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Dinoflagellate cyst assemblages across the Oxfordian/Kimmeridgian boundary (Upper Jurassic) at Flodigarry, Staffin Bay, Isle of Skye, Scotland – a proposed GSSP for the base of the Kimmeridgian

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Key words: dinoflagellate cysts, Oxfordian/Kimmeridgian boundary, Skye, Scotland, "green tide".

Abstract. Examination of seven ammonite-calibrated palynological samples across the Oxfordian/Kimmeridgian boundary in the Flodigarry sections at Staffin Bay, Isle of Skye, northern Scotland, has revealed dinoflagellate cyst assemblages in general terms in line with previous contributions. The sparse occurrence of *Emmetrocysta sarjeantii*, *Perisseiasphaeridium pannosum* and *Senoniasphaera jurassica* slightly above the proposed Oxfordian/Kimmeridgian boundary may be used as a palynological approximation of the base of the Kimmeridgian. The high abundance of tests resembling modern zygnemataceous chlorophycean alga *Spirogyra* in two samples above the Oxfordian/Kimmeridgian boundary horizon is probably associated with increased eutrophication and possible association with "green tides". This bloom is proposed as a palynofloral proxy event for the boundary in the Flodigarry section. According to previous studies, various eutrophication events may have a correlation potential in Subboreal Europe.

INTRODUCTION

Dinoflagellate cysts from strata across the Oxfordian/Kimmeridgian boundary exposed near Flodigarry hamlet, Staffin Bay, Isle of Skye, northwest Scotland (Fig. 1) have been examined as part of a more extensive study of the succession considered as a potential global stratotype section and point (GSSP) for the base of the Kimmeridgian (Matyja *et al.*, 2006; Wierzbowski *et al.*, 2006, 2016, 2018). Although studies of dinoflagellate cysts from the Flodigarry area have been previously undertaken by Riding and Thomas (1997), the stratigraphically significant interval corresponding to subzones c and d of the dinoflagellate Scriniodinium crystallinum Zone (or the corresponding boundary of the dinoflagellate cyst zones DSJ 26 and DSJ 27 of Poulsen, Riding, 2003) was not subdivided by these authors. This was due to the lack of detailed work on the ammonite succession of the Staffin Bay sections at that time, so that detailed sampling of the interval across the Oxfordian/Kimmeridgian boundary was not possible.

The succession studied belongs to the higher part of the Flodigarry Shale Member of the Staffin Bay Formation, and covers an interval from the upper part of Bed 35 up to the lower part of Bed 37, mostly composed of silty clays, except for the prominent marker Bed 36, which represents a band of calcareous nodules. A single sample was taken from Bed 42 representing the higher part of the section (for location of the section and details of the lithology see Matyja *et al.*, 2006, figs 1–3, and earlier papers cited therein; see also Fig. 2, herein).

The ammonites present in the the Flodigarry section belong to the Subboreal family Aulacostephanidae and the Bo-

