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PROCESSES CONTROLLING EOCENE MID-LATITUDE LARGER FORAMINIFERA ACCUMULATIONS: MODELLING OF THE STRATIGRAPHIC ARCHITECTURE OF A FORE-ARC BASIN (PODHALE BASIN, POLAND)

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Abstract: A model for the stratigraphic architecture of the Eocene strata of the Podhale Basin has been developed (Poland, Western Carpathians). Generally, the sedimentation of the basin was controlled by eustatic sea-level changes, and fore-arc spreading in a convergent regime related to the infratatric subduction. During the studied stratigraphic interval the former factor dominated the tectonics. Sedimentation took place during three distinct intervals (composite sequences), which are correlated with the Upper Lutetian/Lower Bartonian, the Middle/Upper Bartonian and the Lower/Upper Priabonian stages. The first two were studied in detail, the third was evaluated on the basis of published data. In the first composite sequence a TST was developed, in the second composite sequence we could distinguish LST, TST, HST and SMST's. Surprisingly, a mass-occurrence of heterosteginids occurred during temperate conditions and higher trophic levels in the SMST. In contrast, a lower trophic level and warmer conditions are indicated in the third composite sequence by *Nummulites fabianii*. Our sequence-stratigraphic data correlate well with the corresponding implications from a recently published composite oxygen isotope record for the Cenozoic.

Key words: Eocene, Central Western Carpathians, Podhale Basin, fore-arc basin, sequence stratigraphy, glacioeustatic sea-level changes, mid-latitude carbonates, larger foraminifers.

Introduction

The Podhale Basin is located in the Inner Western Carpathians, between the Tatra Mts. in the South and the Pieniny Klippen Belt zone in the North (South Poland).

The investigated outcrops are located at the southern border of the Podhale Basin. They are situated between the valleys of Dolina Sucha to the East and Dolina Mała Łąka to the West, south of Zakopane (Fig. 1). From these outcrops 30 sections were studied, using micro- and biofacies analysis as well as geochemical data analysis. Their thickness ranges between 5 and 30 m. Four sections out of thirty have been selected for detailed analysis: the Dolina Sucha Kamienołom, Dolina Sucha, Pod Capkami (a composite section, arranged from four partial-sections near the closed down quarry Pod Capkami) and the Dolina Mała Łąka section.

Previous studies of the Eocene sediments (Bartholdy 1990, 1993; Bartholdy & Bellas 1997, 1998a,b,c; Bartholdy et al. 1995, 1998, 1999) and the evaluation of new literature on micropaleontological investigations on hydrogeological wells and outcrops of the Podhale Basin given by Olszewska & Wieczorek (1998) encouraged our working group to develop an integrated model for the development of the Podhale Basin during the Upper Lutetian–Upper Priabonian interval, in terms of lithology, bio- and sequence-stratigraphy and paleoclimatology/-geography.

Material and methods

For the sedimentological laboratory work and paleontological investigations, samples of unweathered, representative rocks were taken. The distance between the samples was < 0.1 m in average. Microfacies analysis and determination of larger foraminifers (LF) was based on oriented thin-sections, 50–70 µm in thickness. Because of the hardness of the limestones, isolated specimens of LF were not available. Only randomly obtained axial and equatorial sections from LF specimens were studied. It permits to determine the orthophragminids only on morphogroup-level, comp. Ćosović & Drobne (1998). In the genus *Nummulites* only the most significant species were determined. Nummulititids were identified using the taxonomic criteria indicated in Schaub (1981). Isolated planktonic foraminifers were defined following Toumarkine & Luterbacher (1985). For the calcareous nannoplankton determination and zonation the works by Perch-Nielsen (1985) and Martini & Müller (1986) were considered.

Geological setting

The collision of the Apulian and the North European platform (West-European microplate), the subduction of the Out-

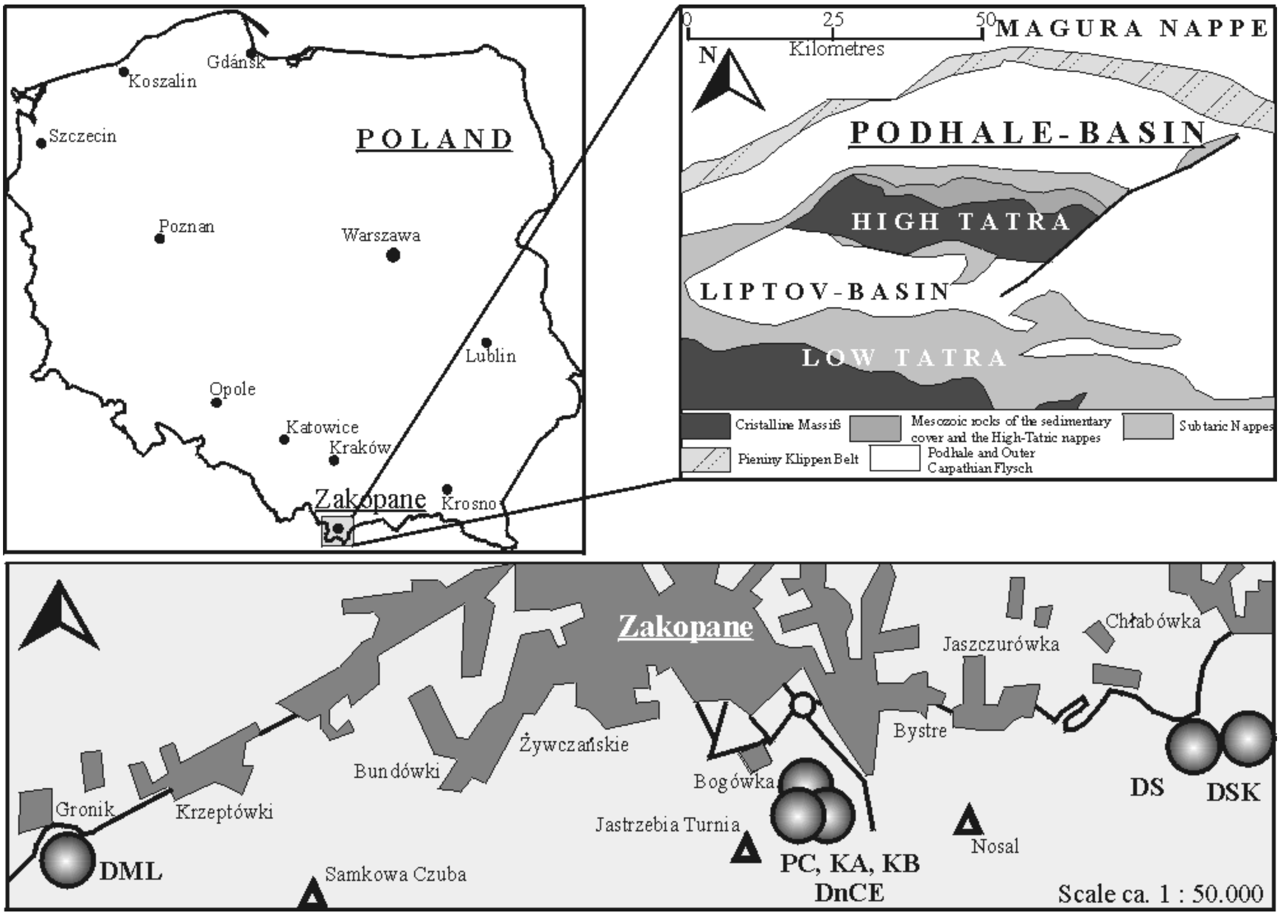


Fig. 1. Geographical and geological location of the Podhale Basin and the studied sections, south of Zakopane.

er Carpathian crust under the Central Western Carpathians (North-Pannonian unit) as well as escape of the Central West-Carpathian segments are regarded as the driving mechanisms which controlled the structural development of this area (comp. Csontos et al. 1992; Soták 1992). The stress-field consisted of two main compressional systems: a NNW-SSE stress-field, perpendicular to the main strikes of the structural belts (Equatorial rift system of the Tethys) and a NE-SW stress-field, parallel to the main strikes of the structural belts (Atlantic–Red Sea–East Carpathian-rift system) (Kozák et al. 1998).

