU - Kraków-Częstochowa Upland.

KCU is part of the Silesian-Kraków Homocline composed mainly of Triassic, Jurassic and Upper Cretaceous deposits (Fig. 4). Locally preserved Permian deposits, together with Mesozoic sediments, are part of the so-called Permo-Mesozoic structural complex (Krokowski 1984; Żaba 1999). The so-called Kraków-Lubliniec Fault Zone runs along the KCU (also called the Kraków-Hamburg Fault Zone; Żaba 1999), which divides the Upland basement into two Paleozoic tectonic blocks: the Upper Silesian and Małopolska terranes (Buła 2002; Żelaźniewicz et al., 2011; Fig. 5). This zone was also active in the Mesozoic and had a significant impact on the development of Late Jurassic facies architecture (Żaba 1999; Matyszkiewicz et al., 2006, 2016).

Fig. 4. Simplified geological map of the Kraków-Czestochowa Upland excluding Quaternary (after Rühle et al. 1977; modified).

The geological structure of KCU is dominated by Upper Jurassic carbonate deposits representing the Lower Oxfordian-Lower Kimmeridgian sedimentary succession (Fig. 6). They are usually underlain by Callovian siliciclastic-carbonate sediments and, locally, by differentiated Palaeozoic substrate. The greatest thicknesses of the Upper Jurassic strata, up to several hundred meters, are reached in the eastern part of the Upland and it gradually decreases to the west. The Upper Jurassic sedimentary succession is characterized by high facies diversity. The most important facies are represented by (i) marl, marly limestone and limestone bedded facies, (ii) massive (means unbedded) limestone facies and (iii) gravity flow deposits (Fig. 6). In the KCU landscape, the most characteristic rock complexes (e.g. Gradziński et al., 2008; Pawelec 2011; Tyc 2024) are built by massive limestone facies representing numerous skeletal- and microbial- grain-dominated carbonate buildups (e.g. Matyszkiewicz et al., 2012; Krajewski et al., 2018). Bedded facies were deposited in depressions between extensive buildup complexes. Nowadays, the Late Jurassic facies architecture is disturbed as a result of differential compaction between bedded and massive facies and Cenozoic faulting (e.g.

Matyszkiewicz and Krajewski 1996; Matyszkiewicz 1997, 1999; Kochman and Matyszkiewicz 2013).

From the paleogeographic point of view, the Polish examples represent a fragment of the vast, eastern part of the Oxfordian-Lower Kimmeridgian Submediterranean Province (e.g. Ziegler 1990; Matyja and Wierzbowski 1995). The Polish part of the carbonate platform is commonly classified as a ramp-type (*sensu* Burchette and Wright 1992) carbonate platform (e.g., Gutowski et al., 2005; Krajewski et al., 2011, 2016, 2017; Olchowy et al., 2019; Olchowy and Krajewski 2020) or open shelf (e.g., Matyja et al., 1989).

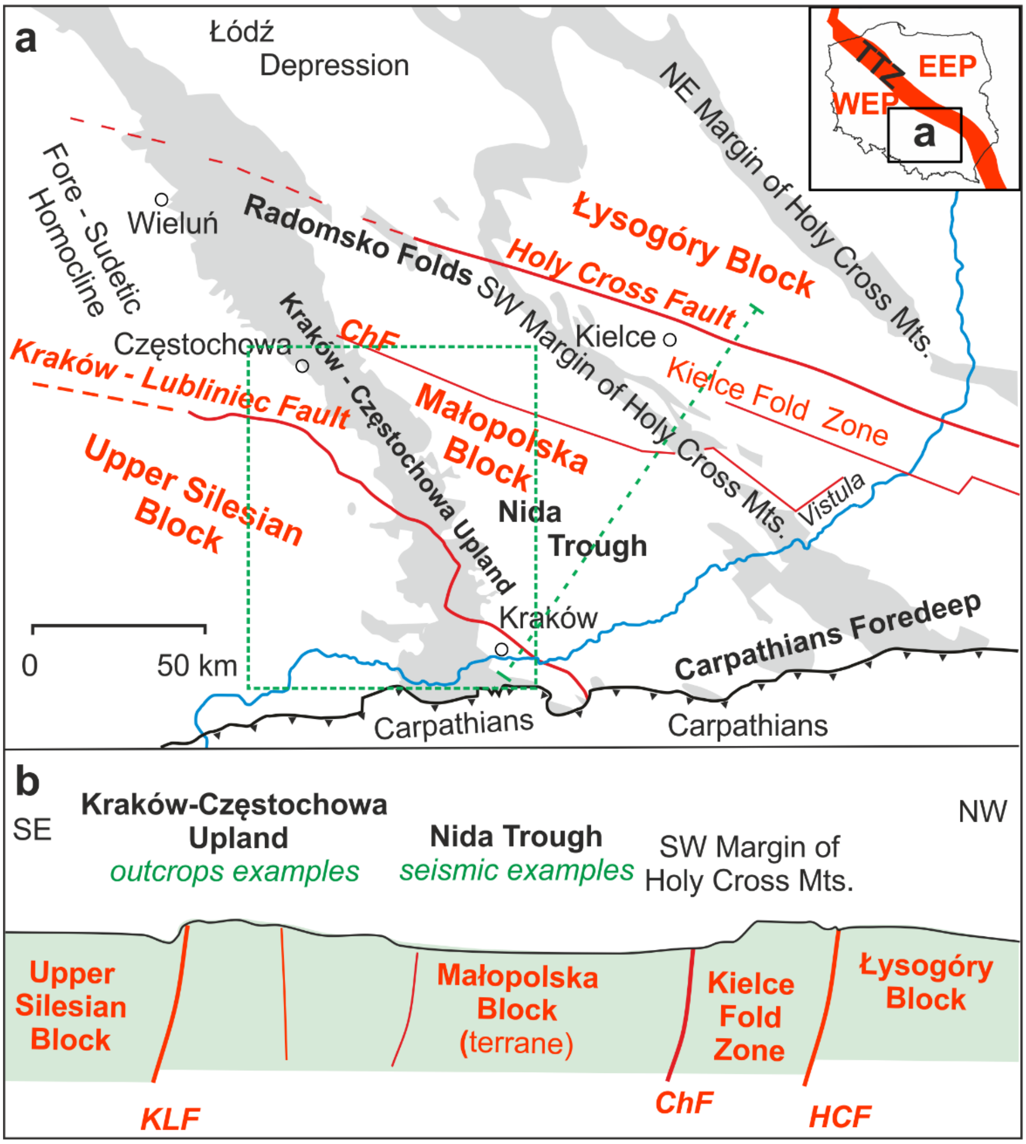


Fig. 5. a - Location of the study areas with Upper Jurassic outcrops and sub-Cenozoic Jurassic subcrops (*grey*) in southern and central Poland (after Pożaryski et al. 1979, modified and simplified by Krajewski et al., 2016). Tectonic structures (in *red*) after Buła (2002). *KLF* Kraków-Lubliniec Fault, *HCF* Holy Cross Fault, *CHF* Chmielnik Fault, *TTZ* Teisseyre-Tornquist Zone, *EEP* East European Platform, *WEP* West European Platform. b - Sketch of main geographical units and main tectonic units in the Paleozoic basement.

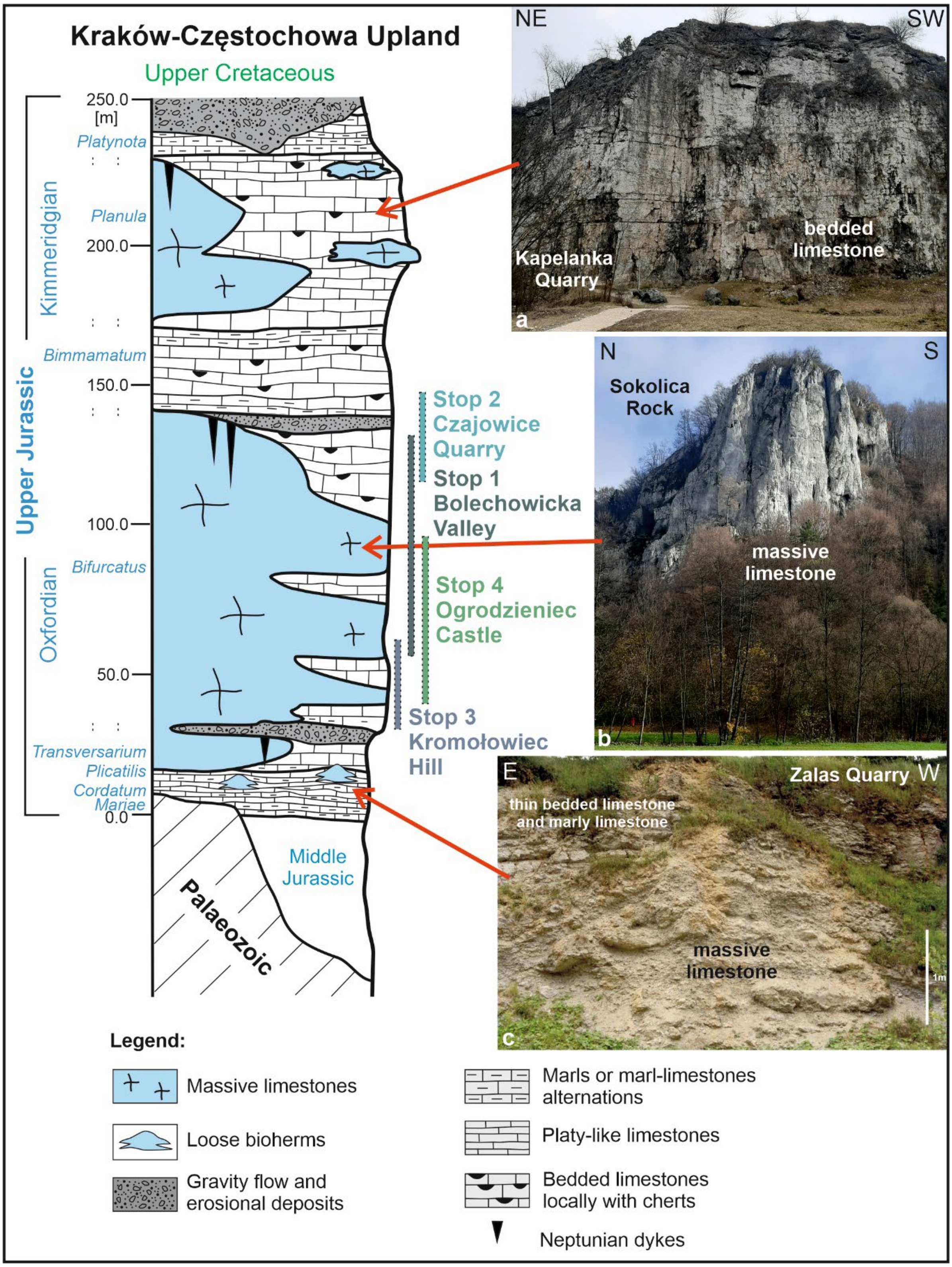


Fig. 6. Lithostratigraphic column of Upper Jurassic strata of the Kraków–Częstochowa Upland (after Krajewski et al., 2018, modified) with the approximate position of the presented Stops 1-4. On the photos examples of the main facies type. a – Kapelanka Quarry; thick-bedded bioclastic limestone facies, the height of rock ~30 m; b – Sokolica Rock, an example of the sponge and microbial-grain dominated carbonate buildups representing massive reef limestone facies; the height of rock ~80 m. c – Zalas Quarry; low-relief carbonate buildup (cluster reef) surrounded by thin-bedded limestone- marl alternations.

The main controlling factors of platform evolution were: (i) sea-level changes, (ii) synsedimentary tectonics and (iii) Paleozoic basement elevations (e.g., Kutek, 1994; Matyszkiewicz, 1997; Gutowski et al., 2005; Matyszkiewicz et al., 2006, 2012, 2016; Krajewski et al., 2011, 2016, 2018; Woźniak et al., 2018; Olchowy et al., 2019). Particularly important factors, which periodically modified the sea-bottom morphology and the paleoenvironmental conditions were synsedimentary extensional tectonic movements (Kutek, 1994; Matyszkiewicz 1997; Matyszkiewicz et al., 2016). The synsedimentary tectonics, related to the rejuvenation of Paleozoic structures (e.g., Żaba, 1999), caused periodic breakup of the carbonate platform into many smaller, fault-controlled intra-platform ridges and basins (e.g., Matyszkiewicz 1997; Matyja and Wierzbowski 2004; Matyszkiewicz et al., 2006, 2012; Krajewski et al., 2016, 2017; Kowal-Kasprzyk et al., 2020). These ridges and basins may have resulted from the NE-trending progradation of the rifting process from southern areas towards the northern Tethys shelf. The opening of the North Atlantic and Tethys Oceans resulted in the Late Jurassic reorganization of the stress field, which also affected the passive, northern margin of the Tethys (e.g., Ziegler, 1990; Allenbach, 2002; Nieto et al., 2012; Krajewski et al., 2016; Matyszkiewicz et al., 2016).

The Upper Jurassic sedimentary succession begins with thin-bedded marl and marly limestone facies up to several meters thick (Fig. 6). They represent condensed layers of the Lower and Middle Oxfordian (up to the Transversarium Zone; Fig 6). In sedimentary succession, these sediments are gradually replaced by thin- and medium-bedded so-called "platy limestone" representing the Middle Oxfordian (Dżułyński 1952; Matyszkiewicz 1997; Fig. 6). In the upper part of the Middle Oxfordian (Transversarium Zone) and Upper Oxfordian-Lower Kimmeridgian (up to Planula Zone; Fig. 6), the massive reef facies and pelitic thick-bedded limestone facies with silification phenomena predominate (for silification details see e.g. Matyszkiewicz et al., 2015; Kochman et al., 2020). The topmost of the sedimentary succession is represented by marls and marly limestone facies included in the Lower Kimmeridgian Platynota Zone (Fig. 6; Matyszkiewicz 1997; Ziółkowski 2007).

The most characteristic feature of the Kraków-Częstochowa Upland (KCU) is the Upper Jurassic white rocks (monadnocks) forming vertical cliffs represents various types of Oxfordian reefs. In the KCU landscape, the reefs form several NW-SE-trending geographical ranges dominated by hard, reefal massive facies, which, together with biostromal thick-bedded facies build vast reef complexes (e.g., Matyszkiewicz, 1997; Matyszkiewicz et al., 2006, 2012). The Oxfordian reef complexes extend to the E and SE towards the Nida Trough (e.g., Złonkiewicz 2009; Słonka and Krzywiec 2020a, 2020b; see seismic analogues) and in the basement of the

Carpathian Foredeep (Gutowski et al., 2005; Matyja, 2009; Krajewski et al., 2011). In the Polish part of the Tethys shelf, the carbonate buildups have started to grow at the beginning of the Middle Oxfordian (Fig. 6c) as small, sponge or sponge-microbial, low-relief, spaced cluster reefs (reef classification *sensu* Riding, 2002) with initial so-called rigid frameworks (rigid framework *sensu* Prat 1982; e.g., Trammer, 1982; Matyszkiewicz et al., 2012). These buildups evolved into the Late Oxfordian: (i) sponge-microbial segment-reefs with so-called laminar frameworks, which, in turn, were later replaced by (ii) microbial-sponge frame-reefs with well-developed reticulate rigid frameworks or microbial-*Crescentiella*- grain dominated agglutinating reefs (for details see e.g., Trammer, 1989; Matyszkiewicz, 1997; Matyszkiewicz et al., 2006, 2012; Olchowy, 2011; Krajewski et al., 2018; Krajewski and Olchowy 2023). The coral carbonate buildups are occasionally observed in the form of patch-reefs or thin biostromes (e.g. Roniewicz and Roniewicz 1971; Krajewski and Olchowy 2023). In sedimentary succession, gravity flow deposits are commonly observed, represented mainly by grain-, mud-, and debris-flow sediments, as well as calciturbidites and olistolites (Fig. 6; e.g. Matyszkiewicz 1997; Barski and Mieszkowski 2014; Woźniak et al., 2018).

One of the key problems of present sedimentological research is the origin of differences in the location of carbonate buildups in selected regions of the Polish part of the Tethys shelf (e.g. Matyszkiewicz et al., 2006; Krajewski et al., 2016). In the case of KCU, the initiation of intensive development of buildings was related to the presence of paleohighs in the substrate. On these elevations, there was intensive production of carbonates, including a particularly intensive development of benthic fauna, which led to the formation of extensive carbonate buildups complexes (Matyszkiewicz 1997; Matyszkiewicz et al., 2006). As these buildings progressed, they merged into larger complexes covering significant areas (Matyszkiewicz 1997; Matyja and Wierzbowski 2004; Matyszkiewicz et al., 2006). The existence of these elevations within the platform is related to the structure of the varied Paleozoic basement. Presumably, all major complexes of carbonate structures in KCU developed above the elevations (e.g. Kutek 1994; Matyszkiewicz 1997; Matyszkiewicz et al. 2006, 2012; Krajewski et al., 2018). Another important factor that controlled the development of facies in the Upland was extensive synsedimentary tectonics related to the activity of the Kraków-Lubliniec tectonic zone (Żaba 1999; Matyszkiewicz et al., 2006, 2012). Several horizons are observed in the sedimentary succession with probably tectonic-induced debris flow deposits and the so-called neptunian dykes filled with detritus and shells of brachiopods (Fig. 6; e.g. Matyszkiewicz 1997; Jędrys and Krajewski, 2007; Matyszkiewicz et al., 2016). Currently, some data indicates that the development of Upper Jurassic reef complexes in KCU was also influenced by hydrothermal processes occurring along the active Kraków-Lubliniec zone, which could significantly modify the sedimentary environment (for details see Matyszkiewicz et al. 2016).

Carbonate depositional systems from a seismic interpretation perspective – an overview

Seismic interpretation of carbonate deposits has always been a challenging task due to their special geological characteristics, ranging from sedimentation processes to mineralogical states (Fontaine et al., 1987; Palaz and Marfurt, 1997; for a detailed description of carbonate depositional environments see e.g. Scholle et al., 1983). Carbonates differ significantly from siliciclastics in that they are not transported (with the exception of turbidites or mass flows), but are largely organically grown, organically precipitated, or geochemically precipitated in situ. Moreover, their production has specific environmental requirements, e.g. organically grown carbonates require clear water with little or no silt contamination, appropriate water temperatures and food supply. Once formed, carbonates undergo radical and rapid diagenetic changes. Mineralogy, petrophysical properties, and mechanical behavior of carbonates result from their sedimentation and diagenesis. Diagenetically altered and organically bound carbonate rocks are capable of maintaining steep marginal slopes and wave-resistant structures. An important aspect of seismic interpretation of carbonate depositional systems is that gradual changes in relative sea level generally cause vertical geometric changes in carbonate platforms (Fontaine et al., 1987). For example, a reefal structure will exhibit significant vertical accretion to adapt to gradual relative sea level rise (Kendall and Schlager, 1981). Facies models, evolution of carbonate platforms, and stratigraphy of carbonate sequences have been extensively discussed by several authors (e.g., Read, 1985; Sarg, 1988; Handford and Loucks, 1993; Schlager, 2002; 2005).

Carbonate deposits often exhibit high seismic reflectivity, which is generally greater than the average reflectivity of clastic rocks. Because of this contrast, carbonates can be analyzed independently, and within a carbonate succession significant velocity differences associated with different lithologies can be distinguished (Fontaine et al., 1987, see for review of seismic facies of carbonate rocks). Seismic data, including the examples presented during this Field Trip, have proven to be very useful in identifying carbonate buildups because they can clearly show the differences in depositional characteristics between the buildup and the overlying strata (Bubb and Hatlelid, 1977; Słonka and Krzywiec, 2020a). It should be remembered, however, not to confuse the term "”carbonate buildup” or “seismic reef" with the sedimentological term "reef" (Badali, 2024). The term “carbonate buildup”, often used in seismic interpretation, is a very general term for all sedimentary carbonate deposits that form positive bathymetric features. Such a term is justified because seismic data as such do not readily distinguish between deposits geologically described as bioherms, reefs, banks, etc. (Bubb and Hatlelid, 1977). Returning to the basics, it is worth to recall the classical interpretation rules that were established during the intense development of seismic stratigraphy in the late 1970s. They summarize the different seismic expressions of carbonate buildups and assume several recognition criteria such as (1) mound-shaped reflection configuration pattern, (2) lateral seismic facies changes between the buildups and enveloping beds, (3) reflections from the edges of buildups including hyperbolic diffractions, (4) onlap of overlying strata, (5) drape effects over the buildups, and (6) the velocity pull-up anomalies (Fig. 7; Słonka and Krzywiec, 2020a; for more details see e.g. Bubb and Hatlelid, 1977; Veeken and Van Moerkerken, 2013; Burgess et al., 2013). Differential compaction (manifested as compaction sag in seismic data) may also indicate the presence of carbonate buildup (Słonka and Krzywiec, 2020a; 2020b).

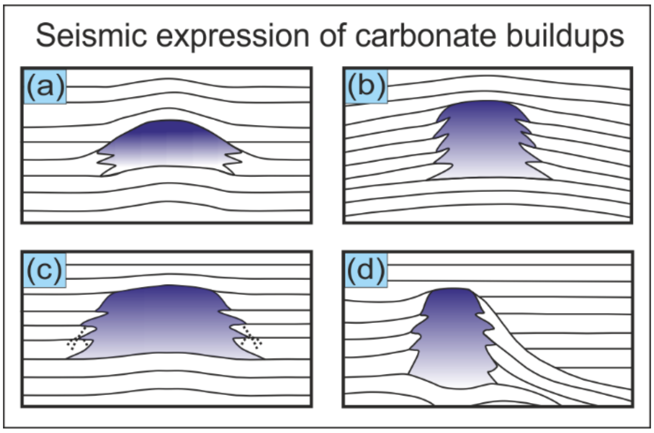


Fig. 7: Common types of seismic expression of carbonate buildups and surrounding sediments (Słonka and Krzywiec, 2020a; based on Bubb and Hatlelid, 1977; Veeken and Van Moerkerken 2013; modified). (a) velocity pull-up and differential compaction, (b) reflection-free with drape effect, (c) reflection-free with edge diffractions, and (d) compaction sag and transgressive onlap.

Over the years, the quality of seismic data has improved. It is now possible to detect various carbonate structures with greater detail and accuracy. It is worth mentioning here some of the numerous papers that have been published dealing with seismic interpretation of carbonate buildups of different ages and from different areas of the world, e.g., offshore Indonesia and Malaysia (Zampetti et al., 2004; Posamentier et al., 2010; Koša, 2015), South China Sea (Wu et al., 2009; Chang et al., 2017), Indus Basin (Shahzad et al., 2018, 2019), offshore Myanmar (Teillet et al., 2020), Philippines (Neuhaus et al., 2004; Fournier and Borgomano, 2007), Northern Australia (Van Tuyl et al., 2018, 2019), South Oman (Borgomano et al., 2004), offshore Vietnam (Fyhn et al., 2013), Northern Lebanon (Abbani et al., 2023), offshore Norway (Philips et al., 2020) or the Barents Sea (Elvebakk et al., 2002; Rafaelsen et al., 2008; Di Lucia et al., 2017). A recent paper by Badali (2024) provides an interesting summary of shallow-water carbonate systems of different ages, with dozens of representative seismic examples discussed in detail.

The seismic examples presented during the fieldtrip are mainly from the Nida Trough (S Poland) where the geological interpretation of seismic data was carried out for the study area located near the town of Pińczów, about 50 km NE of Kraków (Słonka and Krzywiec, 2020a; 2020b). In contrast to the adjacent Kraków-Częstochowa Upland the predominant part of the Nida Trough lacks Jurassic outcrops. The Upper Jurassic rocks are mostly covered by a thick Cretaceous succession and younger deposits. In areas where there are no outcrops, seismic data - calibrated by boreholes that provide information on the stratigraphy and lithology of the drilled rock complexes - have been extremely useful in studying the subsurface geology of the Upper Jurassic sediments. In particular, "seismic-scale" reefs are interesting targets for hydrocarbon exploration, because they often form oil and gas reservoirs in many parts of the world, including the Upper Jurassic examples in southern Poland (Gliniak et al., 2004; Misiarz et al., 2004; Jędrzejowska et al., 2005; Gliniak and Urbaniec, 2005). The subsurface Upper Jurassic (Oxfordian) organogenic limestones underlying the Miocene succession of the Carpathian Foredeep are known to be one of the most important reservoir rocks in this area (Myśliwiec et. al, 2006). Petroleum exploration has also focused on several carbonate buildups in the southernmost part of the Nida Trough, documented by good quality seismic and well data (Gliniak et al., 2005; Jędrzejowska et al., 2005; Urbaniec, 2019).

Other seismic examples shown during the excursion come from W Ukraine, where Jurassic carbonates in the Ukrainian Carpathian Foreland are known very well as good, but risky reservoirs. The biggest discovery related to fractured carbonates is the Rudky field discovered in 1953 and totally produced 26 Billion m3 of gas. Until nowadays the drilling efforts were accomplished based on gravity and old 2D seismic data. The dense 2D network since the 80's was proper to show smaller structures in the carbonates and revealed to smaller discoveries in Bystritsia and Vereshchytske areas. However, so far the understanding on the sedimentary environment was limited to well data. Thanks to new modern 3D seismic surveys shot during the past few years in the Ukrainian Carathian Foreland, the structural and sedimentological characteristics are getting revealed for the Mesozoic layers, including the Jurassic sequence. Geological interpretations can be significantly rectified with the new, high quality seismic imaging.

Stop descriptions

Stop 1. – Bolechowicka Valley (50°09’09’’N/19°47’06’’E; location: Fig. 8).

Facies and microfacies of the Upper Oxfordian reef complex vs. seismic characterization of the facies; problems with interpretation in the fault zone.

