Geologia Sudetica, 2008, 40: 19–31.

Lower Carboniferous bentonites in the Bardo Structural Unit (central Sudetes): geological context, petrology and palaeotectonic setting

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Key words: bentonite, zircon, SHRIMP geochronology, Viséan, Bardo Unit, Sudetes.

Abstract The Lower Carboniferous Paprotnia beds of the Bardo Structural Unit in the central Sudetes, composed predominantly of mudstones with Upper Viséan fossils, include several bentonite layers. The bentonites, composed mainly of kaolinite, illite/smectite and smectite, with minor amounts of quartz, calcite and iron hydroxides, also contain abundant zircons, the features of which indicate their volcanic derivation. The main population of the zircons yielded a SHRIMP U-Pb age of ~ 334 Ma corresponding with, and numerically constraining, the biostratigraphic data. The field evidence, biostratigraphic and geochronological results, together with mineralogical data from the bentonites, indicate continental margin-type sedimentation and contemporaneous volcanic (andesitic-rhyolitic) activity in the neighbouring region during the ongoing Variscan orogeny in central Europe in Late Viséan times.

Manuscript received 9 June 2008, accepted 24 November 2008

INTRODUCTION

Volcanic eruptions are recorded in the stratigraphic successions throughout the Carboniferous and Permian in central Europe, reflecting intense tectonothermal and magmatic activities during the Variscan orogeny. We find these records in molasse-fill intramontane and foreland basins, and in marine sedimentary successions. Apart from their palaeoenvironmental and palaeotectonic signature, the volcanic materials often provide a reliable tool for geochronological studies and, thus, for chronostratigraphic control of orogeny-related geological processes.

Special attention is attracted by fall-out tephras that can be preserved in sedimentary sequences as tonsteins and bentonites. They are mainly composed of secondary clay minerals (mostly after devitrified volcanic glass particles), with minor primary volcanic components and, consequently, they often are of economic interest as regards their specific clay content. However, typically, they also contain accessory volcanic minerals, including zircon and apatite, useful for geochronology and thus for constraining the age of volcano-sedimentary processes.

Volcaniclastic deposits, including bentonites and sedimentary rocks generally referred to as tuffites, have been reported from Silurian through Carboniferous successions in the Sudetes at the NE edge of the Bohemian Massif (Fig. 1; Porębska & Koszowska, 2001; August *et al.*, 2003). However, in most cases, they have not yet been systematically studied.

This paper describes the bentonites in the Upper Viséan Paprotnia beds (called the "Paprotnia series" in earlier works; Haydukiewicz & Muszer, 2002) in the western part of the Bardo Structural Unit (Żelaźniewicz & Aleksandrowski, 2008; hereafter, for simplicity, the Bardo Unit) in the central Sudetes, SW Poland. The distribution of the bentonite layers is shown against a detailed litho-s tratigraphic log. Mineralogical and geochemical characteristics are given to establish the primary nature of these deposits. The biostratigraphic and isotopic age constraints (described in detail in a separate paper, Kryza *et al.*, 2009, in prep.) are referred to, as well as palaeoenvironmental evidence, to propose a general palaeotectonic scenario of the late Viséan basin in which the bentonites of the Paprotnia beds were deposited, within the framework of the ongoing Variscan orogeny and associated volcanic activity.

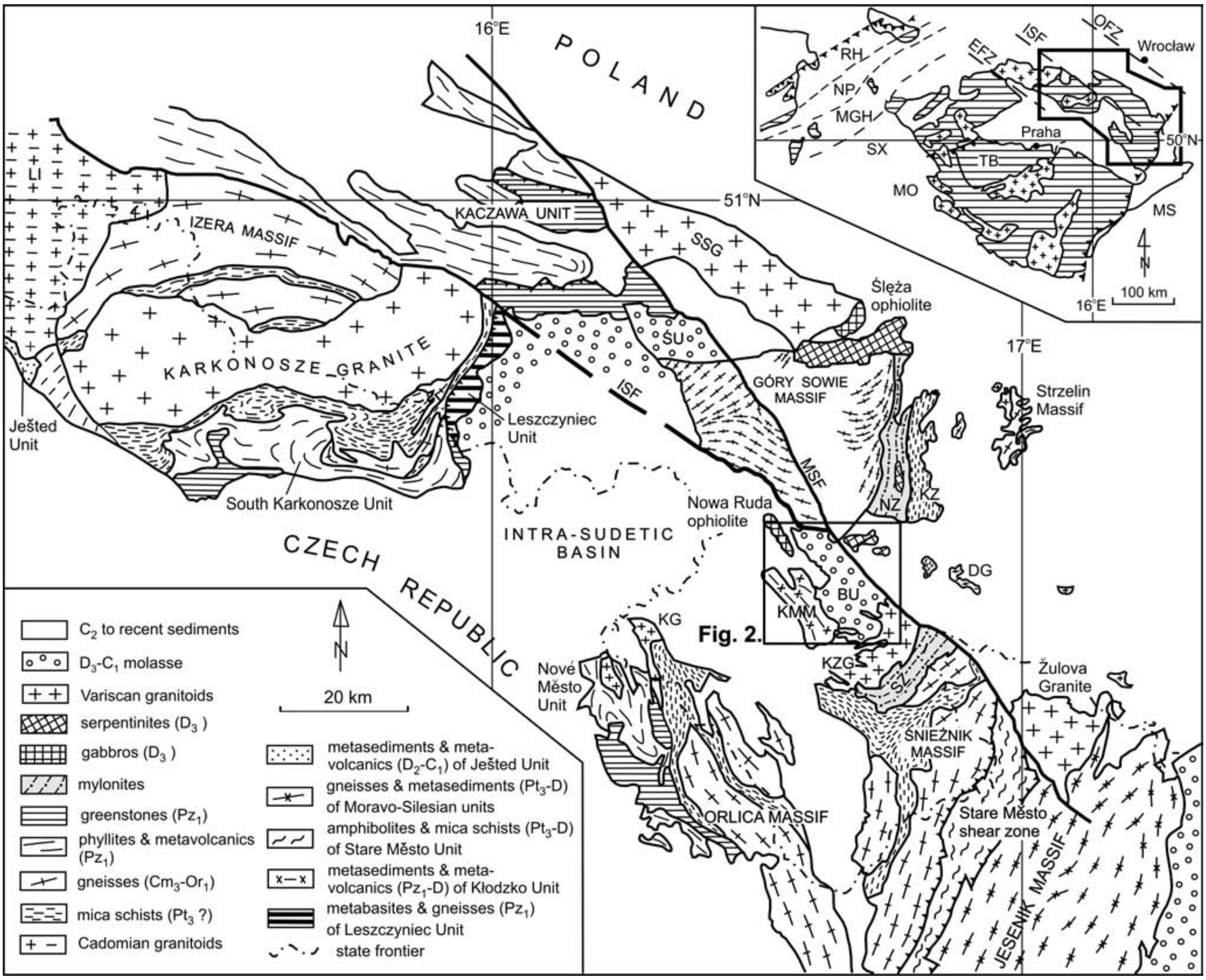


Fig. 1. Geological sketch map of the Sudetes (modified from Aleksandrowski *et al.*, 1997; unit and structure names after Żelaźniewicz & Aleksandrowski, 2008). BU – Bardo Structural Unit; ISF – Intra-Sudetic Fault; KMM – Kłodzko Metamorphic Massif; KZG – Kłodzko-Złoty Stok Granite Pluton; KZ – Kamieniec Ząbkowicki Metamorphic Belt; LI – Lusatia-Izera Massif; NZ – Niemcza Shear Zone; MSF – Marginal Sudetic Fault; SSG – Strzegom-Sobótka Granite Pluton; SZ – Skrzynka Shear Zone; ŚU – Świebodzice Structural Unit. Inset: hachure – pre-Permian crystalline rocks; EFZ – Elbe Fault Zone; ISF – Intra-Sudetic Fault; MGH – Mid-German Crystalline High; MO – Moldanubian Zone; MS – Moravo-Silesian Zone; NP – Northern Phyllite Zone; OFZ – Odra Fault Zone; RH – Rhenohercynian Zone; SX – Saxothuringian Zone. Age assignments: Pt – Neoproterozoic; Cm – Cambrian; Or – Ordovician; D – Devonian; C – Carboniferous; Pz – Early Palaeozoic. Rectangle shows the location of Fig. 2.

