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Calcareous nannofossils from the uppermost Oxfordian and lowermost Kimmeridgian of Staffin Bay, Isle of Skye, northern Scotland

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Key words: calcareous nannofossils, uppermost Oxfordian, lowermost Kimmeridgian.

Abstract. Twenty six samples from the sections at Flodigarry and Digg at Staffin Bay, Isle of Skye, northern Scotland, spanning the stratigraphical interval from the uppermost Oxfordian to the lowermost Kimmeridgian were examined for their calcareous nannofossil content. The study revealed the presence of an assemblage typical of the nannofossil zone NJ15 of the northern European zonation.

INTRODUCTION

The calcareous nannofossils from the uppermost Oxfordian–lowermost Kimmeridgian succession at Staffin Bay, Isle of Skye, have been examined as a part of a wider study of the succession considered as the potential global stratotype (GSSP) of the base of the Kimmeridgian (Matyja *et al.*, 2006; Wierzbowski *et al.*, 2006, 2016, 2018). A location map of the area of study is shown in Fig. 1 (after Matyja *et al.*, 2006). The nannofossils were obtained from ammonite specimens precisely located in the succession, and elaborated in detail by Matyja *et al.* (2006) and Wierzbowski *et al.* (2018). The succession studied belongs to a higher part of the Flodigarry Shale Member of the Staffin Bay Formation, including the stratigraphical interval from the upper part of bed 33 up to bed 44. The deposits are mostly silty clays, shaly clays and clays with thin marker levels of calcareous concretions or nodules (beds 34, 36, 40), and a thin bed of argillaceous sandstone (bed 44); moreover the characteristic marker bed 38 rich in ammonites of the genus *Pictonia* has been recognized (Matyja *et al.*, 2006, and earlier papers cited therein; see Figs 2, 3).

The study of the ammonites showed the presence of ammonites of the Subboreal family Aulacostephanidae, and the Boreal family Cardioceratidae. These ammonites enable recognition of two zonal schemes – the Subboreal and Boreal ones. The Subboreal zonal scheme includes the ammonite Pseudocordata Zone (including the Caledonica, Pseudoyo, Pseudocordata, and Evoluta subzones), the Baylei Zone (including the Densicostata Subzone with the *flodigarriensis* horizon at its base, and the Normandiana Subzone), and the lowermost part of the Cymodoce Zone (the *inconstans* horizon)). The Boreal zonal scheme includes the Rosenkrantzi Zone (with the Marstonense and Rosenkrantzi subzones) and the Bauhini Zone and the lowermost part of the Kitchini Zone (Matyja *et al.*, 2006). The Lower Kimmeridgian boundary is placed at the base of the Subboreal Baylei Zone (*i.e.* at the base of the ammonite *flodigarriensis* horizon) which corresponds to the base of the Boreal Bauhini Zone. This level has been located in the upper part of bed 35 (1.24–1.08 m below bed 36) (Matyja *et al.*, 2006; Wierzbowski *et al.*, 2006, 2016), but recently (Wierzbowski *et al.*, 2018) narrowed to the stratigraphical interval between 1.24 m and 1.26 m below bed 36.