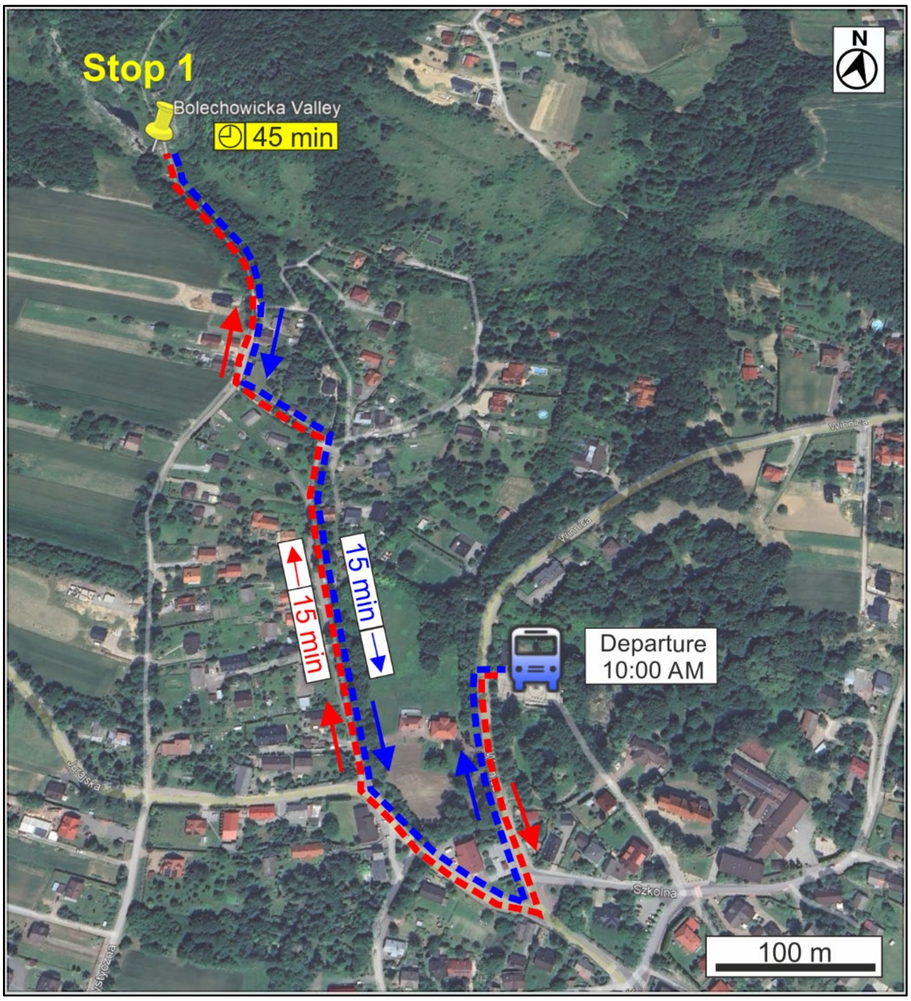


Fig. 8. Location of Stop 1 with a detailed route and estimated travel times. Satellite image map data from *Google Earth* (n.d.).

Outcrop Description

Bolechowicka Valley is located at the northern margin of the Krzeszowice Graben (Figs. 5, 9). In this area, the faults separate the so-called Ojców Block, the main part of the upland, from the Krzeszowice Graben. The exposed rocks represent a sedimentary sequence located from ~100 to 150 m above the bottom of the Oxfordian succession (Fig. 6). Numerous exposures of massive limestone were examined near Bolechowicka Valley (for details see

Matyszkiewicz and Krajewski 1996; Fig. 9). As a result, numerous microfacies were identified and classified into two groups of massive facies: microbial-sponge facies, and microbial-*Crescentiella*-grain dominated facies (Matyszkiewicz and Krajewski 1996). From a stratigraphic point of view, most of the massive facies from the Ojców Block area belong to the Upper Oxfordian Bifurcatus Zone (Fig. 6; Ziółkowski 2007; Krajewski et al., 2018). Younger, detrital and pelitic bedded limestone with marl intercalations (Figs. 6, 9), located near the edge of the Krzeszowice Graben and in the highest parts of the Bolechowice Valley, correspond to the Bimammatum Zone (Ziółkowski, 2007).

The microbial-sponge massive facies can be observed in most rocks of Bolechowicka Valley (Fig. 10a, b). Dominant are microbial-sponge boundstones and bioclastic wackestones, packstones and grainstones (Matyszkiewicz and Krajewski, 1996). Many cavities are geopetally filled, which enables us to determine the inclination of the limestone from its original positions (Fig. 9). The framework is formed mainly by calcified siliceous sponges (*Lithistida* and *Hexactinellida*) overgrown by microbialites, dominated by clotted thrombolites and peloidal stromatolites (Fig. 10b). Commonly observed are brachiopods, echinoids, peloids, tuberoids and abundant fine bioclasts. Frequent are microencrusting organisms, particularly bryozoans, benthic foraminifers (*Nubecularia*, *Bullopora*) and serpulids. In the sedimentary succession of the carbonate buildups (cf. Matyszkiewicz, 1997; Krajewski et al., 2018), up the stratigraphic sequence, the number of sponges decreases in favour of microbialites, mostly agglutinuating and peloidal stromatolites. In the upper parts of the reefs, large amounts of characteristic problematic microencruster *Crescentiella* (*Tubiphytes* in older literature) appear (Matyszkiewicz, 1997; Krajewski et al., 2018). The microencruster *Crescentiella* is interpreted as an encrustation or symbiosis between nubecularid foraminifera or as tube-like structures and cyanobacteria (for details see Senowbari-Daryan et al., 2008; Krajewski and Olchowy 2023). The microbial-*Crescentiella*-grain-dominated facies is also observed in exposures located in the southern part of the valley. Two microfacies varieties are observed: microbial-*Crescentiella* boundstones and *Crescentiella*-bioclastic-coated grain grainstones-rudstones (Fig. 10c, d). Apart from *Crescentiella,* crushed bioclasts: bivalve shells, bryozoans, calcareous sponges, gastropods and echinoderms are common in the coarse grainstones-rudstones. They are accompanied by fine bioclasts, peloids, aggregate grains, intraclasts, oncoids and ooids (Fig. 10c, d).

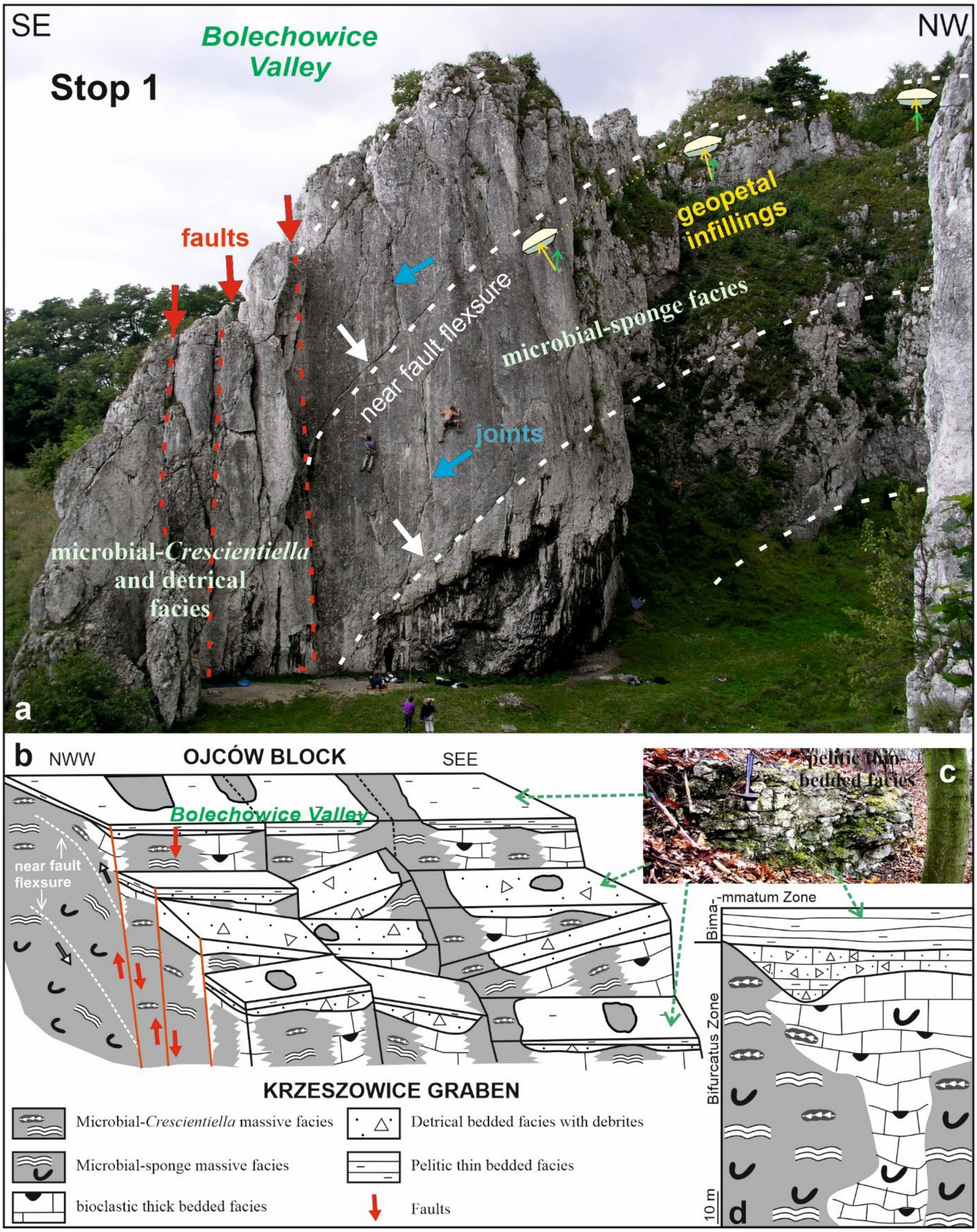


Fig. 9. Stop 1. Bolechowicka Valley. a - Southern part of Bolechowicka Valley, west slope, Filar Pokutników Rock. Filar Pokutników is located within the near-fault flexure (white line and arrows) that passes southwards into brittle deformation with faults (red lines and arrows). Vertical surfaces are joints (blue arrows). b - Position of Bolechowicka Valley in the fault zone that separates the Ojców Block from the Krzeszowice Graben (after Matyszkiewicz and Krajewski, 1996; supplemented). Near-fault flexure passes southward into discontinuous deformations. The total vertical fault's displacement consists of numerous secondary faults, some of which are hinge faults. This caused the dipping of sediments in various directions, accompanied by a fault-related megabreccia. c – pelitic thin-bedded limestone from the uppermost part of the sedimentary succession from Bolechowicka Valley. d – Upper Oxfordian sedimentary succession of the Ojców Block without fault tectonics.

Geological Interpretation

The described carbonate buildups are representative of most of the rock complexes in the Kraków-Częstochowa Upland and record the main stage of reef development in this area (e.g. Matyszkiewicz, 1997; Matyszkiewicz et al., 2012; Krajewski et al., 2018). Similar bioconstructions are widely distributed in the northern shelf of the Tethys Ocean (e.g. Leinfelder et al., 1996; Matyszkiewicz, 1997; Schmid et al., 2001). The microbial-sponge facies developed mostly in a low-energy, nutrient-rich environment. Commonly observed microencrusters, mostly benthic microbial communities, serpulids, bryozoans and foraminifers, also indicate a low-energy environment, low deposition rates and low terrigenous influx. Environmental conditions of these facies are usually interpreted as sea level high-stand mid-ramp, above storm wave base (Leinfelder et al., 1996; Krajewski et al., 2016; 2018; Krajewski and Olchowy 2023). The presence of phototrophic *Crescentiella* and detritus indicates paleodephts between normal and storm wave bases (Leinfelder et al., 1996; Matyszkiewicz, 1997; Krajewski et al., 2018). In this facies, coarse-grained sediments are common, documenting an intensive reworking of material in the wave base zone. In grain-dominated sediments, one can observe coated grains, and green algae pointing to sedimentary conditions close to normal wave base. Transition from microbial-sponge to microbial-*Crescentiella*-grain dominated facies with numerous coated grains can be related to progressive shallowing of the basin in the Upper Oxfordian.

The exposures examined in the Bolechowicka Valley are located in a tectonic zone, which hampers the observations and interpretation of primary facies architecture (Matyszkiewicz and Krajewski, 1996). The primary sedimentary sequence is here disturbed by numerous hinge faults belonging to tectonic megabreccia at the margin of the Krzeszowice Graben (Fig. 9b). Fortunately, analogous and contemporaneous sedimentary sequences can be observed in the vicinity, in undisturbed parts of the Ojców Block (e.g. Krajewski et al., 2018), which enables us to reconstruct the primary sedimentary sequences of the Bolechowice area. Based on the analysis of geopetal infillings found in the numerous growth cavities, it was concluded that rocks forming the southern part of Bolechowicka Valley were tilted from their primary position (Figs. 9b, 10a; Matyszkiewicz and Krajewski 1996). The lack of substantial differences in the lithology of rocks cut by discontinuities advocates the tectonic origin of these surfaces. The vertical discontinuities cutting through the limestones are joints belonging to several joint systems (Krokowski, 1984). In the southernmost part of the valley, these discontinuities are fault surfaces enlarged by karstic dissolution, genetically related to the broad tectonic zone that separates the Ojców Block from the Krzeszowice Graben. Some of these faults follow pre-existing joints. On the contrary, the discontinuities gently dip to the south and are genetically linked to shear surfaces in the fault-adjacent flexures developed at the northern margin of the Krzeszowice Graben (Fig. 9b; Krokowski, 1984). To sum up, complicated facies relationships found in Bolechowicka Valley are the effects of hinge faults and megabreccia zones developed in the tectonic zone separating the Ojców Block from the Krzeszowice Graben.

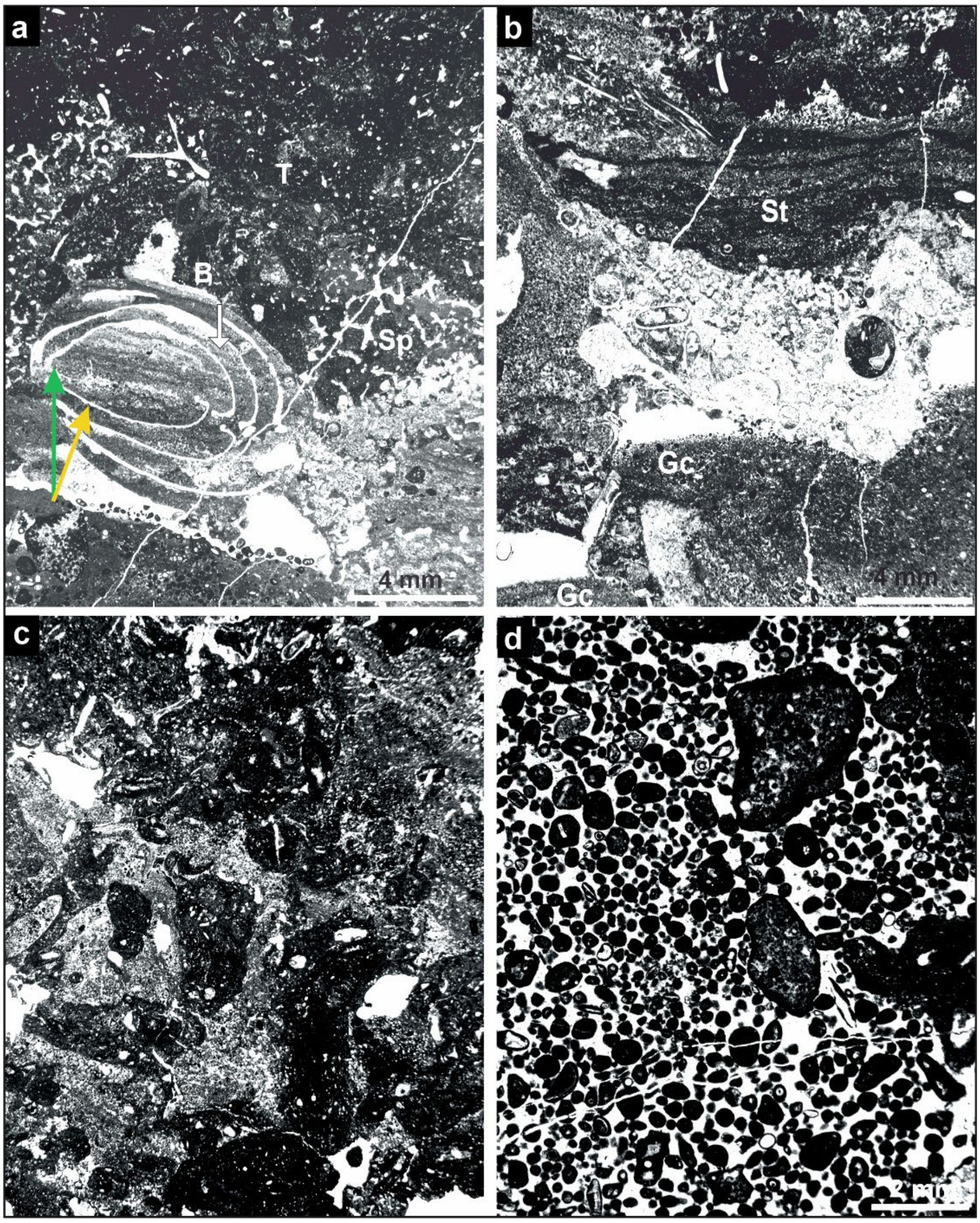


Fig. 10. Microfacies observed in massive limestones of Bolechowicka Valley. a - Microbial-sponge boundstone. Calcified siliceous sponge (Sp) displaying an extensive boring (B) with the shell of the boring organism. Thrombolites are growing on the sponge. The yellow arrow indicates the original top. The present position of the bottom-top direction is indicated by green arrow. b - Microbial-sponge boundstone. Calcified siliceous sponge (Sp), stromatolite (St) and serpulids (S). The presence of a rigid framework is documented by growth cavities with geopetal filling indicating the original position of at the top. c – *Crescentiella*-microbial boundstone. d- Grainstone with numerous *Crescentiella*, small ooids, oncoids, aggregate grains and bioclast.

A subsurface insight of the Upper Jurassic carbonates in southern Poland: seismic facies characterization

Seismic facies analysis, an essential part of seismic stratigraphic interpretation, allows the assignment of seismic reflection patterns to major depositional facies. Seismic facies analysis of the Upper Jurassic carbonate depositional system in the Nida Trough revealed four different types of reflection configurations visible in the seismic data: A) bedded, (B) mounded, (C) contorted chaotic, and (D) chaotic (Słonka and Krzywiec, 2020). The classification was based on reflection configuration, continuity of seismic reflectors, and amplitude characteristics. Identified, distinctive seismic facies are associated with the major depositional environments of the Upper Jurassic in southern Poland, as shown in Fig. 11.

Seismic facies type A is characterized by prominent parallel and highly continuous seismic reflections. This type is clearly observed on seismic data and is common throughout the subsurface interval of the Upper Jurassic strata in the Nida Trough. It was termed the bedded seismic facies (Fig. 11; see Słonka and Krzywiec, 2020a, 2020b). Within Type A, the observed reflection amplitudes are rather high, suggesting significant lithological contrasts between well-stratified deposits. Such variability could be related to the presence of high impedance limestones interbedded with marly layers characterized by much lower acoustic impedance. However, this reflection pattern was also modified by strong intra-bedded interference and seismic tuning effect caused by the seismic response of relatively thin marl-limestone alternations. Generally, seismic facies A refers to bedded limestones and marls (forming the so-called bedded facies; see Matyszkiewicz 1997) that are typical for intra-platform basinal facies. The identified seismic facies also dominate the uppermost part of the Upper Jurassic subsurface interval in the Nida Trough, represented by the J3U seismic-stratigraphic unit (Słonka and Krzywiec, 2020a). The J3U unit overlies the carbonate buildups and intra-platform basinal facies, and its seismic interpretation was related to the so-called shallow-water carbonate platform (Matyja, 2009; Wierzbowski, 2017). These deposits are associated with the inner-ramp oolitic and oncolitic facies (Krajewski et al., 2017; Olchowy et al., 2019). The Type B seismic facies is characterized by a mound-shaped reflection geometry with semi-continuous or partially discontinuous seismic reflections and high to medium reflection amplitude. Such reflection configuration pattern has been well described in literature and is often related to carbonate buildups (Veeken and Van Moerkerken, 2013). Type B is typical of the upper parts of the organic structures identified from seismic data in the Nida Trough (Fig. 11; see Słonka and Krzywiec, 2020b). Seismic facies type C is characterized as contorted to chaotic reflection geometry with medium to strong reflection amplitude. It is mainly observed within the cores of carbonate buildups. The low continuity of the seismic reflections is related to the high energy carbonate deposits that form the reefal bodies (see e.g. Veeken and Van Moerkerken, 2013). Subsequent growth of the carbonate buildup is expressed seismically by a variety of distorted and chaotic reflection patterns (Fig. 11). A frequent occurrence of seismic facies C in the cores of the buildups could be related to their rigid framework, which is characteristic of the microbial-sponge facies (Matyszkiewicz et al., 2012). The Type D seismic facies is characterized by chaotic and low amplitude seismic reflections and can be seen near the edges of carbonate buildups in the seismic data (Fig. 11). This distinctive type of reflection pattern could be associated with high-energy deposits surrounding buildups, which typically form talus that develop in front of a reef complex and contain mixed and reworked debris originating from the reef (Veeken and Van Moerkerken, 2013). The chaotic seismic facies may also be evidence of mass-gravity transport, which was common in this part of the basin at the turn of the Oxfordian and Kimmeridgian, usually forming differentiated debris-flow deposits (Matyszkiewicz et al., 2012; Barski and Mieszkowski 2014; Woźniak et al., 2018).

Seismic interpretation of faults surrounding carbonate buildups (Nida Trough examples)

The present structure of the Nida Trough is dominated by reverse faulting along the fault zones deeply rooted in the Paleozoic and older basement (Fig. 12). Some of these faults may have been active in the Late Jurassic, but their main phase of activity was associated with the Late Cretaceous-Paleogene regional inversion of the Polish Basin (e.g. Scheck-Wenderoth et al., 2008; Krzywiec et al., 2009). The Pre-Mesozoic (Precambrian to Carboniferous) rock complexes belong to the Małopolska Block (Żelaźniewicz et al., 2011), and are covered by Triassic and Middle Jurassic sediments. The seismic image of the Upper Jurassic succession shows considerable lateral thickness variations caused by variable local subsidence patterns in the Late Jurassic (Złonkiewicz, 2006) and later erosion. The Upper Jurassic interval gradually thickens towards the northeast, where the axial, most subsiding part of the Polish Basin, the Mid Polish Trough, was located. The Jurassic–Cretaceous boundary is related to a subtle angular unconformity or disconformity that truncates the Upper Jurassic strata (Fig. 12). The effect of the pre-Cenomanian erosion could be observed for the J3U seismic-stratigraphic unit (Słonka and Krzywiec, 2020a), which represents the uppermost part of the Upper Jurassic interval. Geological interpretation of seismic profile shown in Fig. 12 evidences that some of the J3U horizons form subtle truncation contacts towards the southwest.

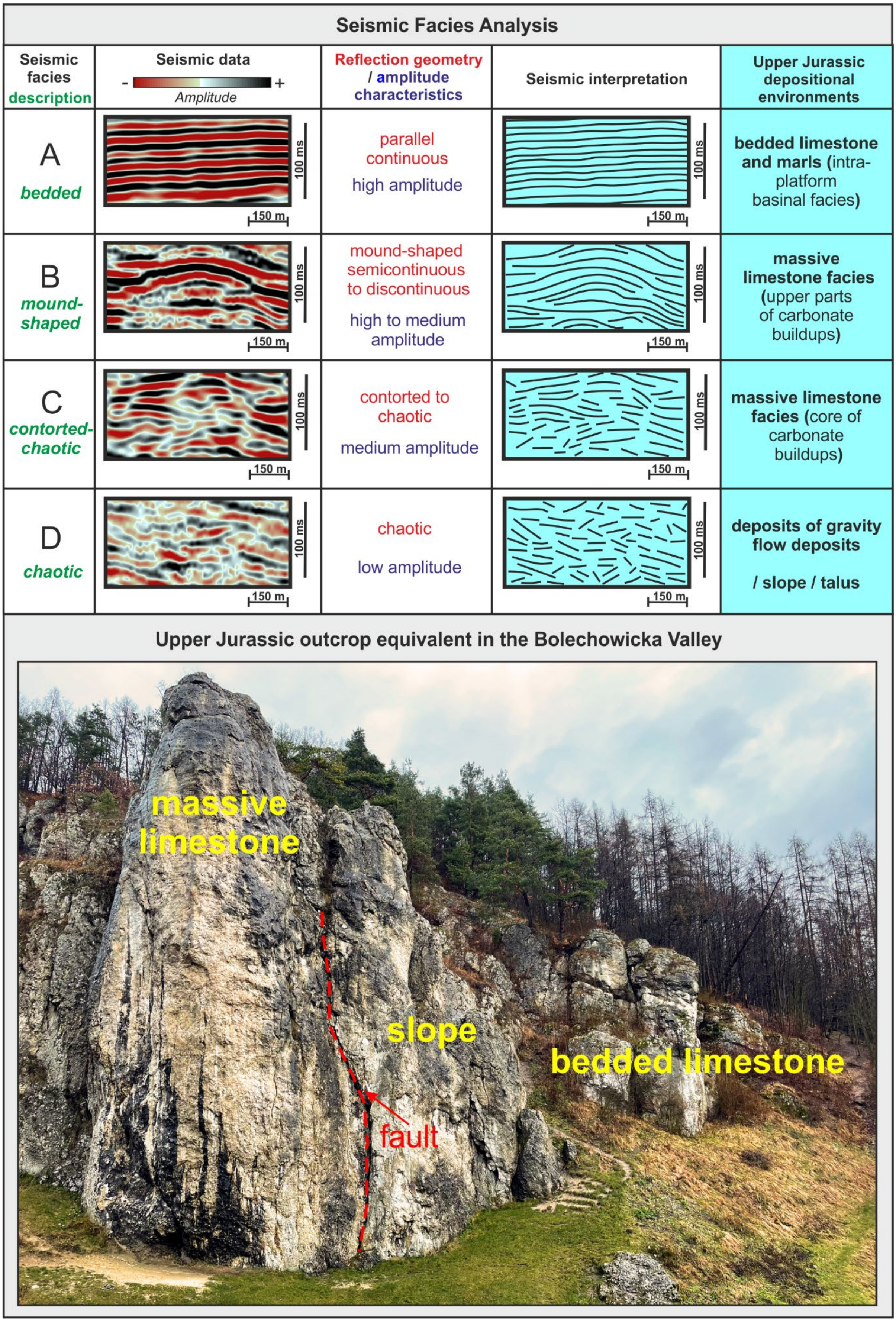


Fig. 11. Seismic facies of the Upper Jurassic subsurface carbonate deposits in the Nida Trough (Słonka and Krzywiec, 2020b) compared with the outcrop equivalents from the Bolechowicka Valley.

