

# DINOFLAGELLATE CYSTS STRATIGRAPHY AND PALYNOFACIES OF OLIGOCENE SEQUENCES IN THE NORTHERN EASTERN CARPATHIANS

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**Abstract** A palynological and palynofacies investigation conducted on Oligocene bituminous rocks of the Tarcău Nappe (Eastern Carpathians) has allowed recovery of marine palynomorphs (dinoflagellate cysts), spores and pollen, associated with an abundant amorphous organic matter. The dinoflagellate cyst taxa (e.g., *Rhombodinium draco*, *Wetzeliella gochtii*, *W. symmetrica*) identified in the top of the Lower Dysodilic Shale Formation and in the mid part of the Kliwa Sandstone Formation support the Rupelian–early Chattian age for these deposits. The palynofacies analysis in the lower part of the section (Lower Menilite and Bituminous Marls formations) show an abundance of marine organic matter, deposited mainly in a distal suboxic–anoxic environment. In contrast, the top of the Lower Dysodilic Shale and Kliwa Sandstone formations contain a large amount of terrestrial organic particles, suggesting a more proximal shelf environment for this interval. The occurrences in the Kliwa Sandstone Formation of some dinocyst taxa such as *Deflandrea*, *Wetzeliella* and *Rhombodinium* indicate the same depositional environment for this geological formation.

**Keywords:** dinoflagellate cyst biostratigraphy, palynofacies, Oligocene, Eastern Carpathians, Romania.

## INTRODUCTION

The Oligocene succession of the Moldavidian Domain from the northern Eastern Carpathians consists of organic-rich beds which have a good to excellent petroleum potential. These include siliceous deposits (Lower Menilite Formation), bituminous marls (Bituminous Marls Formation), black shales (Lower Dysodilic Shale Formation) deposited in a pelagic to hemipelagic depositional environments, followed by quartzarenites (Kliwa Sandstone Formation) sedimented on the shelf (Belayouni et al., 2009).

Previous biostratigraphic studies of these formations were made based on mollusks (Ionesi, 1997; Rusu, 1999), calcareous nannofossils (Melinte, 2005; Melinte-Dobrinescu & Brustur, 2008), fossil fish fauna (Baciu, 2001; Grădianu, 2010) and palynomorphs (Olaru, 1970, 1971, 1978; Țabără, 2010; Țabără et al., 2015). This fossil content marks the Oligocene age for these formations. The mollusk assemblages identified in the Bituminous Marls and Lower Dysodilic Shale formations consists of marker taxa such as *Nuculana westendorpi gracilis*, *Nucula comta*, *Polymedosa convexa*, indicating Rupelian age. The same geological age for the same interval is also supported by calcareous nannofossils, being recorded taxa such as *Reticulofenestra lockeri*, *Transversopontis fibula*, *Lanternitus minutus* and *Chiasmolithus oamaruensis* (Melinte-Dobrinescu & Brustur, 2008). The dinoflagellate cyst taxa *Wetzeliella gochtii* and *Rhombodinium draco*, identified in the Lower Dysodilic Shale Formation (Tarcău and Vrancea Nappes; Țabără et al., 2015), are considered by most authors as a markers for the early Oligocene (e.g. Köthe & Piesker, 2007; Pross et al., 2010). The paleontological content of the Kliwa Sandstone Formation is poor, being mentioned some intercalations with *Ostrea* shells in the lower part of this formation (Bogatu, 1982), as well as some marker taxa of nannofossils (e.g., *Pontosphaera enormis*, *Tri-*

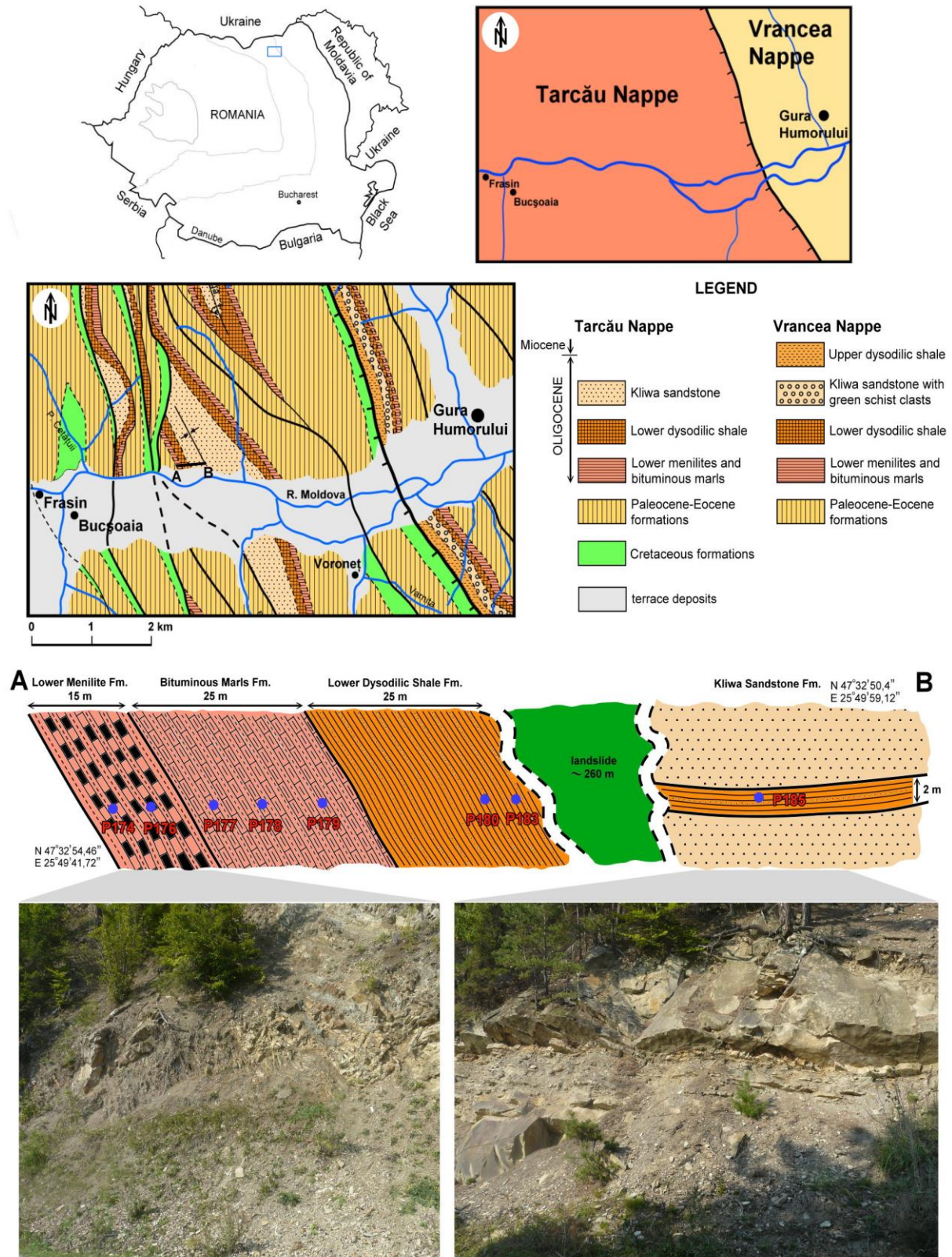
*quetrorhabdulus carinatus*) which indicate NP25 biozone (= late Chattian; Melinte-Dobrinescu & Brustur, 2008).

A different opinion regarding the age assigned to the stratigraphic interval between the Lower Menilite Formation up to Kliwa Sandstone Formation from the Moldavidian Domain was discussed by Belayouni et al. (2009) and Guerrero et al. (2012). Based on a calcareous nannofossil assemblages (e.g., *Helicosphaera recta*, *Triquetrorhabdulus carinatus*), the authors assigned the succession of bituminous rocks (Lower Menilite, Bituminous Marls and Lower Dysodilic Shale formations) to late Rupelian/Chattian–early Aquitanian, and the Kliwa Sandstone Formation (as well as the synchronous geological formations) to Aquitanian, based on *Globoquadrina dehiscens* planktonic foraminifera taxon.