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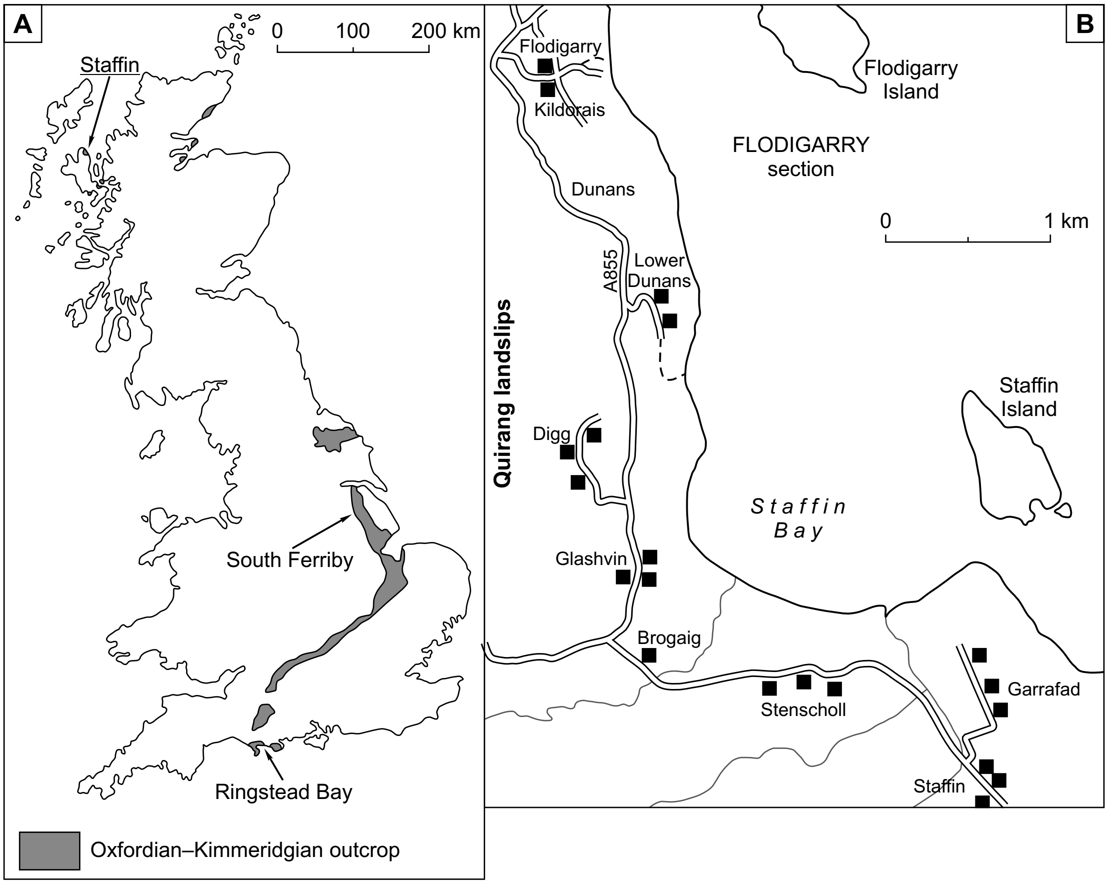


Fig. 1. B. Location map of the Staffin Bay (after Wierzbowski *et al.*, 2006) (the inset A shows the position of the area in Northern Scotland and the most important Oxfordian/Kimmeridgian boundary outcrops in U.K.)

MATERIAL AND METHODS

The main section studied and proposed as the GSSP of the base of the Kimmeridgian is near Flodigarry hamlet in Staffin Bay. It yielded the bulk of the samples taken for calcareous nanofossil indentification, but some additional samples studied herein were also taken from the nearby Digg hamlet section (Fig. 1). Generally 26 samples were examined – 24 from the Flodigarry section (1–24) and 2 from the Digg section (25, 26). Samples (*ca.* 5–10 g) were crushed and concentrated, and smear slides (24 × 24 mm) were made in Canada balsam. The slides were examined for nannoplankton which was then identified and photographed using a light microscope (BiOptic) with crossed nicols at × 1200 magnification with immersion. Samples 1, 6, 7, 9, 11 yielded no nannofossils. In the other samples, the nannofossils are poorly preserved and rare (3–10 specimens per one field of view). A total of 20 nannofossil species, belonging to 12 genera, has been identified (Figs 2, 3; Plate 1).