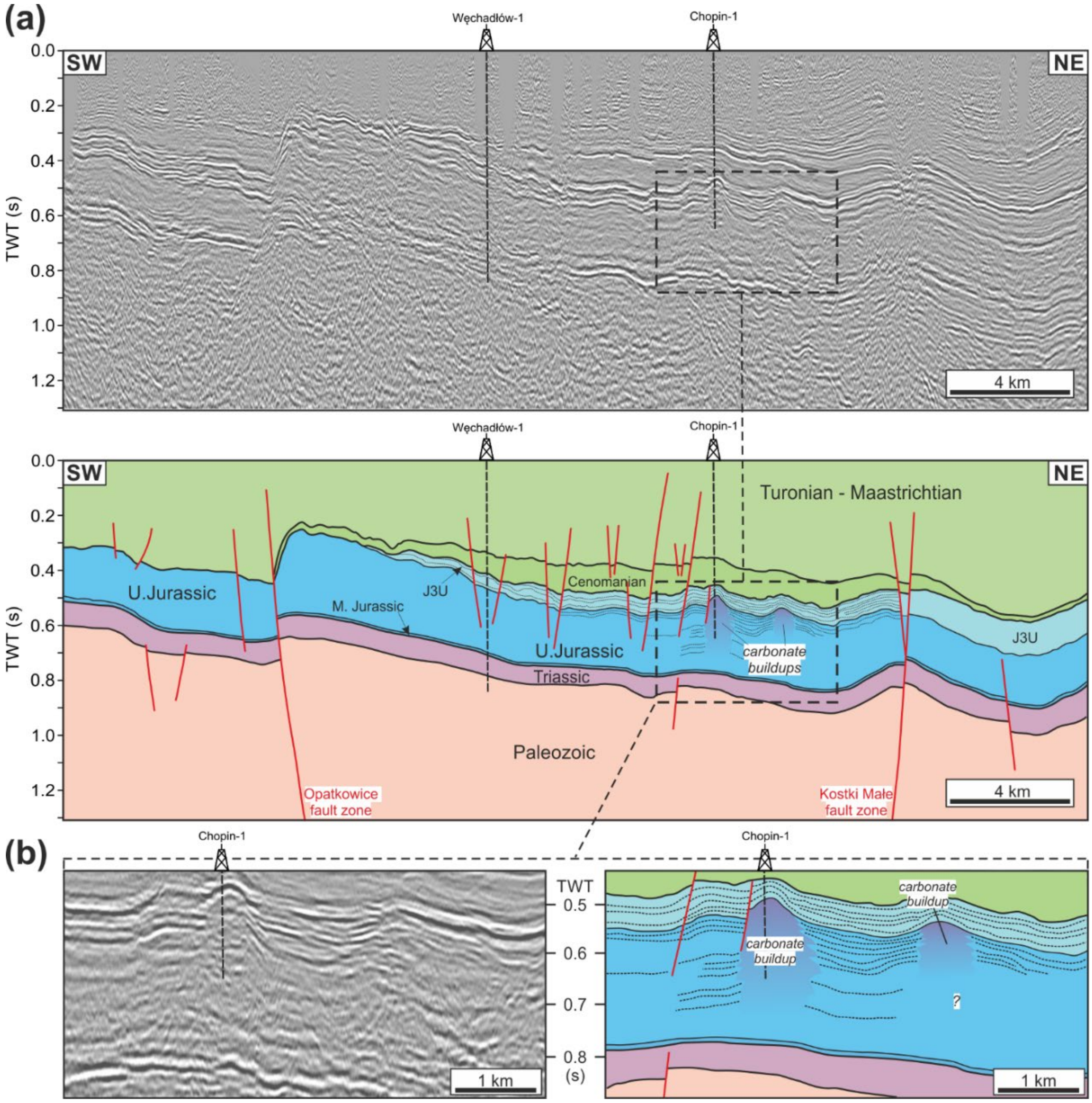


Fig. 12. Uninterpreted and interpreted seismic data from the Nida Trough (Słonka and Krzywiec, 2020a): (a) Major NW-SE fault zones are rooted in the Paleozoic basement and associated with inversion anticlines developed within the Mesozoic cover; (b) Two carbonate buildups were identified in this profile; one of them was partly drilled.

As shown in Fig. 13 seismic data can be the basis for the interpretation of several small-scale faults. Deeper faults cutting the Paleozoic-Triassic-Middle Jurassic interval may be partly related to older phases of tectonic evolution of the area. The margins of the Upper Jurassic carbonate buildups are often cut by normal faults (Fig. 13). Enlargement of the interpreted seismic image shows that carbonate buildup is bordered by the normal fault from its western side, and is also partly dissected by minor faults from its eastern side.

In the seismic interpretation shown in Fig. 13, a more detailed image was provided by the pseudo-relief seismic attribute, which indicates discontinuous reflections also outside the reefal body continuing within its slope, and further into east, towards the bedded facies. In particular, a reefal talus or slope may be cut by normal faults. This scenario is observed in the examples shown in Fig. 13, both at the outcrop and seismic scale.

Fig. 13 also shows evidence of some local syn-depositional tectonic activity as indicated by lateral thickness variations of the J3U seismic-stratigraphic interval. The greater thickness of the JU3 interval observed in the eastern part of the seismic profile may be associated with locally increased subsidence and, consequently, increased accommodation space. Such laterally variable syn-depositional subsidence may have been related to the activity of normal faults adjacent to carbonate buildups (Słonka and Krzywiec, 2020b). The formation of some of the normal faults along the margins of the carbonate buildups also resulted from differential compaction.

The role of differential compaction and its seismic image

Differential compaction and the associated compaction sag effect can be observed above all the identified carbonate buildups in the seismic data. Because these organic structures are generally represented by rigid, massive limestones, they are more resistant to compaction, while the surrounding bedded limestone facies are much more susceptible to compaction. In general, the effect of differential computation observed in the presented seismic examples is expressed by: (i) drape seismic reflections above the carbonate buildup indicating lower compaction (typical of resistant massive limestones), and (ii) compaction sag as evidence of higher compaction, typical of bedded limestones that surround the buildups.

As can be seen in Fig. 14, the seismic horizons surrounding the carbonate bulildups show characteristic compaction sag. This indicates that the rigid carbonate buildups were subjected to much less compaction than the compaction-prone, intra-platform basinal facies (see outcrop analogs of the bedded limestones shown in Fig. 14). Due to the higher compaction of the bedded limestone facies, a characteristic draping of the seismic horizons over the carbonate buildup can be observed in the example presented in Fig. 14. This seismic pattern is visible throughout the Upper Jurassic interval (blue dotted lines) and, to a lesser extent, within the lowermost part of the Upper Cretaceous strata (green dotted lines) as it is shown in Fig. 14.

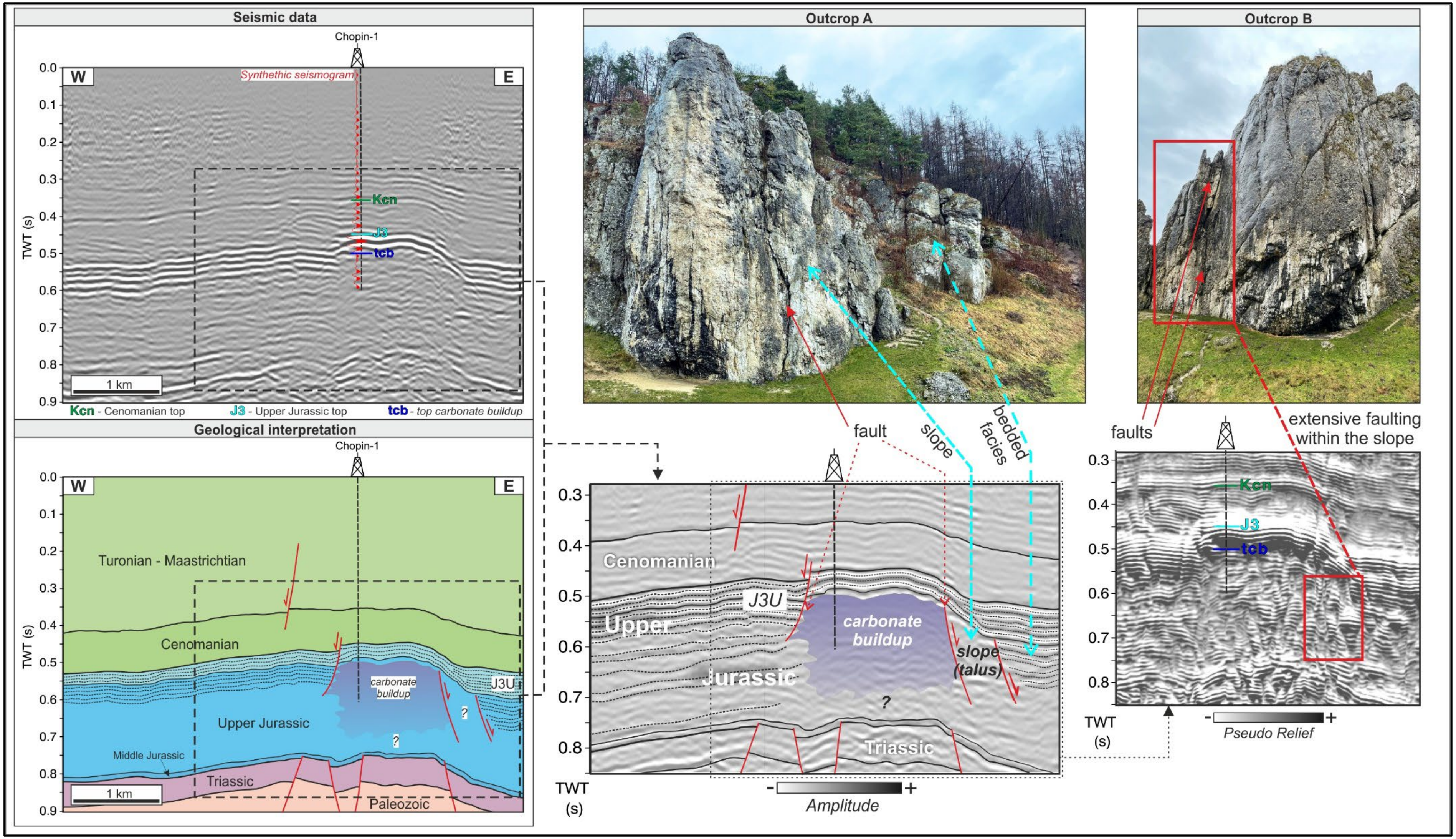


Fig. 13. Examples of seismic data interpretation (Słonka and Krzywiec, 2020a; 2020b) showing the identification of normal faults associated with carbonate buildup margins and compared with their outcrop-scale equivalents.

Laterally variable compaction within the Upper Jurassic carbonate deposits have resulted in laterally variable subsidence during the early Late Cretaceous (Słonka and Krzywiec, 2020b). This is documented by clearly divergent seismic packages within the Cenomanian succession characterized by larger thicknesses over the intra-basinal finer-grained Upper Jurassic deposits and smaller thicknesses above the rigid Upper Jurassic carbonate buildups (Fig. 14).

As noted above, differential compaction may also produce faults within the carbonate succession of laterally variable lithology (see Słonka and Krzywiec, 2020b). The seismic data shown in Fig. 14 clearly illustrate the normal faulting that has developed at the interface between the rigid carbonate accumulation and the adjacent intra-basinal stratified infill. The fault also dissects the entire Cenomanian succession and dies out within the lowermost part of the post-Cenomanian interval. Its listric geometry and dissipation within the Upper Jurassic intra-basinal facies indicate a compactional origin (Słonka and Krzywiec, 2020; see also Burgess et al., 2013).

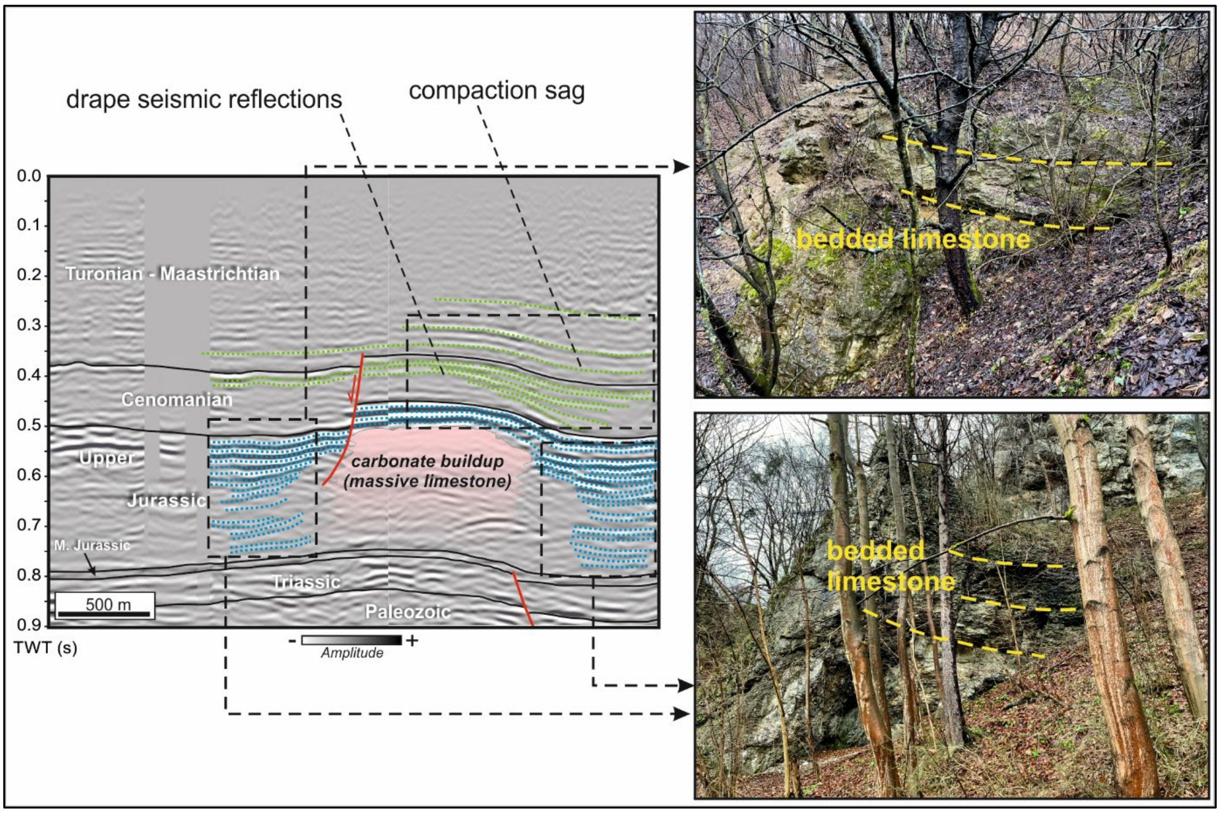


Fig. 14. Interpreted seismic profile across the carbonate buildup (Słonka and Krzywiec, 2020b). The Upper Jurassic interval shows strong compaction sag of the bedded limestone facies (blue dotted lines) surrounding the compaction resistant carbonate buildup. Effect of differential compaction can also be observed within the lower parts of the Upper Cretaceous interval (green dotted lines). The images on the right show outcrop analogs of Upper Jurassic compaction-prone bedded limestones from the Krakow-Częstochowa Upland.

Stop 2. – Czajowice Quarry (50°11’23’’N/19°48’23’’E; location: Fig. 15).

Top of the Ojców Plateau reef complex; the seismic characteristic in the transition zone from massive microbial-grain dominated agglutinating reef to thick compacted inclined bedded facies

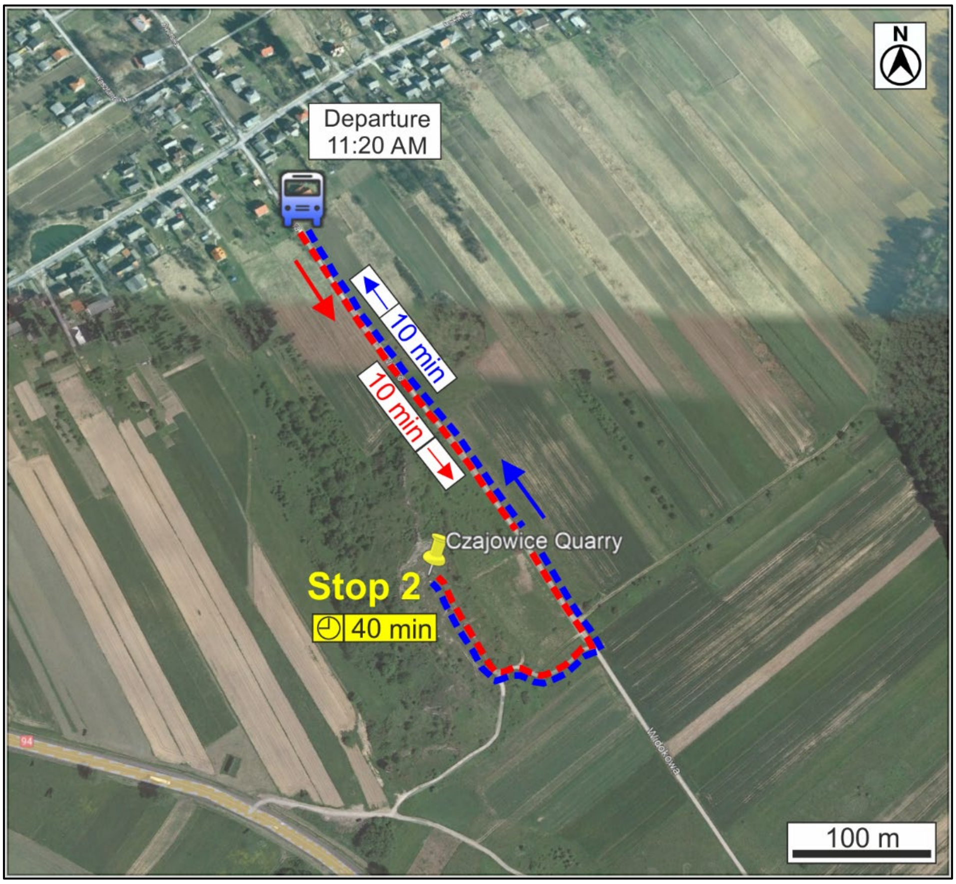


Fig. 15. Location of Stop 2 with a detailed route and estimated travel times. Satellite image map data from *Google Earth* (n.d.).

Outcrop Description

The Czajowice Quarry is located in the central part of the Ojców Plateau, the highest located area on KCU. One of the most important factors that contributed to the formation of the Ojców Plateau in this region is the dominance of erosion-resistant Upper Jurassic massive reef limestone facies (Jędrys and Krajewski 2007; Matyszkiewicz et al., 2012). This area has the most spectacular Upper Jurassic carbonate buildups encountered in the Polish sector of the northern Tethys shelf, which are exposed in the Prądnik River Valley (Ojców National Park) and in the Będkowska Valley (Fig. 16; Krajewski et al., 2018).

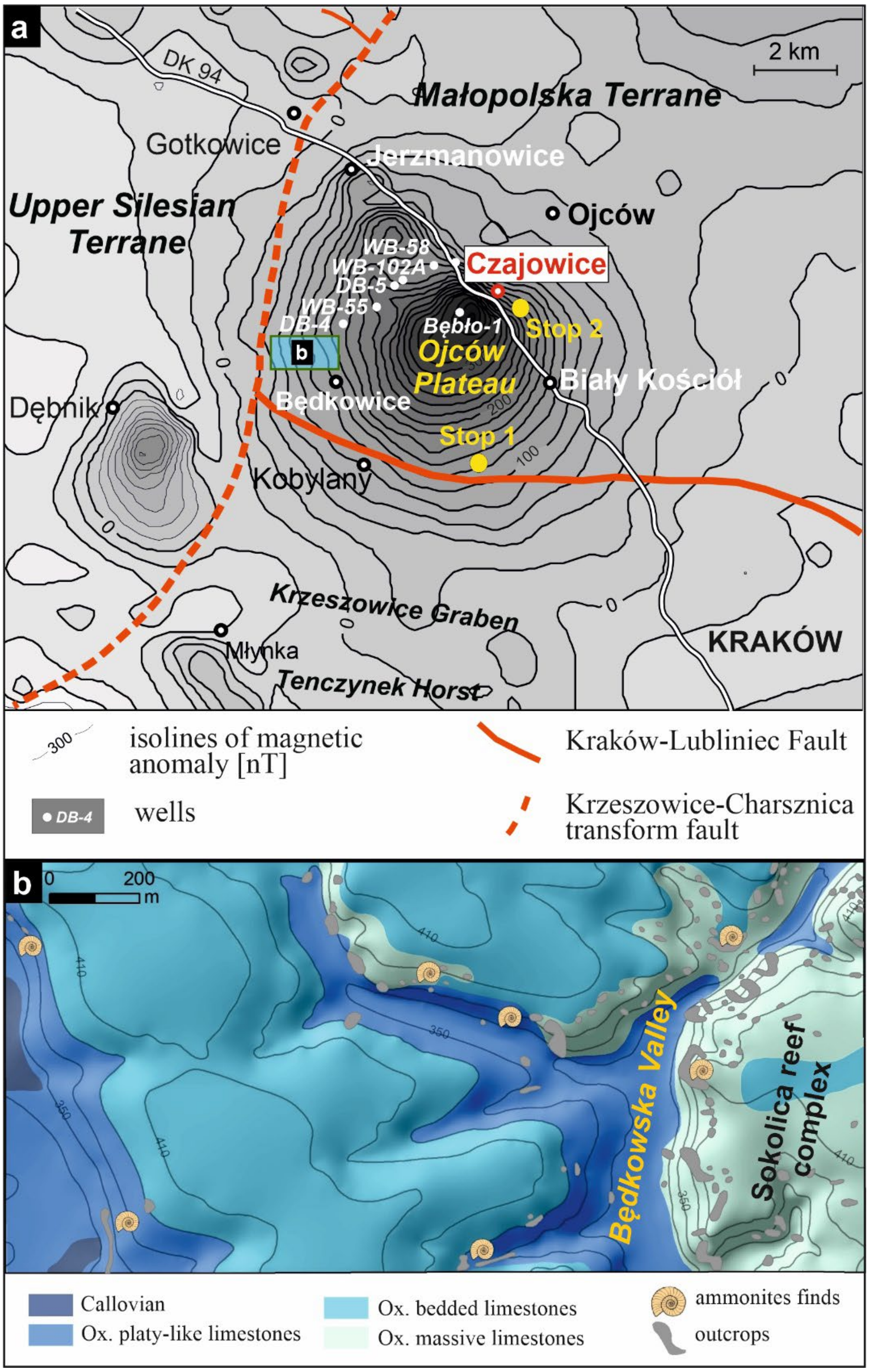


Fig. 16. Ojców Block - Location of the study area (Stop 1 and Stop 2). a - location of the Ojców Plateau on the DT magnetic anomaly map (modified after Jędrys and Krajewski, 2007) and the main tectonic structures after Żelaźniewicz et al. (2011); blue rectangle indicates area shown on Fig. 1b; b – map of the Oxfordian facies with presented reef examples from Będkowska Valley; after Krajewski et al., (2018); see Fig. 20 for seismic equivalent.

The Czajowice quarry (Fig. 17a, b) is located in the transition zone between the bedded and massive reef limestone facies. The sedimentary succession represents the final phase of the main Oxfordian stage of development of carbonate buildups at KCU (Fig. 6). The western part of the quarry is made of hard massive limestone which turns into bedded limestone towards the south and east. Biostratigraphic data (Ziółkowski 2007) indicate that the massive limestone represents the Upper Oxfordian Bifurcatus Zone (Fig. 6). The younger bedded limestone and marly limestone facies described in this area represent the Bimmamatum Zone (Ziółkowski 2007).

In the massive limestone facies, mainly microbial-sponge boundstones are observed. The main rock components are agglutinating and peloidal stromatolites (Jędrys and Krajewski 2007; Matyszkiewicz et al., 2012). Less frequently, layered and clotted thrombolites and dish-shaped calcified siliceous sponges (mainly Hexactinellida) are observed. Bryozoa and brachiopods, microencrusters *Crescentiella* and serpulids are common. Growth cavities and detrital sediments stabilized by microbialites are commonly observed in the sediment (Fig. 17c, d, 18a). The numerous non-skeletal grains include bioclasts, oncoids, ooids and intraclasts (Fig. 18b). Additionally, microbial-*Crescentiella*-grain-dominated limestone facies was observed with a relatively small amount of metazoans. This facies type commonly includes microbialites, bioclasts and coated grains (oncoids, ooids, aggregate grains) that were stabilized by microbial mats. The trapping and bounding of grains was an important process of the bioconstruction accretion.