The aims of the present study are thus the following: (1) identify palynological taxa and palynofacies characteristic of the interval between Lower Menilite Formation up to Kliwa Sandstone Formation; (2) correlation the recorded palynomorph assemblage with other palynological zonation established in the Western/Central Paratethys; and (3) to establish the depositional environments based on palynofacies analysis.

## LOCAL GEOLOGICAL SETTING

The Moldavidian Unit from northern part of the Eastern Carpathians includes, from west to east, the following tectonic nappes: Teleajen, Macla, Audia, Tarcău, Vrancea and Pericarpethian Nappe (Ionesi, 1971; Bădescu, 2005). The Paleogene–Miocene deposits included in various structural units of the Moldavide sometimes display considerable lateral facies variation. Thus, three distinct lithofacies have been identified (Băncilă, 1958; Ionesi, 1971; Grasu et al., 1988) in the Tarcău Nappe: the Fusaru Lithofacies in the west, Moldovați Lithofacies (mixed) in the center, and the Kliwa Lithofacies in the eastern part. In the lithological profiles analysed on the left side of the



**Fig. 1** Geological and tectonic sketch map of the Gura Humorului-Frasin area (after Ionesi, 1971, simplified), with the location of the geological cross-section studied.

Moldova Valley (Fig. 1), the samples were collected only from the Kliwa Lithofacies of the Tarcău Nappe.

The lower Oligocene interval of the Kliwa Lithofacies is characterized by the sedimentation of the Lower Menilite Formation, consisting mainly in silicious material with thin pelitic intercalations, followed by the Bituminous Marls and Lower Dysodilic Shale formations, composed of bituminous shales. These were deposited under anoxic conditions (Amadori et al., 2012), which enhanced organic matter preservation. This organic matter is considered to be autochthonous (marine), its accumulation being uniform throughout the External Flysh basin (Grasu et al., 2007).

The upper Oligocene of the Kliwa Lithofacies is characterized by the occurrence of the Kliwa Sandstone Formation, including white massive, orthoquartzitic sandstones (up to 200 m thick; Ionesi, 1971), interlayered with thin bituminous shales. In this lithofacies, the limit of erosion reached the Kliwa Formation.

## MATERIALS, METHODS AND SAMPLES LOCATION

The studied outcrop is located between Gura Humorului and Frasin localities, on the left side of the Moldova River (Fig. 1). The Paleocene–Oligocene stratigraphic sequence is framed to the Tarcău Nappe (Kliwa Lithofacies) and it occurs as a syncline. From this geological profile, eight samples were collected for the palynological and palynofacies analyses (Fig. 1). The last sample (P185), comes from a bituminous shale interlayer (2 m thick), which is located approximately in the middle part of the Kliwa Sandstone Formation.

For palynological and palynofacies analysis, all samples were processed using standard palynological technique (e.g. Batten, 1999). Approximately 50 g from each sample was treated with HCl (37%) to remove carbonates and HF (48%) to remove the silicate minerals. Denser particles were separated from the organic residue using ZnCl<sub>2</sub> with a density of 2.0 g/cm<sup>3</sup>. The palynological residues were mounted on microscopic slides with glycerin jelly.

The biostratigraphical diagnosis in the present study was obtained based on some dinoflagellates cysts markers, them being correlated with the ranges of the same taxa identified in many Oligocene biostratigraphically calibrated sections from the Northern Hemisphere (Williams et al., 2004; Köthe & Piesker, 2007; Barski & Bojanowski, 2010; Pross et al., 2010; Gradstein et al., 2012; Soliman, 2012; Dybkjær et al., 2012; Egger et al., 2016).

For the palynofacies analysis, at least 300–400 organic particles (> 15 µm) were counted in each sample, these being included at the three main groups of the kerogen constituents proposed by Tyson (1995), Carvalho et al. (2006) and Țabără et al. (2015), namely: Amorphous Organic Matter (AOM) group which includes structureless organic components derived from phytoplankton degradation (also known as granular AOM, marine origin) or degraded higher plant debris (called gelified AOM, terrestrial origin); phytoclasts group which includes opaque and translucent organic particles derived from terrestrial plants (woody tissues, cuticles, membranes); and palynomorphs group (dinocysts, spores and pollen).

The relative proportion of these three groups of organic matters identified in each sample was plotted in AOM–phytoclasts–palynomorphs ternary diagram (Tyson, 1995) for estimation of the depositional environments (Fig. 7).

Fluorescence microscopy was used to establish the AOM origin. Thus, AOM derived from phytoplankton degradation has patchy fluorescence (Pacton et al., 2011), while AOM resulting from the degradation of plant debris is nonfluorescent.

## RESULTS AND INTERPRETATION

### Palynological content

All samples contain fair to well-preserved palynomorph assemblages consisting of dinocysts, fern spores, pollen of gymnosperms and angiosperms, prasinophytes and freshwater algae. This study concentrates mostly on dinocysts as they provide more information to assess the age of the investigated samples. Generally, the Lower Menilite and Bituminous Marls formations exhibits a poor content in palynomorphs, but the diversity increases in the Lower Dysodilic Shale (upper part) and in the Kliwa Sandstone formations. The taxonomic list of palynomorphs and their relative occurrence in the analysed deposits is presented in Table 1. Some of the identified taxa are shown in Fig. 2 and 3.

#### Lower Menilite Formation

The palynological assemblage identified in this formation consists in a low number of taxa. Among dinocysts, *Batiacasphaera* sp. is the most frequently encountered taxon. In the sample P174, two colonies of freshwater algae (namely *Botryococcus*) were identified, probably transported by turbidity flows in a distal area of the basin. The ferns are represented only by *Laevigatosporites* spp. Among gymnosperms, few bisaccate pollen grains of *Pinus* and *Picea* were identified, and angiosperms are represented by herbaceous vegetation (*Graminidites*), palm trees (*Arecipites*) and trees of mixed mesophytic forest (*Fagus*, *Quercus* and *Carya*).

#### Bituminous Marls Formation

The assemblages of this formation show a very low content in palynomorphs. Among dinocysts, only *Batiacasphaera* sp. and *Membranophoridium* sp. occur, and continental palynomorphs are represented mainly of Pinaceae pollen (Table 1).

#### Lower Dysodilic Shale Formation

This formation show a taxonomic diversification (both the dinocysts, as well as the gymnosperms and angiosperms pollen). In the sample P180, *Batiacasphaera* sp. is the most abundant marine palynomorph. Other species were found as well, such as *Wetzeliiella symmetrica*, *Pentadinium laticinctum*, *Rhombodinium draco*, *Deflandrea phosphoritica* (Table 1), in association with continental palynomorphs which are prevalent in Pinaceae pollen (*Pityosporites* spp.), Taxodiaceae (*Inaperturopollenites* spp.) and palm trees pollen (*Monocolpopollenites tranquillus*, *Arecipites*).