The studied Podhale Basin is regarded as a fore-arc basin, located at the north-eastern border of the North-Pannonian unit (Tari et al. 1993). Occurrence of calcalkaline volcanism around the Balaton-lineament indicates the paleogeographic situation of a volcanic arc. Backstripping reconstructions for the Late Eocene time of the Outer Carpathian flysch nappes suggest that the entire Central-Carpathian area must have been paleogeographically located several hundreds of kilometres to the southwest of its present position (Csontos et al. 1992). Opening and subsidence rates within this basin were mainly controlled by collapsed structures due to the effects of subcrustal tectonic erosion at the base of the Tatric units (Baráth et al. 1997; Soták & Bebej 1996; Wagreich 1993; Wagreich & Marschalko 1995). During the Paleogene, the main structural pattern which controlled the basin was characterized by NW-SE compression and NE-SW trending extension (Kováč et al. 1994). The Middle Eocene transgression was generally directed eastward, using marine connections of the Central Western Carpathians and Buda Paleogene basins. Deposition began in the Late Lutetian and ceased in the Late Oligocene up to the Lowermost Miocene (comp. Bartholdy 1997; Olszewska & Wieczorek 1998; Soták 1996). Following Olszewska & Wieczorek (1998), the sedimentation within the basin is generally subdivided into two depositional systems 1) a shelf to slope system, which consists of calcareous and siliciclastic sediments of Middle to Late Eocene age, and 2) a turbiditic sequence (mainly Oligocene), with a distinct coarsening upward trend Zakopane and Chochołow Formation (incl. Ostrysz Beds in its upper part). In the present study we distinguish within the Paleogene depositional system three sedimentary cycles in terms of composite sequences sensu Kerans & Tinker (1997) (Bartholdy 1997; Bartholdy & Bellas 1998a,b,c; Bartholdy et al. 1995, 1999).

Short description and interpretation of selected profiles: Implications for the sequence stratigraphy

Detailed analysis was undertaken on the selected four sections of the 30 outcrops, recorded between the valleys of Do-

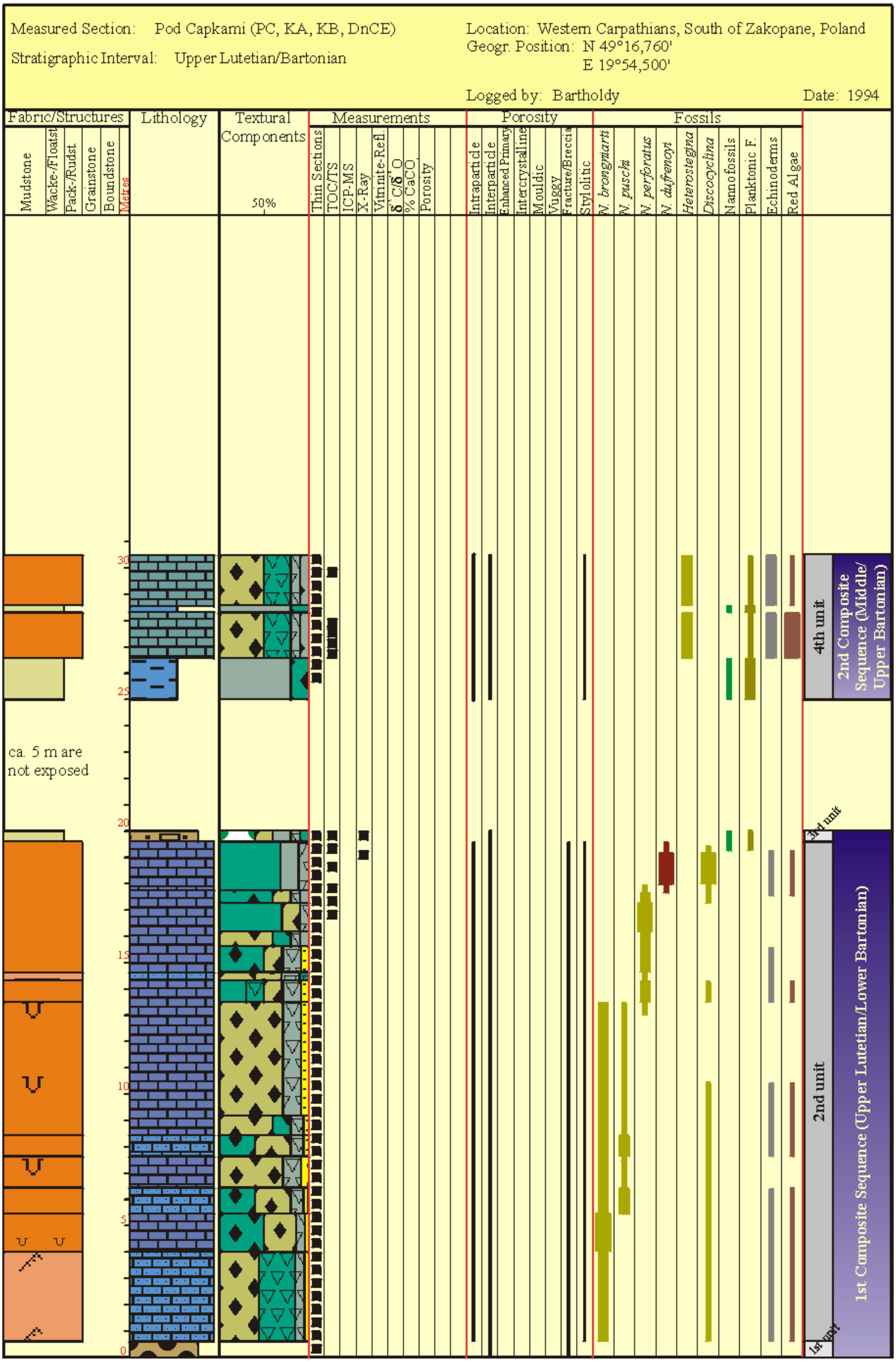


Fig. 2. Composite Pod Capkami section.

lina Sucha and Dolina Mała Łąka. The different composition in terms of lithology and fossil-content justified their selection. The sections are defined as follow:

1) Composite Pod Capkami Section (PC) (Figs. 2, 9):

It integrates data from four outcrops. A general subdivision into four units is possible: The base (1st unit) consists of coarse-grained, marine conglomerate, with clasts up to 1m in diameter and marks the transgressive surface (TS) and a type 1 sequence boundary (SB1). These sediments transgressively overlie Triassic dolomites of the Subtatric nappes (thickness 0.5 to 2 m). Above the conglomerates a transgressive unit (2nd unit) follows: it consists of a thick rudstones succession (ca. 18 to 20 m), intercalated in basinal areas with fine-grained conglomerates. These deepening-upward accumulations contain an association of larger foraminifers showing distinct changes in their shape, structure and morphology (flattening of tests and thinning of wall-lamellas). The succession starts with sediments, rich in *Nummulites brongniarti* [this species is indicative for shoreface, above the low-tide (Bartholdy et al. 1995; Kulka 1985)], then sediments occur where *Nummulites puschi* [protected longshore through, (Bartholdy et al. 1995; Kulka 1985)] and *Nummulites perforatus* [associated in the typical bank facies (Arni 1965; Bartholdy et al. 1995; Kulka 1985)] are predominant. The uppermost part is characterized by *Nummulites dufrenoyi*, *Discocyclina pratti* and *Discocyclina sella*. This transgressive sequence is bounded on the top by the 3rd unit of the section, a glauconitic wackestone (0.3 m), which is regarded as a condensed horizon (maximum flooding surface). It contains glauconite of the same maturity-stage, which is indicative for autochthonous conditions (comp. Amorosi 1995, 1997). Above units 1–3 is a succession of globigerinids bearing marls and allodapic limestones ca. 6 m thick (4th unit). Erosional surfaces, well oriented bio- and lithoclasts and an assemblage of fossils from different depth-zones (echinoderms, red algae, heterosteginids, nummulites, agglutinated and planktonic foraminifers) as well as thin intercalations of marls which are dominated by planktonic foraminifers support our interpretation, that these are bioclastic turbidites. The contact between this fourth unit and units 1–3 is not exposed. Its thickness is calculated from outcrop data as being approximately 5 m. It may well be that it includes sediments deposited in the time of a falling sea-level (another SB2 unconformity).