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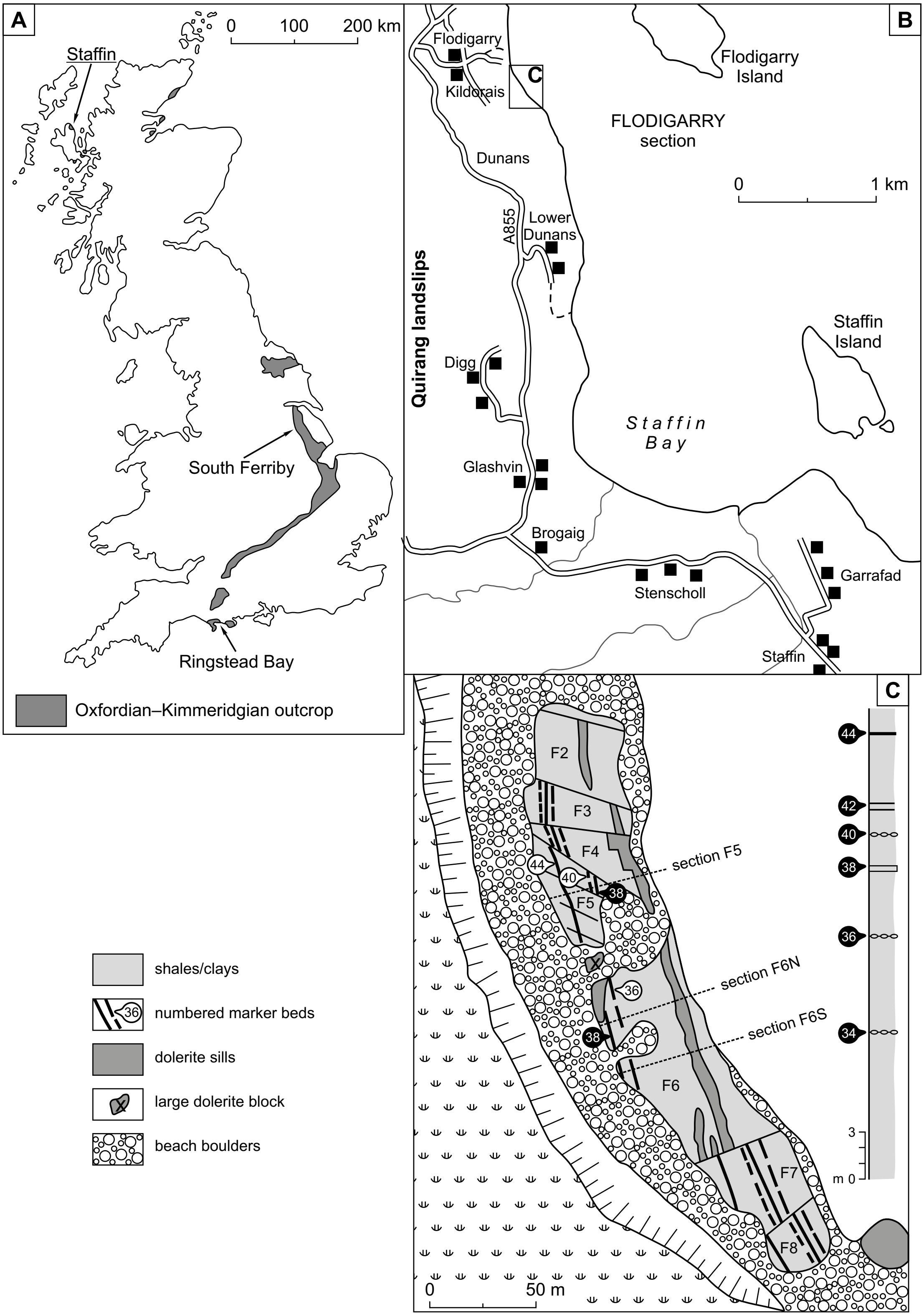

Fig. 1. Location map of study area (after Wierzbowski *et al.*, 2006)

A. The position of the area of study in northern Scotland and the most important Oxfordian/Kimmeridgian boundary outcrops in U.K.; **B, C.** Maps of foreshore at Flodigarry showing the position of the sections studied

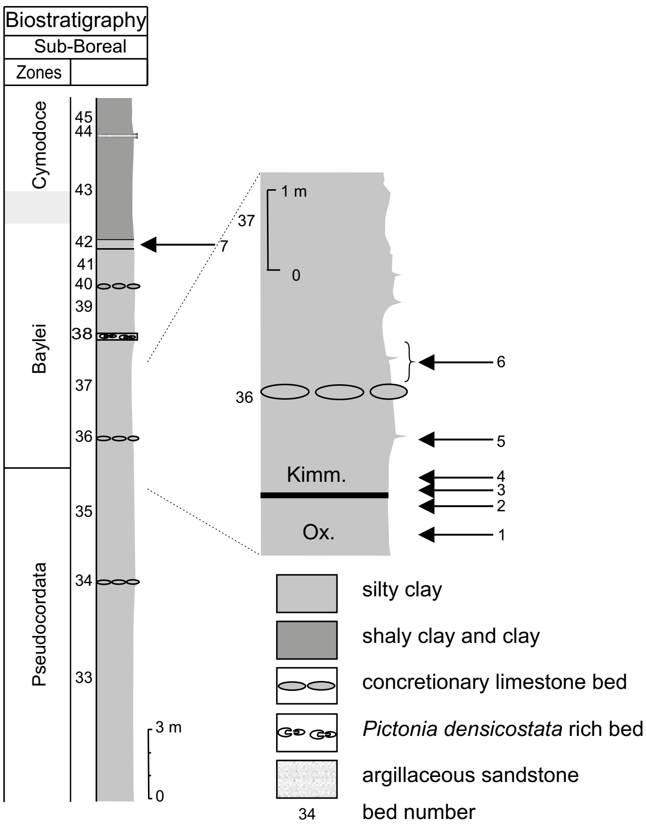

Fig. 2. Simplified columns of the Flodigarry section at Staffin Bay, Isle of Skye, with boundary interval enlarged and with location of palynological samples (after Wierzbowski *et al.*, 2006)