#### Kliwa Sandstone Formation

The sample analyzed from this formation contains a palynological assemblage predominantly in the marine palynomorphs (87%), among these, the *Wetzeliielloideae*-group (*Wetzeliiella* spp. and *Rhombodinium* sp.) and

Table 1. Taxonomic list of palynomorphs identified in the Frasin section

Lithostratigraphic unit	Lower Menilite Fm.		Bituminous Marls Fm.			Lower Dysodilic Shale Fm.		Kliwa Fm.
	P174	P176	P177	P178	P179	P180	P183	P185
<b>Phytoplankton</b>								
<i>Botryococcus</i> sp.	2							
<i>Wetzeliella</i> sp.	1						2	11
<i>Wetzeliella symmetrica</i> Weiler, 1956							1	1
<i>Wetzeliella gochtii</i> Costa & Downie, 1976								11
<i>Wetzeliella spinula</i> (Bujak, 1979) Lentin and Vozzhennikova, 1989								1
<i>Batiacasphaera explanata</i> (Bujak in Bujak et al., 1980) Islam, 1983		3				1		
<i>Batiacasphaera</i> cf. <i>micropapillata</i> Stover, 1977								1
<i>Batiacasphaera</i> sp.		4			1	6		1
<i>Membranophoridium</i> sp.			1					
<i>Tythodiscus</i> sp.					1	1	2	3
<i>Cordosphaeridium cantharellus</i> (Brosius, 1963) Gocht, 1969						1		
<i>Cordosphaeridium</i> sp.							1	3
<i>Pentadinium laticinctum</i> Gerlach, 1961							3	
<i>Spiniferites</i> sp.							2	3
<i>Spiniferites ramosus</i> (Ehrenberg, 1838) Mantell, 1854							1	1
<i>Rhombodinium draco</i> Gocht, 1955							2	10
<i>Rhombodinium</i> sp.								3
<i>Deflandrea phosphoritica</i> Eisenack, 1938							1	11
<i>Deflandrea</i> sp.							1	23
<i>Operculodinium centrocarpum</i> (Deflandre & Cookson, 1955) Wall, 1967								5
<i>Operculodinium</i> sp.							1	3
<i>Lingulodinium</i> cf. <i>machaerophorum</i> (Deflandre & Cookson, 1955) Wall, 1967							1	
<i>Lingulodinium pycnospinosum</i> (Benedek, 1972) Stover & Evitt, 1978								1
<i>Lingulodinium</i> sp.								3
<i>Cleistosphaeridium placacanthum</i> (Deflandre & Cookson, 1955) Eaton et al., 2001								1
<i>Homotryblium tenuispinosum</i> Davey & Williams, 1966								2
<i>Homotryblium</i> sp.								1
<i>Membranophoridium aspinatum</i> Gerlach, 1961								6
<i>Palaeocystodinium</i> sp.								2
<i>Achomosphaera ramulifera</i> (Deflandre, 1937) Evitt, 1963								1
<i>Dapsilodinium pseudocolligerum</i> (Stover, 1977) Bujak et al., 1980								1
<i>Selenopemphix nephroides</i> Benedek, 1972								2

<i>Thalassiphora pelagica</i> (Eisenack, 1954) Eisenack & Gocht, 1960								7
<b>Pteridophyta</b>								
<i>Laevigatosporites</i> sp.		5				6		
<i>Laevigatisporites haardti</i> (Potonié et Venitz, 1934) Thomson et Pflug, 1953						1		
<i>Laevigatisporites nutidus</i> Mamczar, 1960						2		
<i>Laevigatosporites gracilis</i> Wilson and Webster, 1946						1		
<i>Leiotriletes</i> sp.				1				
<i>Retitriletes</i> sp.						1		
<i>Extrapunctatosporis</i> cf. <i>seydaensis</i> Krutzsch, 1967						1		
<i>Extrapunctatosporis</i> sp.						1	1	
<b>Gymnospermatophyta</b>								
<i>Pityosporites</i> sp.	3	3		1	1	12	12	9
<i>Pityosporites alatus</i> (Potonié, 1931) Thomson et Pflug, 1953		1					6	
<i>Pityosporites microalatus</i> (Potonié, 1931) Thomson et Pflug, 1953		1				2	7	3
<i>Pityosporites labdacus</i> (Potonié, 1931) Thomson et Pflug, 1953						3	24	
<i>Pityosporites scopulipites</i> (Wodehouse, 1933) Krutzsch, 1971								1
<i>Piceapollis</i> sp.		1						
<i>Podocarpidites libellus</i> (Potonié, 1931) Krutzsch, 1971							2	
<i>Podocarpidites</i> cf. <i>eocaenicus</i> Krutzsch, 1971							1	
<i>Podocarpidites</i> sp.							3	
<i>Sciadopityspollenites serratus</i> (Potonié et Ven., 1934) Thiergart, 1937		1						
<i>Ginkgo</i> sp.		2				3	2	
<i>Inaperturopollenites</i> sp.						7	3	
<i>Inaperturopollenites hiatus</i> (Potonié, 1931) Thomson et Pflug, 1953						4	4	1
<i>Inaperturopollenites concedipites</i> (Wodehouse, 1933) Krutzsch, 1971						2	1	2
<i>Inaperturopollenites verrupapillatus</i> Trevisan, 1967						1		
<i>Sequoiapollenites</i> sp.						1		
<i>Cupressacites bockwitzensis</i> Krutzsch, 1971						2	1	
<i>Zonalapollenites</i> sp.							1	
<i>Ephedripites</i> sp.							1	
<b>Angiospermatophyta</b>								
<i>Graminidites</i> sp.		4				1	1	
<i>Monocolpopollenites tranquillus</i> (Potonié, 1934) Thomson et Pflug, 1953						4	1	1
<i>Monocolpopollenites</i> sp.						4	2	
<i>Arecipites</i> sp.		1					1	
<i>Faguspollenites</i> cf. <i>subtilis</i> Nagy, 1969		2						
<i>Cyrtillaepollenites megaexactus</i> (Potonié, 1931) Potonié, 1960		2						
<i>Quercopollenites</i> sp.		1					1	
<i>Tricolporopollenites microhenrici</i> (Potonié, 1930) Krutzsch, 1960		1				1	2	

<i>Ilexpollenites</i> sp.							2	
<i>Tricolporopollenites</i> sp.		4	1				7	1
<i>Araliaceoipollenites edmundi</i> (Potonié, 1931) Potonié, 1951							1	
<i>Tricolpopollenites liblarensis</i> (Thomson, 1950) Thomson et Pflug, 1953							1	
<i>Myricipites</i> sp.		1						
<i>Myricipites bituitus</i> (Potonié, 1931) Nagy, 1969						1	3	
<i>Myricipites rurensis</i> (Pflug et Thomson, 1953) Nagy, 1969							1	
<i>Coryluspollenites</i> sp.							3	
<i>Caryapollenites simplex</i> (Potonié, 1931) Krutzsch, 1960							6	
<i>Caryapollenites</i> sp.		1						
<i>Platycaryapollenites</i> sp.						1		
<i>Aceripollenites</i> sp.							1	

Deflandrea-group (e.g., *Deflandrea phosphoritica*) being the most frequently identified. Rare occurrences of other dinocysts taxa such as *Operculodinium centrocarpum*, *Lingulodinium pycnospinosum*, *Homotryblium tenuispinosum*, *Membranophoridium aspinatum* and *Selenopemphix nephroides* are confirmed. The continental palynomorphs are represented mainly by Pinaceae pollen, whereas the Taxodiaceae pollen (*Inaperturopollenites* spp.) and some angiosperms constitute a minor fraction.

#### Age assignment

The dinocyst assemblages from the studied section contain few taxa known to represent biostratigraphic markers for the Oligocene. The age determination was made based on the First Appearance Datum (FAD) and Last Appearance Datum (LAD) of the taxa, recorded in many Oligocene biostratigraphically calibrated sections (more details in Materials and Methods).