2) and 3) Dolina Sucha Kamienołom (DSK) and Dolina Sucha Sections (DS) (Figs. 3, 9):

The section in the DSK Section starts with a thick (5 m) conglomeratic bed (1st unit). Overlain by a 3 m measuring package (2nd unit), consisting of graded rudstones, dolomitic and calcareous sandstones and fine-grained conglomerates. The 3rd unit (0.5 m in thickness) is characterized by leaves and wood remains (comp. Głazek & Zastawniak 1998) and a sharp intrastratal change of bioturbation. These markers are considered to be indications of change between anoxic and oxic conditions with corresponding lower and higher nutrient content. Geochemical analysis of the total organic carbon (TOC) and total sulphur (TS) content in the sediments supports these investigations (comp. Bartholdy et al. 1998; Leventhal 1983). The sediments were deposited during a relative low stand in terms of the sea-level. The uppermost 5 m of the DSK section (4th unit), represents a transgressive system, consisting of pack- and rudstones with a high percentage of red algae at the top.

The DS Section is a continuation of the DSK section. It begins with 0.9 m of red algae rudstones from the prementioned transgressive system (1st unit). These are overlain by 3 m of packstones with bioclasts of LF, *Nummulites* and Orthophragminae, and a high percentage of planktonic foraminifers (2nd unit). Such sediments may represent a relatively high stand in sea-level. The last 4 m of the section (3rd unit), consist of a *Heterostegina*-echinoderms rudstone, which exhibits a shallowing-upward tendency, and a relatively slow fall in sea-level (Shelf Margins Systems Tract).

4) Dolina Mała Łąka Section (DML) (Figs. 4, 9):

This section can be subdivided into four major parts: The 1st unit of the section (4 m) consists of fine-grained conglomerates and wackestones with glauconite (less than 5 %) of variable maturity (parautochthonous/allochthonous glauconit; comp. Amorosi 1995, 1997) and smaller benthonic foraminifers (sediments of a relatively lowstand in sea-level). The 2nd unit represents the flooding of the shelf area. This flooding caused a "turn on" of the carbonate factory. The sediment consists of parallel bedded red algae packstones and bindstones (3.5 m). A rapid transgression is regarded as a "shut down" the carbonate factory, resulting in a "drowning unconformity"; the top of the 2nd unit is bounded by a hardground (0.1 m), which is regarded as the mfs. The hardground at the base of this unit and its fine-grained composition and the reduced thickness point to a starvation in the sedimentation. The 3rd unit is represented by a 0.9 m rudstone, rich in planktonic foraminifers and red algae which developed during times of a relative highstand in sea-level. In contrast, bioclastic limestones with intercalated coarse bioclastic layers are indicative for the 4th unit of the section (ca. 8 m). It is represented by red algae rich rudstones, with Orthophragminae, *Nummulites* (smaller species), planktonic foraminifers and intercalations of thin, centimetric bedded sandstones. This succession was developed during a relatively slow fall in sea-level. At the base we observed a 0.5 m thick bed of dolomitic sandstones (redeposited rocks, not insitu dolomitization). It is regarded as a characteristic marker for the SB2 sequence boundary in a marine shelf position.

Sequence stratigraphy and depositional-systems analysis

Geotectonic setting and sequence stratigraphy

The Podhale Basin is a fore-arc basin in type. Usually, in fore-arc basins, the regional tectonism is the main factor in controlling the stratigraphic architecture. In most cases it is evident that folding, faulting, tilting and tectonic subsidence

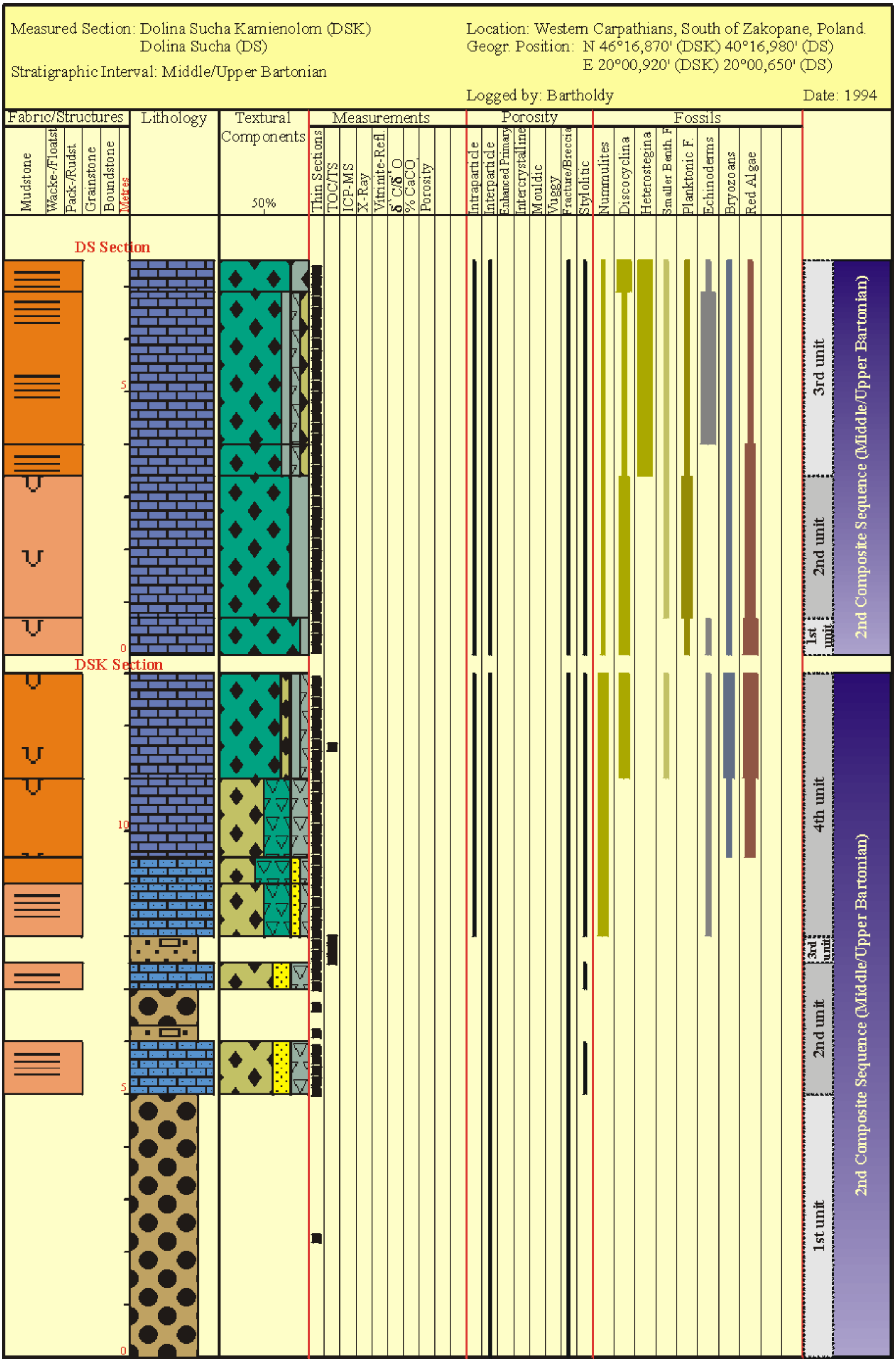


Fig. 3. Dolina Sucha Kamienołom and Dolina Sucha section.