The bedded limestone facies can be observed in the southern part of the quarry where they show lateral variability in microfacies types. In the transitional zone between massive and bedded limestone, there are mainly detrital sediments constituting the reef talus. These are mainly bioclastic-intraclastic-coated grain packstone-grainstone-rudstone. Towards depression, grain-supported deposits gradually turn into mud-supported bioclastic wackestone. In the transitional zone, the beds are inclined (Fig. 17a, b), which is mainly the result of differences in compaction between massive and bedded facies (e.g. Matyszkiewicz 1999; Kochman and Matyszkiewicz 2013). In the basins between individual reefs, the bedded limestones lie horizontally. According to Kochman and Matyszkiewicz (2013), the amount of mechanical compaction in massive reef limestone at KCU was ~ 0% due to the so-called existence of a rigid framework, while in the proximal parts of the slopes of carbonate buildups, it reached ~ 27% (for details regarding KCU examples see Matyszkiewicz 1999; Kochman and Matyszkiewicz 2013).

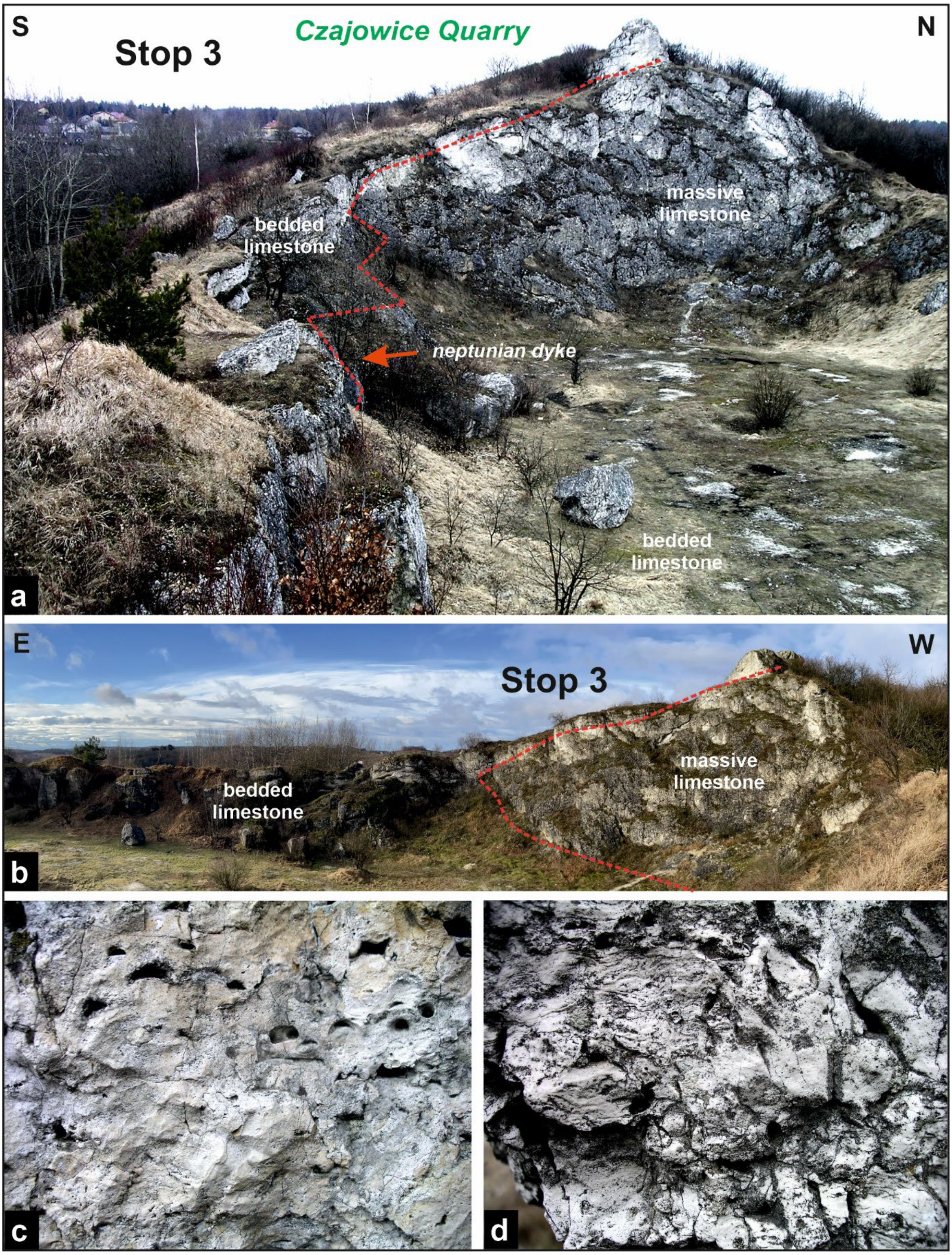


Fig. 17. Limestone facies from Czajowice Quarry. a, b – General view of the quarry. In the western part massive microbial-sponge carbonate buildup; in the southern part detrital bedded limestone; the red arrow indicates neptunian dykes in the transitional zone between massive and bedded facies. c – microbial-grain dominated boundstone with numerous growth and stromatactis-like cavities. d – example of the stromatolite visible in the massive limestone.

In the southern part of the quarry, a fragment of the so-called neptunian dyke is observed (Fig. 18c). The neptunain dyke is filled with bioclastic-intraclastic rudstone, floatstone, grainstone sediments and brachiopod shells (Fig. 18c-f; for details see Matyszkiewicz et al., 2016). The neptunian dykes are filled by Oxfordian sediments derived from the erosion of massive limestones. The dykes fill fissures that have opened synsedimentary in the massive limestones due to local extension of the basin along the Kraków Lubliniec Fault Zone, reactivating along older Paleozoic structural directions (e.g. Matyszkiewicz 1997; Jędrys and Krajewski 2007; Matyszkiewicz et al., 2016; Brachaniec et al., 2018).

Geological Interpretation

The quarry sedimentary succession observed in Czajowice represents the upper part of the reef complex (Fig. 16; Ojców Reef Complex). In most cases, the massive limestone facies represent microbial-sponge open-frame reefs and Agglutinated Microbial Reefs (*sensu* Riding 2002; for details see Matyszkiewicz et al., 2012). The reef complex is located on an elevation formed on the intrusion as a result of local differences in subsidence between the Permian batholith intrusion and the surrounding Paleozoic sedimentary deposits (Żaba 1999; Buła 2000; Markowiak et al., 2019). The batholith represent one of several similar structures developed on the edge of the Małopolska and Upper Silesian terranes along the Kraków-Lubliniec Fault Zone (Fig. 16; Żaba 1999; Buła 2000). The presence of a batholith was confirmed by drilling and by an extensive magnetic anomaly (Fig. 16a). The presence of this anomaly is associated with polymetallic mineralization around the intrusion (e.g., Bednarek et al., 1985; Harańczyk et al., 1995; Buła 2002; Markowiak et al., 2019). In the Late Jurassic, there was intense aggradational growth of the numerous reefs at the sea bottom elevation, which in the subsequent stages, due to progradation evolution, created the vast Ojców Reef Complex. The elevated position of this sedimentary area was additionally accentuated due to synsedimentary tectonics, as indicated by the presence in this area of neptunian dykes as well as debris flow sediments developed along fault zones (Matyszkiewicz 1997; Jędrys and Krajewski 2007; Ziółkowski 2007; Matyszkiewicz et al., 2012, 2016).

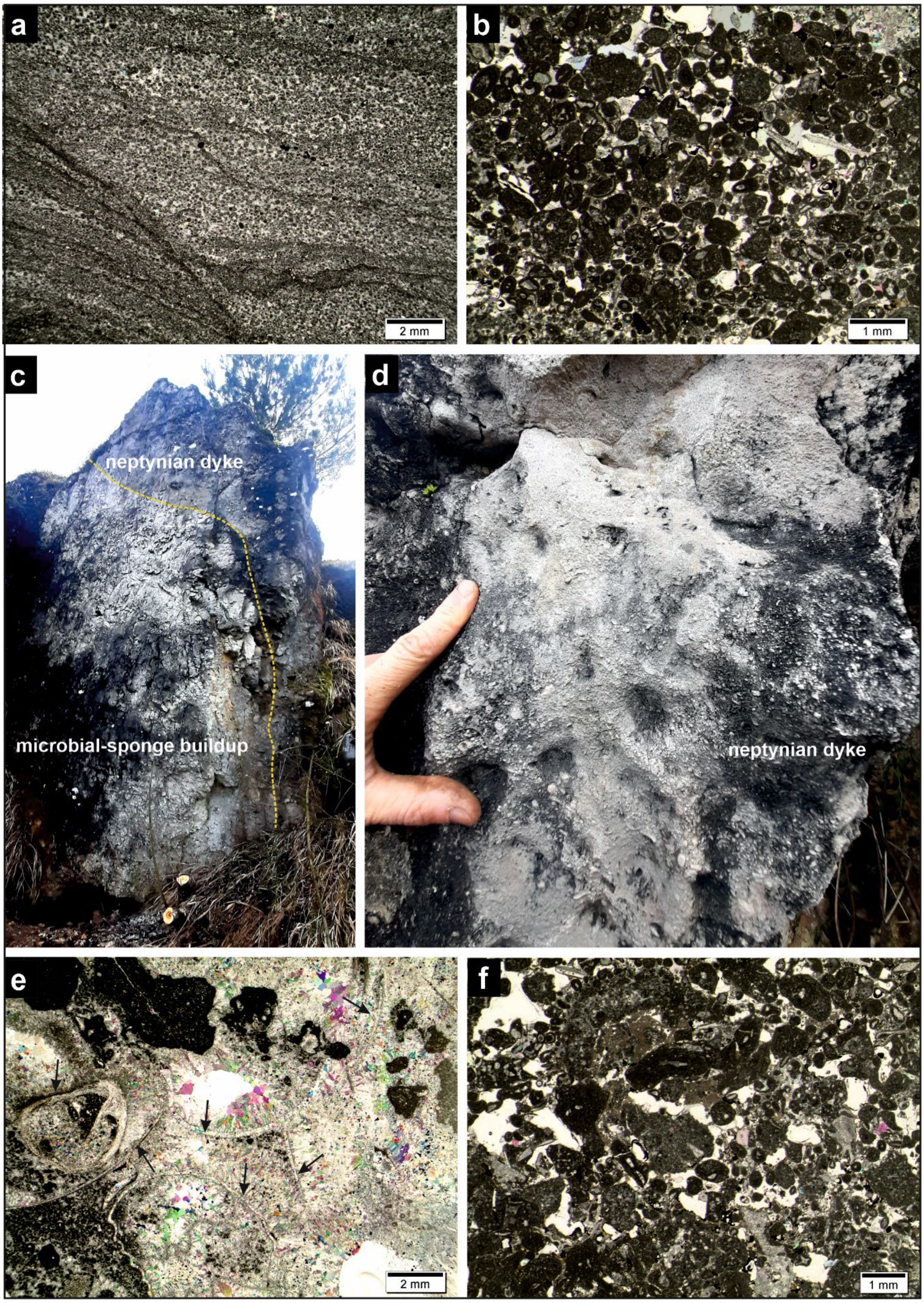


Fig. 18. Microfacies observed in limestones of Czajowice Quarry. a – microbial boundstone with well visible two generations of peloidal stromatolites. b – coated grain grainstone with small ooids, aggregate grains and oncoids. c- neptunian dyke; d- rudstone/grainstone sediment infilling neptunian dyke; e– brachiopod shells observed in neptunian dykes; f – grainstone-rudstone filling neptunian dyke with numerous coated grains, intraclasts and bioclasts.

Lateral seismic facies changes from massive to bedded facies

The seismic examples shown in Fig. 19 represent common types of seismic expression of carbonate buildups (see Fig. 7) that were discussed in the Introduction. The Upper Jurassic subsurface structures from the Nida Trough show significant positive relief and a mound-shaped reflection pattern. Characteristic "depositional wings" associated with the edges of the buildup and the drape effect over the structure can also be seen. Lateral seismic facies changes are clearly visible in the seismic data. Mound-shaped seismic facies that represent carbonate buildups laterally pass into the parallel and continuous seismic reflections related to bedded carbonate deposits (Słonka and Krzywiec, 2020a). This is an illustration of the transition from massive to bedded facies observed in the outcrop examples presented in Stop 2. The only difference is the scale between the seismic data and these outcrop analogs (Fig. 19). To get a better idea of the scale comparison and to find good visual proportions, it is necessary to present another field example from the neighbouring Sokolica Reef Complex, shown in Fig. 20. Sokolica Reef Complex, located in the Będkowska Valley, is an ideal example of 'seismic-scale' carbonate buildup that can be observed in the field. This outcrop also has its great seismic equivalent found in the subsurface Upper Jurassic succession in Nida Trough. The similarity between them is not only in scale, but also in geometry, as can be seen in Fig. 20. The lateral seismic facies changes between the massive- and the bedded facies mentioned above can also be clearly seen in the seismic example presented here. It should be noted that the adjacent bedded facies is not present in the Sokolica reef field example. This is due to later erosion, leaving only the resistant massive limestones, which formed the carbonate buildup.

Seismic attributes can enhance the subsurface image compared to standard amplitude data, as shown in Fig. 19, and then improve the geological interpretation. The bedded seismic facies show very high continuity in the instantaneous phase attribute. The carbonate buildups, on the other hand, showed a distorted image of the instantaneous phase. Because the instantaneous phase attribute highlights the continuity of seismic reflections, it provides a better distinction between bedded limestones and massive limestones. The pseudo-relief attribute revealed more reflections within the reefal body and much better accentuated its contours compared to the original amplitude seismic data (Słonka and Krzywiec, 2020b). Tiny and distorted seismic reflections observed in the pseudo-relief attribute image allow detection of the high-energy sedimentary environment characteristic of reefs, as well as mapping the edges (depositional wings) of the structure (Fig. 19).

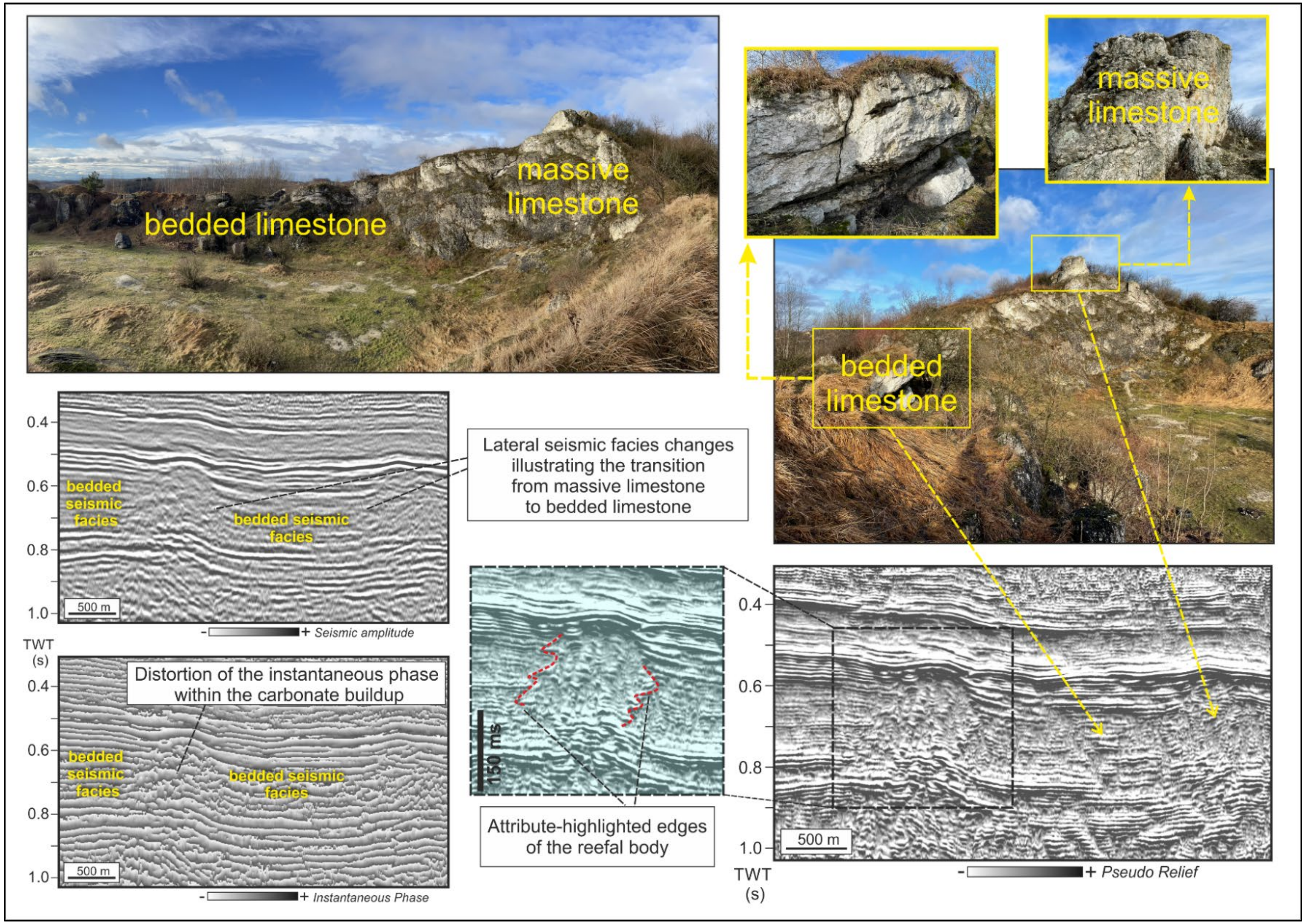


Fig. 19. Lateral seismic facies changes identified from different types of seismic data (standard amplitude versus attributes) showing the Upper Jurassic carbonate succession in the Nida Trough (Słonka and Krzywiec, 2020b). The seismic examples are compared with their outcrop equivalents from the Czajowice Quarry (Stop 2).

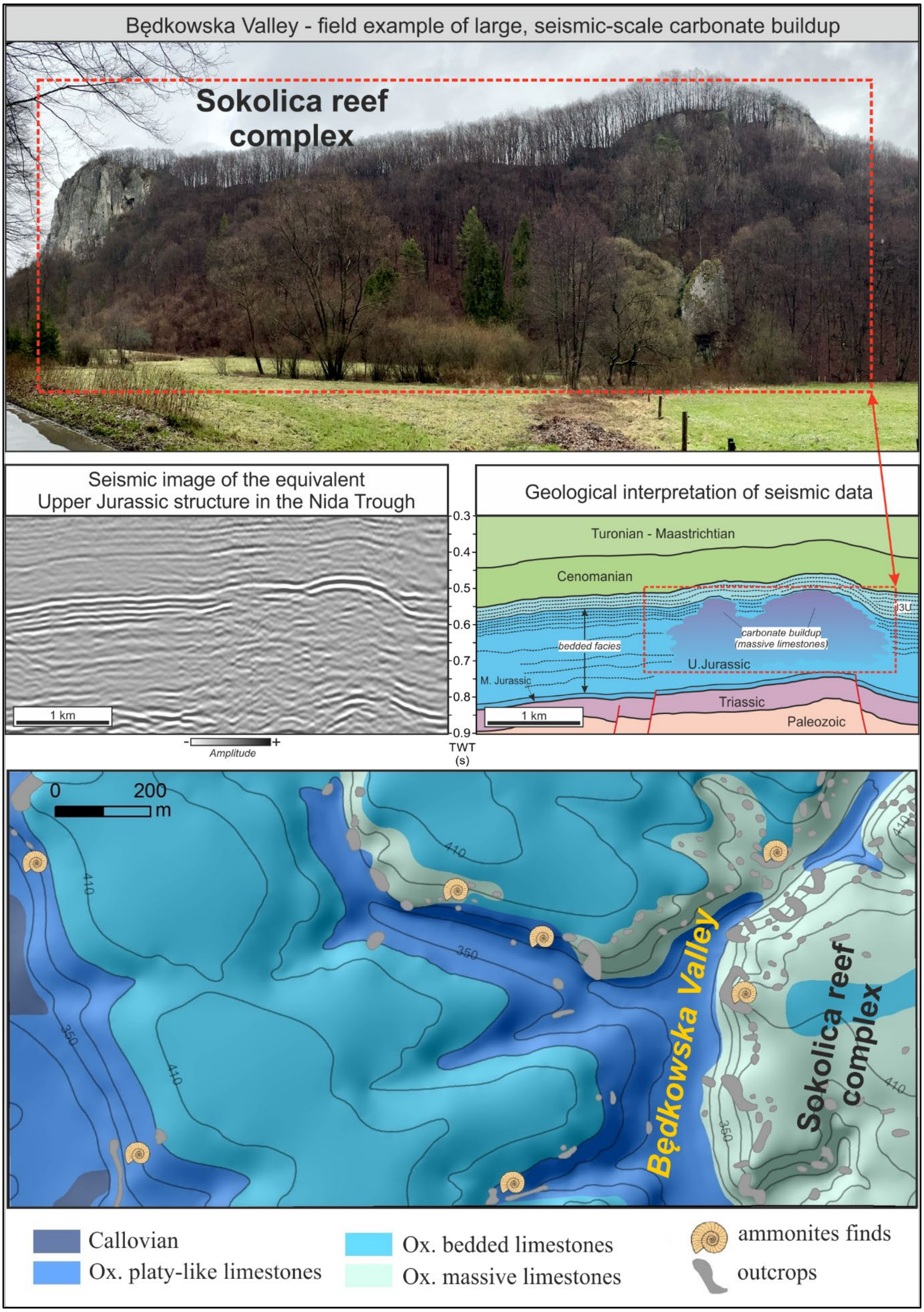


Fig. 20. Large, seismic-scale carbonate buildup complex of Sokolica Hill (Będkowska Valley; after Krajewski et al., 2018) and the corresponding seismic data equivalent of similar Upper Jurassic complex in the Nida Trough (uninterpreted seismic image and its geological interpretation; Słonka and Krzywiec, 2020a).

Seismic image of the carbonate platform in S Poland versus examples from W Ukraine

The depositional architecture of the Upper Jurassic carbonate succession in the Nida Trough resembles a carbonate system observed in the Krakow-Częstochowa Upland (Słonka and Krzywiec, 2020a; 2020b). Seismic interpretation shows that the subsurface Upper Jurassic interval is characterized by the presence of carbonate buildup complexes surrounded by diverse bedded facies (Słonka and Krzywiec, 2020a, 2020b; for comparison see Dżułyński, 1952; Matyja and Wierzbowski, 2004; Matyszkiewicz et al., 2012; Krajewski et al., 2018). Similar to the exposed Upper Jurassic succession in the KCU, the subsurface interval in the Nida Trough is characterized by strong local vertical and lateral thicknesses and facies variability (Słonka and Krzywiec, 2020a; 2020b).

The seismic example presented in Fig. 21 clearly shows the depositional architecture of the subsurface Upper Jurassic succession in the Nida Trough, which is in a "seismic scale" equivalent to the system observed in the outcrops of the KCU. Mound-shaped seismic facies representing carbonate buildups laterally pass into the parallel and continuous seismic reflections of bedded carbonate deposits representing intra-buildup sub-basins (Słonka and Krzywiec, 2020a; 2020b), which are associated with various intra-platform basinal facies described in detail from the surface deposits (Matyszkiewicz et al., 2012; Krajewski et al., 2018).

As mentioned above, the Polish part of the Upper Jurassic carbonate platform is commonly classified as a ramp-type (*sensu* Burchette and Wright 1992) carbonate platform (e.g., Gutowski et al., 2005; Krajewski et al., 2011, 2016, 2017; Olchowy et al., 2019; Olchowy and Krajewski 2020) or open shelf (e.g., Matyja et al., 1989), whereas the presented Ukrainian examples of Upper Jurassic reefs represent a rimmed carbonate platform (e.g. Krajewski et al., 2020; see Fig. 22 –map).

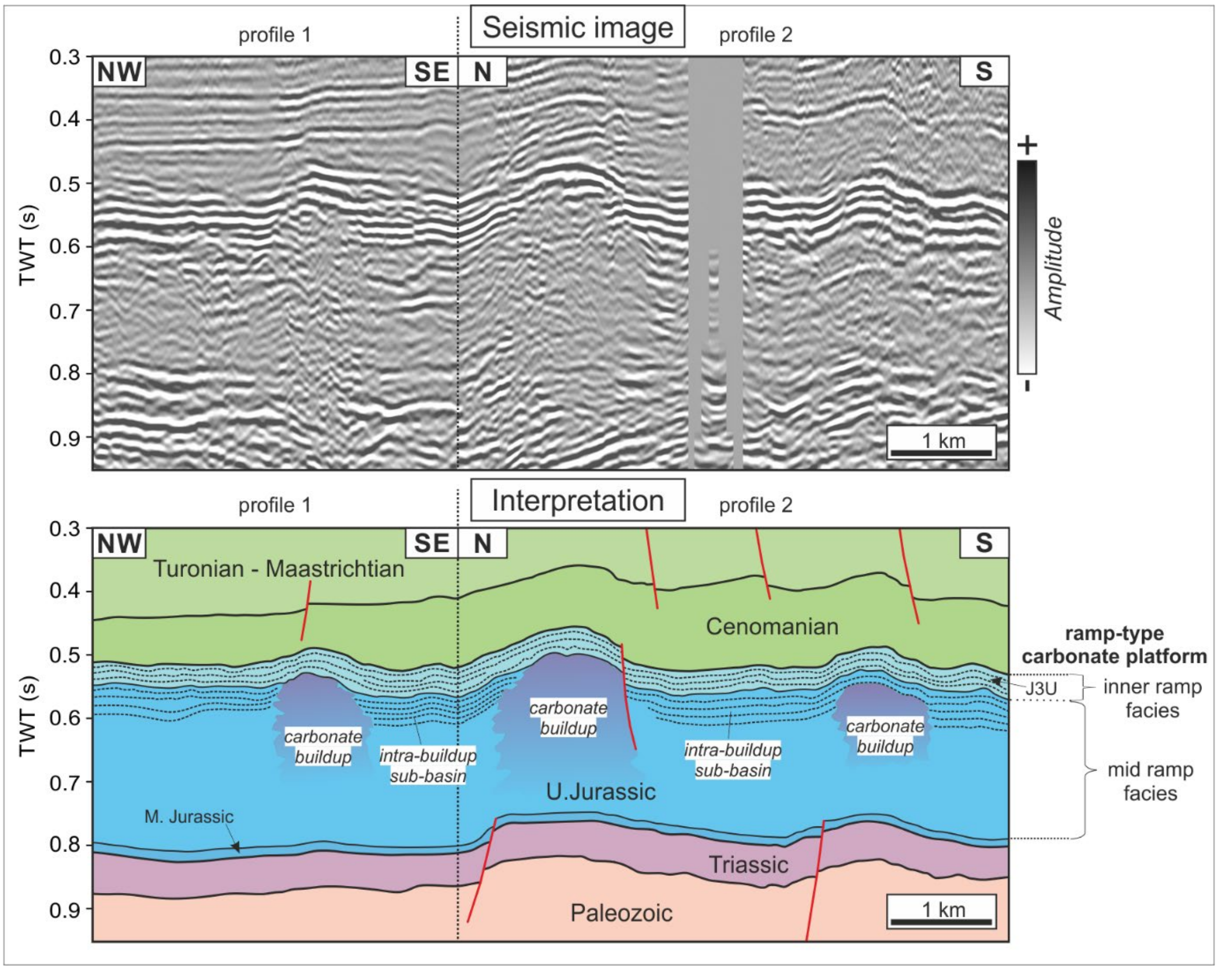


Fig. 21. Uninterpreted and interpreted seismic transect with distinctive elements of depositional architecture of the Upper Jurassic ramp-type carbonate platform in the Nida Trough: 1) large carbonate buildups represented mid-ramp facies, 2) intra-buildup sub-basins, represented by mid-ramp bedded facies, and iii) inner-ramp facies of J3U seismic-stratigraphic unit (Słonka and Krzywiec, 2020a).