The following marker taxa were identified and used for biostratigraphic interpretation (Fig. 4):

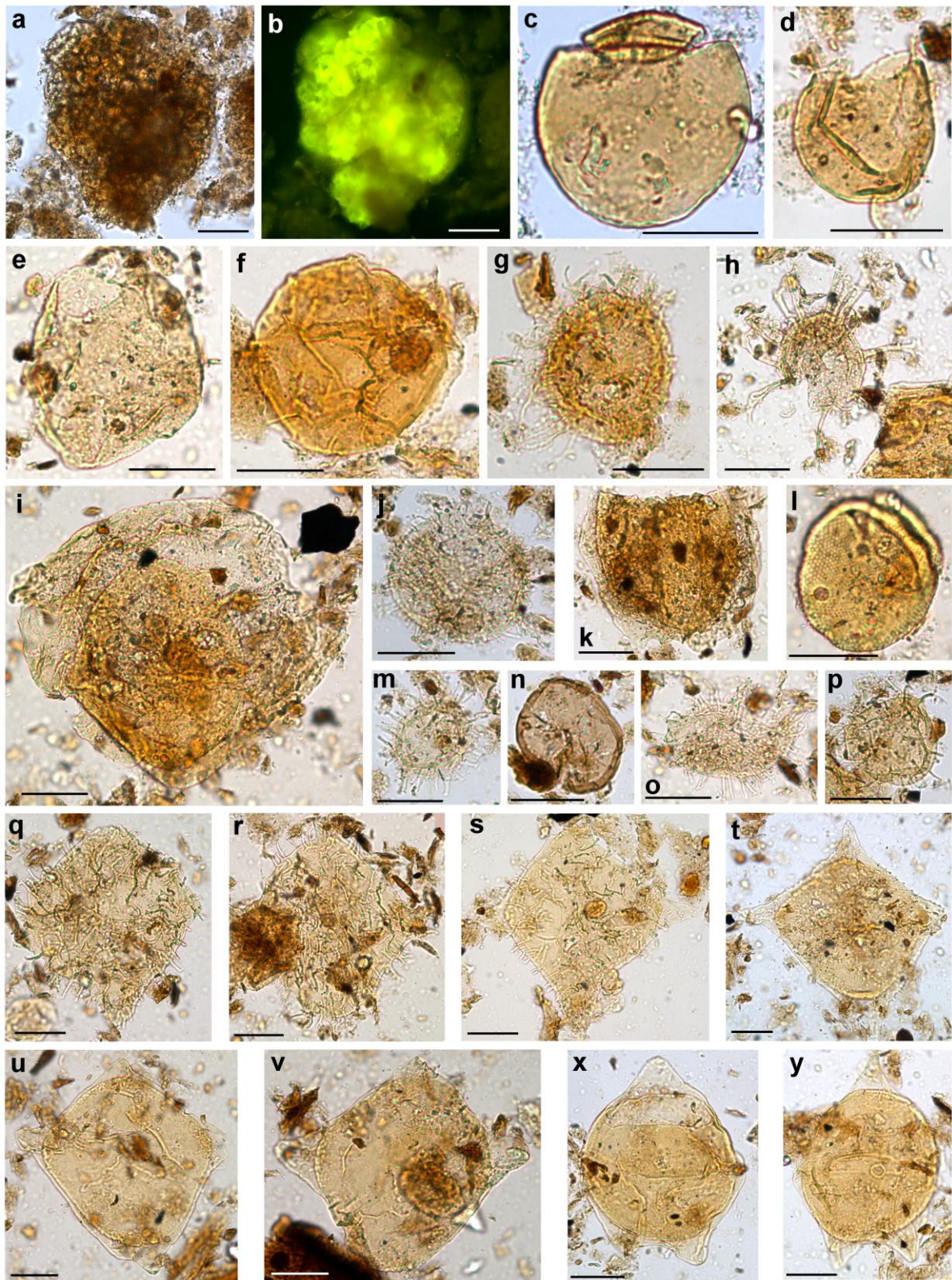
- *Rhombodinium draco* was identified in the Lower Dysodilic Shale and in the Kliwa Sandstone formations. According to Vandenberghe et al. (2012) and Williams et al. (2004), the FAD of this taxon marks the mid part of Bartonian, which corresponds to the lower part of the calcareous nannofossils biozone NP17. The LAD of *Rhombodinium draco* is dated at the mid part of the Rupelian (top of the dinocyst biozone D14; ~ 30 Ma.) in Northwestern Europe (Williams et al., 2004; Vandenberghe et al., 2012), or this bio-event is deemed to occur at the Rupelian–Chattian boundary in Germany (Köthe & Piesker, 2007), Belgium (Van Simaey et al., 2005), North Sea Basin (Schjøler, 2005) and Austria (Sachsenhofer et al., 2010; Soliman, 2012). According to Powell (1992), the last occurrence of the same species defines the top of the dinocyst biozone Lxa (lower part of Chattian). *R. draco* has also been found in Rupelian deposits of the Krosno Formation from southern Poland (Barski & Bojanowski, 2010), the Magura Formation (Gedl, 2005) and the Maikop Formation, Azerbaijan (Bechtel et al., 2013). In the Eastern Carpathians, this taxon has also been identified in the Lower Dysodilic Shale Formation (Slănic section; Țabără et al., 2015).

- *Wetzelia gochti* occurs in the studied section only in the Kliwa Sandstone Formation and this taxon is considered by most authors as a marker for Rupelian. According to Williams et al. (2004) and Vandenberghe et al. (2012), the presence of *Wetzelia gochti* indicates a range from the lowermost Rupelian (the base of dinocyst biozone D14; ~ 33 Ma.) to the middle part of the Chattian (lower part of subzone “c” of biozone D15). Powell (1992) indicated that the FAD of *W. gochti* marks the base of dinocyst biozone Wgo (early Rupelian) and LAD of this taxon coincides with the Rupelian/Chattian boundary. Pross et al. (2010), in the Umbria–Marche Basin of Central Italy, assigned *W. gochti* to the early Rupelian–middle Chattian (between 33.1 and 26.4 Ma.). In Germany, Köthe & Piesker (2007) stated that the LAD of the *W. gochti* is synchronous with the Rupelian–Chattian boundary, and in the northern part of Europe, Van Simaey et al. (2005) described it in the Rupelian–middle Chattian. Bati (2015) record this taxon in the lower Rupelian deposits assigned to the Maykop Formation (South Caspian Basin) and another occurrence is reported by Soliman (2012) from the Eggerding Formation (Rupelian) of North Alpine Foreland Basin, Austria.

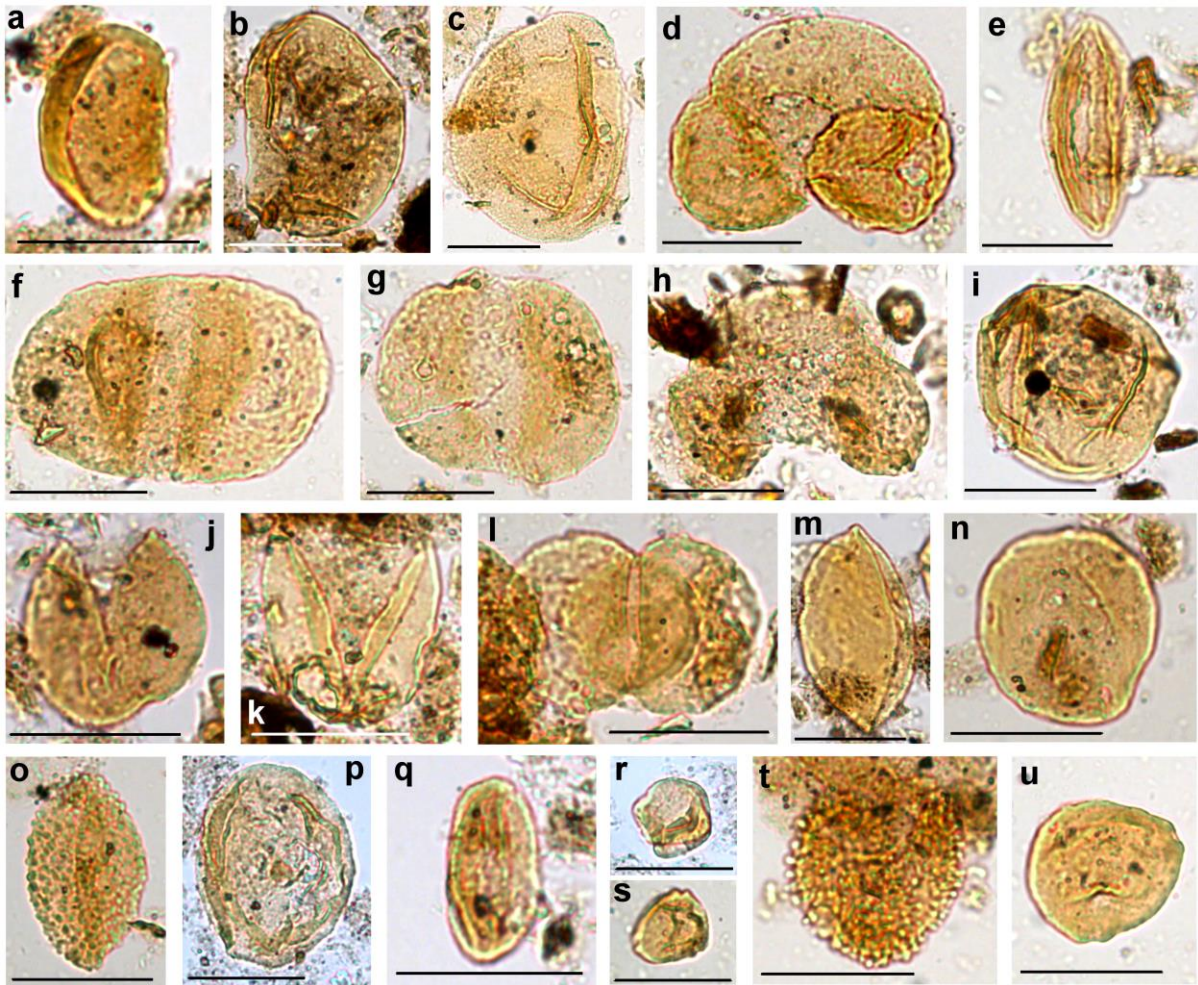
- *Wetzelia symmetrica* was identified in the Lower Dysodilic Shale and Kliwa Sandstone formations. Generally, this taxon is considered as a marker for Rupelian and its LAD has been determined at the lower Chattian in Italy (Pross et al., 2010), Belgium (Van Simaey et al., 2005) and North Sea Basin (Dybkjær et al., 2012). In the North Alpine Foreland Basin from Austria, Soliman (2012) reported this species only in the Rupelian deposits (Eggerding Formation).