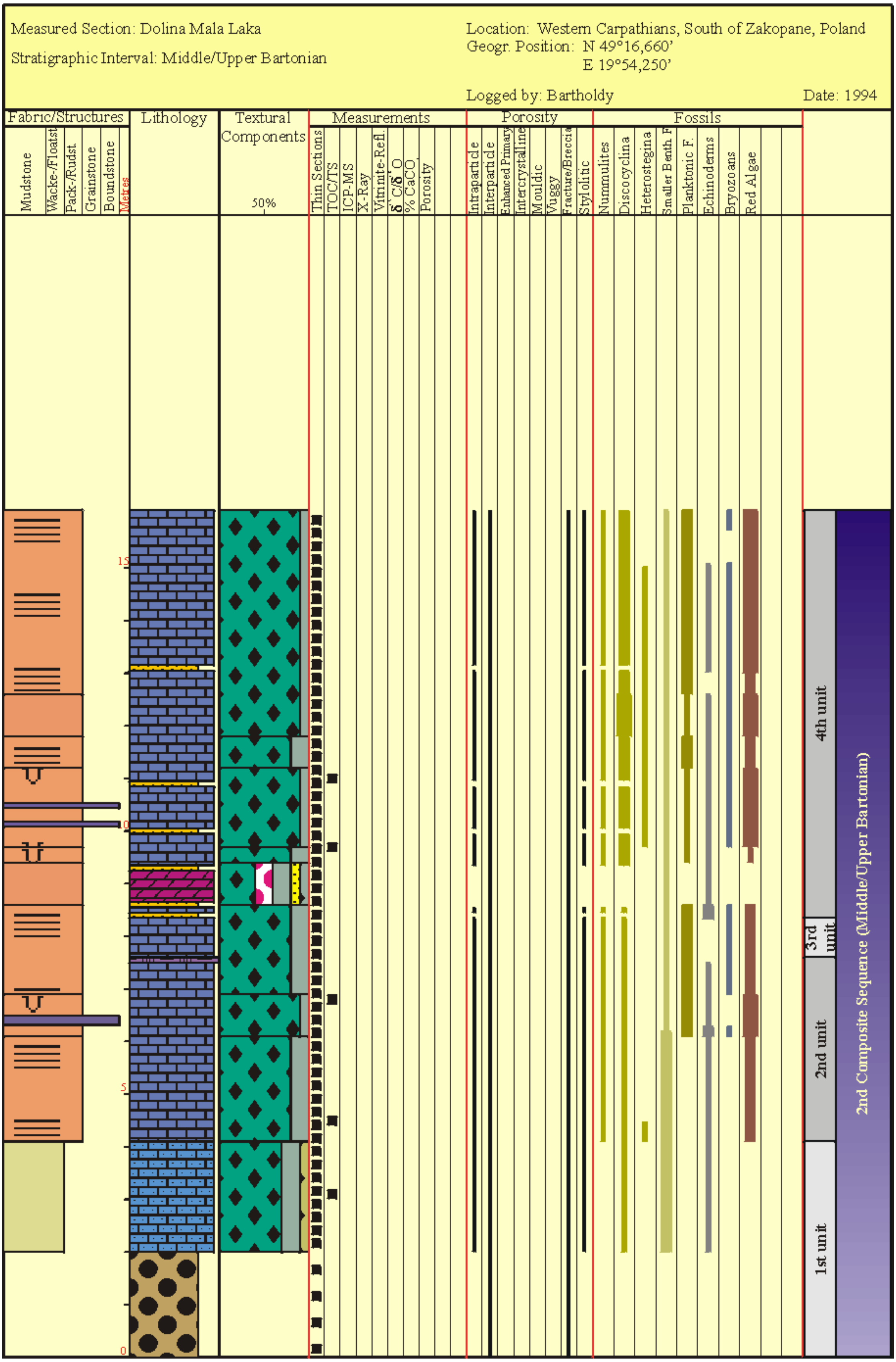


Fig. 4. Dolina Mała Łąka Section.

and/or uplift are the major sedimentary controls. Correlations with the Global Cycle Chart seem forced and unconvincing. Moreover, biostratigraphic evidence for the correlations is extremely limited (Miall 1997). The stage of knowledge of the basinal architecture and its relationship to relevant subduction parameters in fore-arc basins is limited. The convergence rate at the trench, the dip of the subducted slab and the velocity of the arc massif to the rollback of the subducted slab are considered to be the mainly factors in the basin development (Busby & Ingersoll 1995).

The north-eastward escape movement of the Pannonian units during the Paleogene was accompanied by trench-fault deformation of the Central Carpathians and the closure of the Outer Carpathians with subsequent shortening (Csontos et al. 1992). The controlling mechanism of deformation in the Outer Carpathians and extension in the Inner Carpathians with the subsequent opening of sedimentary basins (e.g. Podhale Basin) is considered to be characterized by a slower rate of motion of the arc massif relative to the rollback of the subduction slab, possibly combined with the growth of the sediment load of the fore-arc basin and collapsed structures due to effects of the infratatric subduction (comp. Baráth et al. 1997; Miall 1997; Soták & Bebej 1996; Wagreich 1993). During the deposition of the studied sediments no major tectonic events occurred. The Prepyrennean phase of folding took place between the base of the calcareous nannofossil NP 13 Zone and the middle part of the NP 14 (Early/Middle Eocene boundary) Zone sensu Martini & Müller (1986). The next folding phase, namely the Ilyrian, began gradually from west to east at the lowermost part of the calcareous nannofossil NP 18 Zone (Middle/Late Eocene boundary) following Köhler & Salaj (1997). Therefore, it is evident that sea-level fluctuations played the dominant role in the depositional facies architecture of the Podhale Basin, over the regional tectonic control, at least for the studied Upper Lutetian to Upper Priabonian time-span (Bartholdy & Bellas 1997).

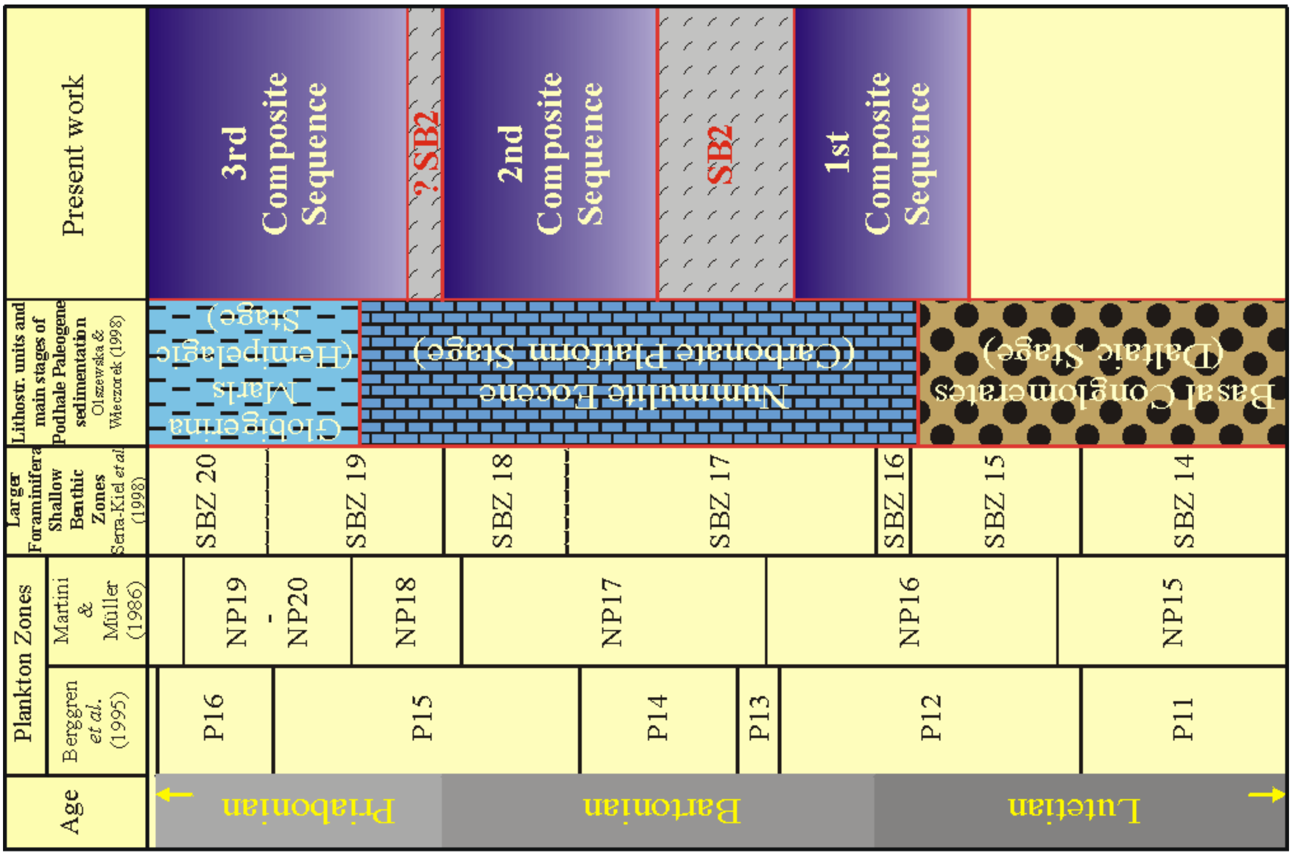
Sedimentation in this interval of time took place during three distinct cycles (composite sequences), which are correlated with the Upper Lutetian/Lower Bartonian, the Middle/Upper Bartonian and the Early Priabonian stages respectively (Figs. 5, 9). The first two composite sequences were studied in detail and their ages determined by larger- and planktonic foraminifers and calcareous nannofossils integrated biostratigraphy, while, the third one was evaluated on the base of synthesizing previous literature and our unpublished data (Bieda 1963; Roniewicz 1969; Kulka 1985; Olszewska & Wieczorek 1998).