real family Cardioceratidae. Studies by the authors listed above has enabled the recognition of the Pseudocordata Zone with the Caledonica, Pseudoyo, Pseudocordata and Evoluta subzones, indicating the presence of the standard uppermost Oxfordian Subboreal sequence, and the lowermost Kimmeridgian Baylei Zone with the Densicostata and Normandiana subzones. The boundary between the uppermost part of the Pseudocordata Zone – the Evoluta Subzone, and the lowermost part of the Baylei Zone – the Densicostata Subzone, and the *flodigarriensis* horizon, occurring at its base, are treated as the base of the Kimmeridgian Stage. This base is placed in a very narrow interval, located originally in a 0.16 m interval (1.24–1.08 m) below Bed 36 (Matyja *et al.*, 2006), and recently narrowed to the level of 1.24–1.26 m below Bed 36 (Wierzbowski *et al.*, 2018). This level corresponds to the boundary of the Rosenkrantzi Zone and the Bauhini Zone, as based on the ammonite succession of the family Cardioceratidae in the Boreal subdivision (Matyja *et al.*, 2006; Wierzbowski *et al.*, 2006, 2016, 2018).

The samples for the dinoflagellate cyst study have been obtained from ammonite specimens carefully located in the succession and elaborated in detail by Matyja *et al.* (2006) and Wierzbowski *et al.* (2018). Six samples, located in the crucial interval between the uppermost part of Bed 35 and the lowermost part of Bed 37, and a single sample from Bed 42 have been studied for dinoflagellate cysts but three of them (2, 3 – 1.44 and 1.24 m below Bed 36; and 7 from Bed 42) have yielded very poor material, and/or were strongly enriched in plant debris, which made extracting of the cysts difficult. In turn, four samples have yielded fairly rich and well preserved dinoflagellate cysts, as discussed below. In stratigraphical order they include: sample 1 at 1.8 m below Bed 36 (corresponding to the Evoluta Subzone of the Pseudocordata Zone); sample 4 at 1.08 m below Bed 36 (corresponding to the *flodigarriensis* horizon of the lowermost part of the Baylei Zone); sample 5 at 0.60 m below Bed 36 (corresponding to the *flodigarriensis* horizon of the lowermost part of the Baylei Zone), and sample 6 located between the top of Bed 36 and 0.5 m above (corresponding to the *flodigarriensis* horizon of the lowermost part of the Baylei Zone) (Fig. 2). The samples cover the Oxfordian/Kimmeridgian boundary of the proposed GSSP section, which is placed between samples 1 and 4 (in fact between samples 2 and 3 which are, however, very poorly fossiliferous).

MATERIAL AND METHODS

Seven palynological samples were prepared using standard palynological procedures. An average of 10 g of sediment per sample was treated with 30% HCl for carbonate removal and 70% HF for silicate removal. The residues were sieved over a 15-μm mesh sieve and separate by heavy liquid ($ZnCl_2$, d = 2 g/cm^3). The organic matter was placed on a slide, using partly glycerine jelly and UV cured glue as the mounting media. The seven samples have yielded organic-walled dinoflagellate cysts in various proportions. As a limited number of dinoflagellate cyst specimens per slide were available for analysis, five slides per each sample have been counted to obtain the total number of dinoflagellate cysts, providing the quantitative data presented on the range chart (Tab. 1). The dinoflagellate cysts in the studied material showed a low level of thermal maturity and have been adversely affected by the crystallization of pyrite framboids, and therefore all samples were routinely examined under phase contrast during the preliminary study. After the first stage of sample examination, oxidation proceeded with 5 min. HNO_3 acid and KOH treatment removing the pyrite and most delicate tissues including green algae. However, the persisting predominance of insoluble terrestrial particles consisting of opaque and translucent wood fragments and sporomorphs and post-crystallization damage to the cyst surfaces still obscured the dinoflagellate cysts and impeded

Table 1

Quantitative range chart with dinoflagellate cysts taxa occurring in the Oxfordian/Kimmeridgian boundary interval in the Flodigarry section at Staffin Bay, Isle of Skye