Seismic data examples from Western Ukraine are shown in Fig. 23 and Fig 24. Mesozoic is covered with limited thickness (1-40m) Carpathian siliciclastics and the Badenian gypsum-anhydrite (10-50m), which later is the strongest marker level on every seismic line, whether it is old or new. In the Jurassic two sequences can be distinguished, the Upper Jurassic with dim seismic image and weak reflectors, while the underlying Middle Jurassic has a strong reflector package. The difference is due to the lithology. Recent modern drilling penetrated homogenous carbonate in the Upper Jurassic and heterogenous carbonate intercalated with organic rich shale layers in the Middle Jurassic.

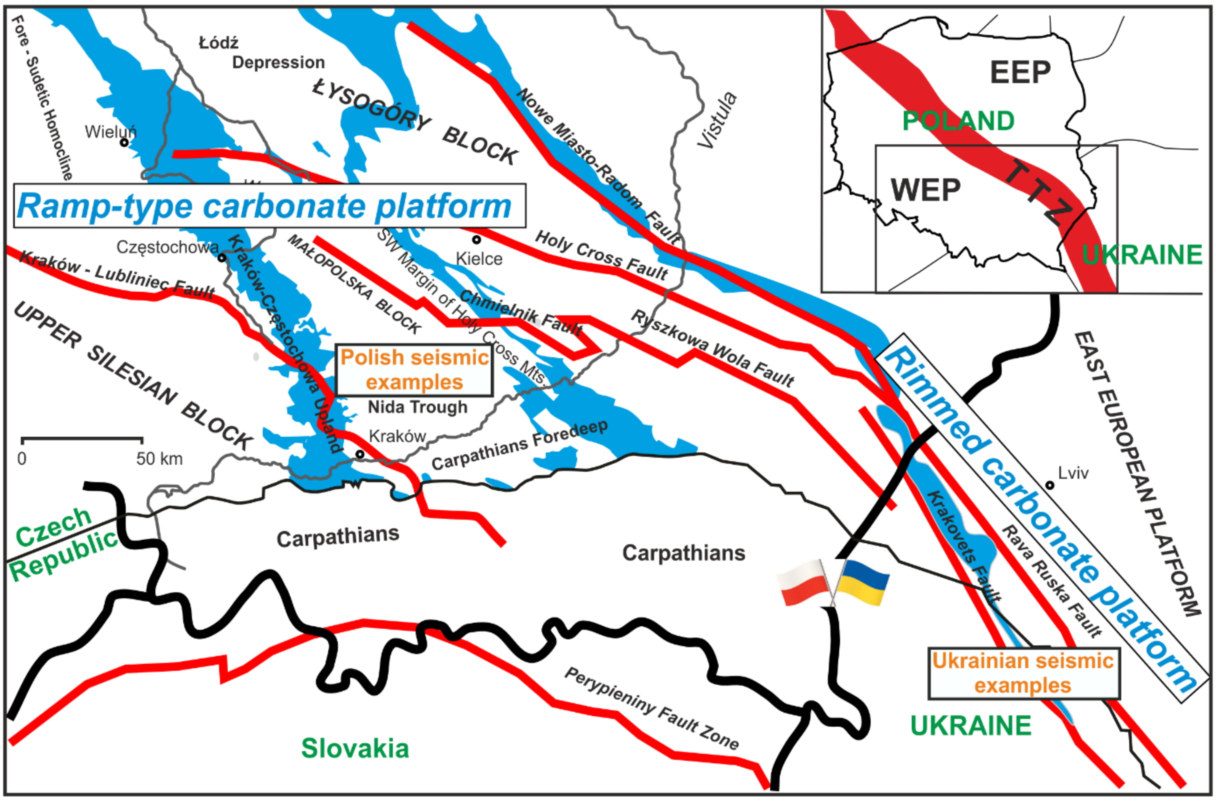
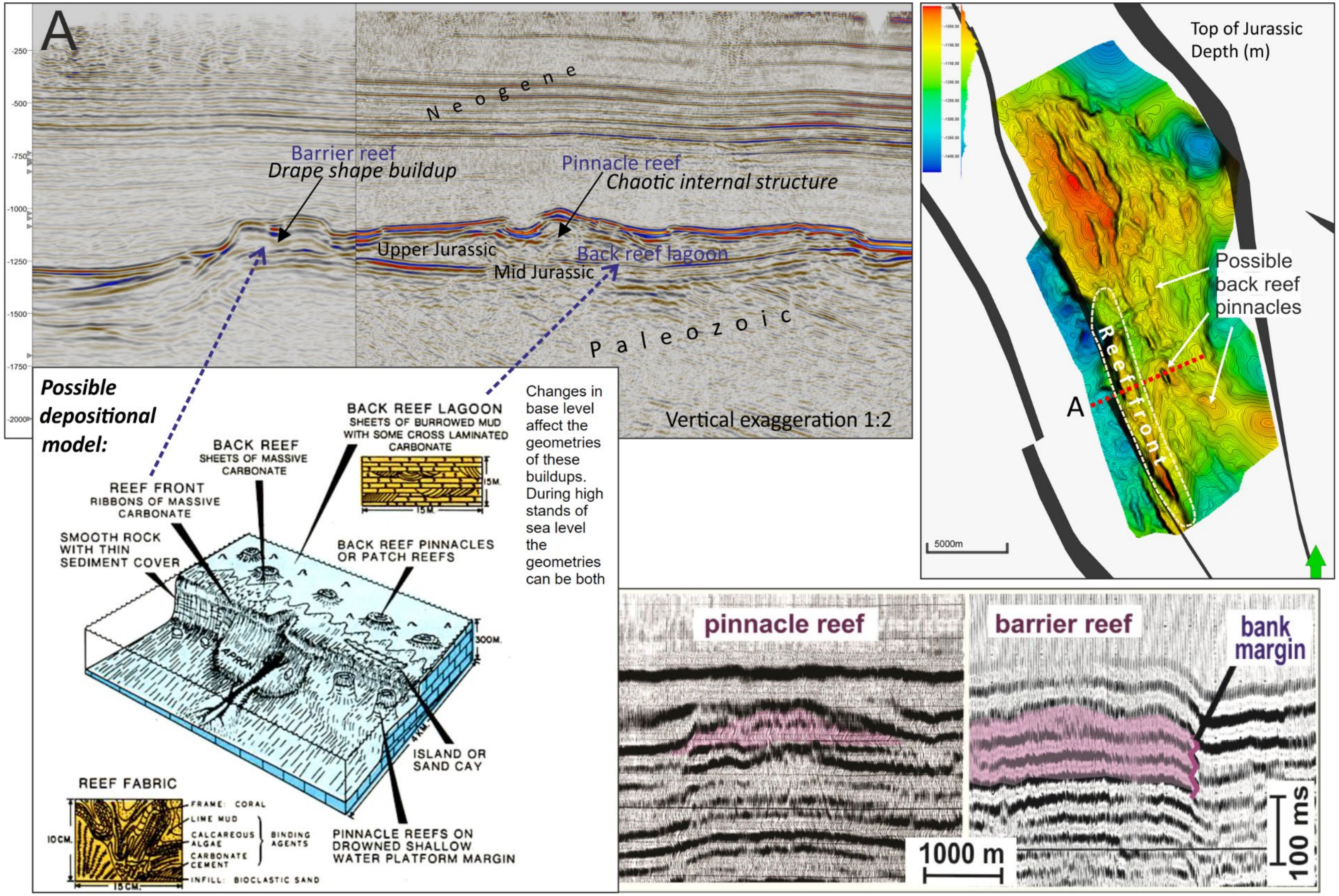


Fig. 22. Location map of the study areas with Upper Jurassic outcrops and sub-Cenozoic Jurassic subcrops (blue) in southern and central Poland and western Ukraine (after M. Krajewski). Tectonic regional subdivision of the south-eastern part of Poland and western Ukraine at the sub-Mesozoic palaeosurface after Buła and Habryn (2011); modified. The Upper Jurassic (Oxfordian-Kimmeridgian) extensive depositional system in southern and central Poland represents a ramp-type carbonate platform (e.g. Olchowy et al., 2019). The Upper Jurassic (Oxfordian-Kimmeridgian) narrow depositional system in western Ukraine represents a rimmed carbonate platform (e.g. Krajewski et al., 2020).

On the modern seismic data differential erosion of the Upper Jurassic can be recognized where the gypsum-anhydrite is covering it. Seismic images showing two possible types of carbonate build ups, barrier reefs and pinnacle reefs. Barrier reefs have horizontally layered internal structure, while the pinnacle reef facies is chaotic. Massive tight carbonates are drilled in the barrier reef. The presence of them can explain the visible image of the differential erosion, around the buildups the carbonate debris could have eroded more intensely. A more detailed work on the carbonates is presented on the poster of Csizmeg et al (2024) during the conference.

The locations of the barrier reefs are strongly correlating with the major tectonic boundaries, faults. These faults probably reactivated multiple times since the Mesozoic. During the conference Sralla and Csizmeg (2024) presenting the relationship of the tectonic and Mesozoic thickness variations in the Foreland Basin including a possible interpretation of the major regional fault reactivations.



http://www.sepmstrata.org/page.aspx?pageid=90

Lavoie et al. 2013

Figure 77: Seismic profiles illustrating mounded features interpreted as Devonian (Williams Island Formation) pinnacle and barrier reefs.

Fig. 23. Example of seismic section from the Ukrainian Carpathian Foreland Basin crossing the two types of Upper Jurassic carbonate buildups and its geological interpretation

(see Csizmeg et al 2024; Sralla and Csizmeg 2024)

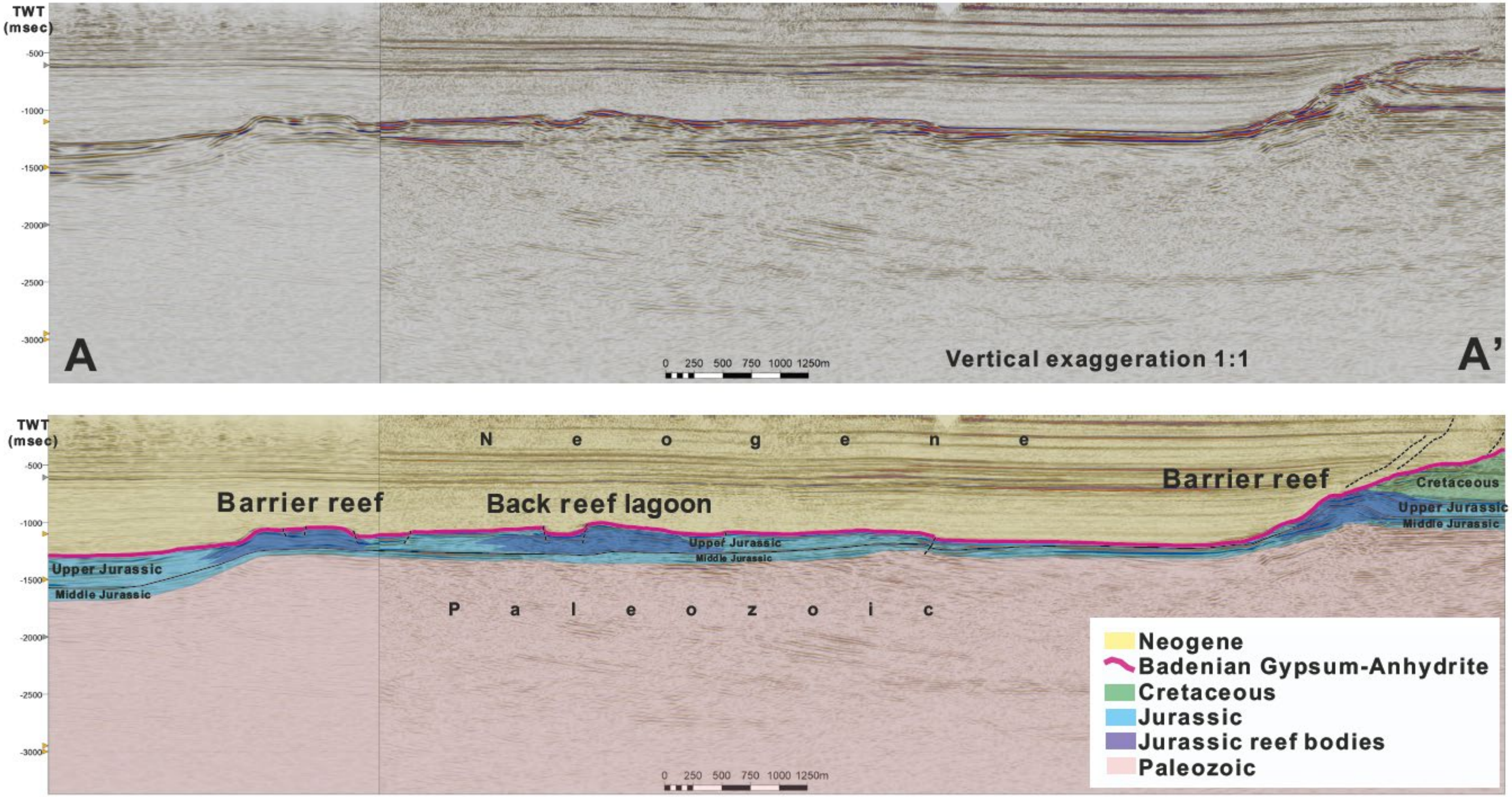


Fig. 24. Uninterpreted and interpreted seismic section from the Ukrainian Carpathian Foreland Basin crossing the Upper Jurassic carbonate depositional system (see Csizmeg et al 2024; Sralla and Csizmeg 2024).

Stop 3. – Kromołowiec Hill-view point (50°23’58’’N/19°26’06’’E; location: Fig. 25).

Isolated Niegowonice-Grabowa microbial-sponge and microbial-grain dominated reef complex and surrounding pelitic basinal facies; the problem of lateral and verical extend of the large seismic interpreted carbonate buildups.

Fig. 25. Location of Stop 3 with a detailed route and estimated travel times. Satellite image map data from *Google Earth* (n.d.).

Outcrop Description

The Kromołowiec Hill is situated in the central part of Kraków-Częstochowa Upland (Fig. 4), and represents the marginal part of the tectonic Niegowonice-Grabowa Block, which is the western part of the Smoleń-Niegowonice Range (Irmiński, 1995; Matyszkiewicz et al., 2006). Oxfordian sedimentary succession in the Kromołowiec area attains a thickness of 80 m (Irmiński, 1995). The sedimentary succession begins with Lower-Middle Oxfordian thin-bedded marls, marly limestones, and medium pelitic-bioclastic bedded limestones with sponges which can be observed in the nearby Niegowonice Quarry (Irmiński, 1995; Głowniak, 2006). Stratigraphically upwards, these sediments grade into the Upper Oxfordian (Matyja and Wierzbowski, 1992) bedded and massive limestone facies.

In the outcrops located on Kromołowiec Hill, a transition zone is observed between the massive limestone facies forming the Niegowoniece-Grabowa Reef Complex and the basinal bedded facies, filling the inta-platform basin (Figs. 26a, 27b). The transitional facies is observed between a small quarry on the northern margin of the hill where bedded facies are noted, and the central part of the hill built by massive reef facies. The width of the transition zone is approximately 100 m (Fig. 26a).

In the lower part of the quarry, thin-bedded "platy" of limestone and marly limestone are noted (Fig 27c). Upwards, they grade into medium-thick-bedded limestones. Initially, the sediment is dominated by bioclastic wackestone, but changes upwards into coarse-grained grainstone and rudstone inclined towards the central part of the hill. Grain-dominated bioclastic-coated grain packstone, grainstone and rudstone with numerous intraclasts and skeletal detritus dominate here (Fig. 26e). The formation and position of the sedimentary successions in the quarry indicates that the grain-supported sediments represent slope facies dominated by grain-flow deposits redeposited from the reef complex (Fig. 27b, d). In this area, on the edges of the reef complex, in addition to grain-flow deposits, submarine slums, debris flow sediments, and proximal and distal turbidites are also observed (Bednarek et al., 1985; Kutek and Zapaśnik 1992; Barski and Mieszkowski, 2014).

The central part of Kromołowiec Hill consists of hard lithified massive limestone (Fig. 26a). Initially, in the lowest parts of the rocks, these are microbial-sponge frame reef facies. This facies type is dominated by microbialites, mainly peloidal stromatolites and layered thrombolites, while sponges are less common (Figs. 26b, c, 28a, b). The main part of Kromołowiec Hill consists of very hard lithified massive limestones representing microbial-*Crescentiella*-coated grain facies and coated grain-bioclastic facies (Fig. 26d, 28c-d; for details see Krajewski and Olchowy 2023). Compared to other massive limestones at KCU, particular attention is paid to massive coated grains formed by ooids, oncoids, bioclasts and microbial crusts mainly agglutinating or peloidal stromatolites. Also noteworthy is the above-average content of *Crescentiella* and early cements. Individual specimens of *Crescentiella* are often connected with microbial crusts. The skeletal metazoans are rare and represented by calcified siliceous sponges, calcareous sclerosponges, and corals (mainly empty caverns of dissolved aragonite skeleton corals).

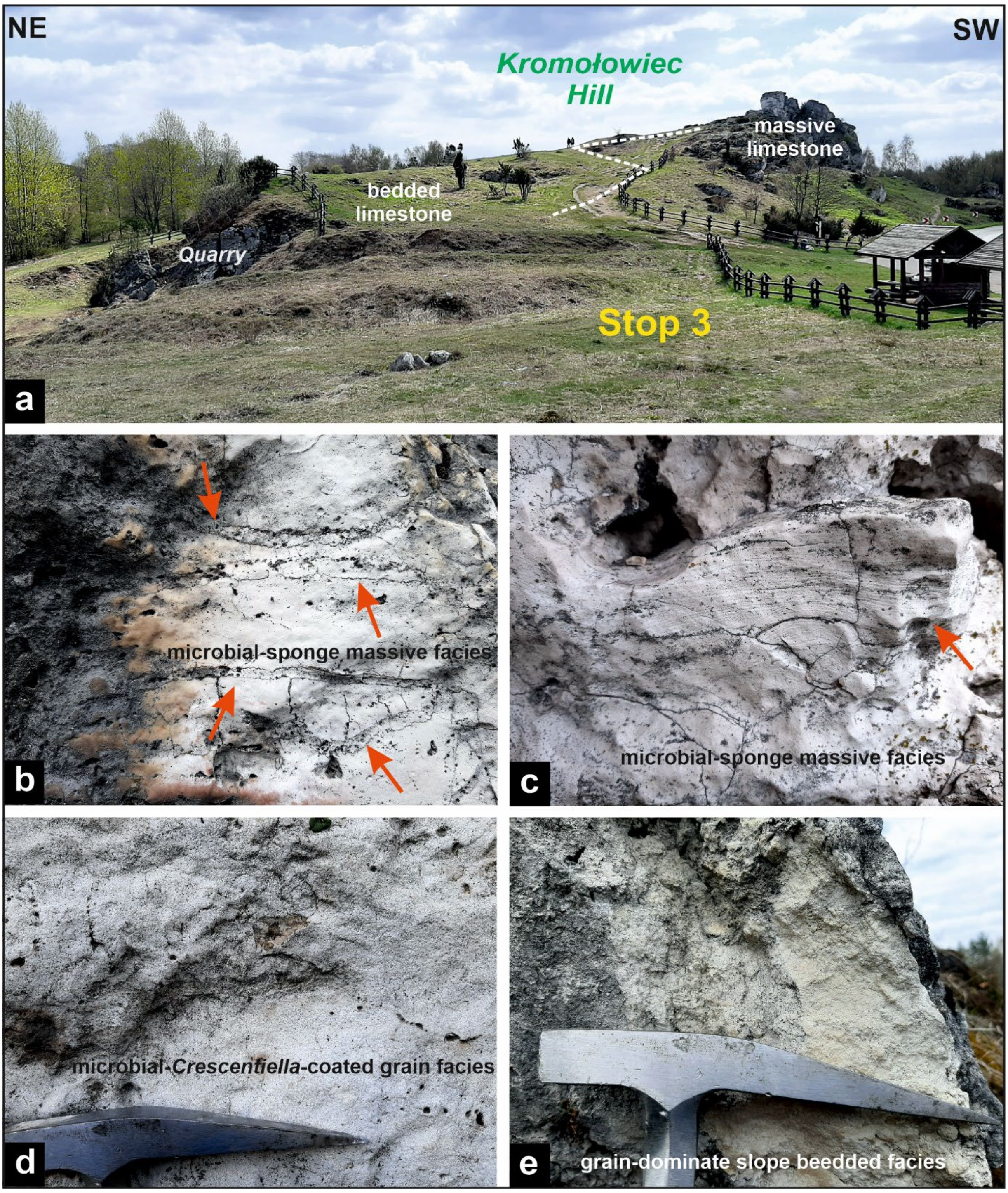


Fig. 26. Stop 3 – Kromołowiec Hill. a – General view with visible marginal part of the carbonate buildups complex. On the right, strongly lithified massive limestone; on the left small quarry with thin and thick-bedded facies. b, c – the lower part of the carbonate buildups with well visible calcified sponges and microbialites (arrows). d – upper and marginal part of the carbonate buildups with dominated by coated grain and *Crescentiella* microencrusters stabilized by microbialites. e – grain-dominated bedded facies in the uppermost part of the quarry represent talus of the buildup.

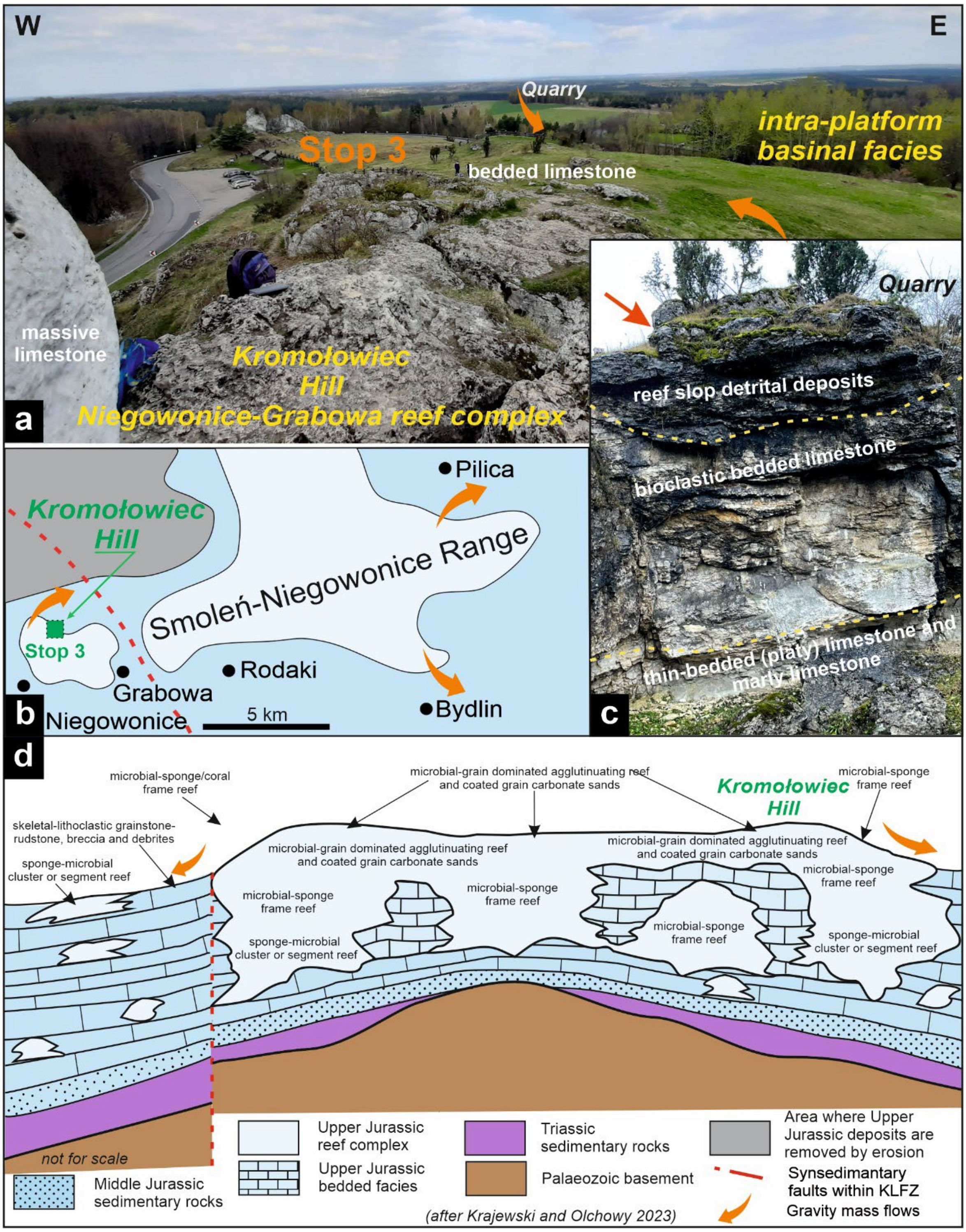


Fig. 27. Palaeosetting of the Grabowa-Niegowonice isolated reef complex (Smoleń-Niegowonice Range; see also Matyszkiewicz et al. 2006) based on the example of Kromołowiec Hill area (Krajewski and Olchowy 2023). a – Viev from Niegowonice-Grabowa reef complex. b - Sketch with facies distribution. The central part of the isolated Upper Jurassic reef complex was developed on tectonically active elevation. The Kromołowiec Hill was situated on the marginal part of the reef complex. Mostly pelitic (dark blue) and gravity flow sediments were deposited toward the north direction from the Kromołowiec Hill (arrows). c - sedimentary succession observed in the quarry with redeposited slope deposits in the upper part of the quarry. d- Palaeosetting model of the Niegowonice-Grabowa complex showing facies changes in the marginal part of the reef complex. The reef complex was situated on an elevation on the marginal part of the Małopolska and Upper Silesian terranes (for details see Krajewski and Olchowy 2023).