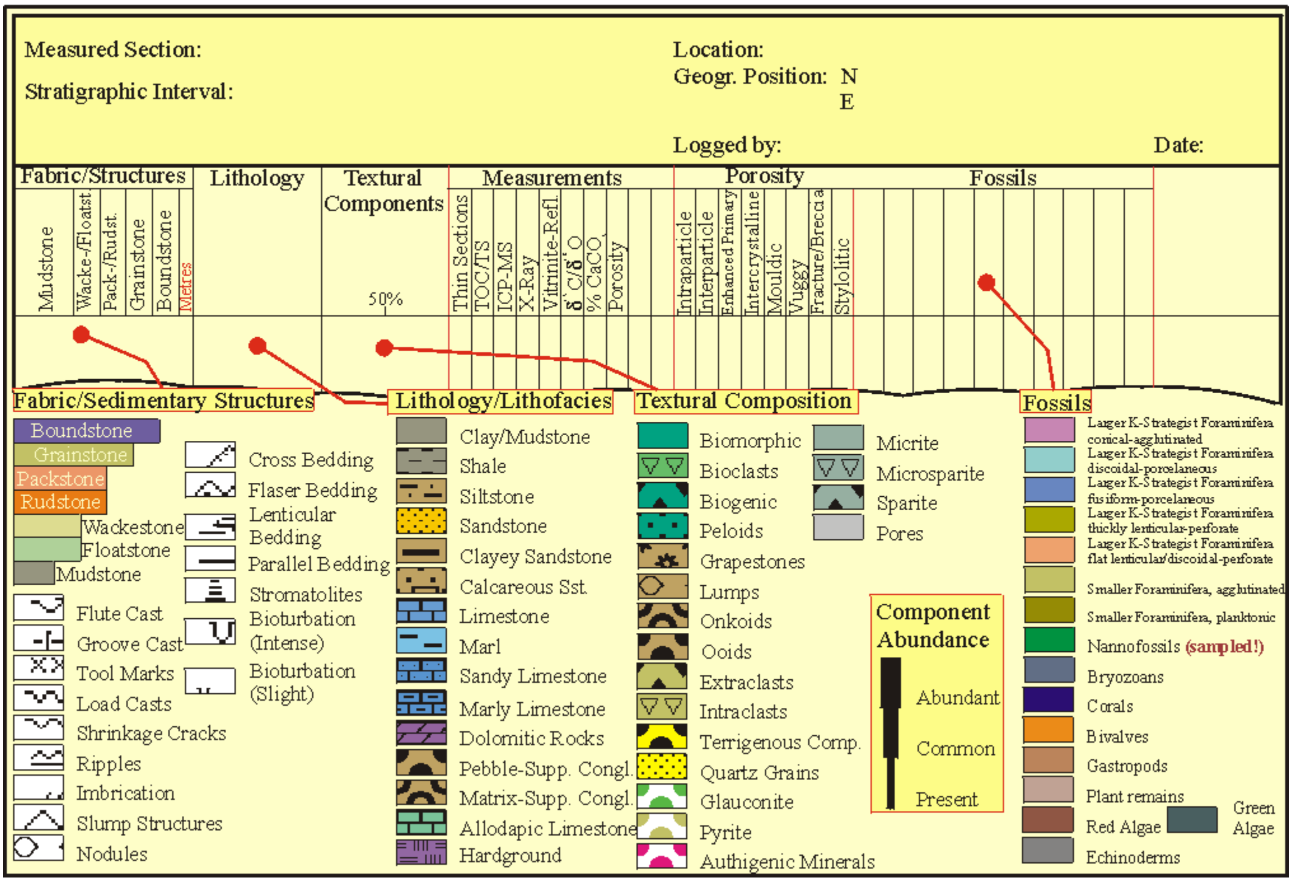
During the first composite sequence (cs 1), initially a Transgressive Systems Tract (TST) was developed. It is well represented in the first part of the studied PC composite section (Fig. 9). This TST was characterized by the "turn on" of the carbonate factory (Bartholdy 1997; Bartholdy & Bellas 1998a,b) and a typical deepening-upward association of the LF-communities (comp. Drobne & Ćosović 1998; Hallock 1979, 1985; Hallock et al. 1991; Hohenegger 1995, 1996; Hottinger 1983, 1984, 1996, 1997; Kecskeméti 1989; Loucks et al. 1998a,b; Pignatti 1991, 1998). The record is bounded on the top by a condensed section consisting of glauconitic Marls which represent the mfs (top of the first part of the PC section, Fig. 9) (Bartholdy 1997; Bartholdy & Bellas 1998a,b,c).

At the base of the second composite sequence (cs 2) a Lowstand Systems Tract (LST) was recognized. It shows a succession of fine-grained conglomerates, sandstones, calcareous intercalations and glauconitic wackestones (lower part of the DSK/DML section, Fig. 9). The TST developed on the top of it is characterized by another "turn on" of the carbonate factory (like the first depositional cycle), which was caused by flooding of the shallow shelf areas. It is represented by pack- and rudstones, rich in red algae (upper part of the DSK and lower part of the DS section, Fig. 9). A hardground ("drowning unconformity") in the DML section (comp. with the remarks, given in the description of the DML section) marks both, the mfs and the boundary to the Highstand Systems Tract (HST). The HST sediments consist of relatively thin layers of packstones rich in planktonic foraminifers (lower part of the DS and middle part of the DML section, Fig. 9). During the time of a relatively slow fall of the sea-level and when the sea-level does not drop below the edge of the shelf, SB2 type unconformities are developed. Times of maximum rate of the sea-level fall are represented by sequence boundaries (Miall 1997). Such markers of the SB2 boundary were recorded along the studied sections. They are represented by intercalations of dolomitic sandstones or a distinct shift by the clastical influx within the basin derived from the land-area (middle part of the DS and DML section, Fig. 9). Moreover, during time intervals of relatively slow fall in sea-level Shelf Margin Systems Tracts (SMST) were developed as well (comp. also Miall 1997). Mass-occurrence of heterosteginids and echinoderms were recorded in these SMST's (upper part of the DS, DML and PC section, Fig. 9).

Considering the younger calcareous sediments, field and published data point to the existence of a third composite sequence. A transgressive and a highstand phase could be recognized. The TS should be correlable with the occurrence of *Nummulites fabianii* during the "turn on" of the carbonate factory, while the marls with globigerinids could very well represent the HST (Fig. 5).

With the Ilyrian phase the third sedimentation cycle ends. After a stratigraphic gap the deposition of the Szaflary-Formation (Priabonian to Early Rupelian and the Zakopane-(Rupelian to Early Chattian) and Chochołow-Formations (Chattian) followed in the Podhale Basin (comp. Bartholdy et al. 1995; Olszewska & Wieczorek 1998). Köhler & Salaj (1997) noted that the beginning of the Ilyrian phase did not take place in an equal time-interval, but it gets younger eastwards NP 18–NP 21 calcareous nannofossil zones sensu Martini 1971 (planktonic foraminiferal zones P 15–P 17). This diachronism fits well in the stratigraphic data given for the Globigerina Marls from the Priabonian by Olszewska & Wieczorek (1998) (P 15–P 16 zones) (Figs. 5, 9). Soták (1998) described a turbididite fan system on the Central Carpathian Paleogene with fault controlled lowstand deposition of the Šambron Beds (Eastern Slovakia) in the Upper Eocene (39–36 Ma) as an equivalent for the Szaflary Formation. Because of the data given above we exclude major tectonic events as the controlling factors for the basin depositional architecture. Eustatic sea-level changes are evidently recorded. On the basis of a newly constructed composite oxygen isotope record, changes in the volume of the polar ice-sheets