- *Membranophoridium aspinatum* is encountered only in the Kliwa Sandstone Formation. According to Bati (2015), *M. aspinatum* has its first occurrence in the latest Eocene from South Caspian Basin and persist up to the Rupelian in Poland (Barski & Bojanowski, 2010) or lower Chattian from Austria (Soliman, 2012).

On the basis of co-occurrence of the marker taxa previously presented, a Rupelian–early Chattian age (dinocyst zones D14–D15b) is suggested for the studied interval assigned at the Lower Dysodilic Shale Formation up to the middle part of the Kliwa Sandstone Formation.



**Fig. 2** Dinoflagellate assemblages from the studied section (scale bar 30  $\mu$ m). **a, b.** *Botryococcus* sp. (transmitted light and fluorescence; P174); **c.** *Batiacasphaera explanata* (P176); **d.** *Batiacasphaera* sp. (P180); **e.** *Batiacasphaera* cf. *micropapillata* (P185); **f.** *Pentadinium laticinctum* (P183); **g.** *Lingulodinium* cf. *machaerophorum* (P183); **h.** *Homotryblum tenuispinosum* (P185); **i.** *Thalassiphora pelagica* (P185); **j.** *Operculodinium centrocarpum* (P185); **k.** *Membranophoridium aspinatum* (P185); **l.** *Tythodiscus* sp. (P185); **m.** *Dapsilidinium pseudocolligerum* (P185); **n.** *Selenopemphix nephroides* (P185); **o.** *Cleistosphaeridium placacanthum* (P185); **p.** *Spiniferites* sp. (P185); **q, r.** *Wetzeliella gochtii* (P185); **s.** *Wetzeliella symmetrica* (P183); **t.** *Wetzeliella spinula* (P185); **u, v.** *Rhombodinium draco* (P185); **x, y.** *Deflandrea phosphoritica* (P185).



**Fig. 3** Spores and pollen taxa from the studied section (scale bar 30  $\mu$ m). **a.** *Laevigatosporites gracilis* (P180); **b.** *Laevigatosporites nutidus* (P180); **c.** *Extrapunctatosporis* sp. (P183); **d.** *Pityosporites labdacus* (P183); **e.** *Ephedripites* sp. (P183); **f.** *Pityosporites alatus* (P183); **g.** *Pityosporites microalatus* (P183); **h.** *Pityosporites scopulipites* (P185); **i.** *Inaperturopollenites concedipites* (P180); **j.** *Inaperturopollenites hiatus* (P180); **k.** *Cupressacites bockwitzensis* (P180); **l.** *Podocarpidites libellus* (P183); **m.** *Monocolpopollenites tranquillus* (P180); **n.** *Caryapollenites simplex* (P183); **o.** *Arecipites* sp. (P183); **p.** *Faguspollenites* cf. *subtilis* (P176); **q.** *Tricolporopollenites microhenrici* (P180); **r.** *Cyrlaceapollenites megaxactus* (P176); **s.** *Myricipites bituitus* (P183); **t.** *Ilexpollenites* sp. (P183); **u.** *Coryluspollenites* sp. (P183).

This is consistent with the age suggested by the mollusks (Ionesi, 1997; Rusu, 1999), calcareous nannoplankton (Melinte-Dobrinescu & Brustur, 2008) and dinocysts (Țabără et al., 2015). In the samples P174 to P179 (assigned to the Lower Menilite and Bituminous Marls formations) were not recorded marker taxa to estimate the geological age.

#### Palynofacies data and palaeoenvironmental reconstruction

Generally, dispersed organic matter content of sediments from neritic and marginal marine environments is consisting of two main components: organic matter derived from the continent (phytoclasts, spores and pollen, gelified AOM) and organic matter produced in the marine domain (such as dinocysts and granular AOM).

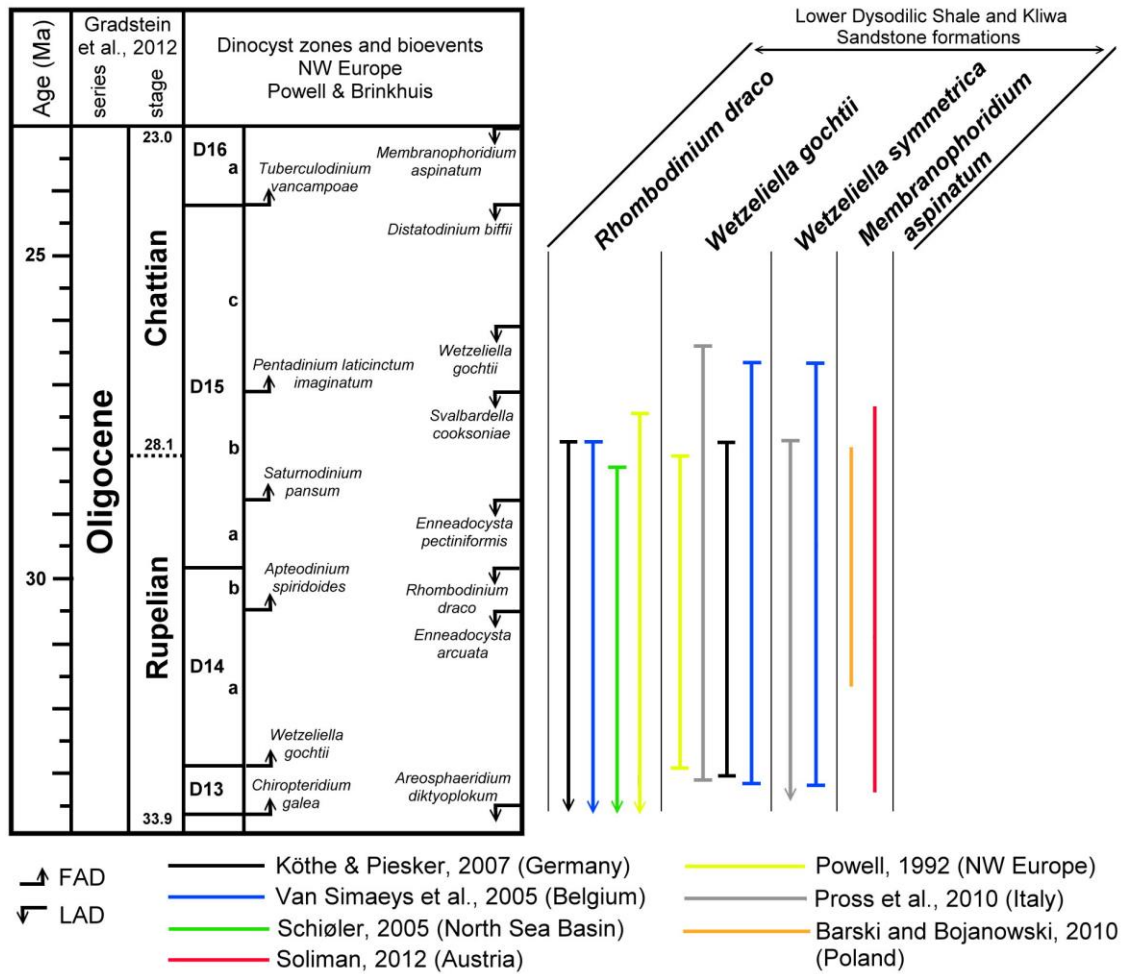
Plotted palynofacies data on a Tyson (1995) ternary diagram, as well as the composition of dinocyst assemblages, were used to interpret depositional environments.