Geological Interpretation

The Kromołowiec Hill represents a transitional zone extending between an elevated isolated reef complex with a maximum lateral extension of up to 3 km and a deeper basin situated further to the north (Fig. 28b, d; Kutek and Zapaśnik, 1992; Matyszkiewicz et al., 2006). The particularly intensive development of the reef complex in the study area was enhanced by the presence of a sea bottom elevation on the northern Tethyan shelf margin (Irmiński, 1995; Matyszkiewicz et al., 2006). Similar to examples from Stop 2, the existence of this elevation was associated with Palaeozoic bedrock and synsedimentary tectonics (Matyszkiewicz et al., 2006).

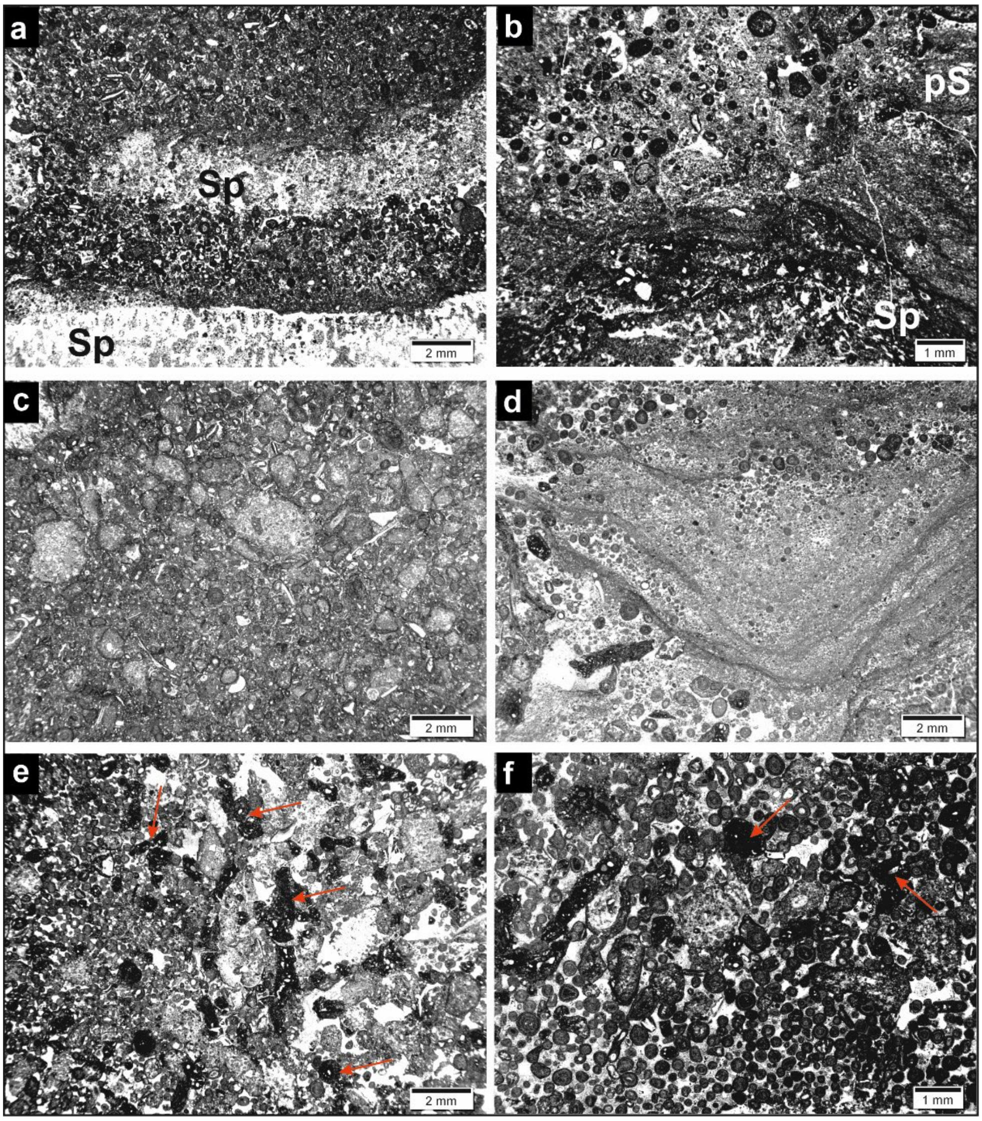


Fig. 28. Kromołowiec Hill. Microfacies of the bedded (a, c) and massive (b, e, f) limestone facies. a – sponge floatstone with numerous redeposited coated grains and bioclasts; talus of the buildups. b – microbial-sponge boundstone with sponge (Sp) and peloidal stromatolite (pS); in the upper part coated grain-bioclastic packstone/grainstone. c – coated grain-intraclastic packstone-rudstone; carbonate buildup slope deposits. d – microbial-grain dominated boundstone; numerous grains stabilized by microbial crusts. e, f – coated grain-Crescentiella microencruster with numerous ooids and Crescentiella (arrows)

Lateral and vertical extent of seismically interpreted carbonate structures

The lateral extent of the carbonate buildups interpreted from seismic data in the Nida Trough is typically in the range of 400-1000 m. The observed cumulative height of the large complexes often exceeds 250-300 m. This means that the vertical size and lateral extent of the subsurface structures identified in the Nida Trough are generally comparable to the large carbonate complexes documented in the KCU (see Matyja and Wierzbowski, 2006; Matyszkiewicz et al, 2006, 2012; Słonka and Krzywiec, 2020a). The seismic example shown in Fig 29 allows a better understanding of the scale of the subsurface equivalents. It was compared with the outcrop in Kromołowiec Hill, which is only a part of much larger, isolated "seismic-scale" reef. Comparison shows the similarity between the subsurface large carbonate structure observed in seismic and the entire Grabowa-Niegowonice isolated reef complex.

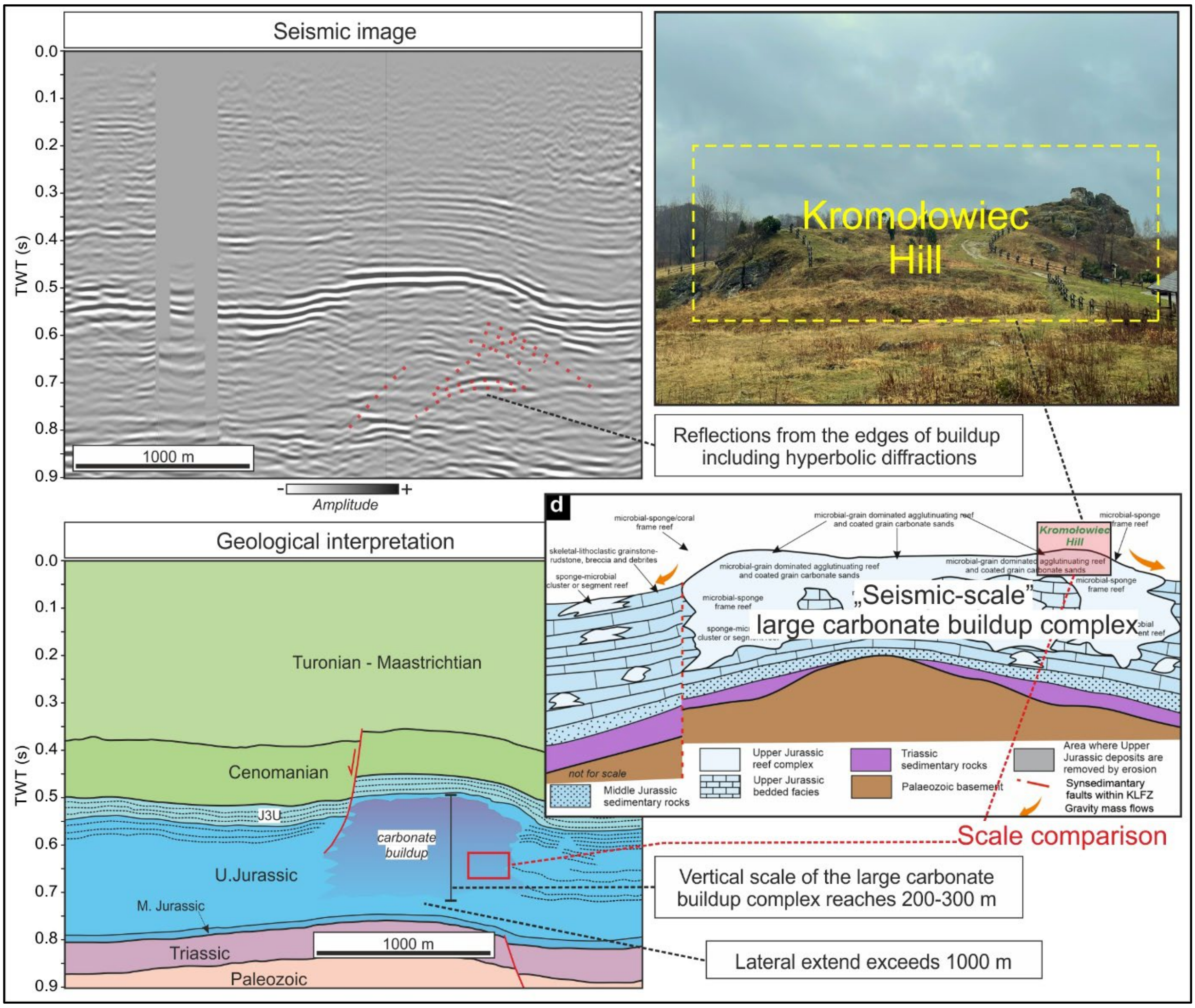


Fig. 29. Example of a seismically interpreted large subsurface carbonate buildup complex from the Upper Jurassic succession in the Nida Trough compared with the Kromołowiec Hill outcrop, which is part of the Grabowa-Niegowonice isolated reef complex (d-after Krajewski and Olchowy 2023) of similar ("seismic-scale") size (Słonka and Krzywiec, 2020a).

Stop 4. Podzamcze – Ogrodzieniec Castle (50°27'13''N/19°33'07''E; location: Fig. 30).

Stages and development of rigid framework in the sponge-microbial reef; the problems with seismic interpretation of the initial stadium of buildups and pull-up effect.

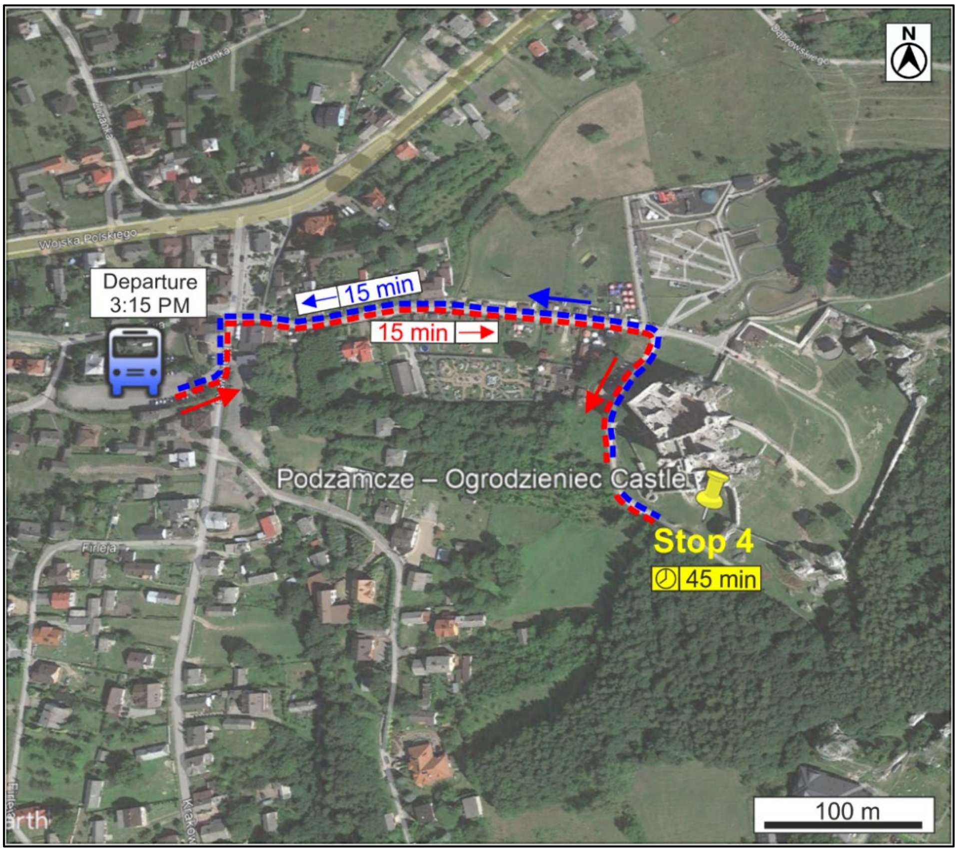


Fig. 30. Location of Stop 4 with a detailed route and estimated travel times. Satellite image map data from *Google Earth* (n.d.).

Outcrop description

The Ogrodzieniec Castle Hill in Podzamcze village is located in the central part of the Kraków-Częstochowa Upland and from a geographical point of view; this area belongs to the Zborów-Ogrodzieniec Range. Spectacular castle ruins are situated on the Upper Jurassic massive reef limestone facies (Fig. 31). In the substratum and areas surrounding the castle hill, the bioclastic bedded limestone facies can be observed. The massive limestone facies mainly represent the Upper Oxfordian (Bifurcatus Zone; Matyja and Wierzbowski 2006) sponge-microbial reef complex (Matyszkiewicz et al. 2001). The lower part of the massive limestone is approximately 40–50 m above the Callovian/Oxfordian boundary (Fig. 6).

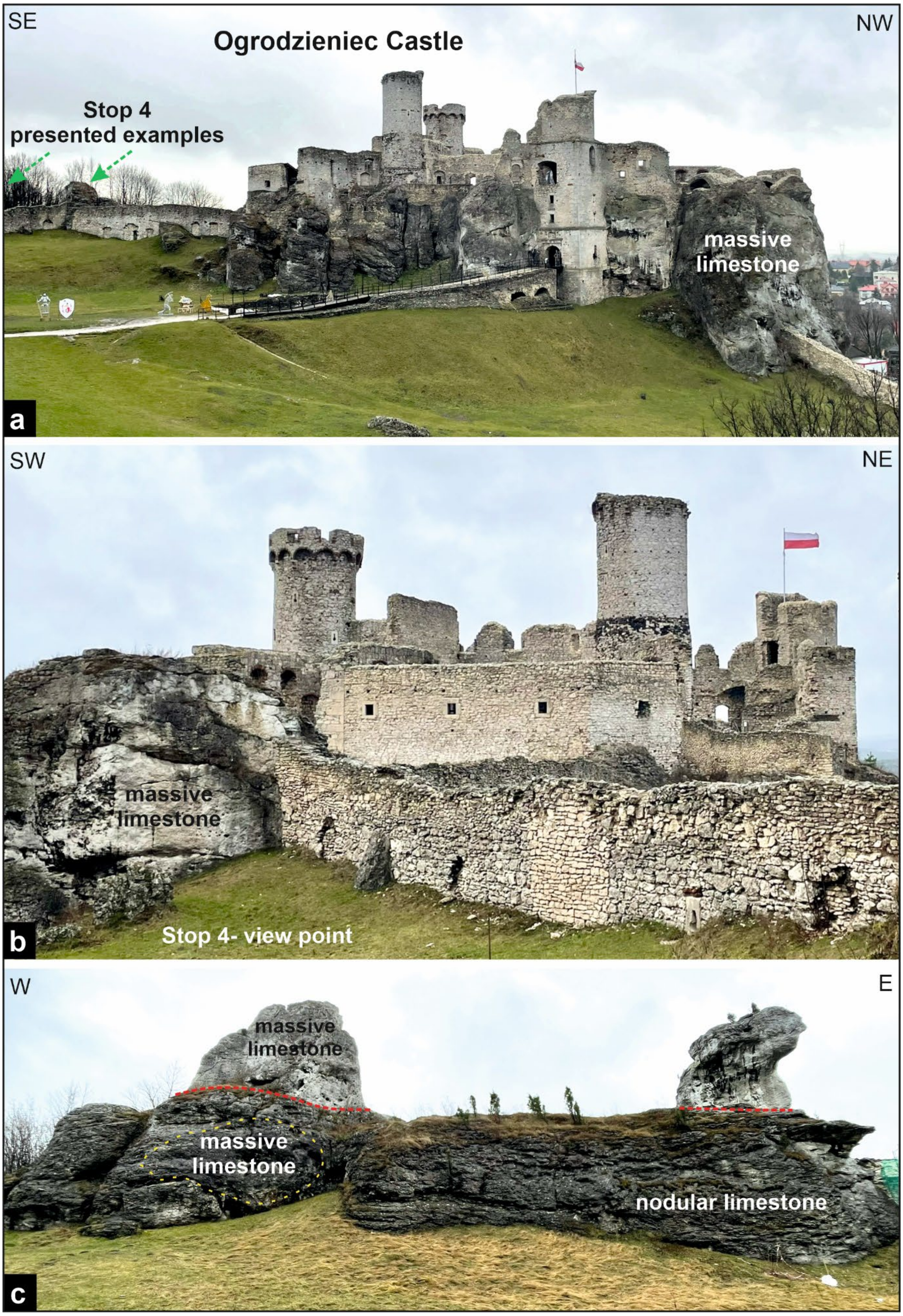


Fig. 31. Stop 4. Podzamcze, Ogrodzieniec Castle Hill. a, b- Location of the Stop 4. The central part of the hill with massive limestone facies. c – Stop 4. In the lower part of the outcrops nodular limestone with irregular bedding and lenses massive limestone. In the upper part massive limestone.

In the sedimentary succession of the rocks, two- or three intervals can be observed (Fig. 32a,b; Matyszkiewicz et al., 2001). The lower parts of the rocks, at intervals of up to several meters, represent nodular irregular bedded limestone. The nodular limestone is formed mainly by pelitic limestones with numerous platy sponges (Matyszkiewicz et al., 2001). The transition zone between the nodular and the underlying bioclastic bedded limestone is gradual and indistinct. Up the sedimentary succession, the nodular limestone passes into the hard lithified massive limestone facies. Initially, in the lower and marginal parts of the massive limestone, laminar horizons are visible (Fig. 31c, 32a-d) with cm-dm scale thin intervals, often created by subsequent generations of platy sponges and microbial structures developed on sponge skeletons, separated by fine bioclast-pelitic wackestone (for details see Matyszkiewicz et al., 2001). In the marginal part of the massive limestone in the transitional zone to the bedded facies (mostly eroded) they are often inclined as a result of differences of compaction processes (Fig. 32c, d). Upwards the sedimentary succession, the mentioned laminar horizons gradually disappear. The upper part of the rocks is represented by massive limestone in which the amount of sponges is gradually decreasing, while the number of microbial structures is increasing, forming highly lithified sponge-microbial boundstone (Matyszkiewicz et al., 2001).

Geological Interpretation

Sedimentary succession in the outcrops documents the early stage of development of reef complexes on KCU and subsequent stages of the development of the internal reef structure with so-called rigid framework (*sensu* Prat 1982; Matyszkiewicz 1997; Matyszkiewicz et al., 2001; Matyszkiewucz and Kochman 2016). The rigid framework is the synsedimentary lithified bioconstruction created by successive generations of benthic organisms with numerous growth cavities. The development of bioconstruction types at KCU was characterized by varying degrees of rigid framework development (Matyszkiewicz et al., 2001). The initial rigid framework represents the first phase (Phase 1; Fig. 32b, e) of the development of bioconstruction created by sponge and sponge-microbial associations and pelitic/bioclastic sediments. In this phase, the rigid framework was developed in its initial stages, often resulting in a nodular texture created by hard lithified nodules and pelitic matrix. This type of building had a very heterogeneous internal structure, consisting of two components, i.e. the initial, delicate and brittle rigid framework and the soft allomicrite filling the spaces between the frames (Matyszkiewicz et al., 2001).

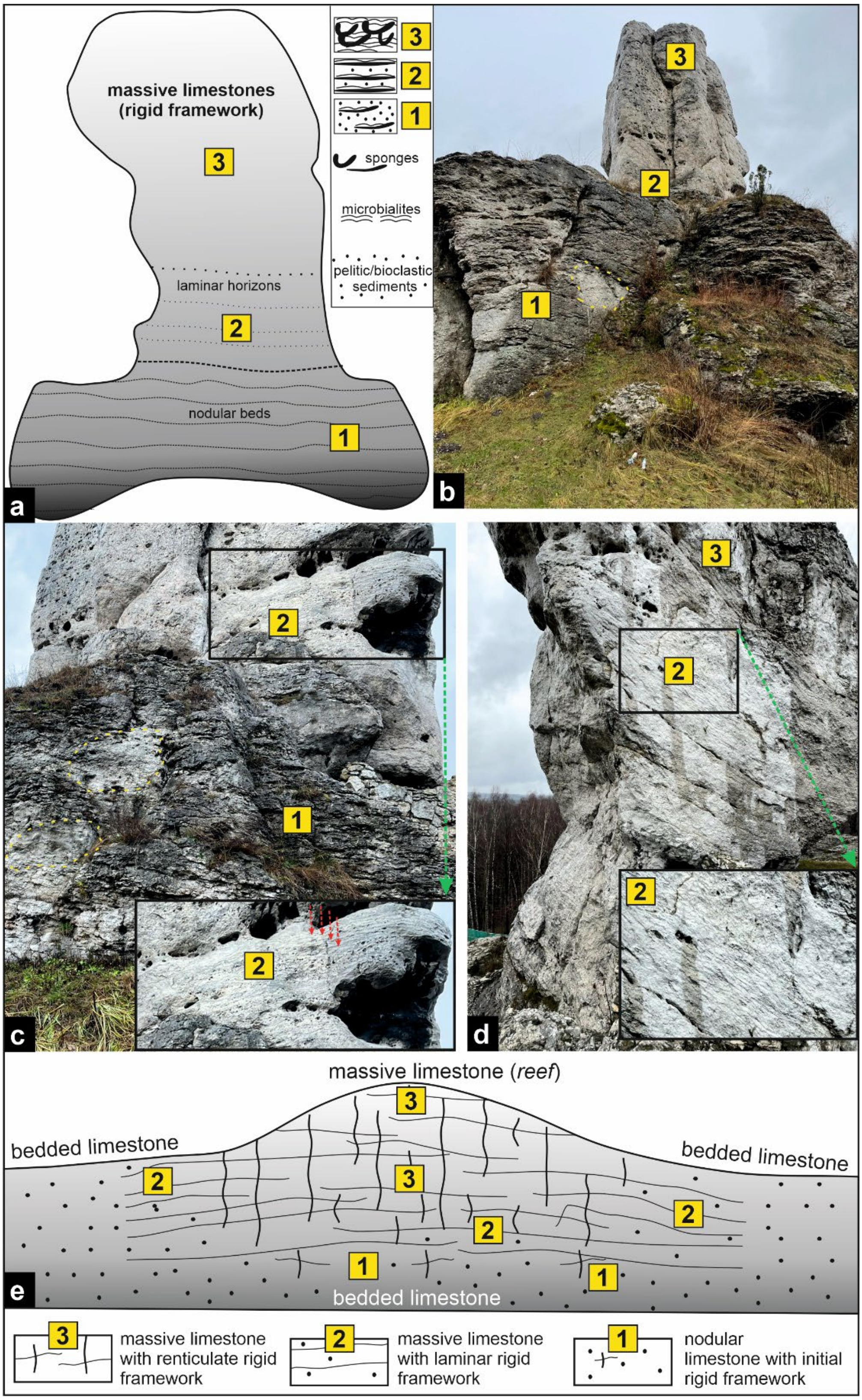


Fig. 32. Stop 4 Nodular and massive limestone. Rigid framework development phases observed in carbonate buildup succession. a- A sketch of a rock showing the characteristic phases of development of carbonate buildups. b-d Various examples showing phases of rigid framework development. 1- initial phase, sponges and mud-supported matrix dominate. 2 - development of the laminar framework created by numerous generations of sponges and microbialites and mud-supported sediments (see enlargements). 3 - microbial-sponge boundstone creating a reticulate rigid framework. e – simplified model of carbonate buildups.

In early diagenesis, due to differences in the susceptibility to compaction between the initial rigid framework and soft allomicrite, the sediment disintegrated under the weight of the overburden, resulting in a specific nodular texture of the rocks. The most intense phase of growth of carbonate buildups in which the subsequent phases (2 and 3 phases; Fig. 32) of the development of the rigid framework is observed (Pratt 1982; Kochman and Matyszkiewicz 2013; Matyszkiewicz and Kochman 2016). In the vertical sedimentary succession, above the sponge-pelitic nodular limestone (phase 1-initial rigid framework; Fig. 32) there are sponge-dominated limestones with laminar horizons (phase 2 -laminar rigid framework) which gradually pass into sponge-microbial limestone with a well-developed reticulate rigid framework (phase 3). Laminar rigid framework is also observed in the external parts of carbonate buildups (Fig. 32).