Sample	*Chlorophycae* algae	*Ambonosphaera ? staffinensis*	*Atopodinium haromense*	*Endoscrinium galeritum*	*Endoscrinium luridum*	*Gonyaulacysta dentata*	*Gonyaulacysta jurassica jurassica*	*Leptodinium subtile*	*Pareodinia ceratophora*	*Cribroperidinium globatum*	*Rhynchodiniopsis cladophora*	*Scriniodinium crystallinum*	*Sentusidinium-Barbatacysta-Pilosidinium* Group	*Systematophora areolata*	*Prolixosphaeridium anasillum*	*Tubotuberella apatela*	*Valensiella ovulum*	*Glossodinium dimorphum*	*Scriniodinium dictyotum papillatum*	*Scriniodinium inritibile*	*Adnatosphaeridium caulleryi*	*Scriniodinium dictyotum osmingtonense*	*Hystrichosphaerina? orbifera*	*Gonyaulacysta eisenackii*	*Dingodinium jurassicum*	*Ellipsoidictyum cinctum*	*Emmetrocysta sarjeantii*	*Perisseiasphaeridium pannosum*	*Senoniasphaera jurassica*	*Senoniasphaera aff. jurassica*	*Sirmiodinium grossii*	*Dingodinium tuberosum*	
7		3	6				9			2	5		22												5	2					2		Kimmeridgian
6		6	9	1	4		12	6		7	7	16	36		2	1		3		4	1				4	7		2	3			5	
5	X	22	14	2	3		35	8		3	14	49	62	3	4	2	2	4	33	6	2	6	3	2		14	5	3	2	2	6		
4	X	9	12	5	7		32	12	9	11	19	41	57	7	7			6	47	9	4	8	5	4	5	12	8						
3							12		6				43																				
2							6				9		46			6																	Ox.
1		15	16	37	21	5	27	23	18	21	22	16	43	16	5	17	12	8															

Ox. – Oxfordian; X for chlorophycea algae is equivalent of one cell chain per dinoflagellate cyst specimen in average

taxonomic assignment. Therefore, all samples after oxidation were examined under interference contrast technique (Zeiss Axioscope microscope) due to the pale and translucent character of dinoflagellate cyst walls. Microphotographs were taken using a 12 MPx digital camera installed on a Nikon Eclipse 600 microscope with a phase-contrast facility. The remaining palynological residues preserved by thymol water solution in tubes and slides are housed in the collection of the Faculty of Geology, University of Warsaw. Selected dinoflagellate cyst taxa recovered in this study are documented in Plates 1 and 2.

RESULTS

The analyzed palynological samples are located in reference to the base of Bed 36 in the published Flodigarry section (Riding, Thomas, 1997; Wierzbowski *et al.*, 2018). Four samples have yielded abundant organic matter, rich in marine and terrestrial palynomorphs. Three samples are impoverished in organic walled dinoflagellate cysts with terrestrial derived tissues and amorphous organic matter (AOM) predominating. In total, 31 dinoflagellate species and one chlorophycae algae have been identified (Tab. 1). The majority of the taxa, however, are long-ranging (Riding, Thomas, 1992; Poulsen, Riding, 2003) and do not have age-diagnostic value. Across the Oxfordian/Kimmeridgian boundary interval the dinoflagellate cyst taxa include common and consistently present: *Ambonosphaera* ? *staffinensis*, *Endoscrinium galeritum*, *Gonyaulacysta jurassica jurassica*, *Leptodinium subtile*, *Rhynchodiniopsis cladophora*, *Scriniodinium crystallinum*, *S. dictyotum papillatum*, and the *Sentusidinium-Barbatacysta-Pilosidinium* Group. Above the boundary some sparse inceptions of taxa characteristic of the lowermost Kimmeridgian, including *Perisseiasphaeridium pannosum*, *Senoniasphaera jurassica* and *Emmetrocysta sarjeantii*, can be utilised as boundary markers. The detailed distribution of all recovered dinoflagellate taxa is shown in the range chart (Tab. 1).

SAMPLE CHARACTERISTICS

Latest Oxfordian

Sample 1

The sample yields a relatively impoverished dinoflagellate cyst assemblage. The most representative taxa include *Endoscrinium galeritum*, *Leptodinium subtile*, *Cribroperidinium globatum* and forms with an apical arecheopyle belonging to the *Sentusidinium-Barbatacysta-Pilosidinium* Group. Organic matter is dominated by wood and diversified land-derived tissues including cuticle and resin particles. Some AOM is also discernible.

Sample 2

The organic matter is dominated by AOM and terrestrial palynomorphs. Occasionally, specimens of the *Sentusidiniu m-Barbatacysta-Pilosidinium* Group and foraminifera test linings are present within the assemblages. Observation via UV-excited fluorescence of the AOM has revealed the dominance of terrestrial particles as the primary constituents of the matter including miospores, pollen grains and spores.

Earliest Kimmeridgian

Sample 3

As in sample 2, the kerogen displays a high abundance of AOM and an influx of terrestrial palynomorphs. Rare specimens of forms with an apical archeopyle represented by the *Sentusidinium-Barbatacysta-Pilosidinium* Group occur within the assemblage. Moreover, a few foraminiferal test linings are present. Observations via UV-excited fluorescence has proved the same dominance of terrestrial particles as in sample 2.