GEOLOGICAL SETTING AND THE LITHOSTRATIGRAPHY OF THE BARDO SUCCESSIONS

The Bardo Unit in the central Sudetes (Fig. 1) is composed of Palaeozoic allochthonous and autochthonous/parautochthonous sedimentary successions (Wajsprych, 1986, 1995). The allochthonous succession contains large olistoliths of Lower Palaeozoic (Ordovician and Silurian) and Devonian deep marine strata, embedded in Viséan wildflysh (Haydukiewicz, 1990), whereas the autochthonous/parautochthonous succession is composed of Upper Devonian – Lower Carboniferous strata (Fig. 2), capped by the flysch deposits. The autochthonous succession is interpreted to represent sedimentation in an evolving intramontane or continental-margin basin during the Variscan orogeny. The succession was folded at the turn of the Early/Late Carboniferous into E–W trending folds and subsequently refolded during the Late Carboniferous into NE–SW trending folds (Oberc, 1972).

The lithostratigraphic log of the Bardo autochthonous/parautochthonous successions (Fig. 3) is composed, according to Wajsprych (1995), of several informal units: formations, "series" and sequences. Although their age is based on palaeontological data, the reconstruction of the primary stratigraphic succession is difficult because of the complicated tectonic framework. The oldest sedimentary rocks in the autochthonous succession, the Wapnica For-

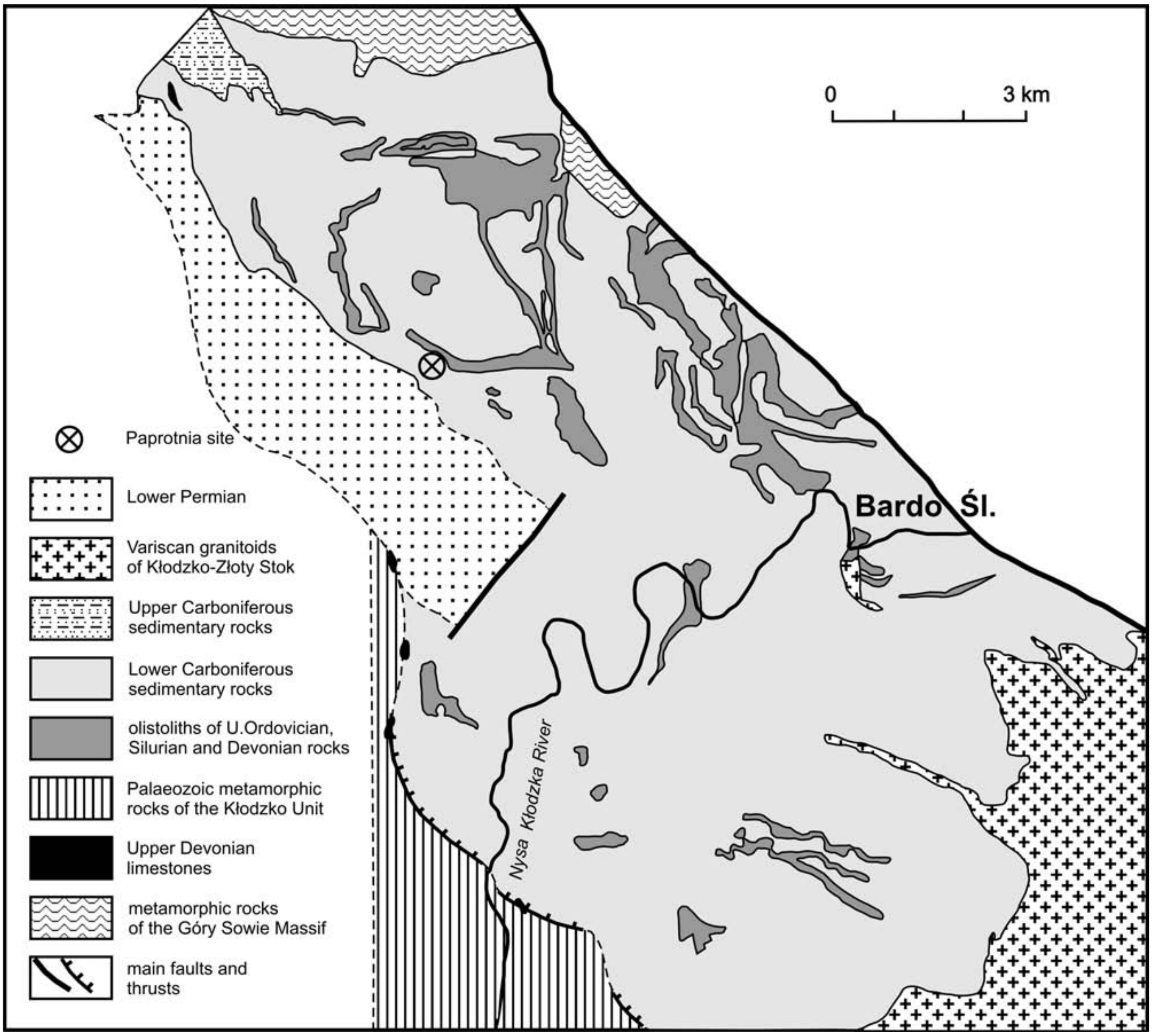


Fig. 2. Geological map of the Bardo Structural Unit and location of the Paprotnia site (based on Oberc, 1957 and Haydukiewicz & Muszer, 2002).

mation (Fig. 3), are represented by marine carbonates (gabbro and limestone breccia, basal limestone, main limestone, and Clymenia and Gattendorfia limestones); they range in age from the Upper Devonian (the lower part of this succession probably represents Frasnian, whereas the overlaying main and Clymenia limestones belong to the Famennian – from *marginifera* to the Lower *praesulcata* conodont zones; see Haydukiewicz, 1990) to the Lower Tournaisian (*Gattendorfia* stage; Weyer, 1965; Dzik, 1997). They are about 60 meters thick and occur only in some isolated outcrops along the western edge of the Bardo Unit (Fig. 2). The next lithostratigraphic unit is the Gołogłowy Formation – fragmentarily preserved as dark gray or black siliceous and clayey shales, up to several centimeters thick. They contain early Tournaisian conodonts (Haydukiewicz, 1990). These shales are overlain by the Nowa Wieś Formation and the Wojbórz Formation, the latter composed mainly of calcareous deposits, formerly known as the "Kohlenkalk" limestone (Oberc, 1957, and references therein). The Nowa Wieś Formation is found only in the northern part of the Bardo Unit and is composed of coarse-grained turbidite siliciclastic- to boulder-bearing mass-flow deposits, containing both crystalline (mostly gneiss) and carbonate (mostly bioclastic limestone) clasts (Wajsprych, 1995). The Nowa Wieś Formation is more than 300 m thick and it is of early Carboniferous age, from the late Tournaisian to early Viséan, documented by conodonts and foraminifers (Głuszek & Tomaś, 1993; Chorowska & Radlicz, 1994). A stratigraphic equivalent of this unit in central part of the Bardo Unit is probably the Wojbórz Formation, composed of lithic breccias with intercalations of bioclastic limestone and volcaniclastic breccias (Wajsprych, 1995).