The quantitative investigations of the organic matter from the Lower Menilite Formation revealed a large amount of AOM, the granular type of marine origin being predomi-

nantly in the sample P176 (95%; Fig. 5). The presence of many coccoid bodies (bacteria or algae) and extracellular polymeric substance (EPS) on this AOM (Fig. 6 a, b) suggest that it is mainly of microbial origin. AOM fluorescence is either weak or absent (Fig. 6, b), perhaps due to bacterial degradation under dysoxic or anoxic conditions, which can lead to decreased fluorescence. However, sometimes granular AOM shows a patchy fluorescence (Bituminous Marls Formation; Fig. 6, d), suggesting its marine origin (derived from phytoplankton degradation; Paction et al., 2011). Gelified AOM of terrestrial origin sometimes occurs in association with granular AOM.

The continental phytoclasts in the Lower Menilite Formation are rarely identified (2–4%), being present some opaque and translucent particles. These facies were deposited in a proximal suboxic–anoxic shelf to distal suboxic–anoxic basin (Fig. 7). In the sample P174, some colonies of freshwater algae (e.g. *Botryococcus*) were identified, suggesting a proximal sedimentary environment for this interval, while the sample P176 contains only *Batiacaspheara* specimens (among dinocysts) indicating a





**Fig. 4** Range chart of the dinoflagellate cysts used in this study. Correlation with previously published dinocyst zonation within Germany (Köthe & Piesker, 2007), the North Sea Basin (Schiøler, 2005), Austria (Soliman, 2012), Italy (Pross et al., 2010), Belgium (Van Simaey et al., 2005), Northwest Europe (Powell, 1992) and Poland (Barski & Bojanowski, 2010) are shown. Dinocyst biozones and bioevents according to Powell & Brinkhuis (in Vandenberghe et al., 2012).

more offshore environment (Brinkhuis & Zachariasse, 1988).

The Bituminous Marls Formation contains a large amount of organic matter, this being prevalent in the granular AOM (74–84%; Fig. 5) and gelified AOM (Fig. 8, a). The granular AOM contains, as in the Lower Menilite Formation, many coccooid bodies and EPS. The opaque and translucent phytoclasts are rarely identified (2–3%), usually small in size (< 20µm). The palynomorphs also have rare occurrences (< 1%), being identified some grains of Pinaceae pollen and dinocysts. Particulate organic matter assemblages plot in field IX of the Tyson’s (1995) diagram (Fig. 7) indicates that deposition occurred within a distal suboxic–anoxic basin. A (hemi-) pelagic depositional environment has also been proposed by Amadori et al. (2012) for this formation. A high percentage of autochthonous marine organic matter (type II kerogen) and low concentrations of land plant-derived biomarkers (cadalenes, diterpenoids) was also determined by Sachsenhofer et al. (2015) from the Bituminous Marls Formation of the Eastern Carpathians.

In the upper part of a Lower Dysodilic Shale Formation, a decrease in the amount of the granular AOM (marine origin) and a higher proportion in translucent phytoclasts

have been observed (Fig. 5). The AOM identified in this formation it is granular and gelified type (Fig. 8, b), also contains EPS and coccooid bodies, and it is mixed with allochthonous organic particles such as translucent and opaque phytoclasts and continental palynomorphs. The translucent and opaque phytoclasts are generally small in size, and the most common palynomorphs are assigned to the Pinaceae and *Taxodium* pollen.

Among dinoflagellates, the presence of *Batiacasphaera* taxon in the sample P180 indicates a more offshore environment. According to Tyson (1995), this palynofacies content corresponds to a proximal suboxic–anoxic shelf, but this environment is more well defined in the top of the Lower Dysodilic Shale Formation (sample P183; Fig. 7). At this stratigraphic level, in the palynological assemblages first occur dinocysts such as *Wetzeliiella* and *Deflandrea* which indicate nutrient-rich near-shore environment (Pross & Schmiedl, 2002) or lagoon/estuarine environment (Jaramillo & Oboh-Ikuenobe, 1999). From the lower part of this formation identified in the same geological section, Ţabără et al. (2015) describe a palynofacies dominated by granular AOM (> 95%), suggesting a more distal environment, similar to that of the Bituminous Marls Formation.

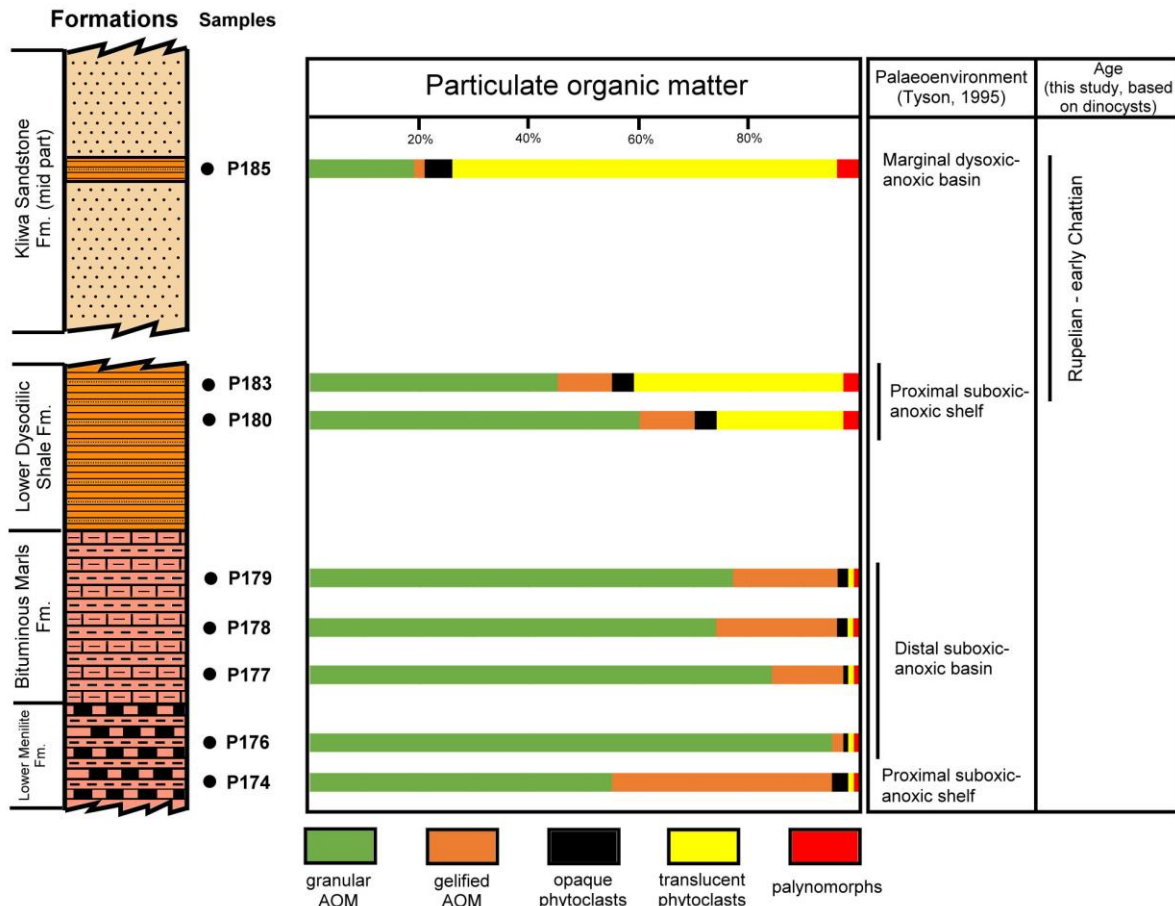


Fig. 5 Relative abundances of particulate organic matter from the analyzed samples (percentage calculated to Total Sedimentary Organic Matter).