Sample 4

This sample yields fairly rich and well preserved dinoflagellate cysts. The most abundant marine dinoflagellate cysts are *Scriniodinium crystallinum*, *S. dictyotum papillatum* and *Gonyaulacysta jurassica jurassica.* Numerous chlorophyceae alga, represented by colonial chains of single cells provide a distinctive feature. An inception of the rare skolochorate taxon *Emmetrocysta sarjeantii* is observed in this sample. Beside marine microplankton, the rest of the organic content of the sample is represented by pollen grains, spores and rich terrestrial debris.

Sample 5

The sample is characterized by a diverse dinoflagellate cyst assemblage exhibiting a good state of preservation of the organic matter. *Ambonosphaera*? *staffinensis*, *Gonyaulacysta jurassica jurassica*, *Scriniodinium crystallinum* and *S. dictyotum papillatum* are the dominant marine components. Rare specimens of *Perisseiasphaeridium pannosum* and *Senoniasphaera jurassica* (with the archeopyle rarely developed) appear for the first time in this sample. The chlorophyceae algal bloom is comparable to that in sample 4. Associated organic matter comprises pollen grains, spores and various terrestrial debris.

Sample 6

A reduction in the abundance and diversity of marine plankton is observed in this sample, along with the organic matter content. Only a few taxa from the underlying sample 5 were recovered and the assemblage is generally characterized by an increased abundance of terrestrial components.

Sample 7

The predominance of land-derived kerogen is the key feature of the sample, comprising large wood particles, cuticle, pollen grains and spores. The dinoflagellate cysts include *Ambonosphaera*? *staffinensis*, *Atopodinium haromense*, *Gonyaulacysta jurassica jurassica*, *Cribroperidinium globatum*, *Rhynchodiniopsis cladophora*, the *Sentusidinium-Barbatacysta-Pilosidinium* Group, *Dingodinium jurassicum* and *Ellipsoidictyum cinctum*.

DISCUSSION

Examination of seven ammonite-calibrated palynological samples from across the Oxfordian/Kimmeridgian boundary in the Flodigarry section at Staffin Bay, Isle of Skye, northern Scotland, has revealed organic-walled dinoflagellate cyst assemblages that are generally consistent with previous contributions (Gitmez, 1970; Riding, Thomas, 1997). However, only a small number of characteristic dinoflagellate cyst bioevents including extinctions and inceptions or significant quantitative variations have been established. Two samples (2, 3) spanning the ammonite boundary horizon are practically barren of dinoflagellate cysts, being dominated by terrestrial organic matter and AOM. UV-excited fluorescence of the omnipresent AOM confirms its terrestrial primary components. This fact unequivocally suggests restricted marine conditions that occurred in the sedimentary basin, which probably influenced the sharp ammonite fauna threshold (see Wierzbowski *et al.*, 2018)

Inceptions of *Emmetrocysta sarjeantii* in sample 4, and *Perisseiasphaeridium pannosum* and *Senoniasphaera jurassica* in sample 5 are important dinoflagellate bioevents above the proposed Oxfordian/Kimmeridgian boundary. The inception of *Perisseiasphaeridium pannosum* was documented by Riding and Thomas (1997) in the Staffin Bay section slightly above Bed 36, which proves its usefulness for boundary recognition. *Emmetrocysta sarjeantii,* originally described by Gitmez (1970) from the Kimmeridge Clay (*Liostrea delta* Bed), Osmington Mills, Dorset, is probably a proxy species for the boundary level, however its low abundance in the studied material requires additional examination to confirm its inception level. *Senoniasphaera jurassica*, published by Gitmez and Sarjeant (1972) from the Baylei Zone in Staffin Bay, is a widely accepted marker for the base of the Baylei Zone (*e.g.* Riding, Thomas, 1992). Many specimens of forms concordant with the definition of the base of the Baylei Zone have been recovered in the studied material. However, only a few represent cysts with a typical apical archeopyle.

There are also a few quantitative observations within the dinoflagellate cyst assemblages supporting the identification of the boundary level. These include the evidently increasing abundance of *Gonyaulacysta jurassica jurassica*, *Scriniodinium crystallinum*, and *S. dictyotum papillatum* in two samples (4, 5) above the boundary level.