According to Wajsprych (1995), the probable next lithostratigraphical unit is the "Winna Góra sequence", which consists of several varied facies, one of them being

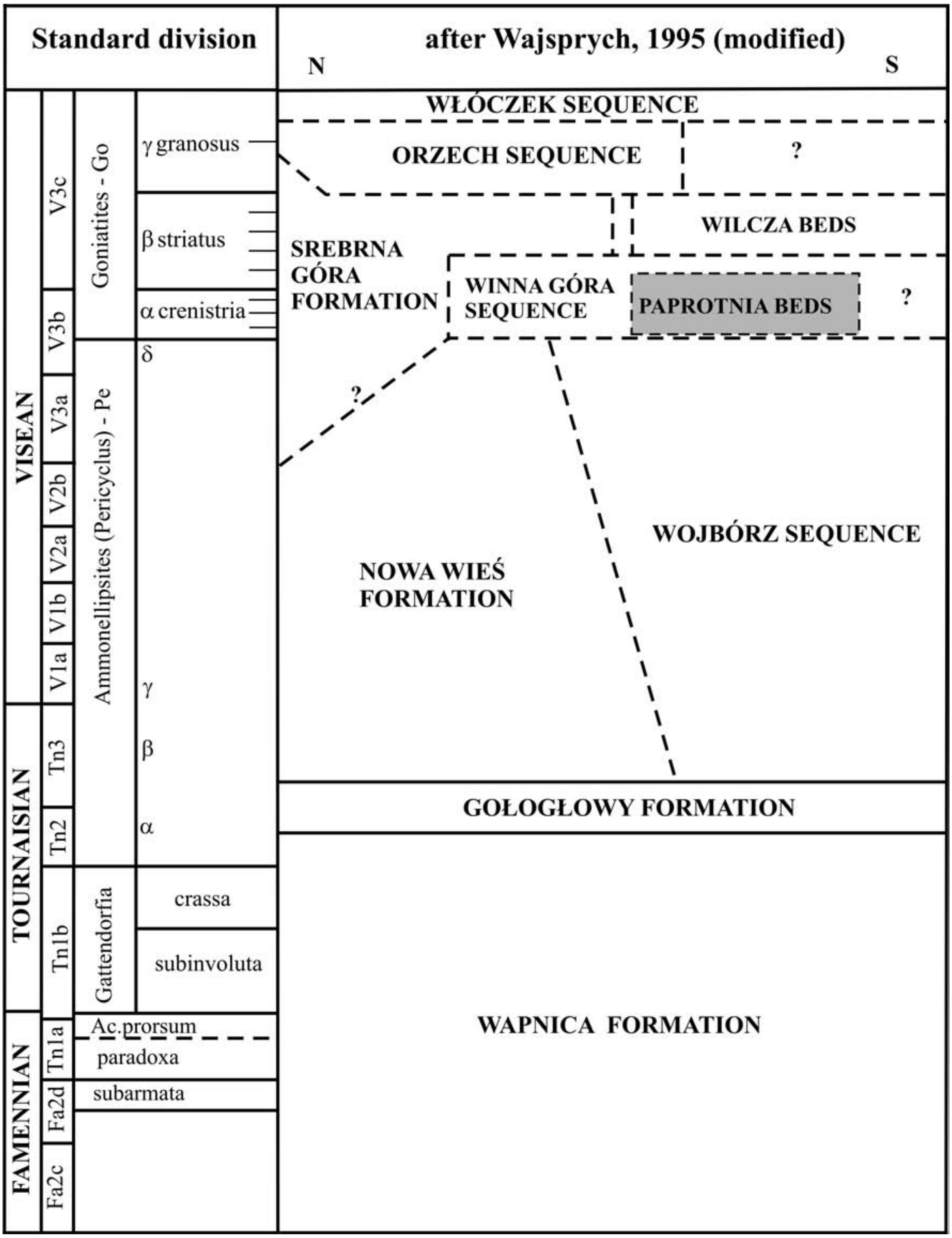
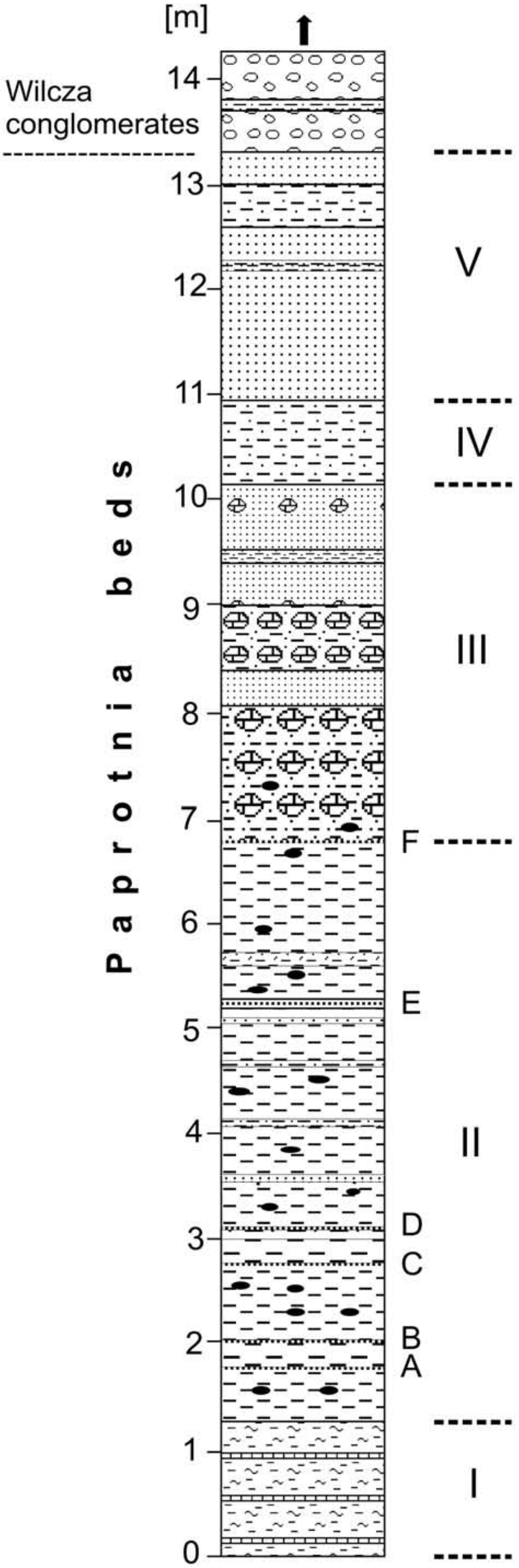


Fig. 3. Generalized lithostratigraphic scheme of the Bardo autochthonous/parautochthonous successions (according to Wajsprych, 1995, modified).

called the Paprotnia beds. The Paprotnia beds occur only in the western part of the Bardo Unit (Fig. 2) and it is composed of claystones in its lower part, and mudstones and greywackes in its middle and upper part. Carbonate intercalations are subordinate. The deposits contain abundant benthic fossils, whereas nektonic species are less numerous. The palaeontological record indicates that the Paprotnia beds belong to the ammonoid *G. crenistria* zone, which corresponds with the Asbian (regional substage) of the Upper Viséan (V3b) (Haydukiewicz & Muszer, 2002). The Paprotnia beds contain several thin (2–10 cm) bentonite layers (Haydukiewicz & Muszer, 2002). This unit is overlain by polymictic conglomerates with sandstone and mudstone intercalations of the Wilcza beds (Figs 3, 4; Wajsprych, 1995).