Present work
3rd Composite Sequence
? SB2
2nd Composite Sequence
SB2
1st Composite Sequence
Lithostr. units and main stages of Podhale Paleogene sedimentation
Olszewska & Wieczorek (1998)
Globigerina Marls (Hemipelagic Stage)
Nummulite Eocene (Carbonate Platform Stage)
Basal Conglomerates (Deltaic Stage)
Larger Foraminifera Shallow Benthic Zones
Serra-Kiel et al. (1998)
SBZ 20
SBZ 19
SBZ 18
SBZ 17
SBZ 16
SBZ 15
SBZ 14
Plankton Zones
Martini & Müller (1986)
NP19 - NP20
NP18
NP17
NP16
NP15
Berggren et al. (1995)
P16
P15
P14
P13
P12
P11
Age
Priabonian
Bartonian
Lutetian


Measured Section:
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Location:
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Fabric/Structures
Mudstone
Wacke-/Floatst.
Pack-/Rudst.
Grainstone
Boundstone
Metres
Lithology
Textural Components
50%
Measurements
Thin Sections
TOC/TS
ICP-MS
X-Ray
Vitrinite-Refl.
δ13C/δ18O
%CaCO3
Porosity
Porosity
Intraparticle
Interparticle
Enhanced Primary
Intercrystalline
Mouldic
Vuggy
Fracture/Breccia
Stylolitic
Fossils
Fabric/Sedimentary Structures
Boundstone
Grainstone
Packstone
Rudstone
Wackestone
Floatstone
Mudstone
Cross Bedding
Flaser Bedding
Lenticular Bedding
Parallel Bedding
Stromatolites
Bioturbation (Intense)
Bioturbation (Slight)
Flute Cast
Groove Cast
Tool Marks
Load Casts
Shrinkage Cracks
Ripples
Imbrication
Slump Structures
Nodules
Lithology/Lithofacies
Clay/Mudstone
Shale
Siltstone
Sandstone
Clayey Sandstone
Calcareous Sst.
Limestone
Marl
Sandy Limestone
Marly Limestone
Dolomitic Rocks
Pebble-Supp. Congl.
Matrix-Supp. Congl.
Allodapic Limestone
Hardground
Textural Composition
Biomorphic
Bioclasts
Biogenic
Peloids
Grapestones
Lumps
Onkoids
Ooids
Extraclasts
Intraclasts
Terrigenous Comp.
Quartz Grains
Glauconite
Pyrite
Authigenic Minerals
Micrite
Microsparite
Sparite
Pores
Component Abundance
Abundant
Common
Present
Fossils
Larger K-Strategist Foraminifera conical-agglutinated
Larger K-Strategist Foraminifera discoidal-porcelaneous
Larger K-Strategist Foraminifera fusiform-porcelaneous
Larger K-Strategist Foraminifera thickly lenticular-perforate
Larger K-Strategist Foraminifera flat lenticular/discoidal-perforate
Smaller Foraminifera, agglutinated
Smaller Foraminifera, planktonic
Nannofossils (sampled!)
Bryozoans
Corals
Bivalves
Gastropods
Plant remains
Red Algae
Green Algae
Echinoderms

due to growth and/or melting were in response to the rise and fall of sea level. A correlation between eustatic curves derived from sequence stratigraphic studies indicates that glacial eustasy has been the main factor in the regulation of the global eustatic changes in the sea-level since the Middle Eocene (Abreu & Anderson 1998). Correlations among data for sequence boundaries of Hardenbol et al. (in press), data of the above oxygen-isotope record, and those concerning development of the Podhale Basin during the Lutetian to Priabonian are possible, and underline the dominance of eustatic sea-level changes over regional-tectonic events in the studied area. Specifically in the time interval Upper Lutetian to Lower Priabonian, the sequence stratigraphic cycles of Hardenbol et al. (in press) are generally correlated with the recorded three depositional cycles in the Podhale Basin (Fig. 8). Moreover, the glacioeustatic events EBi1 and EPi1 of Abreu & Anderson (1998) are also correlable with the proposed regressional phases in the studied area.

Biostratigraphy

The foraminiferal assemblages and calcareous nannofossils identified in the studied sediments enable dating from the Upper Lutetian to the Priabonian. In this paper we correlate stages and nannoplankton zonations (NP sensu Martini & Müller 1986) with shallow benthic zonation (SBZ sensu Serra-Kiel et al. 1998) (Fig. 5).

The cs 1, containing the rich LF fauna in the investigated sections, belongs to the SBZ 17 shallow benthic zone. From the top of this section we were able to isolate calcareous nannofossils, whose age estimations range from the Middle to Upper part of the NP 16 Zone (cna1, Fig. 9).

From the base of the cs 2 (marls in the PC Profile) another association of calcareous nannofossils could be identified, which was biostratigraphically placed between the Lower and Middle part of NP 17 Zone (cna2, Fig. 9). Isolated planktonic foraminifers indicate the P 12 Zone sensu Berggren et al. (1995). The following sediments of the SMST of the cs 2 belong to the SBZ 18 zone. From a marly layer from the PC composite section within the allodapic limestones an association of calcareous nannofossils was also isolated (cna3, Fig. 9), which indicate the Middle to Upper part of the NP 17 Zone.

The LF association from the cs 3 with *N. fabianii* indicate the SBZ 19 Zone. This shallow benthic zone is partly correlable to the NP 18 and the NP 19/20 zones. Olszewska & Wieczorek (1998) described under the term “Globigerina Marls” marly sediments from the supposed sea-level highstand (“hemipelagic stage”) intercalated in or overlying their “Nummulitic strata”, and they placed them into the P 15 to P 16 planktonic foraminiferal zones sensu Berggren et al. (1995).

Fig. 5. Legend for outcrop descriptions and correlation of the plankton zones sensu Berggren et al. (1995) and Martini & Müller (1986), larger foraminifers shallow benthic zones sensu Serra-Kiel et al. (1998), lithostratigraphic units and main stages of Podhale Paleogene sedimentation sensu Olszewska & Wieczorek (1998) and the three composite sequences of the Podhale Paleogene, presented in the present work.

Correlation of shallow benthic zones (SBZ) sensu Serra-Kiel et al. (1998), biostratigraphic data, given from Berggren et al. (1995) and our previous data suggest uncertainities between correlations of the Carpathian realm and the Tethys realm, situated western of the studied area.

Paleogeography and Paleoenvironment

As previously noted, the collision of Apulia and Europa induced an escape movement of the Central Western Carpathians to the North-Eastward direction. Therefore a paleogeographical location several hundred kilometers to the south-west in relation to its present position is discussed for the studied area of the Inner Carpathians. The Pieniny Klippen Belt is considered to be the northern border of the studied area. Palinspastic reconstructions there resulted in transport rates of some 200–250 km from the Early Miocene and 400 km from the Oligocene (Oszczypko & Slaczka 1985; Csontos et al. 1992).

In the cs 1, the rich and diverse fauna of large *Nummulites* and orthophragminids is a reference to an optimum in climate and a low nutrient level (Hottinger 1996). It is correlable with our bio- and sequence-stratigraphical data and data published by Oberhänsli (1996) for an optimum in climate in the Lower Bartonian (SBZ 17). In the cs 2, by contrast to the warm optimum, a relative cooling event in the upper Bartonian is reported by the previous author, and was also recorded in the studied sections: It can be correlated with rich LF accumulations of *Heterostegina*, rare small globular *Nummulites* and Orthophragminae (representatives of *D. augustae* and *Orbitoclypeus chudeaui* morphogroup). The occurrence of red algae, bryozoans and echinoderms inform us about the trophic level (mesotrophication to eutrophication), at least at local level (Bartholdy & Bellas 1997). Furthermore, the occurrence of the former organisms and the lack of corals, green algae and components like grapestones and ooids indicate temperate conditions as well (comp. Betzler et al. 1997; Braga et al. 1996; Hollaus & Hottinger 1997). Considering the recently published oxygen-isotope curve in the upper SBZ 17 Zone, our data correlate well with the EBi1 shift to cooler temperatures (comp. Abreu & Anderson 1998).

For the first composite sequence (cs 1, Upper Lutetian to Lower Bartonian) our model (Fig. 6) suggests long term, more or less stable environmental conditions. It is characterized by gradual development of the successions (background dominated: dominated by long-term stable processes and environmental changes). Five parts may be distinguished there: 1) a shore face area with clastic sediments, 2) back bank facies in a longshore trough with a characteristic association of Larger Foraminifera (LF), 3) longshore bar, which under these stable environmental conditions is constructed by a monospecific Nummulitic association (bank facies), 4) shallow to deep neritic succession of distinct LF communities with a depth dependence in morphoshape (fore bank facies) and 5) deep water deposits of the slope to bathyal with glauconite, calcareous nannofossils (cna1) and globigerinids in it.