Finally, an important phenomenon occurring above the Oxfordian/Kimmeridgian boundary level (samples 4, 5) is the specific acme of chlorophyceae algae, with high abundance of tests resembling modern *Spirogyra* which can form "green tides" (Fletcher, 1996). "Green tides" composed of green algae (Phylum Chlorophyta) are most common in temperate latitudes. They are ephemeral, extremely productive, and usually associated with eutrophication. The blooms have an ability to influence the diversity of local marine communities. Evidence of an algal bloom recorded in two samples only is proposed as a supporting boundary marker in the Flodigarry section. According to previous studies (Wierzbowski *et al.*, 2015, 2016), various eutrophication events probably have a correlative potential for the base of the Kimmeridgian in Subboreal Europe. Wierzbowski *et al.* (2015) have described a characteristic radiolarian horizon expressed by a specific faunal association in the earliest Kimmeridgian of northern Poland. This rich planktonic assemblage composed of radiolarians, calcareous nannofossils, and planktonic foraminifera occurring in the sections indicates, according to these authors, the presence of nutrient-rich waters.

CONCLUSIONS

Examination of seven ammonite-calibrated palynological samples across the Oxfordian/Kimmeridgian boundary in the Flodigarry section at Staffin Bay, Isle of Skye, has revealed organic-walled dinoflagellate cyst assemblages generally similar to those described by Gitmez (1970) and Riding, Thomas (1997) from this locality. Stratigraphic inceptions of *Emmetrocysta sarjeantii*, *Perisseiasphaeridium pannosum* and *Senoniasphaera jurassica* slightly above the proposed Oxfordian/Kimmeridgian boundary horizon are suggested as palynological proxies for the base of the Kimmeridgian. The increasing abundance of *Gonyaulacysta jurassica jurassica*, *Scriniodinium crystallinum*, and *S. dictyotum papillatum* above the boundary level may serve as supporting indices for the Oxfordian/Kimmeridgian boundary. A chlorophyceae algal bloom is proposed as a boundary marker in the Flodigarry section; it probably has a correlative potential for the omnipresent eutrophication event at the base of Kimmeridgian.

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Plates

PLATE 1

Selected dinoflagellate cysts observed across the Oxfordian/Kimmeridgian boundary interval in the Flodigarry section at Staffin Bay, Isle of Skye

Fig. 1. *Scriniodinium dictyotum papillatum* (Gitmez, 1970) Jan du Chêne *et al.*, 1986, sample 4

Fig. 2. *Hystrichosphaerina* ? *orbifera* (Klement, 1960), Fauconnier and Masure, 2004, sample 1

Fig. 3. *Scriniodinium crystallinum* (Deflandre, 1938) Klement, 1960, sample 2

Fig. 4. *Rhynchodiniopsis cladophora* (Deflandre, 1939) Below, 1981, sample 4

Fig. 5. *Ellipsoidictyum cinctum* Klement, 1960, sample 5

Fig. 6. *Perisseiasphaeridium pannosum* Davey & Williams, 1966, sample 5

Fig. 7. *Prolixosphaeridium anasillum* Erkmen & Sarjeant, 1980, sample 5

Fig. 8. *Emmetrocysta sarjeantii* (Gitmez, 1970) Courtinat, 1989, sample 4

Fig. 9. *Chlorophycae* algae test, colour and state of preservation prove its position *in situ*, sample 4