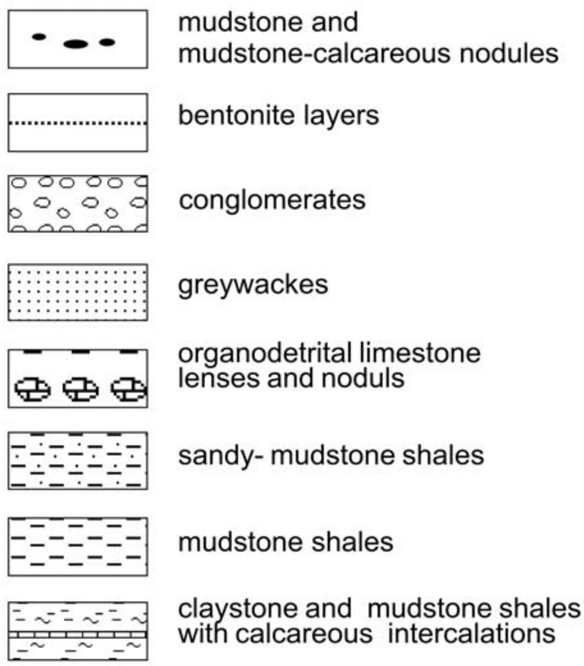


Fig. 4. The Paprotnia section – lithological column and distribution of taphocoenoses (designated as I – V). A – G = bentonite layers. (based on Haydukiewicz & Muszer, 2002).

The Srebrna Góra Formation, up to 450 m thick, and representing the allochthonous succession (Fig. 3) is found only in the north-eastern part of the Bardo Unit (Wajsprych, 1995). It is described as a flysch and wildflysch sequence composed of lithologies of the Zdanów-Bardo-Młynów "subcomplex" (Wajsprych, 1986, 1995). The assumed middle- or upper Viséan age of the Srebrna Góra Formation is based on the underlying and paleontologically documented Nowa Wieś Formation (Chorowska & Radlicz, 1994) of the autochthonous succession, and on the last finding of the strobilus (*Flemingites* or *Lepidostrobus*) in a clayey-mudstone bed of the Srebrna Góra Formation (Muszer & Haydukiewicz, 2006). According to Wajsprych (1995), a range of features (e.g. pebble composition, presence of specific lithological slabs, slide sheets and olistoliths) suggest a correlation of the Wilcza beds with the Srebrna Góra Formation.

The Srebrna Góra wildflysch is overlain by the Orzech "sequence", which is the higher flysch unit, but composed mostly of volcaniclastic material (Wajsprych, 1995). The uppermost lithostratigraphic unit in the northern part of the Bardo Unit is the Włóczek "sequence" (Fig. 3), composed of terrigenic sedimentary material (*see* Wajsprych, 1995), which is probably uppermost Viséan in age.

METHODS

Our detailed studies of the bentonites refer to the previous field and stratigraphical investigations carried out by Haydukiewicz and Muszer, and the stratigraphic methods used were described in the previous paper (Haydukiewicz & Muszer, 2002).

Several bentonite samples (~ 1 kg each) from all six bentonite layers (designated as A to F on Fig. 4) in the Paprotnia beds were collected for mineralogical and petrographic investigations. The mineralogical investigations of the bentonites included X-ray diffraction (SIEMENS D5005, Co radiation, Fe filter) and complex thermal analysis: DTA, TGA, DTG (DERIVATOGRAPH 1500Q). Separation of the clay fraction and treatment with glycol were done following Jackson's procedure (Kulesza-Wiewióra & Wojciechowski, 1980). The smectite proportion in illite/smectite (I/S) minerals and their ordering were measured based on the relative intensity of peaks (002) and (003), using Środoń's (1984) method. The paleotemperatures of clay mineral formation were calculated according to Šucha *et al.* (1993).

The heavy mineral fraction was separated using the conventional heavy liquid (sodium polytungstate) procedure. Careful examination under the polarizing microscope (Jurasik, 2006) helped to select one sample (A) for SHRIMP dating.

Here, we present the results of field studies (referring also to the earlier published data), mineralogical and petrological characteristics of the bentonites, biostratigraphic and geochronological age constraints and, finally, the palaeoenvironmental and palaeotectonic scenario within the framework of Variscan orogenic and volcanic activity. The geochronological data and their stratigraphic inferences are discussed in a separate paper (Kryza *et al.*, 2009, in prep.).

RESULTS

Field observations

The best exposure of the Paprotnia beds is located in the western part of the Bardo Unit (Fig. 2). As yet, these beds have not been documented in the eastern and southern parts of the Bardo Unit, so they might be buried there under the allochthonous successions (Wajsprych, 1995). The section studied is exposed on the southern slope of Papro- tnia hill, about 1.5 km east of the village of Czerwieńczyce, in the road-escarpment of the path from Czerwieńczyce to Wojbórz.

The exposed section of the Paprotnia beds, about 13.7 m thick (Fig. 4), are mainly composed of shales (claystone and mudstone), greywackes and subordinate carbonates. Six intercalations of thin pale-yellow bentonite layers were also observed in several horizons. The strata dip at 50-60° to the north. Unfortunately, the contact with the underlying succession is not exposed. In the topmost part of the section, the Paprotnia beds pass gradually into polymictic conglomerates of the Wilcza beds (Fig. 3; Wajsprych, 1995), apparently heralding the allochthonous successin.

The lowermost part of the section comprises greenish-grey and grey clayey and silty shales. Their individual layers are several centimetres thick; some of them are thin laminated. The shales are mainly composed of quartz, feldspars, chlorite, clay minerals and calcite. A few intercalations of thin dark-grey micritic limestone (beds up to 3 cm thick) occur within the shales. These deposits are overlain by dark-grey and dark-olive shales. Upwards, they are intercalated with thin (2–4 cm) layers of grey claystones and greywackes. In this part of the section, six bentonite layers, assigned as A–F, and 1–10 cm thick, were ascertained (Fig. 4). Also, irregularly distributed small mudstone nodules can be found within the 5.3 m thick shale package.