Seismic analogs: interpretation of the internal structure of carbonate buildups, their initial state and the influence of pull-up artifacts

Seismic stratigraphic interpretation, supported by detailed analysis of well data, proved that the Upper Jurassic carbonate buildups in the Nida Trough, similar to their field equivalents in the KCU, represent thick (250-300 m) and heterogeneous complexes (Słonka and Krzywiec, 2020b). Precise well-to-seismic ties and 1D seismic stratigraphic analysis were performed on the key calibration wells to provide answers about the internal structure of large subsurface reefs, such as the one, drilled by the Belvedere-1 exploration well, shown in Fig 33. The high correlation obtained between the synthetic seismogram, the real seismic traces and the lithological and facies changes within the Upper Jurassic interval allowed a detailed geological interpretation.

The carbonate buildup drilled by Belvedere-1 well, consists of the two rigid massive limestone intervals, separated by a medium hard platy-like limestone (Fig. 33). This suggests the two main stages of reef development, which included subsequent growth phases associated with the presence of massive limestones (the two massive limestone intervals – A and B – are shown in Fig. 33; for more information, see Słonka and Krzywiec, 2020b). Higher gamma-ray log values over the top of the carbonate buildup indicate with marly and marly limestone deposits associated with the seismically interpreted "marly zone" (Słonka and Krzywiec, 2020b). The appearance of marly facies is related to temporary changes in Late Jurassic sedimentation characterized by drowning episodes and demise of the carbonate buildups (Kutek, 1994; Krajewski et al., 2017).

The uppermost part of the Upper Jurassic interval corresponds to the J3U seismic-stratigraphic unit (Słonka and Krzywiec, 2020a), which is characterized by high-amplitude seismic horizons (Fig. 33). The J3U interval interpreted in seismic data from the Nida Trough is associated with shallow water carbonate sedimentation (Matyja, 2009), which began to dominate after the disappearance of carbonate buildups (Słonka and Krzywiec, 2020b). It comprises various oolitic and oncolitic facies (characterized by high seismic velocities), alternated by marly limestones and marls (i.e. inner-ramp facies, Krajewski et al. 2017, see e.g. Wierzbowski, 2017). The above-mentioned alternations are visible as high peaks on the gamma-ray (Fig. 33). However, due to their low thickness it was not possible to distinguish them on seismic image without additional information from the well logs, as these layers are below the vertical seismic resolution. Therefore, the seismic image of the J3U interval is partially scattered by intra-bedded signal interference, caused by strong overlap of reflection signals from the seismically "fast" oolitic limestones and marly intercalations. This is the reason why this seismic-stratigraphic unit is expressed by a series of high amplitude positive and negative seismic horizons in the entire study area (Słonka and Krzywiec, 2020b).

The initial stage of carbonate buildup is partly associated with the aforementioned initial rigid framework, while the massive limestone packages that form the main part of the reef complex are mainly characterized by the reticular and laminar rigid frameworks (two major developmental stages have been identified, for details see Fig. 33). Compared to the fully developed intervals above, the lithologies of the initial part of the carbonate buildup are characterized by relatively lower seismic velocities, with values similar to the adjacent bedded limestones. In order to verify the interpretation of the initial phase of the reef complex, a seismic modelling approach has been applied (Słonka et al., 2024).

Seismic forward modelling of the carbonate buildup was based on previous seismic-stratigraphic interpretations (Słonka and Krzywiec, 2020a; 2020b) and the detailed 1D velocity model obtained from the well log data, correlated with lithology and facies (Belvedere-1 well). The seismic-geological model assumed eight characteristic seismic (velocity) intervals in the Upper Jurassic, associated with major lithologic and facies complexes, and it was verified by outcrop analogues from KCU (Słonka et al., 2024).

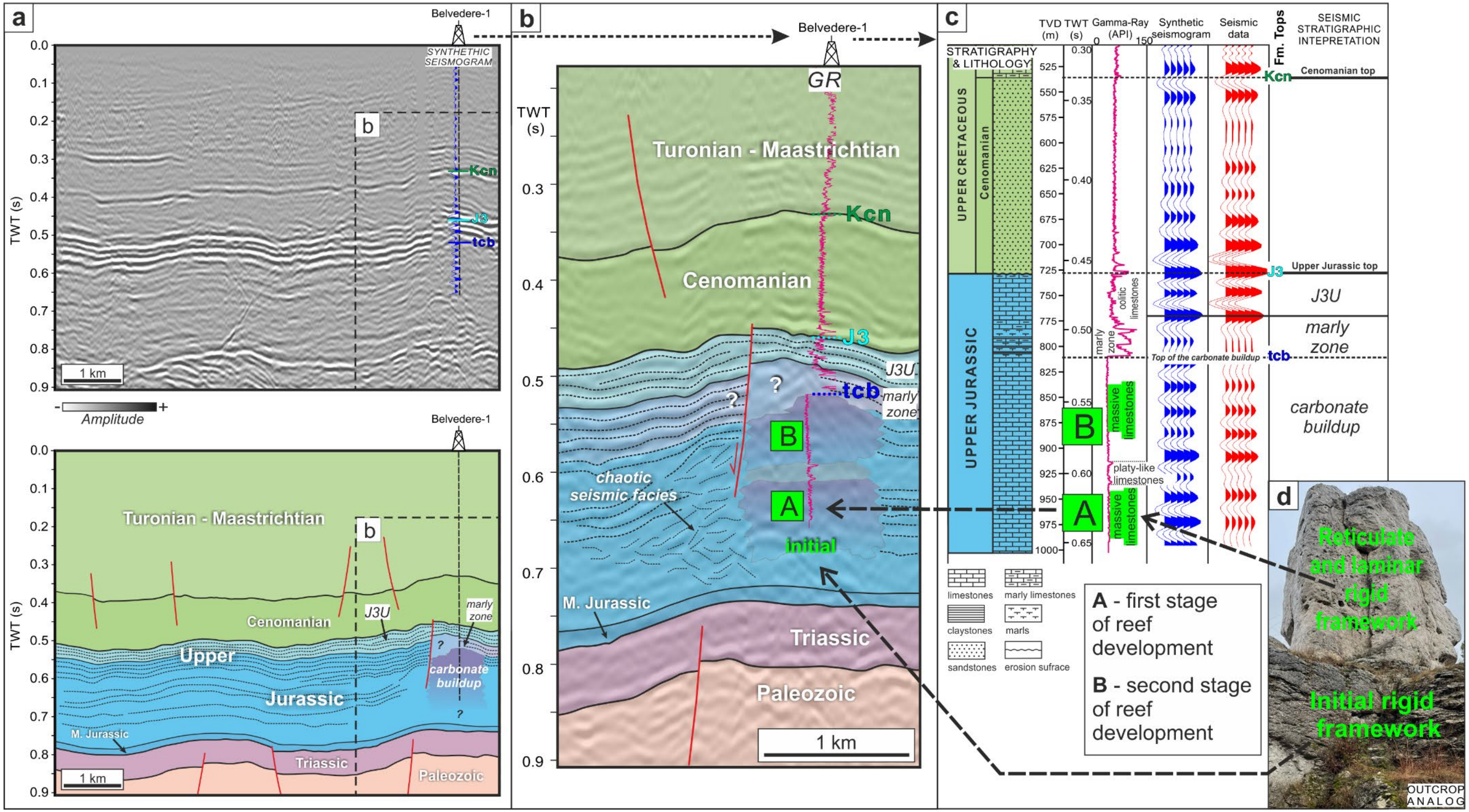


Fig. 33. (a) Uninterpreted and interpreted seismic profile across the carbonate buildup complex drilled by Belvedere-1 well in the Nida Trough (Słonka and Krzywiec, 2020a; 2020b). (b) zoom in on the carbonate buildup complex and its seismic-stratigraphic interpretation (c) well-to-seismic tie result with detailed 1D seismic-stratigraphic analysis (d) outcrop equivalents from the Stop 4 showing the vertical transition from initial to laminar and reticulate rigid framework of massive limestone.

The seismic modelling results are shown in Fig. 34 (Słonka et al., 2024). For each synthetic section, a zero offset method of theoretical wave-field simulation was used. Seismic intervals (2-6) represent different lithological and facies intervals of the carbonate buildup complex. The theoretical response from the top of each modelled horizon is shown in the synthetic section of Fig. 34a. Synthetic seismic horizons were compared with the real seismic data crossing the carbonate buildup and the correlation obtained was very precise (Fig 34b).

Seismic horizons (2-6) represent intervals mainly associated with the rigid framework of the reef (e.g., successive levels of massive limestones). This resulted in their high to medium amplitude response. On the other hand, the seismic modelling assumed that the velocity values characteristic of the initial part of the buildup (represented by seismic interval 1) are similar to the adjacent bedded deposits typical of the lower intervals of the Upper Jurassic succession, following the lithologies observed in the field (Słonka et al., 2024). Synthetic data simulation of the initial part of the buildup showed relatively low impedance contrasts, producing a low amplitude, dim reflection seismic response. Such a scenario clearly corresponds to the real seismic image as shown in Figure 34b.

In other words, the correct geological interpretation of seismic data may also depend on the stage of development of the given carbonate buildup. In particular, the amount of its rigid framework, which is characterized by the highest seismic velocities within the entire complex, resulting in strong reflection amplitudes. Such intervals are easy to identify, whereas the initial parts of the structure are often difficult to identify from seismic data due to the lack of significant acoustic impedance contrasts within the lower intervals of the studied Upper Jurassic succession (Słonka et al., 2024).

Another important aspect of the seismic interpretation of carbonate buildups is to understand how processing artifacts such as velocity pull-ups, may distort imaging of reef substratum. The velocity pull-up effect observed beneath the carbonate buildups (Fig. 34) results from lateral seismic velocity contracts between the massive and bedded limestones. The interval velocity of the massive limestones drilled by exploration wells in the Nida Trough is about 5000-5500 m/s, which is significantly higher than the seismic velocity of the corresponding bedded limestones, which is about 3800-5000 m/s (Słonka and Krzywiec, 2020a). Lateral seismic velocity variations between the massive and bedded carbonates can exceed 10% and may be responsible for producing some pull-ups beneath the seismically faster carbonate buildups. It is then likely that for at least some of the morphological heights located beneath the carbonate buildups in the analyzed time-seismic data, velocity pull-ups may have distorted their true geometries (Słonka and Krzywiec, 2020a

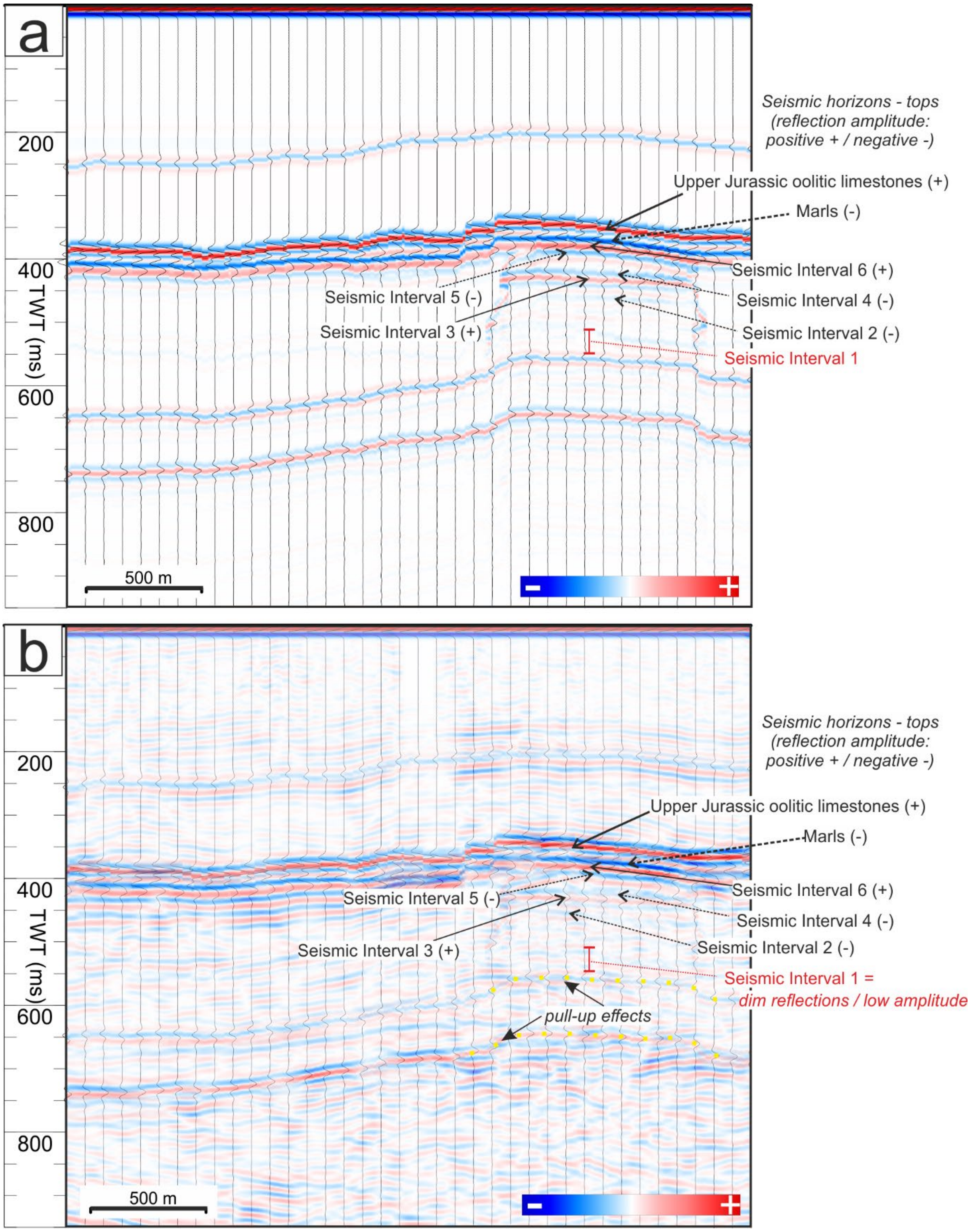


Fig. 34. (a) Synthetic seismic section across the large carbonate buildup complex (b) Synthetic seismic section compared to the real seismic profile (superimposed). Low velocities of the initial rigid framework, similar to adjacent bedded sediments, resulted in low impedance contrast within the initial part of the carbonate buildup. This resulted in weak reflections observed in both synthetic and real seismic data (interval is being marked with red). Note the distortion of the substratum geometry due to pull-up effect (marked with yellow dotted lines) (Słonka et al., 2024).

The problem of the pull-up effect is fairly easy for interpreters to recognize and is universal, as it appears in seismic images of carbonate buildup in time domain data from various carbonate deposits around the world. For example, a similar role of high-velocity reef intervals in generating velocity pull-up effects beneath the carbonate buildups has been described for time-seismic data characterizing the large Miocene accumulations in Luconia, Malaysia (e.g., Zampetti et al., 2004; Rankey et al., 2019) or numerous isolated accumulations from the northwestern shelf of Australia (Saquab and Bourget, 2016) (see Słonka and Krzywiec, 2020a).

To illustrate the influence of the pull-up effect, simple theoretical seismic modelling was performed and the calculated synthetic sections are shown in Fig. 35. The results obtained revealed that the pull-up effect locally deformed the actual geometry of the substrate of carbonate buildup, suggesting its higher elevation than in reality (Słonka et al., 2024).

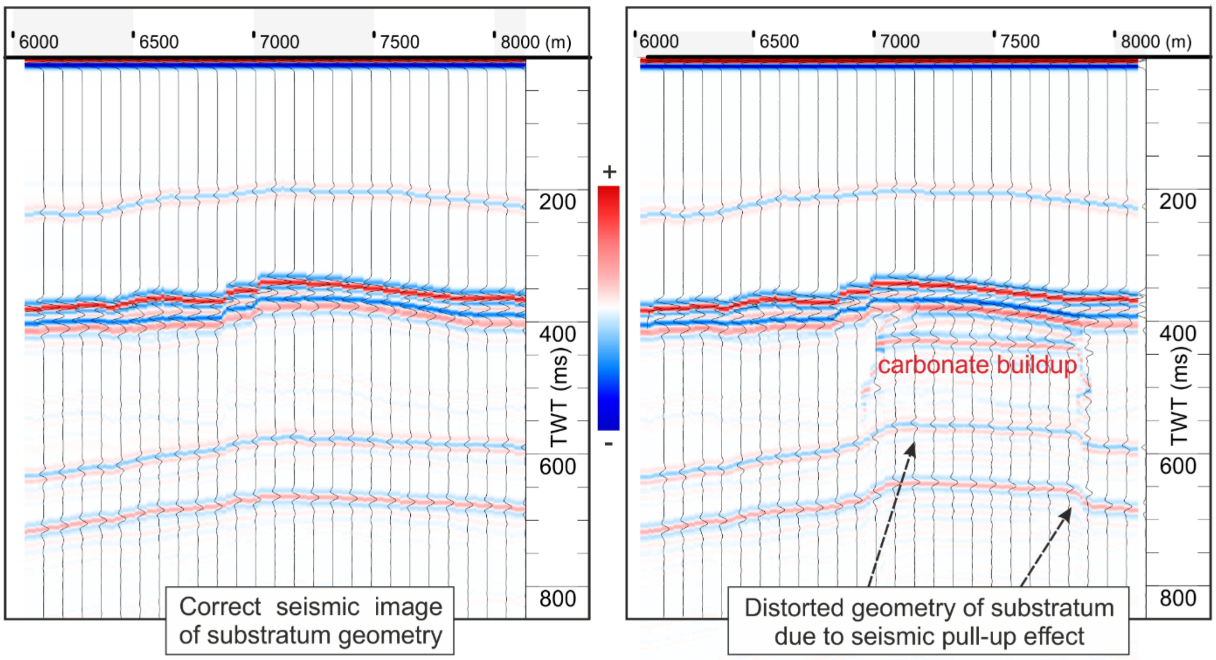


Fig. 35. Simple seismic modelling study illustrating the influence of the pull-up effect on the correct seismic interpretation of the substratum of the carbonate buildup (Słonka et al., 2024). Left, synthetic section calculated for a theoretical model assuming no carbonate buildup. The Upper Jurassic interval is characterized by velocities of 4200 m/s, typical for bedded limestone facies. The seismic image of the substratum geometry is correct due to the lack of lateral velocity contrasts above. The synthetic section on the right shows the modelling results assuming the presence of the Upper Jurassic carbonate buildup, characterized by a complex high-velocity model. As a result, a pull-up effect is created that distorts the true image of the substratum geometry. Misunderstanding the genesis of these seismic artifacts can lead to incorrect geological interpretations and misconceptions about the true morphology of the strata beneath the carbonate buildup.

Literature:

Abbani, G., Adelinet, M., Inati, L., Bailly, C., Nader, F. 2023. Seismic characterization of Cenomanian–Turonian carbonate platform based on sedimentological and geophysical investigation of onshore analogue outcrop (northern Lebanon). Geophysical Prospecting: 1–17.

Allenbach, R.P. 2002. The ups and downs of 'Tectonic Quiescence' - recognizing differential subsidence in the epicontinental sea in the Oxfordian in the Swiss Jura Mountains. Sediment Geol., 150: 323–342.

Badali, M. 2024. Seismic expression of shallow-water carbonate structures through geologic time. Interpretation, 12(2): 119–149.

Barski, M., Mieszkowski, R. 2014. Upper Jurassic large-scale debris flow deposits in interbiohermal basins of the sponge megafacies in Poland – new insights. Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, 272: 47–59.

Bednarek, J., Górecka, E., Zapaśnik, T. 1985. Tectonically controlled development of ore mineralization in Jurassic sequence of the Silesian–Cracovian Monocline. Ann Soc Geol Polon., 53: 43–62 (in Polish with English summary).

Borgomano, J.R.F., Peters, J. M. 2004.Outcrop and seismic expressions of coral reefs, carbonate platforms, and adjacent deposits in the Tertiary of the Salalah Basin, South Oman. In: Eberli et al. (eds,), Seismic imaging of carbonate reservoirs and systems. AAPG Memoir, 81: 251–266.

Brachaniec, T., Salamon, M.A., Szopa, K., Gedl, P., Brom, K.R., Leśko, K. 2016. Origin of Jurassic Cretaceous neptunian dikes from the Cracow-Czestochowa Upland in southern Poland. Geobios, 49: 155–165.

Bubb J.N., Hatlelid, W.G. 1977. Seismic recognition of carbonate buildups. In: Payton, C.E. (ed.), Seismic Stratigraphy – Applications to Hydrocarbon Exploration. AAPG Memoir 26: 185–204.

Buła, Z. 2002. Geological Atlas of the Palaeozoic without the Permian in the border zone of the Upper Silesian and Małopolska Blocks. Explanatory text. Państwowy Instytut Geologiczny, Warszawa. (in Polish with English summary).

Buła, Z., Habryn, R. 2011. Precambrian and Palaeozoic basement of the Carpathian foredeep and the adjacent Outer Carpathians (SE Poland and western Ukraine). Ann Soc Geol Pol 81:221–239.

Burchette, T.P., Wright, V.P. 1992. Carbonate ramp depositional systems. Sediment Geol., 79: 3–57.

Burgess, P.M., Winefield, P., Minzoni, M., Elders, C. 2013. Methods for identification of isolated carbonate buildups from seismic reflection data, AAPG Bulletin, 97: 1071–1098.

Chang, J., Hsu, H., Liu, C., Lee, T., Chiu, S., Su, C., Ma, Y., Chiu, Y., Hung, H., Lin, Y., Chiu, C. 2017. Seismic sequence stratigraphic analysis of the carbonate platform, north offshore Taiping Island, Dangerous Grounds, South China Sea. Tectonophysics, 702:70–81.

Csizmeg, J., Biliavska, M., Korynevych, T., Pakulyak, V., Bodlak, V., Mykhalevych, I., Olsen, M., Mamus, P., Ficarra, A., Hunda, M., Sralla, B. 2024. Jurassic carbonate buildups in the Carpathian Foreland Basin of Ukraine – Relation of facies, tectonics and erosion. AAPG Europe Region Conference 2024, Krakow, Poland

Dadlez, R. 1997. Epicontinental basins in Poland: Devonian to Cretaceous – relationship between the crystalline basement and sedimentary infill. Geological Quarterly, 41: 419-432.

Dadlez, R., Narkiewicz, M., Stephenson, R.A., Visser, M.T.M., Van Wees, J-D. 1995. Tectonic evolution of the Mid-Polish Trough: modelling implications and significance for central European geology. Tectonophysics, 252: 179–195.

Dadlez, R., Marek, S., Pokorski, J. (Eds.) 2000. Geological Map of Poland without Cainozoic Deposits (1:1 000 000). Polish Geological Institute, Warszawa, Poland.

Di Lucia, M., Sayago, J., Frijia, G., Cotti, A., Sitta, A., Mutti, M. 2017. Facies and seismic analysis of the Late Carboniferous – Early Permian Finnmark carbonate platform (southern Norwegian Barents Sea): An assessment of the carbonate factories and depositional geometries. Mar. Petrol. Geol., 79: 372–393.

Dżułyński, S. 1952. The origin of the Upper Jurassic limestones in the Cracow area. Rocznik Polskiego Towarzystwa Geologicznego, 21: 125–180. (in Polish with English summary)

Elvebakk, G., Hunt, D. W., Stemmerik, L. 2002. From isolated buildups to buildup mosaics: 3D seismic sheds new light on upper Carboniferous–Permian fault controlled carbonate buildups, Norwegian Barents Sea. Sediment. Geol., 152: 7–17.

Fontaine, J. M., Cussey R., Lacaze J., Lanaud R., Yapaudjian, L. 1987. Seismic Interpretation of Carbonate Depositional Environments. AAPG Bulletin, 71: 281–297.

Fournier, F., Borgomano, J. 2007. Geological significance of seismic reflections and imaging of the reservoir architecture in the Malampaya gas field (Philippines), AAPG Bulletin, 91: 235–258.

Gliniak P., Laskowicz, R., Urbaniec, A., Leśniak, G., Such, P. 2004. The facies development and reservoir properties in Late Jurassic carbonate sediments in the central Carpathian foreland. In: Swennen et al. (Eds.), Deformation, Fluid Flow and Reservoir Appraisal in Foreland Fold. AAPG Hedberg Ser., 1: 347–355.

Gliniak, P., Urbaniec, A. 2005. Geophysical characteristic of Oxfordian bioherms in the Carpathian foreland area in the aspect of new techniques of hydrocarbons searching. Nafta-Gaz, 61: 343–348 (in Polish with English summary).

Głowniak, E. 2006. Correlation of the zonal schemes at the Middle-Upper Oxfordian (Jurassic) boundary in the Submediterranean Province: Poland and Switzerland. Acta Geol Polon., 56: 33–50

Gradziński, M., Gradziński, R., Jach, R. 2008. Geologia, rzeźba i zjawiska krasowe okolic Ojcowa. Monografia Ojcowskiego Parku Narodowego, Przyroda red., Klasa A., Partyka J. Ojców, 31-95. (in Polish)

Gutowski, J., Popadyuk, I., Olszewska, B. 2005. Late Jurassic–earliest Cretaceous evolution of the epicontinental sedimentary basin of southeastern Poland and Western Ukraine. Geol Quart., 49: 31–44.

Handford C., Loucks, R.G. 1993. Carbonate sequence stratigraphy: recent developments and applications. Chapter 1: Carbonate depositional sequences and systems tracts - Responses of carbonate platform to relative sea-level changes. AAPG Memoir 57: 3–41.