Fig. 10. *Gonyaulacysta jurassica jurassica* Deflandre, 1939, sample 1

Fig. 11. *Atopodinium haromense* Thomas and Cox, 1988, sample 5

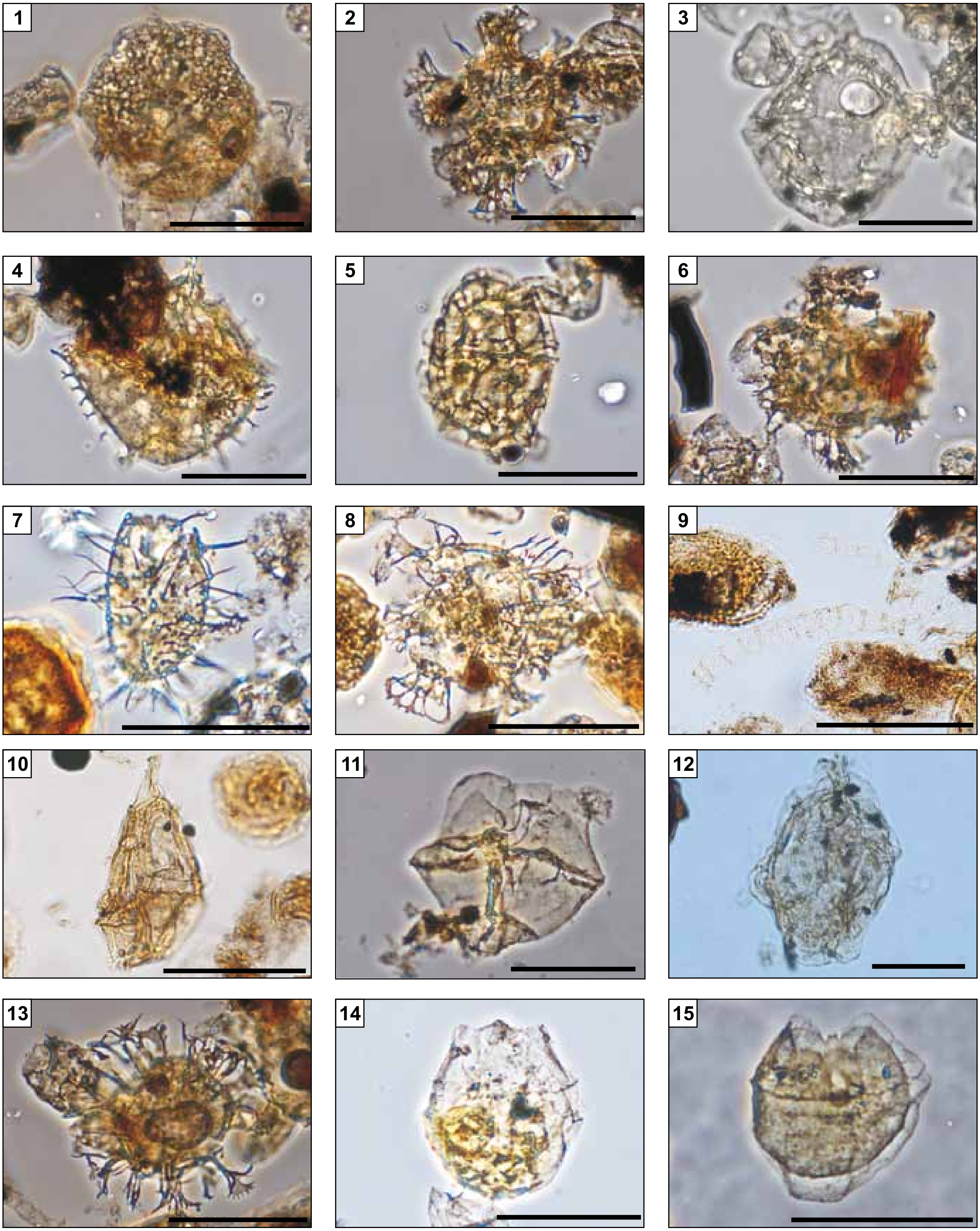
Fig. 12. *Endoscrinium galeritum* (Deflandre, 1939) Vozzhennikova, 1967, sample 1

Fig. 13. *Adnatosphaeridium caulleryi* (Deflandre, 1939) Williams and Downie, 1969, sample 1

Fig. 14. *Senoniasphaera* aff. *jurassica* (Gitmez and Sarjeant, 1972) Lentin and Williams, 1976, sample 5

Fig. 15. *Ambonosphaera*? *staffinensis* (Gitmez, 1970) Poulsen and Riding, 1992, sample 5

Photomicrographs were taken in transmitted light and with phase contrast. The scale of 50 micrometres is presented in each micrograph



Marcin BARSKI – Dinoflagellate cyst assemblages across the Oxfordian/Kimmeridgian boundary (Upper Jurassic) at Flodigarry, Staffin Bay, Isle of Skye, Scotland – a proposed GSSP for the base of the Kimmeridgian

PLATE 2

Selected dinoflagellate cysts observed across the Oxfordian/Kimmeridgian boundary interval in the Flodigarry section at Staffin Bay, Isle of Skye

Fig. 1. *Endoscrinium luridum* (Deflandre, 1939) Gocht, 1970, sample 4

Fig. 2. *Cribroperidinium globatum* (Gitmez and Sarjeant, 1972) Helenes, 1984, sample 5

Fig. 3, 4. *Senoniasphaera jurassica* (Gitmez and Sarjeant, 1972) Lentin and Williams, 1976, sample 5. Photomicrograph taken with interference contrast. Two foci show two wall layers continuously separated around the cyst (circumacavate)

Fig. 5. *Scriniodinium inritibile* Riley in Fisher and Riley, 1980, sample 5

Fig. 6. *Sirmiodinium grossii* Alberti, 1961, sample 7

Fig. 7. *Glossodinium dimorphum* Ioannides *et al.*, 1977, sample 5

Fig. 8. *Leptodinium subtile* Klement, 1969, sample 1

Fig. 9. UV-excited fluorescence showing the dominance of terrestrial particles dispersed in AOM, sample 3