A small scale, rapid change in microfacies types marks the second composite sequence of our model (cs 2, Middle/Upper Bartonian) (Fig. 7). The following subdivisions have

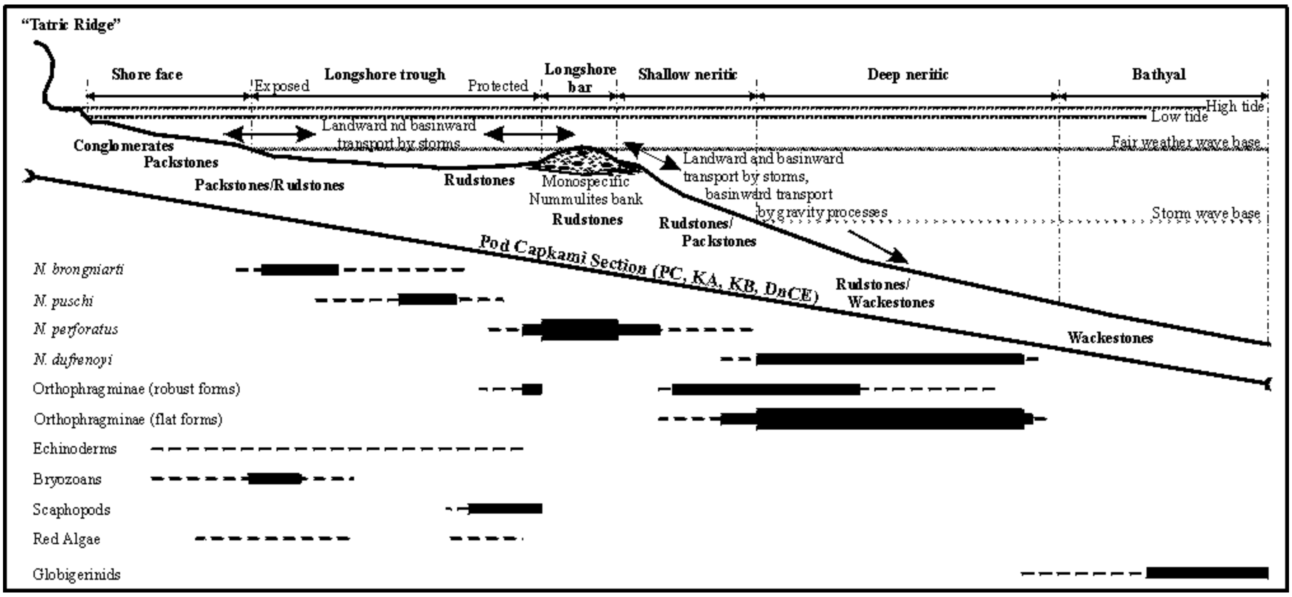

Fig. 6. Two dimensional model of the southern Podhale Basin (Middle Lutetian/Lower Bartonian), showing general depositional systems, distribution of selected fossils and lithology. Data were integrated from Arni (1965), Bartholdy et al. (1995), Bartholdy & Bellas (1998c), Hohenegger (1994, 1995), Hottinger (1983, 1988, 1996), Kulka (1985) and Loucks et al. (1998a,b).

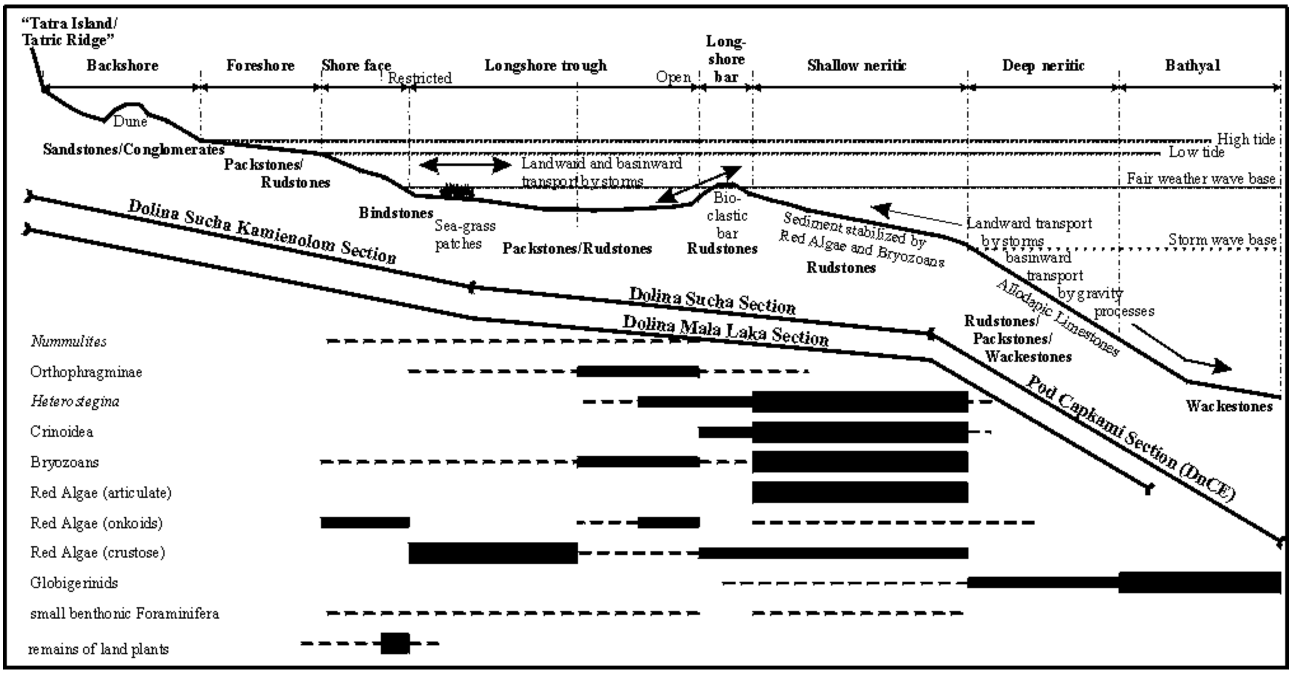

Fig. 7. Two dimensional model of the southern Podhale Basin (Middle/Upper Bartonian) showing general depositional systems, distribution of selected fossils and lithology. Data were integrated from Arni (1965), Bartholdy et al. (1995), Bartholdy & Bellas (1998c), Hohenegger (1994, 1995), Hottinger (1983, 1988, 1996), Kulka (1985) and Loucks et al. (1998a,b).

been distinguished: 1) a back- and foreshore setting with clastic sedimentation, 2) longshore trough setting with partly restricted, oligotrophic conditions, land-plant remains, in deeper parts a mass-occurrence of crustose red algae, 3) a longshore bar, consisting of bioclastic material, 4) a shallow neritic area with a biogenetic stabilized bottom and *Heterostegina* sp. and 5) deep neritic to bathyal parts of the basin with calcareous turbidites and the globigerinid bearing marls with calcareous nannofossil associations (cna2 & cna3). Unstable environmental conditions are supposed for this second cycle by the model (event dominated: dominated by short-term processes and environmental changes), with a distinct decrease in the diversity of the recognized LF communities.