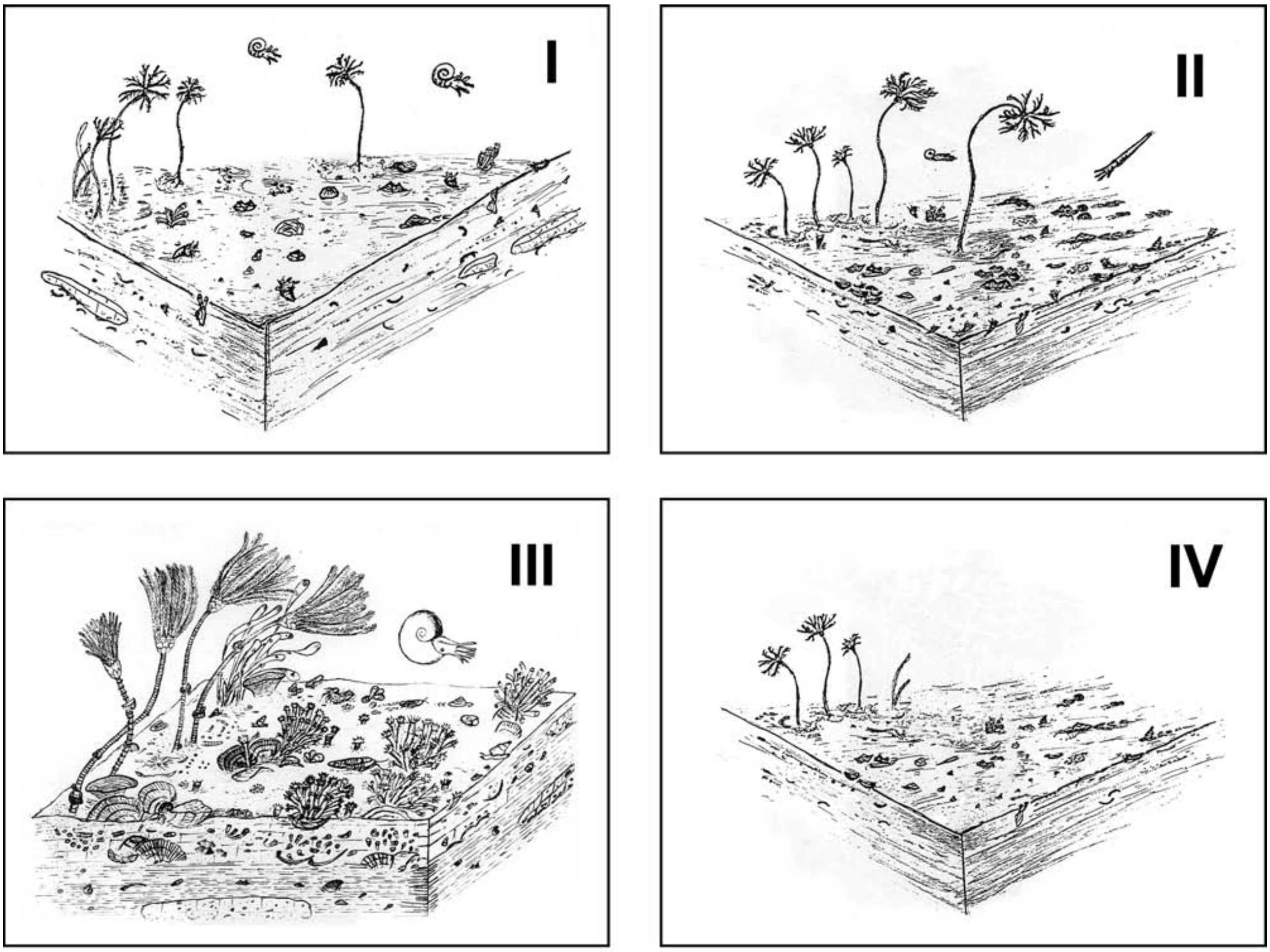
The middle part of the section comprises sandy-muddy shales and greywackes with lenses and nodules of dark-grey organodetrital limestones, which usually form distinct horizons. The abundance of the carbonate lenses sharply decreases upwards. In most cases, the lower part of a given lens is composed of bioclastic packstone, whereas its upper part consists of poorly fossiliferous fine-grained wackestone. The lenses are up to 40 cm thick.

The middle part of the section is overlain by greywackes containing rare sandy and muddy shale intercalations. These greywackes terminate the Paprotnia beds and are overlain by the polymictic Wilcza conglomerates (Fig. 4).

Biostratigraphic evidence – a review

The Paprotnia beds contain a very rich palaeontological record, studied earlier by many geologists and palaeontologists (see Schmidt, 1925; Paeckelmann, 1930, 1931; Kuhne, 1930; Górecka, 1958; Żakowa, 1963; Górecka & Mamet, 1970; Fedorowski, 1971). In most cases, these investigations were restricted to determining the species composition of selected systematic groups, and to defining the chronostratigraphical affiliation of their host strata. Only Górecka (1958) and Fedorowski (1971) described the vertical distribution of certain groups (flora and corals) and most abundant other fossils present in this section. More recently, Haydukiewicz and Muszer (2002) studied the beds and their palaeontological record in detail. Analysis of the stratigraphic distribution of the fossils, the character of their accumulation, their state of preservation and their taxonomic composition were used by these authors to reconstruct the environmental conditions under which the organisms might have existed.

The age of the Paprotnia beds were determined based on the findings of brachiopods, goniatites, corals and foraminifers (Schmidt, 1925; Paeckelmann, 1930, 1931; Górecka & Mamet, 1970; Fedorowski, 1971, Haydukiewicz & Muszer, 2002). Goniatites are poorly preserved and most of them represent the genera *Goniatites* and *Nomismoceras*. The presence of *Goniatites crenistria* Phill. is evidence of a Late Viséan age (*IIIa crenistria* dobe) of these deposits (Haydukiewicz & Muszer, 2002). According to



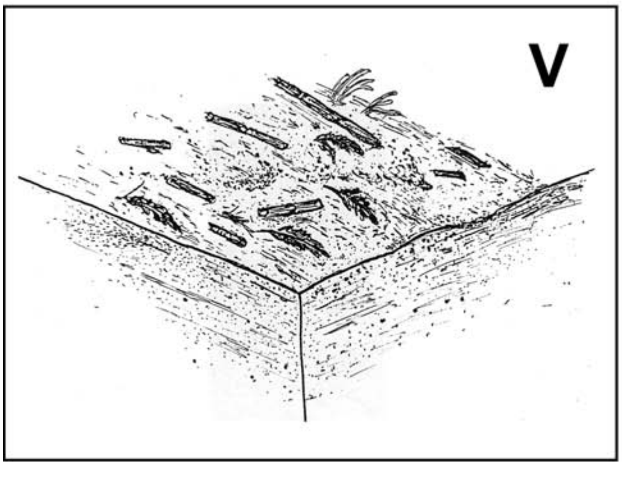


Fig. 5. Models of communities (taphocenoses) in the Paprotnia beds (see text for description). Taphocenoses: I – mid- or outer shelf, oxygen-deficient waters below wave base; II – oxygenated waters, between the storm wave and fair weather wave base; III – turbulent environment, well-oxygenated, warm shallow water of subtidal sea; IV – shallow sea floor, short periods of low-energy interrupted by rapid terrigenic inputs; V – land-proximal environment, short transportation distance.

Górecka & Mamet (1970), foraminifers that occur in this locality are characteristic of the *Archaediscus karreri-Howchinia gibba-Valvulinella youngi* Zone coinciding with the *crenistria IIIa* Zone. Fedorowski (1971), analysing the frequency of various species of rugose coral, recognized a few assemblages that are typical of the D_2 coral zone of the British nomenclature. Furthermore, the sclerotioid grains occurring in these deposits (see Haydukiewicz & Muszer, 2002) have never been found in deposits older than the Upper Viséan (Bless *et al.*, 1976). Consequently, the palaeontological record in total indicates that the beds belongs to the ammonoid *G. crenistria* Zone which corresponds with the Asbian (regional substage) of the Upper Viséan (V3b) (Haydukiewicz & Muszer, 2002).

The macrofossils from the Paprotnia section represent taxonomically diverse benthic and nektonic assemblages (see Haydukiewicz & Muszer, 2002). The rich benthic fauna is clearly dominated by brachiopods and corals (mainly colonial rugosa). Pelecypods, gastropods, fragments of crinoids, bryozoa colonies, and trilobites are common. Numerous ichnofossils, the richness of which increases upwards, are also present. They are mostly rep-

Table 1

General characteristics of the five taphocoenoses defined in the Paprotnia beds
(based on Haydukiewicz & Muszer, 2002)