Harańczyk, C., Lankosz, M., Wolska, A. 1995. Granodiorite of Jerzmanowice porphyries and Cu–Mo ores. Rudy Metale 40, 334–341. (in Polish with English summary)

Irmiński, W. 1995. Górnojurajski kompleks biohermalny w okolicach Niegowonic i Grabowej k. Zawiercia. Prz Geol., 43: 853–858. (in Polish)

Jarosiński, M., Poprawa, P., Ziegler, P.A, 2009. Cenozoic dynamic evolution of the Polish Platform. Geological Quarterly, 53, 3-26.

Jędrys, J., Krajewski, M. 2007. Wykształcenie i rozwój górnojurajskich osadów okolic Bębła na tle budowy podmezozoicznego podłoża, Wyżyna Krakowska. Tomy Jurajskie, 4: 95–102. (in Polish)

Jędrzejowska-Tyczkowska, H., Misiarz, P., Golonka, J., Przejczowska, A. 2005. Outrop information and seismic analogs in analysis of Jurassic buildups (Poland). Proceedings of the 67th EAGE Conference & Exhibition, Madrid, p. 295.

Kendall C, Schalger, W. 1981. Carbonates and relative changes in sea level. Marine Geology, 44: 181–212.

Kochman, A., Matyszkiewicz, J. 2013. Experimental method for estimation of compaction in the Oxfordian bedded limestones of the southern Krakow-Czestochowa Upland, Southern Poland. Acta Geol Polon., 63: 681–696.

Kochman, A., Kozłowski, A., Matyszkiewicz, J. 2020. Epigenetic siliceous rocks from the southern part of the Kraków-Częstochowa Upland (Southern Poland) and their relation to Upper Jurassic early diagenetic chert concretions. Sedimentary Geology, 401: 105636.

Koša, E. 2015. Sea-level changes, shoreline journeys, and the seismic stratigraphy of Central Luconia, Miocene-present, offshore Sarawak, NW Borneo. Mar. Petrol. Geol., 59: 35–55.

Kowal-Kasprzyk, J., Krajewski, M., Gedl, P. 2020. The oldest stage of the Outer Carpathian evolution in the light of Oxfordian–Kimmeridgian exotic clast studies (southern Poland). Facies, 66:11.

Krajewski, M., Matyszkiewicz, J., Król, K., Olszewska, B. 2011. Facies of the Upper Jurassic–Lower Cretaceous deposits from the southern part of the Carpathian Foredeep basement in the Kraków–Rzeszów area (southern Poland). Annales Societatis Geologorum Poloniae, 81: 269–290.

Krajewski, M., Olchowy, P., Felisiak, I. 2016. Late Jurassic facies architecture of the Złoczew Graben: implications for the evolution of the tectonic-controlled northern peri-Tethyan shelf (Upper Oxfordian–Lower Kimmeridgian, Poland). Facies, 62:4.

Krajewski, M., Olchowy, P., Zatoń, M., Bajda, T. 2017. Kimmeridgian hardground-sequence boundary from the Mesozoic margin of the Holy Cross Mountains (central Poland): implications for the evolution of the northern Tethyan carbonate shelf. Facies, 63:15.

Krajewski, M., Olchowy, P., Rudziński, D. 2018. Sedimentary successions in the Middle-Upper Oxfordian reef deposits from the southern part of the Kraków-Częstochowa Upland (Southern Poland). Geol Quart., 62: 653–668.

Krajewski, M., Ferré, B., Salamon, M.A. 2020. Cyrtocrinids (Cyrtocrin ida, Crinoidea) and other associated crinoids from the Jurassic (Kimmeridgian–Tithonian)–Cretaceous (Berriasian–Barremian) of the Carpathian Foredeep basement (western Ukraine). Geobios 60:61–77.

Krajewski, M., Olchowy, P. 2023. The role of the microencruster-microbial reef-building consortium in organic reefs evolution (Late Jurassic, northern Tethys shelf, southern Poland). Facies 69, 4.

Krokowski, J. 1984. Mezoskopowe studia strukturalne w osadach permsko-mezozoicznych południowo-wschodniej części Wyżyny Śląsko-Krakowskiej. Rocznik Polskiego Towarzystwa Geologicznego, 54: 79-121. (in Polish with English summary)

Krzywiec, P. 2002. Mid-Polish Trough inversion – seismic examples, main mechanisms, and its relationship to the Alpine-Carpathian collision. EGU Stephan Mueller Spec. Publ. Series, 1: 151–165.

Krzywiec P. 2006. Structural inversion of the Pomeranian and Kuiavian segments of the Mid-Polish Trough – lateral variations in timing and structural style. Geological Quarterly, 51, 151–168.

Krzywiec, P., Gutowski, J., Walaszczyk, I., Wróbel, G., Wybraniec, S. 2009. Tectonostratigraphic model of the Late Cretaceous inversion along the Nowe Miasto – Zawichost fault zone, SE Mid-Polish Trough. Geological Quarterly, 53: 27–48.

Krzywiec, P., Stachowska, A., Stypa, A. 2018. The only way is up – on Mesozoic uplifts and basin inversion events in SE Poland. In: Kilhams, B., Kukla, P. A., Mazur, S., McKie, T., Mijnlieff, H. F. & van Ojik, K. (eds.), Mesozoic Resource Potential in the Southern Permian Basin. Geol. Soc., London, Spec. Publ., 469: 33-57.

Kutek, J. 1994. Jurassic tectonic events in south-eastern Poland. Acta Geologica Polonica, 44: 167–221.

Kutek, J., Zapaśnik, T. 1992. Bydlin, large scale synsedimentary mass movements of Late Oxfordian. In: Matyja, B.A., Wierzbowski, A., Radwański, A., (eds) Oxfordian & Kimmeridgian joint workinggroups meeting, Warszawa, Intern Subcom Jurassic Strat, Guidebook and Abstracts, pp 22–26.

Lavoie, D., Pinet, N., Dietrich, J., Zhang, S., Hu, K., Asselin, E., Chen, Z., Bertrand, R., Galloway, J., Decker, V., Budkewitsch, P., Armstrong, D., Nicolas, M., Reyes, J., Kohn, B.P., Duchesne, M.J., Brake, V., Keating, P., Craven, J. Roberts, B. 2013. Geological framework, basin evolution, hydrocarbon system data and conceptual hydrocarbon plays for the Hudson Bay and Foxe basins, Canadian Arctic. Geological Survey Of Canada, Open File 7363, 200p.

Leinfelder, R.R,, Werner, W., Nose, M., Schmidm D.U., Krautter, M., Laternser, R., Takacs, M., Hartmann, D. 1996. Paleoecology, growth parameters and dynamics of coral, sponge and microbialite reefs from the Late Jurassic. Göttinger Arb Geol Paläont Sb., 2: 227–248.

Markowiak, M., Czarniak, P., Habryn, R. 2019. Searching for granitoid intrusion as the source of polymetallic mineralization in the NW area of Kraków using geophysical methods. Prz. Geol., 67: 465–477 (in Polish with English summary)

Matyja, B.A. 2009. Development of the Mid-Polish Trough versus Late Jurassic evolution in the Carpathian Foredeep area. Geological Quarterly, 53: 49–62.

Matyja, B.A., Gutowski, J., Wierzbowski, A. 1989. The open shelf carbonate platform succession at the Oxfordian/Kimmeridgian boundary in the SW margin of the Holy Cross Mts: stratigraphy, facies and ecological implications. Acta Geologica Polonica, 39: 29–48.

Matyja, B.A., Wierzbowski, A. 1992. Kromołowiec Hill, the biohermal complex to basin transitional zone topography; Oxfordian, Bifurcatus and Bimammatum Zones. In: Matyja, B.A., Wierzbowski, A., Radwański, A. (eds), Oxfordian & Kimmeridgian joint working groups meeting, Guidebook and Abstracts. International Subcommission on Jurassic Stratigraphy, Warszawa, pp. 46–47.

Matyja, B.A., Wierzbowski, A. 1995. Biogeographic differentiation of the Oxfordian and Early Kimmeridgian ammonite faunas of Europe, and its stratigraphic consequences. Acta Geol. Polon., 45 (1/2), 1-8. Warszawa.

Matyja, B.A., Wierzbowski, A. 2004. Stratigraphy and facies development in the Upper Jurassic of the Krakow-Częstochowa Upland and the Wieluń Upland]. In: Partyka, J, (ed.), Zrożnicowanie i przemiany środowiska przyrodniczo-kulturowego Wyżyny Krakowsko- Częstochowskiej. Tom 1: Przyroda, Ojcowski Park Narodowy, Ojców, 13–26. (in Polish with English summary).

Matyja, B.A., Wierzbowski, A. 2006. Podzamcze, viewpoint, massive limestones (Upper Oxfordian, Bifurcatus Zone). In: Wierzbowski, A., Aubrecht, R., Golonka, J., Gutowski, J., Krobicki, M., Matyja, B.A., Pieńkowski, G., Uchman, A. (eds), Field trip guidebook. 7th International Congress on the Jurassic System, Kraków, Poland. Polish Geological Institute, Warszawa, pp. 143–144.

Matyszkiewicz, J. 1997. Microfacies, sedimentation and some aspects of diagenesis of Upper Jurassic sediments from the elevated part of the Northern peri-Tethyan Shelf: a comparative study on the Lochen area (Schwäbische Alb) and the Cracow area (Cracow– Wielun Upland, Poland). Berliner Geo Abh E 21:1–111.

Matyszkiewicz, J. 1999. Sea-bottom relief versus differential compaction in ancient platform carbonates: a critical reassessment of an example from Upper Jurassic of the Cracow–Wieluń Upland. Annales Societatis Geologorum Poloniae, 69: 63–79.

Matyszkiewicz, J., Krajewski, M. 1996. Lithology and sedimentation of Upper Jurassic massive limestones near Bolechowice, Kraków-Wieluń Upland, south Poland. Ann Soc Geol Polon., 66: 285–301.

Matyszkiewicz, J., Kochman, A. 2016. Pressure dissolution features in Oxfordian microbial-sponge buildups with pseudonodular texture, Kraków Upland, Poland. Annales Societatis Geologorum Poloniae, 86: 355–377.

Matyszkiewicz, J., Gadomska, A., Porębska, E. 2001. Upper Jurassic carbonate buildups from the Ogrodzieniec area. Zeszyty Naukowe AGH, Geologia, 27: 219-241. (in Polish with English summary).

Matyszkiewicz, J., Krajewski, M., Kędzierski, J. 2006. Origin and evolution of an Upper Jurassic complex of carbonate buildups from Zegarowe Rocks (Kraków–Wieluń Upland, Poland). Facies, 52: 249–263.

Matyszkiewicz, J., Kochman, A., Duś, A. 2012. Influence of local sedimentary conditions on development of microbialites in the Oxfordian carbonate buildups from the southern part of the Kraków-Częstochowa Upland (south Poland). Sedimentary Geol., 263-264: 109–132.

Matyszkiewicz, J., Kochman, A., Rzepa, G., Gołębiowska, B., Krajewski, M., Gajdzik, K., Żaba, J. 2015. Epigenetic silicification of the Upper Oxfordian limestone in the Sokole Hills (Kraków-Częstochowa Upland): relationship to facies development and tectonics. Acta Geologica Polonica, 65: 181–203.

Matyszkiewicz, J., Krajewski, M., Kochman, A., Kozłowski, A., Duliński, M. 2016. Oxfordian neptunian dykes with brachiopods from the southern part of the Kraków-Częstochowa Upland (southern Poland) and their links to hydrothermal vents. Facies, 62: 1–28.

Mazur, S., Scheck-Wenderoth, M., Krzywiec, P. 2005. Different modes of the Late Cretaceous–Early Tertiary inversion in the North German and Polish basins, Int. J. Earth Sci., 94, 782–798.

Misiarz P., Jędrzejowska-Tyczkowska, H., Oszczypko, N., Golonka, J., Olszewska, B., Matyszkiewicz, J. 2004. Oxfordian bioherms from the central part of the Carpathian foreland (Poland) - seismic modeling results. Proceedings of the AAPG Regional Conference with GSA, Prague, Czech Republic, pp. 94.

Myśliwiec, M., Borys, Z., Bosak, B., Liszka, B., Madej, K., Maksym, A., Oleszkiewicz, K., Pietrusiak, M., Plezia, B., Staryszak, G., Świętnicka, G., Zielińska, C., Zychowicz, K., Gliniak, P., Florek, R., Zacharski, J., Urbaniec, A., Górka, A., Karnkowski P., Karnkowski, P.H. 2006. Hydrocarbon resources of the Polish Carpathian Foredeep: Reservoirs, traps, and selected hydrocarbon fields. In: Golonka, J, Picha, F.J. (Eds.), The Carpathians and their foreland: Geology and hydrocarbon resources. AAPG Memoir, 84: 351–393.

Neuhaus, D., Borgomano, J., Jauffred, J.-C., Mercadier, C., Olotu, S., Grötsch, J. 2004. Quantitative seismic reservoir characterization of an Oligocene–Miocene carbonate buildup: Malampaya field, Philippines. In: Eberli et al. (Eds.), Seismic imaging of carbonate reservoirs and systems: AAPG Memoir, 81: 169–183.

Nieto, L.M., Reolid, M., Molina, J.M., Ruiz-Ortiz, P.A., Jiménez-Millán, J., Rey, J. 2012. Evolution of pelagic swells from hardground analysis (Bathonian-Oxfordian, Eastern External Subbetic, southern Spain). Facies, 58: 389–414.

Olchowy, P. 2011. Possible origin of stromatactis-like cavities in Upper Jurassic sediments from the Wielkanoc quarry near Gołcza (Kraków-Częstochowa Upland, southern Poland) –experimental studies. Facies, 57: 613–625.

Olchowy, P., Krajewski, M. 2020. Lower Kimmeridgian facies and sedimentary succession of a shallow-water coated-grain-dominated carbonate ramp of the northern peri-Tethyan shelf: an example from the Radomsko Folds (central Poland). Geol Quart., 64: 969–987.

Olchowy, P., Krajewski, M., Felisiak, I. 2019. Late Jurassic facies succession of the Kleszczów Graben area (southern border of the Łódź Depression, peri-Tethyan shelf, central Poland). Geol Quart., 63: 657–681.

Pawelec, H. 2011. Periglacial evolution of slopes — Rock control versus climate factors (Cracow Upland, S. Poland) Geomorphology, 132: 139–152.

Pharaoh, T.C., Dusar, M., Geluk, M.C., Kockel, F., Krawczyk, C.M., Krzywiec, P., Scheck-Wenderoth, M., Thybo, H., Vejbæk, O.V. van Wees, J.D., 2010. Tectonic Evolution. – In: Doornenbal, J.C. and Stevenson, A.G. (Eds): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten): 25-57.

Philips, T., Jackson, C.A.L., Bell, R., Valencia, A. 2020. Rivers, reefs, and deltas; Geomorphological evolution of the Jurassic of the Farsund Basin, offshore southern Norway. Petroleum Geoscience, 26: 81–100.

Piwocki, M., 2004. Paleogen. In: Peryt, T.M., Piwocki, M. (Eds): Budowa Geologiczna Polski, Stratygrafia, Kenozoik, I (3a). Polish Geological Institute, Warsaw, 22–71 (in Polish).

Piwocki, M., Badura, J., Przybylski, B., 2004. Neogen. [in]: Peryt, T.M., Piwocki, M. (Eds): Budowa Geologiczna Polski, Stratygrafia, Kenozoik, I (3a). Polish Geological Institute, Warsaw, 71–118 (in Polish).

Posamentier, H. W., Laurin, P., Warmath, A., Purnama, M., Drajat, D. 2010. Seismic stratigraphy and geomorphology of Oligocene to Miocene carbonate buildups offshore Madura, Indonesia. In: Morgan et al. (Eds.), Cenozoic carbonate systems of Australasia. SEPM Spec. P., 95: 175–194.

Pożaryski, W. (ed.) 1979. Geological Map of Poland and Surrounding Countries without Cenozoic (Carpathians without Quaternary), 1:1000000. Wydawnictwa Geologiczne, Warszawa.

Pratt, B. R. 1982. Stromatolitic framework of carbonate mud-mounds. Journal of Sedimentary Petrology, 52: 1203–1227.

Rafaelsen, B., Elvebakk, G., Andreassen, K., Stemmerik, L., Colpaert, A., Samuelsberg, T. J. 2008. From detached to attached carbonate buildup complexes — 3D seismic data from the upper Palaeozoic, Finnmark Platform, southwestern Barents Sea, Sediment. Geol., 206: 17–32.

Rankey, E. C., Schlaich, M., Mokhtar, S., Ghon, G., Ali, S. H., Poppelreiter, M. 2019. Seismic architecture of a Miocene isolated carbonate platform and associated off-platform strata (Central Luconia Province, offshore Malaysia), Mar. Petrol. Geol., 102, 477–495.

Read J.F. 1985. Carbonate Platform Facies Models. AAPG Bulletin, 69: 1–21.

Resak, M., Narkiewicz, M., Littke, R. 2008. New basin modelling results from the Polish part of the Central European Basin system: implications for the Late Cretaceous-Early Paleogene structural inversion. Intern. Jour. Earth Sci., 97: 955-972.

Riding, R. 2002. Structure and composition of organic reefs and carbonate mud mounds: Concepts and categories. Earth Sci Rev, 58: 163–231.

Roniewicz, E., Roniewicz, P. 1971. Upper Jurassic coral assemblages of the Central Polish Uplands. Acta Geologica Polonica, 21: 399–424.

Rühle, E., Ciuk, E., Osika, R., Znosko, J. 1977. Mapa geologiczna Polski bez osadów czwartorzedowych 1:500 000. Inst. Geol. (in Polish)

Sarg J.F. 1988. Carbonate Sequence Stratigraphy. SEPM Spec. Publ., 42: 155–182.

Saqab, M. M., Bourget, J. 2016. Seismic geomorphology and evolution of early mid Miocene isolated carbonate build-ups in the Timor Sea, North West Shelf of Australia, Mar. Geol., 369, 224–245.

Scheck-Wenderoth, M., Krzywiec, P., Zuhlke, R., Maystrenko, Y., Froitzheim, N. 2008. Permian to Cretaceous tectonics. In: McCann, T. (Ed.), The Geology of Central Europe Volume 2: Mesozoic and Cenozoic.The Geological Society of London, pp. 999–1030.

Schmid, D.U., Leinfelder, R.R., Nose, M. 2001. Growth dynamics and ecology of Upper Jurassic mounds, with comparisons to Mid-Palaeozoic mounds. Sediment Geol., 145: 343–376.

Schlager W. 2002. Sedimentology and Sequence Stratigraphy of Carbonate Rocks. Short course in carbonate sedimentology. Vrije Universiteit/Earth and Life Sciences, Amsterdam.

Schlager W. 2005. Carbonate Sedimentology and Sequence Stratigraphy. SEPM Concepts in Sedimentology and Paleontology Series no. 8., Tulsa.

Scholle P.A., Bebout D.G., Moore, C.H. 1983. Carbonate depositional environments. AAPG Memoir 33, Tulsa.

Senowbari-Daryan, B., Bucur, I.I., Schlagintweit, F., Săsarăn, E., Matyszkiewicz, J. 2008. Crescentiella, a new name for “Tubiphytes” morronensis Crescenti 1969: an enigmatic Jurassic–Cretaceous microfossil. Geol Croatica., 61:185–214.

Shahzad, K., Betzler, C., Ahmed, N., Qayyum, F., Spezzaferri, S., Qadir, A., 2018. Growth and demise of a Paleogene isolated carbonate platform of the Offshore Indus Basin, Pakistan: effects of regional and local controlling factors. Int. J. Earth Sci. (Geol Rundsch), 107: 481–504.

Shahzad, K., Betzler, C., Qayyum, F. 2019. Controls on the Paleogene carbonate platform growth under greenhouse climate conditions (Offshore Indus Basin). Mar. Petrol. Geol., 101: 519–539.

Słonka, Ł., Krzywiec, P. 2020a. Upper Jurassic carbonate buildups in the Miechów Trough, southern Poland – insights from seismic data interpretations. Solid Earth, 11: 1097–1119.

Słonka, Ł., Krzywiec, P. 2020b. Seismic characteristics and development of the Upper Jurassic carbonate buildups from the Miechów Trough (Southern Poland): Geosciences, 10: 1–32.

Słonka, Ł., Krajewski M., Krzywiec, P. 2024. Seismic modelling of the Upper Jurassic subsurface carbonate buildups in southern Poland – verification of their internal structure supported by the outcrop analogs and estimation of the influence of pull-up artifacts on seismic data interpretation. AAPG Europe Region Conference 2024, Krakow, Poland.

Sralla, B., Csizmeg, J. 2024. Late Miocene Compressional Reactivation of Mesozoic Half-Grabens in the Ukrainian Carpathian Foreland Basin: Insights from Seismic Surveys. AAPG Europe Region Conference 2024, Krakow, Poland

Stephenson, R.A., Narkiewicz, M., Dadlez, R., Van Wees, J-D., Andriessen, P. 2003. Tectonic subsidence modelling of the Polish Basin in the light of new data on crustal structure and magnitude of inversion. Sedimentary Geology, 156: 59–70.

Teillet, T., F. Fournier, J. Borgomano, and F. Hong, 2020, Origin of seismic reflections in a carbonate gas field, Lower Miocene, offshore Myanmar: Mar. Petrol. Geol, 113: 104110.

Trammer, J. 1989. Middle to Upper Oxfordian sponges of the Polish Jura. Acta Geol Polon., 39: 49–91.

Trammer, J., 1982. Lower to Middle Oxfordian sponges of the Polish Jura. Acta Geologica Polonica, 32: 1–39.

Tyc, A. 2024. Kraków-Częstochowa Upland – Monadnocks amd Relic Caves. In: Migoń, P., Jancewicz, K. (Eds.), Landscapes and Landform of Poland. Springer 385-401 p.

Urbaniec, A. 2019. Lithofacial development of the Upper Jurassic and Lower Cretaceous deposits in the Dąbrowa Tarnowska-Dębica area based on the 3D seismic interpretation. Unpublished PhD Thesis (in Polish only). Faculty of Geology, Geophysics and Environmental Protection of AGH, Kraków.

Van Tuyl, J., Alves, T. M., Cherns, L. 2018. Geometric and depositional responses of carbonate build-ups to Miocene sea level and regional tectonics offshore northwest Australia. Mar. Petrol. Geol., 94: 144–165.

Van Tuyl, J., Alves, T., Cherns, L., Antonatos, G., Burgess, P., Masiero, I. 2019. Geomorphological evidence of carbonate build-up demise on equatorial margins: A case study from offshore northwest Australia, Mar. Petrol. Geol., 104: 125–149.

Veeken, P., Van Moerkerken, B. 2013. Seismic Stratigraphy and Depositional Facies Models. EAGE Publications, Houten, 494 pp.

Voigt, T., Kley, J., Voigt, S. 2021, Dawn and dusk of Late Cretaceous basin inversion in central Europe. Solid Earth, 12, 1443–1471

Wierzbowski, A .2017. The Lower Kimmeridgian of the Wieluń Upland and adjoining regions in central Poland: Lithostratigraphy, ammonite stratigraphy (upper Planula/Platynota to Divisum zones), palaeogeography and climate-controlled cycles. Volumina Jurassica, 2017, 15: 41–120.

Woźniak, T., Bania, G., Mościcki, W.J., Ćwiklik, M. 2018. Electrical resistivity tomography (ERT) and sedimentological analysis applied to investigation of Upper Jurassic limestones from the Krzeszowice Graben (Kraków Upland, southern Poland). Geol Quart., 62: 287–302.

Wu., S., Yuan, S., Zhang, G., Ma, Y., Mi, L., Xu, N. 2009. Seismic characteristics of a reef carbonate reservoir and implications for hydrocarbon exploration in deepwater of the Qiongdongnan Basin, northern South China Sea. Mar. Petrol. Geol., 26: 817–823.

Zampetti, V., Schlager, W., van Konijnenburg, J. H., Everts, A. J. 2004. Architecture and growth history of a Miocene carbonate platform from 3D seismic reflection data; Luconia Province, offshore Sarawak, Malaysia. Mar. Petrol. Geol., 21: 517–534.

Ziegler, P.A. 1990. Geological Atlas of Western and Central Europe, 2nd edition. Shell Internationale Petroleum Maatschappij B.V. and Geological Society Publishing House, Bath, 239 pp.

Ziółkowski, P., 2007. Stratygrafia i zróżnicowanie facjalne górnej jury wschodniej części Wyżyny Krakowskiej. Tomy Jurajskie, 4: 25– 38. (in Polish)

Złonkiewicz, Z. 2006. Evolution of the Miechów Depression basin in the Jurassic as a result of regional tectonical changes. Prz Geol., 54: 534–540 (in Polish with English summary).

Złonkiewicz, Z. 2009. The Callovian and Upper Jurassic section in the Nida Trough. Prz Geol., 57: 521–530. (in Polish with English summary)

Żaba, J. 1999. The structural evolution of Lower Paleozoic succession in the Upper Silesia Block and Małopolska Block border zone, southern Poland (in Polish with Engish summary). Prace Państwowego Instytutu Geologicznego, 166: 1–162.

Żelaźniewicz, A., Aleksandrowski, P., Buła, Z., Karnkowski, P.H., Konon, A., Oszczypko, N., Ślączka, A., Żaba, J,, Żytko, K. 2011. Regionalizacja tektoniczna Polski (in Polish). Komitet Nauk Geologicznych PAN, Wrocław (in Polish with English summary).

Żytko K., Gucik, S., Ryłko, W., Oszczypko, N., Zając, R., Garlicka, I., Nemčok, J., Elias, M., Mencik, E., Dvorak, J., Stranik, Z., Rakus, M., Matejovska, O. 1988. Geological map of the Western Outer Carpathians and their foreland without Quaternary formations (1:500 000). In: Poprawa, D., Nemčok, J. (Eds.), Geological Atlas of the Western Outer Carpathians and their Foreland. Polish Geological Institute, Warszawa, Poland.

Web Pages:

Carbonate Facies, SEPM Strata:
http://www.sepmstrata.org/page.aspx?pageid=90

Europe Regional Conference
28-29 May 2024 | Krakow, Poland

AAPG