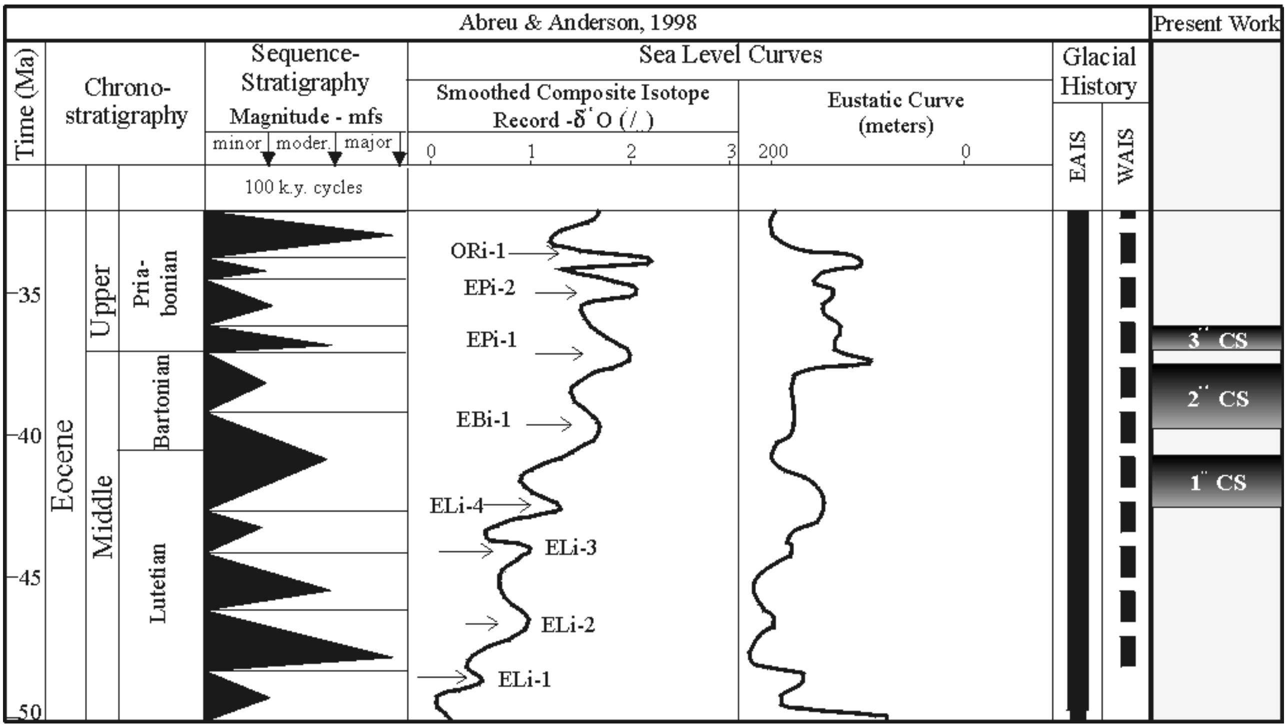

Fig. 8. Correlation of the time scale from Berggren et al. (1995), sequence boundaries of Hardenbol et al. (in press), smoothed composite $\delta^{18}O$ record, the eustatic curves of Haq et al. (1987) and Mitchum et al. (1994) and the glacial history (**solid bars** in the column indicate strong evidence for ice-sheet existence, **dashed lines** indicated early phases of ice-sheet development; EAIS = East Antarctica Ice-Sheet, WAIS = West Antarctica Ice-Sheet), redrawn from Abreu & Anderson (1998) and the composite sequences of the present study.

Conclusions

1) During the Middle to early Upper Eocene Epoch the stratigraphic architecture of the fore-arc Podhale Basin in S. Poland was mainly controlled by a mechanism of glacioeustatic sea-level changes.

2) The basin sedimentation took place in three depositional cycles: 1 — Upper Lutetian to Lower Bartonian, 2 — Middle to Upper Bartonian and 3 — Lower/Upper Priabonian.

3) Distinct changes of the rich LF communities in space and time incorporated enormous information about the *first composite sequence*. They resulted from gradual changes in climate, paleogeographical rearrangement and subsequent species evolution (mainly background dominated processes). This cycle's TST is characterized by low nutrients and warm climate. Data on changes in the shape of species with increasing depth are also evident.

4) A regression produced a stratigraphic unconformity on the basin margins (postulated SB2). In the investigated area it included the middle part of the Bartonian stage. Considering the oxygen-isotope record it correlates well with the EBi1 glacioeustatic event.

5) For the Middle to Upper Bartonian the sedimentation model is represented by a *second composite sequence* where temperate and unstable environmental conditions predominated (event dominated). It is characterized by the occurrence of heterosteginids, red algae, echinoderm and bryozoans limestones. The record of the former LF's during a falling stage in sea-level is highly notable (upper SBZ 18 Zone, Upper Bartonian).

6) Consequently, a new stratigraphic unconformity (SB2) is produced. It incorporated the Bartonian/Priabonian boundary. Considering the oxygen-isotope record it correlates well with the EPi1 event.

7) In the Lower Priabonian, a *third composite sequence* developed, starting with a new transgression. LF accumulations especially of *N. fabianii* point to the last optimal environmental conditions, before the next important tectonic phase (Ilyrian) initiated higher rates in the subsidence of the basin and tectonic activities, which favourite accumulation of thick successions of the Podhale Flysch deposits.

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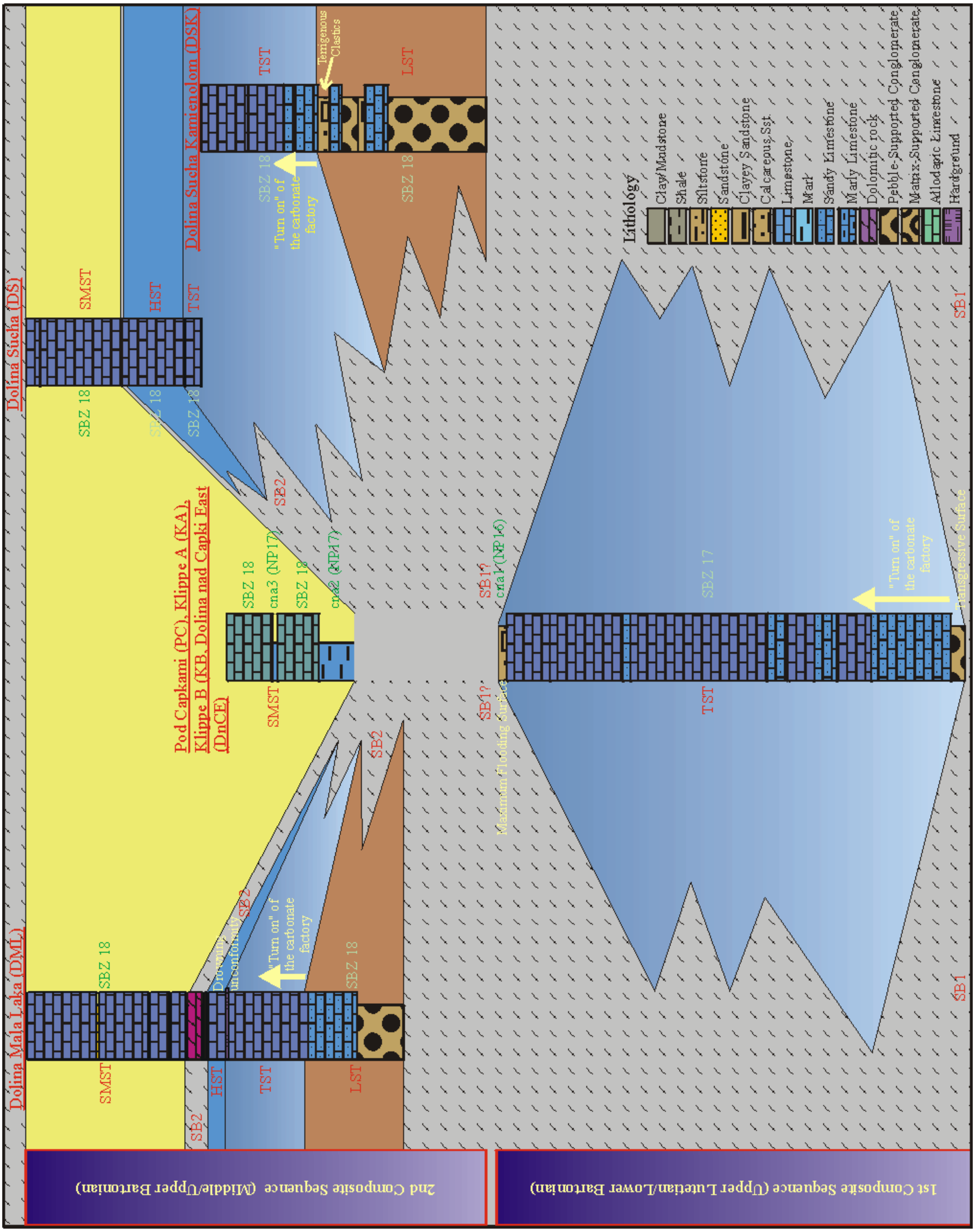

Fig. 9. Sequence-stratigraphic correlation of the studied sections.

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