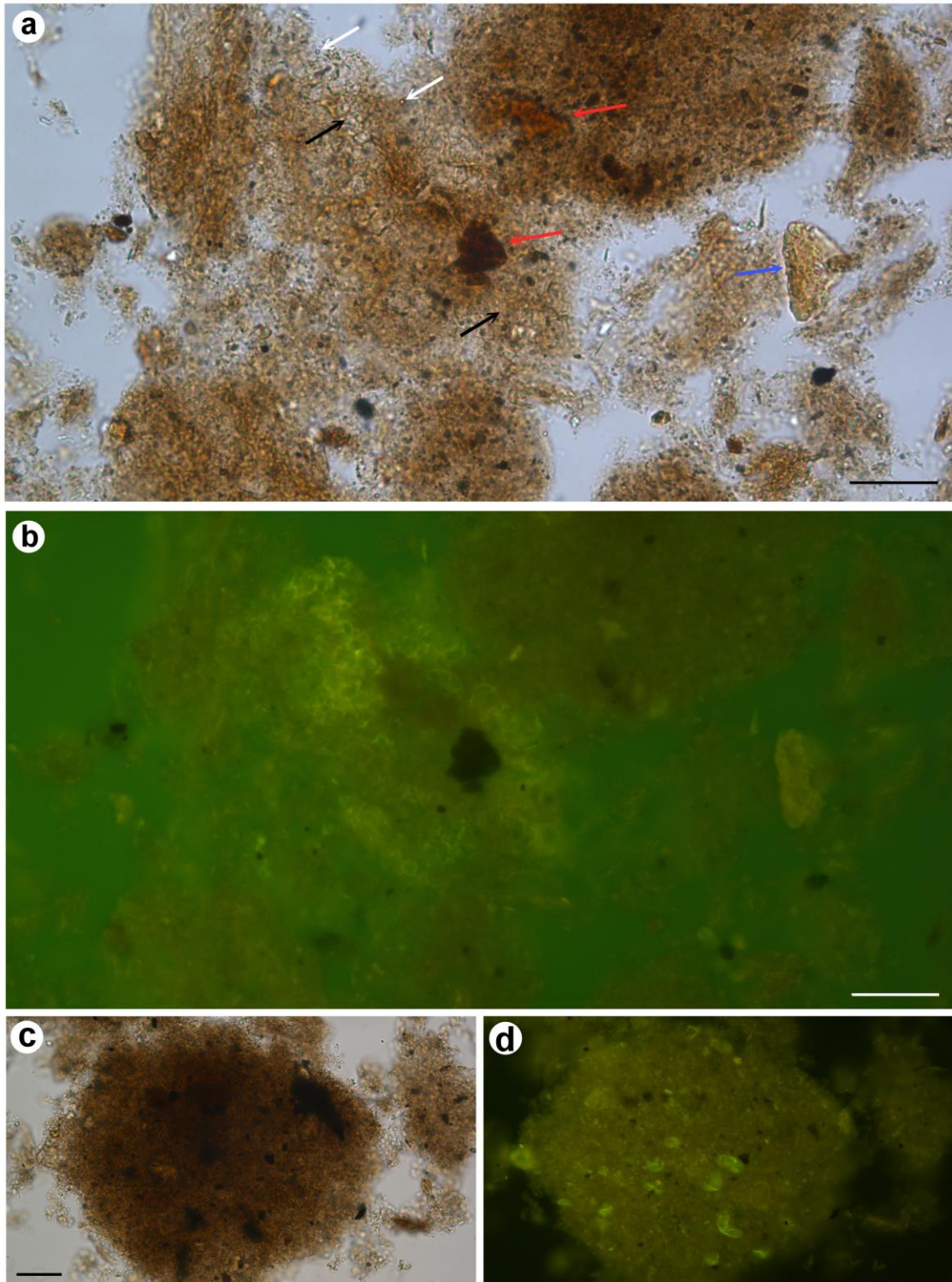
The middle part of the Kliwa Sandstone Formation (sample P185) comprises a palynofacies dominated by translucent phytoclasts (~70%; Fig. 5), some of these woody tissues sometimes being large in size (Fig. 8, c). Other phytoclasts such as opaque particles, some biodegraded cuticles and tracheid tissues, are rarely identified. The marine organic matter exhibits a decrease in abundance (up to 20% of the total assemblage). This palynofacies suggests a marginal dysoxic–anoxic basin (Fig. 7).

The most common palynomorphs identified in the sample P185 are the dinocysts (87%). Among these, the *Deflandrea*-group, *Wetzeliella* and *Rhombodinium* are the most common taxa. This assemblage indicates an increased nutrient (e.g., phosphate and nitrate) content, but in well-mixed rather than stratified (coastal) waters (Pross & Schmiedl, 2002; Sluijs et al., 2005; Sachsenhofer et al., 2010; Soliman, 2012). Another dinocyst taxon (i.e. *Thalassiphora pelagica*) identified in this assemblage, also suggests growth in nutrient-rich water masses and a low-oxygen shelf environment (Köthe, 1990; Pross & Schmiedl, 2002).

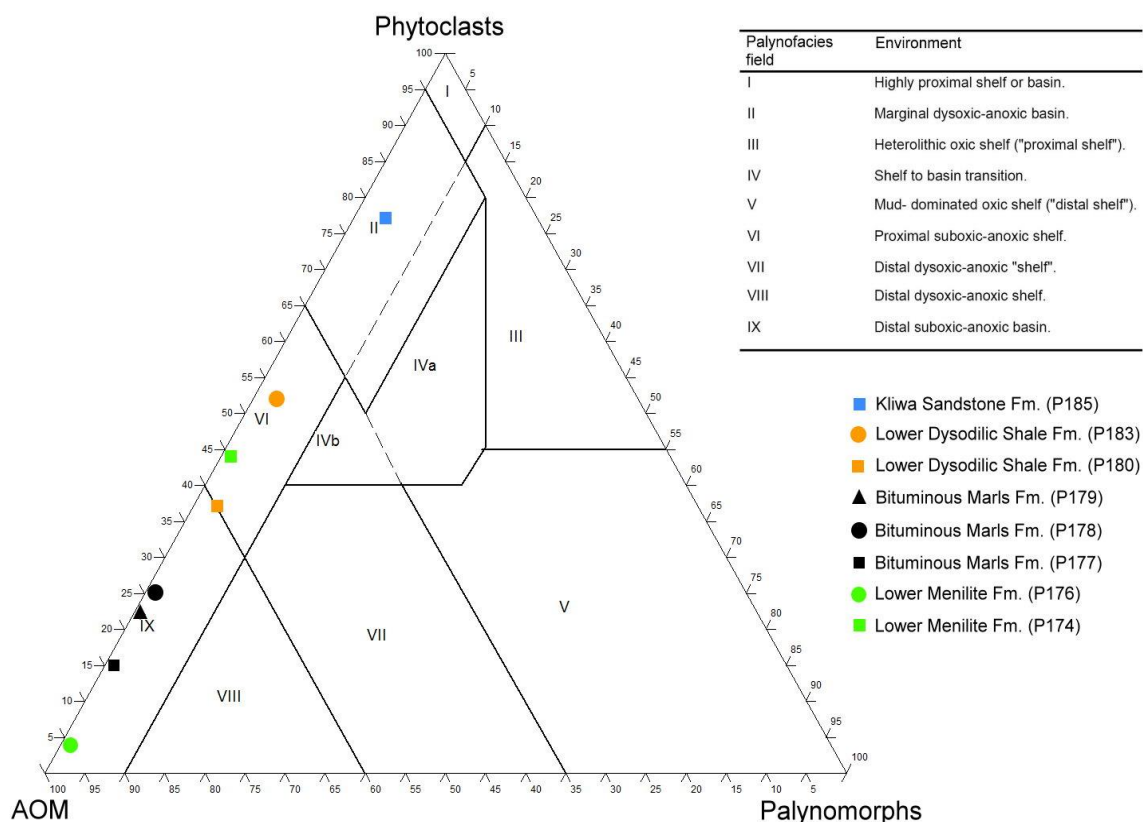
## CONCLUSIONS

This study describes biostratigraphical data inferred based on dinocyst bioevents, as well as the palynofacies content from an Oligocene sequence of the Tarcău Nappe. The main conclusions are the following:

- the dinocyst assemblages identified to the top of the Lower Dysodilic Shale Formation and to the middle part of the Kliwa Sandstone Formation indicate a Rupelian–early Chattian age. Important biostratigraphic event markers for this age are the occurrence of *Wetzeliella gochtii* (FAD in lowermost Rupelian, the base of dinocyst zone D14) and the presence of *Rhombodinium draco*, *Wetzeliella gochtii* and *W. symmetrica* (LADs in early Chattian, subzone “b” of dinocyst zone D15). The palynological content identified in the Lower Menilite and Bituminous Marls formations does not contain marker taxa to estimate the geological age.
- the palynofacies analysis indicates a high content of granular AOM of microbial and phytoplanktonic origin in the Lower Menilite and Bituminous Marls formations, while to the top of the Lower Dysodilic Shale and the Kliwa Sandstone formations, the kerogen consists mainly in phytoclasts (e.g., translucent and opaque particles, gelified AOM), suggesting a strong terrestrial influx.
- according to the palynofacies analysis, a distal suboxic–anoxic environment defines especially the lower part of the sequence, followed by a more proximal shelf environment to the top of the Lower Dysodilic Shale and of the Kliwa Sandstone formations. Moreover, the high frequency of the dinocyst taxa such as *Deflandrea*, *Wetzeliella* and *Rhombodinium* in the Kliwa Sandstone Formation indicate a nutrient-rich near-shore environment or lagoon/estuarine zones.



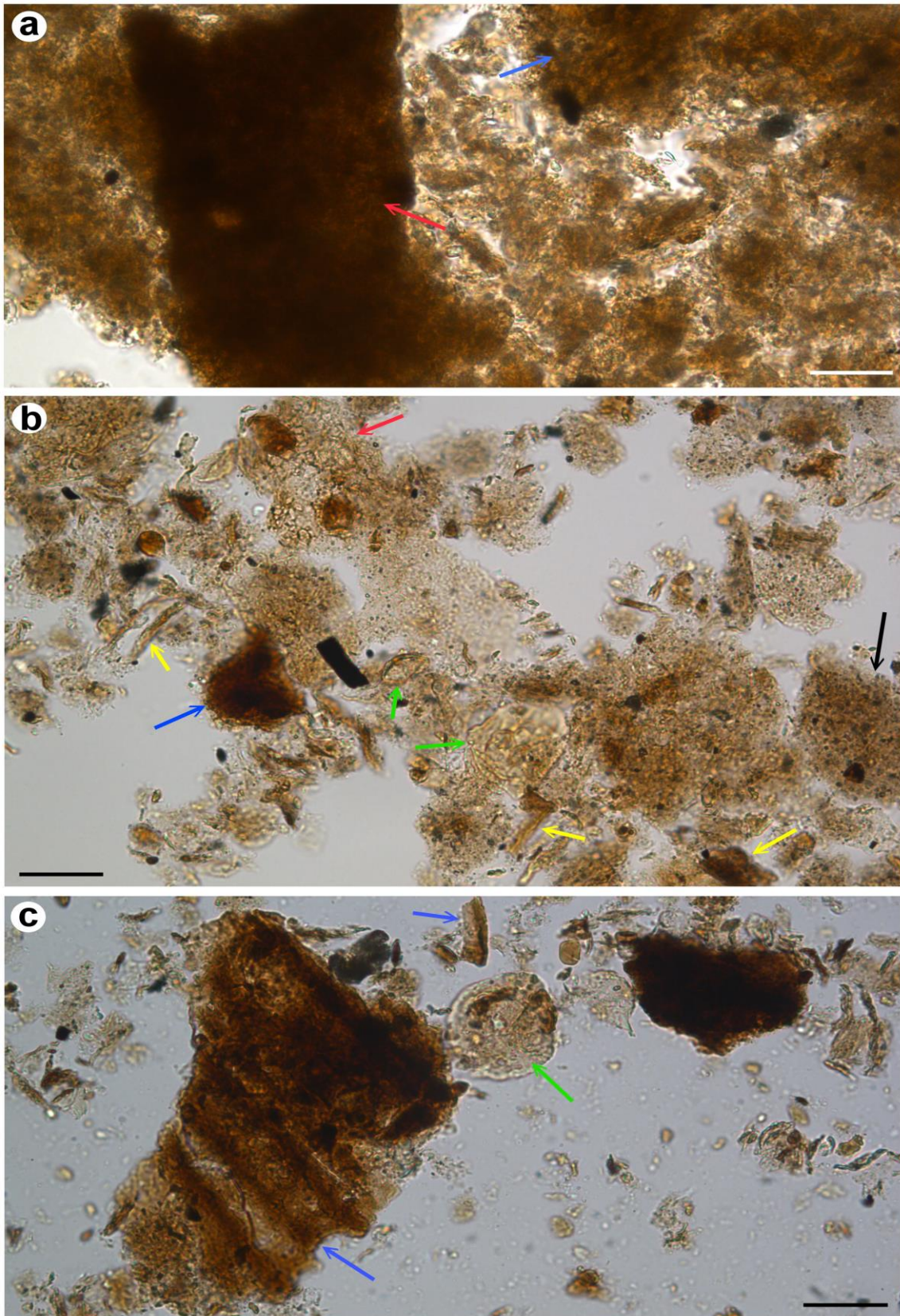
**Fig. 6** In a palynological slide under natural light and blue-light fluorescence, the representative palynofacies from the Lower Menilite and Bituminous Marls formations. Scale bar: 30  $\mu\text{m}$ . **a** - abundant granular AOM with brown color in association with EPS (black arrow, tiny filaments forming an alveolar network), coccoid bodies (bacteria or algae, white arrow), gelified AOM (red arrow) and palynomorphs (blue arrow). The color and abundance of AOM suggest a dysoxic–anoxic environment (P174); **b** - idem previous image (blue-light fluorescence), AOM exhibits weak fluorescence; **c** - brown granular AOM (P178); **d** - idem previous image (blue-light fluorescence), AOM shows a patchy fluorescence.



**Fig. 7.** Ternary kerogen plots (Tyson, 1995) for the Lower Menilite Formation up to Kliwa Sandstone Formation, with inferred depositional environments.

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**Fig. 8** The representative palynofacies from the Bituminous Marls, Lower Dysodilic Shale and Kliwa Sandstone formations. Scale bar: 30  $\mu\text{m}$ . **a** - abundant AOM (granular and gelified; Bituminous Marls Fm., sample P178) with dark brown color. Granular AOM (blue arrow), gelified AOM (red arrow); **b** - granular AOM with a light-brown color (black arrow), EPS (red arrow) mixed with continental organic particles such as translucent phytoclasts (yellow arrow), gelified AOM (blue arrow) and palynomorphs (green arrow) (Lower Dysodilic Shale Fm., sample P180); **c** - brown woody tissue large in size (blue arrow), in association with continental palynomorphs (green arrow) and other terrestrial organic particles (Kliwa Sandstone Fm., sample P185).

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