Fig. 10. Chlorophycae algae tests, higher magnification showing a colony structure, sample 5

Fig. 11. General view of organic matter content in sample 7

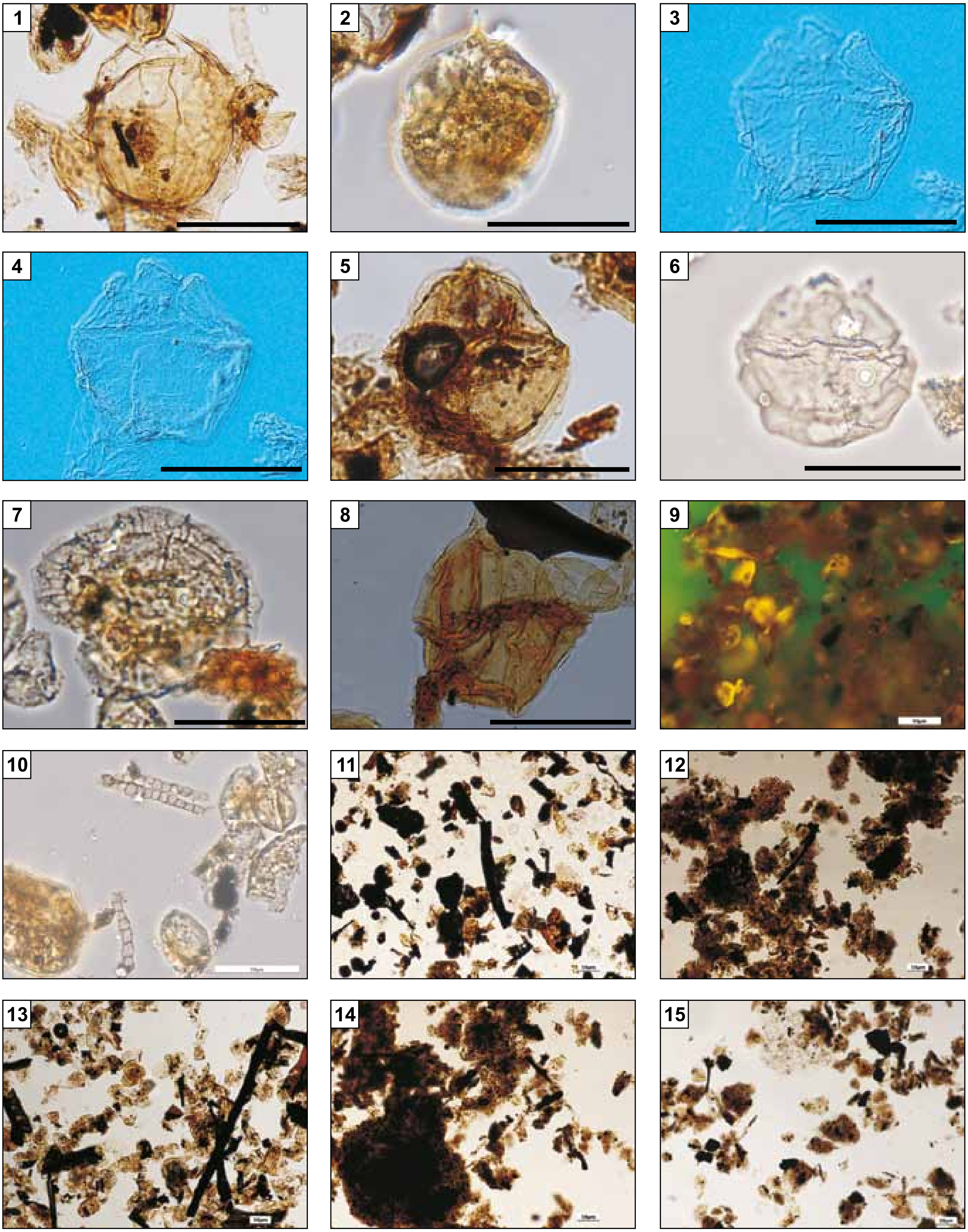
Fig. 12. General view of organic matter content in sample 3

Fig. 13. General view of organic matter content in sample 4

Fig. 14. General view of organic matter content in sample 2

Fig. 15. General view of organic matter content in sample 1

Photomicrographs were taken in transmitted light and with phase contrast. The scale of 50 micrometres is presented in each micrograph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