Taphocoenosis	I	II	III	IV	V
Components	goniatites, orthoconic nautiloids, small spiriferids, thin-shelled chonetids, productids,gastropods, scarce pelcypods, ostracods, foraminifers, algal detritus, calcareous spines, terrestial plant detritus, epifaunal suspension, deposit feeders	solitary rugosa, crinoidal columnals, trilobites, bryozoans, few cephalopods, spiriferids, productids, chonetid valves, foraminifers, ostracods, calcareous algal remains, ichnofossils, sessile epifauna (brachiopods, corals, bryozoans), free-burrowing bivalves, shallow burrowers, rare crinoids, trilobites, gastropods, cephalopods	frequent benthonic organisms, decreasing amount of goniatites and nautiloids, bush corals (*Lithostrotion*, *Diphyphyllum*), productoid valves, brachiopods, chonetids, rare spiriferids, algal debris, ostracods, foraminifers, trace fossils (burrows)	scarce brachiopods, infaunal pelecypods, bryozoans, crinoidal stems, foraminifers, ostracods, small gastropods, calcareous algae detritus, trace fossils (burrows)	plant fossils only, faunal remains absent, asterocalamite stems, lepidodendron, fern leaves and seeds
Dominant lithology	laminated clayey-muddy shales	muddy shales, greywacke intercalations,bentonite layers	mudstones,organodetrital limestone lenses	greywackes,muddy shale intercalations	greywackes
Environment	mid- or outer shelf, oxygen-deficient waters below wave base	oxygenated waters, between the storm wave and fair weather wave base	turbulent environment, well-oxygenated, warm shallow water of subtidal sea	shallow sea floor, short periods of low-energy interrupted by rapid terrigenic inputs	land-proximal environment, short transportation distance

resented by burrows, feeding (fodinichnia) and dwelling (domichnia) traces. Fossils of nektonic organisms, such as goniatites and nautiloids, are less common. The strata of this section also contain microfossils: ostracods, foraminifers, numerous fragments of calcareous algae, different kinds of calcareous tubes and spines (some of them are probably of polychaetid and brachiopod origin). The macrofloral elements (larger fragments of fern leaves and lycopsids, sphenopsid and horsetail stems), diminutive plant debris and sclerotioid grains are distributed in nearly all the lithologies. Small fragments of fossil charcoal are also common throughout this section.

Five taphocoenoses, differing in the relative abundance of particular taxonomic groups and the size and state of preservation of specimens, were described in the the Paprotnia section (Haydukiewicz & Muszer, 2002). Their vertical succession is coincidental with changes in lithology (Fig. 4).

The main components of taphocoenosis I are goniatites and orthoconic nautiloids, small spiriferids, thin-shelled chonetids, productids (*Chonetipustula*), gastropods (*Ptychomphalus*) and scarce pelecypods (mainly *Aviculopecten*, *Streblochondria*, *Protoschizodus*) (Table 1). Terrestial plant detritus with some distinguishable fragmentary horsetail stems and fern leaves are also abundant. The benthic community is mainly represented by epifaunal suspension and deposit feeders, which inhabited a clayey-muddy soft ground.

Taphocoenosis I may have been deposited in mid- or outer shelf conditions. The low taxonomic diversity of this community, the small size of benthic taxa, the thin shells and lack of bioturbation may indicate oxygen-deficient bottom waters (see Kammer *et al.*, 1986). The thinly laminated sediment and lack of signs of transport of the benthic skeletal material suggests a quiet water environment below wave base (Fig. 5).

Taphocoenosis II, compared to the previous one, is enriched in solitary rugose corals, fragments of crinoid columnals, trilobites and bryozoan colonies, whereas the relative abundance of cephalopods decreases (Fig. 5). The fossils of this community are usually irregularly dispersed in a package of shales containing greywacke intercalations and thin bentonite layers. A decrease in the amount of benthic fauna is noticeable within the greystone intercalations (containing only scarce shell debris and plant remains) and in the interval of shales with thin bentonite layers (A–D), and just below the thickest one (E). However, above this last layer, a progressive increase is documented (Haydu- kiewicz & Muszer, 2002).

Taphocoenosis II was most likely accumulated in an environment located between the storm wave and fair weather wave bases, in oxygenated water. The progressive increase in species richness in this taphocoenosis compared to the previous one, the dominance of epifaunal suspension feeders, and the presence of bioturbation in the host sediment may be regarded as evidence of aerobic conditions. The benthic organisms of this taphocoenosis may have existed in an environment with a gradually increasing influx of terrigenic material and bottom water turbulence. Intercalations of greywackes containing only shell debris and floral remains (horsetail stems, fern leaves) may indicate short episodes of rapid clastic delivery from the inshore part of the sedimentary basin. The progressive increase of fossils, recorded above the thickest bentonite layer, may indicate water fertilization, which could lead to intensification of phytoplankton and zooplankton development, which in turn could encourage the growth of suspension-feeders.

The fauna of assemblage III developed in a turbulent environment of well-oxygenated and relatively warm shallow water. The relatively high frequency of particular benthic organisms, the decrease in the amount of goniatites and the gradual disappearance of nautiloids is characteristic of this taphocoenosis (Fig. 5).

The diverse benthic biota, the remnant of which is represented by the fossils of taphocoenosis III, occurring in the middle part of the section, is one which colonized a shallow subtidal sea floor with moderate to periodically higher energy conditions. It can be assumed that the organisms of this community lived in turbulent conditions in shallow well-oxygenated waters, and that the abundance of corals and dasycladales may indicate a relatively warm-water environment.

The organisms of taphocoenosis IV reflect renewed settling of the shallow seafloor during a short period of low energy conditions interrupted by the rapid delivery of a large quantity of terrigenic deposits. It is composed of scarce, diminutive brachiopods, infaunal pelecypods *Edmondia*, fragments of bryozoan colonies and crinoid stems (Fig. 5). The macrofossils are usually fragmentally preserved and associated with foraminifers, ostracods, small gastropods and calcareous algae detritus, which is only distributed in the lower part of this sedimentary package. The drastically reduced fossil assemblage (taphocoenosis IV), occurring only in the thin mudstone shales intercalated with the greywackes overlying the host deposits of taphocoenosis III, reflects renewed settling of only the eurytopic organisms. The poor state of preservation of shells, and the scarce preserved trace fossils point to a high-energy environment of near-shore conditions. The repeatedly changing conditions generated by sediment-laden currents could have made colonization by benthic organisms impossible.

The uppermost part of the Paprotnia section is composed mainly of greywackes, which contain only the remains of terrestial plants (taphocoenosis V), indicating proximity to land. This group is only represented by plant fossils; faunal remains are totally absent (Fig. 5). Among them, the most numerous are asterocalamite stems. *Lepidodendron* remains, fern leaves (mainly of *Sphenopteridium* and *Cardiopteris*) and seeds are less abundant. The floral remains of taphocoenosis V suggest proximity to land and a short transport distance.

Both the lithological and paleontological features of the Paprotnia beds indicate gradual environmental changes from offshore to onshore conditions. The Paprotnia beds, together with the overlying Wilcza conglomerates, terminate the autochthonous succession of the Bardo Complex (Fig. 3).

The bentonites: mineralogy, origin and transformation

The six bentonite layers (Fig. 4) are easily visible within the gray shales and graywackes in the lower part of the Paprotnia beds through their bright yellowish colour. Their thicknesses vary from less than 1 cm to ~ 10 cm. Locally, they are variable in thickness and slightly faulted (Fig. 6).

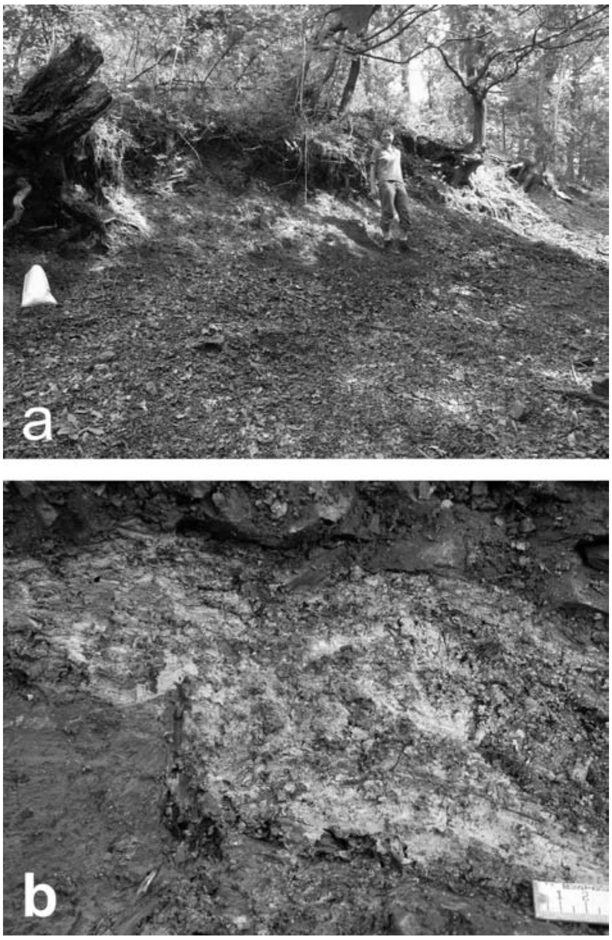


Fig. 6. (a) – exposure of the Paprotnia beds. (b) – the thickest exposed bentonite (notice tectonic deformation).

The mineral composition of all the bentonite layers is similar. The major clay minerals in the bentonites are: I/S mixed-layer mineral and kaolinite, both occurring in similar proportions (Fig. 7, Table 2). Smectite and illite have also been detected in two of the six bentonite layers.

All the samples analysed contain small amounts of iron hydroxides. Secondary calcite (up to 10% by volume) occurs as: (a) small grains dispersed in the groundmass, (b) lens-like small aggregates, and (c) thin (up to 4 mm) veins of fibrous crystals, particularly common in the upper parts of some of the bentonite layers. No relics of primary magmatic minerals (e.g. feldspar or biotite), except for accessory zircons (see below), were observed.

Summing up, the mineral composition (clay minerals, calcite) of the bentonites from the Paprotnia beds supports their pyroclastic derivation and points to a probable intermediate composition of the parent volcanic material.

The measured proportion of smectite S (20–30%) in the mixed-layer I/S packets, based on the position of peaks corresponding to (002) and (003), is between 20 and 30% (Fig. 7). Such a proportion and Reichweite $R \geq 1$ indicate that the maximum diagenetic paleotemperatures in these rocks could have attained ~ 130–160°C (August, 2006; Środoń, 1995).

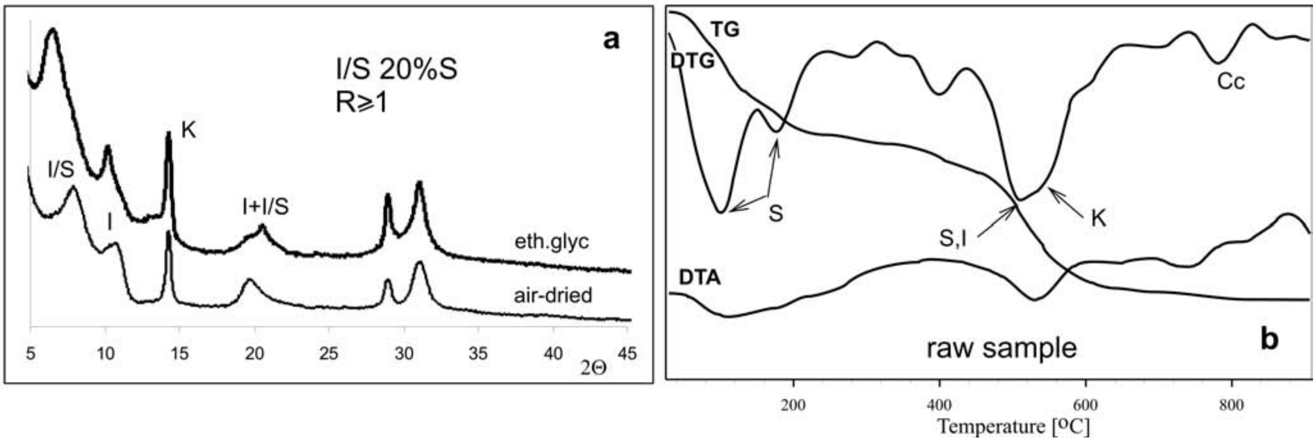


Fig. 7. (a) – XRD pattern of bentonite A (air-dried and glycolated sample); (b) DTA, TG and DTG curves of bentonite A, Cc – calcite, I – illite, I/S – illite-smectite, K – kaolinite, S – smectite; R – Reichweite index.

Table 2

Selected mineralogical characteristics of the bentonite layers in the Paprotnia beds

Bentonite layers	Smectite & I/S %	Kaolinite %	Quartz (silica)	FeOOH %	Calcite %	Euhedral zircon
A	30	35	+	2	3	+
B	30	50	+	1	0	+
C	25	35	+	2	9.5	+
D	20	35	+	3	0	+
E	35	45	+	2	4.5	+
F	35	45	+	2	2	+

SHRIMP ZIRCON GEOCHRONOLOGY – A SYNOPSIS

The results of geochronological investigations are presented and discussed in more detail in a separate paper (Kryza *et al.*, 2009, in prep.). Here, we report only the basic zircon characteristics and their mean concordia age that constrains their stratigraphic position.

The zircons in bentonite A are subhedral to euhedral, short- to normal-prismatic, colourless and transparent, with fairly common oval and needle-like inclusions (Fig. 8). In cathodoluminescence (CL) images they often show regular "magmatic-type" zonation. $^{232}Th/^{238}U$ ratio is rather uniform, between 0.33–0.62, typical of igneous zircons (Kryza *et al.*, 2009, in prep.).

The main population of thirteen zircons (out of the total 15 grains analysed) yielded ^{206}Pb-^{238}U ages scattered between 313±5 and 343±5 Ma. The mean Concordia age calculated for nine points of this main population (excluding significantly younger grains and a positively discordant one) is 334±4 Ma. An alternative interpretation is that the age of one single grain which is nearly perfectly concordant: 337±4 Ma (discordance D = –1%) is the best approximation of the true magmatic age (Kryza *et al.*, 2009, in prep.).

DISCUSSION AND CONCLUSION

According to Wajsprych (1995), the uppermost part of the autochthonous succession (the Paprotnia beds) accumulated during the "*crenistria* transgression" and is regarded as a temporal shallower-water equivalent of the *crenistria* Limestone (cd III α, Upper Viséan). The *crenistria* Limestone is widespread in the Kulm facies of Variscan Europe and forms a set of three limestone beds (*see* Jackson, 1990; Warnke, 1997) that contain, predominantly, a pelagic fauna represented mainly by planktonic, pseudoplanktonic and nektonic organisms, whereas fossils of benthic organisms are usually rare.

The lithology and the succession of biotic components (taphocoenoses) in the excavated part of the Paprotnia beds reflect a gradual change from deeper to shallower water sedimentation (Haydukiewicz & Muszer, 2002). Consequently, the Paprotnia beds represent the shallower facies equivalent of the pelagic *crenistria* Limestone. The similarity of the Late Viséan lithological and paleontological records of the Bardo Unit to the adjacent Intra-Sudetic Basin (the Szczawno Formation; Żakowa, 1968; Bossowski *et al.*, 1995) and the Góry Sowie Massif (Sokolec beds, clayey-greywackes series, Żakowa, 1966,

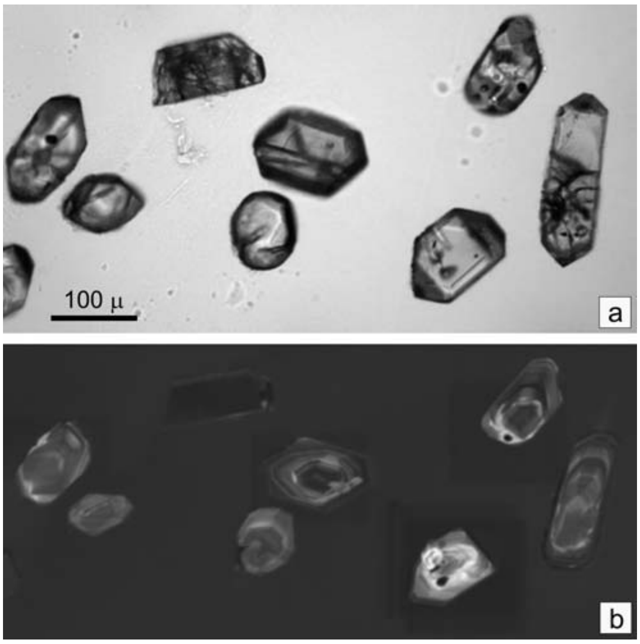


Fig. 8. Zircons from bentonite A, (a) – in transmitted plane polarized light, and (b) –in cathodoluminescence.

1968) suggests a shallow-water environment in the Sudetic part of the wide mid-European Variscan basin at that time. A scheme of palaeotectonic scenario for the central Sudetes in late Viséan times is shown in Fig. 9. The Paprotnia beds were deposited in the shallowing-up continental margin (or intramontane) Bardo basin, located south-east of the uplifting, since Famennian times, Góry Sowie Massif.

The K-bentonites in the Paprotnia beds are records of synsedimentary volcanic activity and subsequent diagenetic alteration of the fine-grained pyroclastic sediments. The pyroclastic derivation is confirmed by the presence of fresh zircon crystals, with features typical of volcanic origin. The mineral composition of the Paprotnia bentonites (mixed-layered illite/smectite, kaolinite and illite, and calcite), as well as the abundance of volcanic zircon grains, suggest a likely intermediate volcanic magma. The progressive increase in fossils, observed above the thickest bentonite layer, may indicate fertilization of the seawater, leading to intense development of phyto-plankton and zooplankton.

The volcaniclastic material contained, as a major component, volcanic glass which in the shallow-marine environment was quickly changed into smectite. This early smectite was subsequently transformed partly into illite, and the measured proportion of the smectite S, ~ 20–30%, in I/S packets, and R ≥ 1, indicate that the maximum diagenetic palaeotemperatures in that rock succession could have been around 130–160°C (Šucha *et al.*, 1993). The lack of major magmatic components, such as feldspars and biotite, in the bentonite indicates a strong diagenetic transformation of the pyroclastic material.

The SHRIMP ages of volcanic zircon grains from the bentonite studied fit well with the Viséan age based on biostratigraphic evidence. The radiometric ages for the Asbian (lower part of the Upper Viséan) in central and west Europe, derived mainly from ash layers, using U-Pb zircon IDTIM dating, are between 337 and 332 Ma (Menning *et al.*, 2006). Our data of 334±4 Ma are in good agreement, within analytical error, with those results.

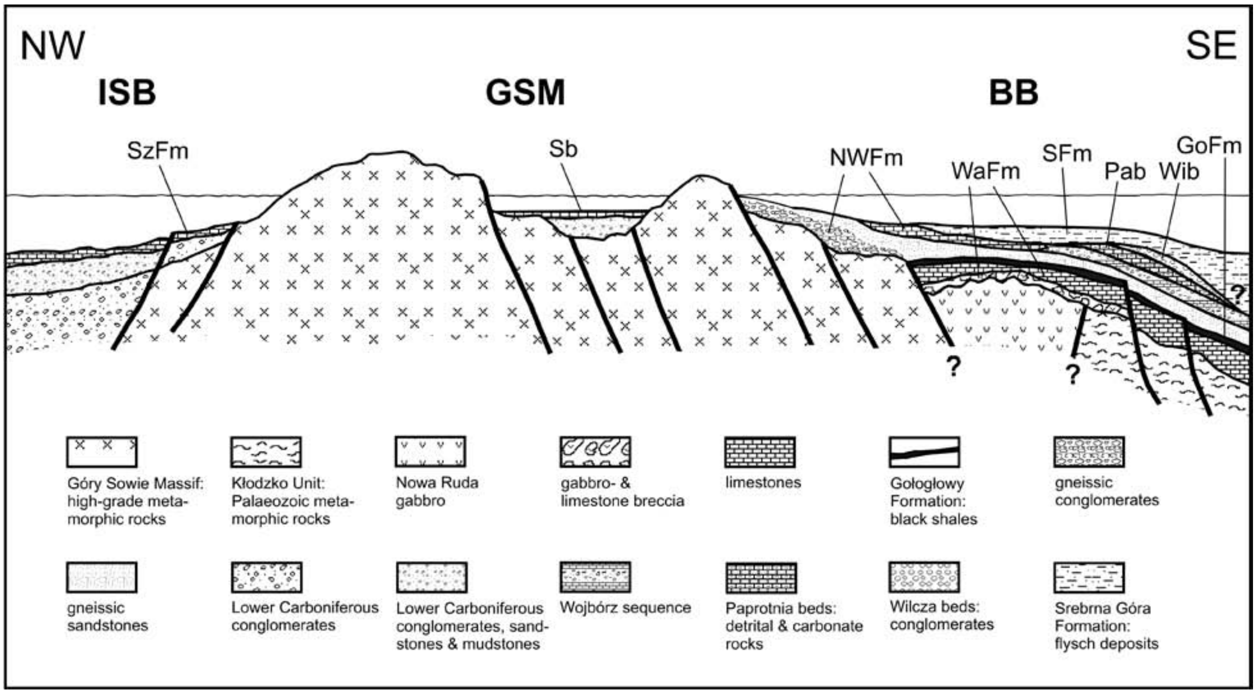


Fig. 9. Palaeotectonic scenario for the Bardo basin during the late Viséan. BB – Bardo basin; GoFm – Gołogłowy Formation; GSM – Góry Sowie Gneiss Massif; ISB – Intra-Sudetic basin; NWFm – Nowa Wieś Formation; Sb – Sokolec beds; SFm – Srebrna Góra Formation; SzFm – Szczawno Formation; Pab – Paprotnia beds; WaFm – Wapnica Formation; Wib – Wilcza beds.

The new geochronological data from the bentonite further constrain volcanic activities in the region during the Viséan. The Paprotnia beds are a continental margin (or intramontane) basin succession documenting a gradual environmental change from offshore to onshore conditions (Haydukiewicz & Muszer, 2002), and deposited during the ongoing Variscan orogeny. By the late Viséan, internal parts of the orogen ("klippen"), such as the Góry Sowie Massif, must have been partly exhumed (starting already in Famennian times) and supplying detritus to neighbouring basins, including the Bardo basin and the intramontane Intra-Sudetic basin (Fig. 9).

The volcanic source supplying ash material to the bentonite layers could have been located in the Intra-Sudetic Basin, where Lower Carboniferous andesites and rhyodacites were documented (Awdankiewicz, 1999). However, their effusive, i.e. *sensu stricto* volcanic nature has recently been questioned in some of the localities, using SHRIMP zircon dating that indicate their younger age and, consequently, subvolcanic, intrusive character (Awdankiewicz & Kryza, 2009, in preparation). We should also keep in mind that the fine volcanic material can be transported over thousands of kilometres, so the actual source could have been located very far from the place of deposition.

Acknowledgments

The study was supported by the internal grants of Wrocław University, 2022/W/ING and 1017/S/ING. Jan Zalasiewicz is thanked for careful correction of an earlier version of this paper.

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