RESULTS

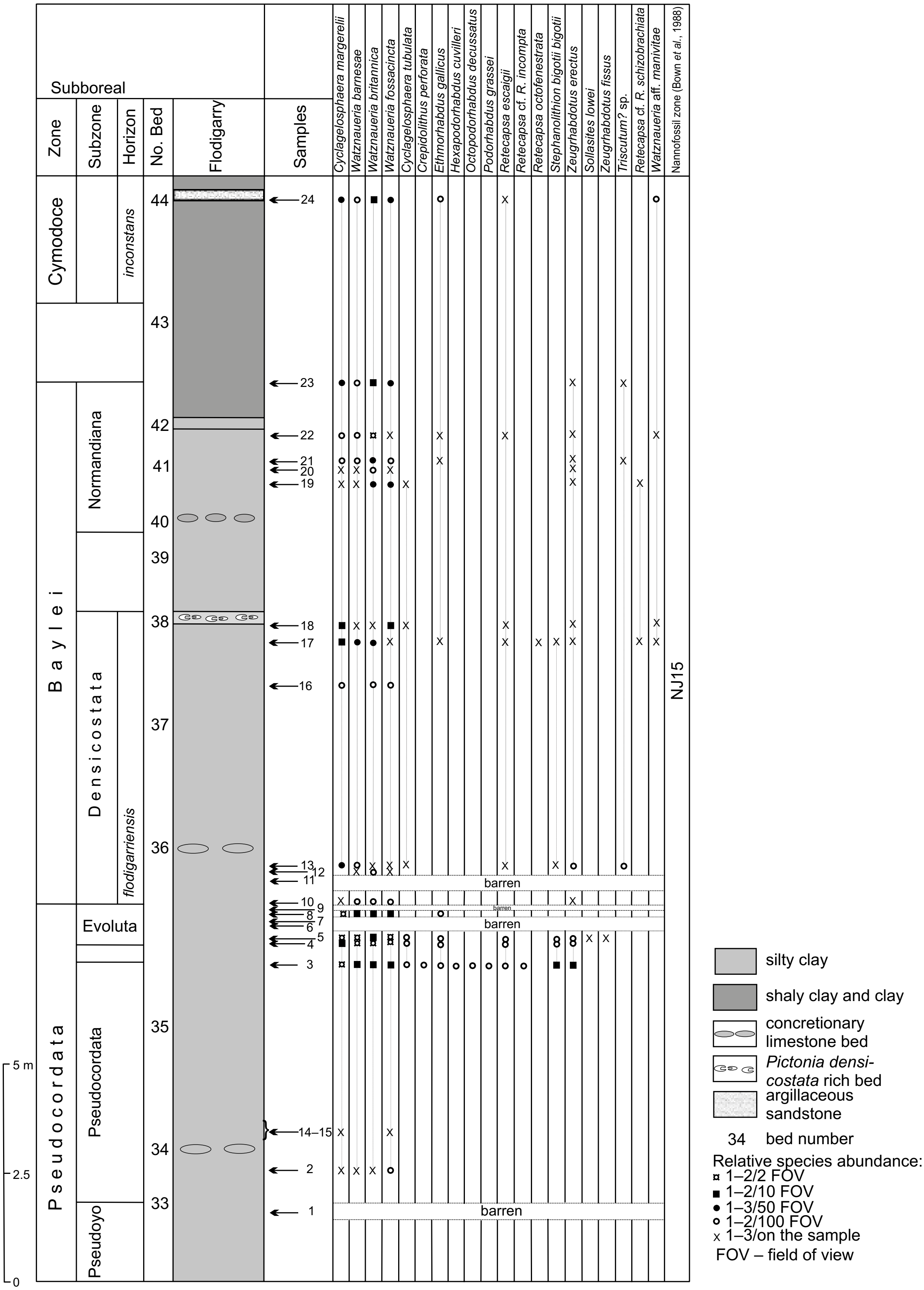
The species recognized are illustrated in Pl. 1, and the stratigraphical position of the particular samples and their taxonomic composition are commented on below (see also Figs 2, 3).

Sample 2 (uppermost part of bed 33) of the lowermost part of the Pseudocordata Subzone of the Pseudocordata Zone yielded: *Cyclagelosphaera margerelii* Noël, *Watznaueria barnesae* (Black) Perch-Nielsen, *W. britannica* (Stradner) Reinhardt, *W. fossacincta* (Black) Bown in Bown and Cooper.

→

Fig. 2. Distribution of nannofossils in the Flodigarry section (Isle of Skye, northern Scotland); ammonite zonation after Wierzbowski *et al.* (2018)

White blocks indicate the intervals of uncertain correlation


Subboreal
Zone
Subzone
Horizon
No. Bed
Flodigarry
Samples
Cyclagelosphaera margerelii
Watznaueria barnesae
Watznaueria britannica
Watznaueria fossacincta
Cyclagelosphaera tubulata
Crepidolithus perforata
Ethmorhabdus gallicus
Hexapodorhabdus cuvillieri
Octopodorhabdus decussatus
Podorhabdus grassei
Retecapsa escaigii
Retecapsa cf. R. incompta
Retecapsa octofenestrata
Stephanolithion bigotii bigotii
Zeugrhabdotus erectus
Sollasites lowei
Zeugrhabdotus fissus
Triscutum? sp.
Retecapsa cf. R. schizobrachiata
Watznaueria aff. manivitae
Nannofossil zone (Bown et al., 1988)
Cymodoce
inconstans
B a y l e i
Normandiana
D e n s i c o s t a t a
flodigarriensis
Evoluta
P s e u d o c o r d a t a
Pseudocordata
Pseudoyo
NJ15
barren
5 m
2.5
0
silty clay
shaly clay and clay
concretionary limestone bed
Pictonia densi-costata rich bed
argillaceous sandstone
34 bed number
Relative species abundance:
¤ 1–2/2 FOV
■ 1–2/10 FOV
● 1–3/50 FOV
○ 1–2/100 FOV
x 1–3/on the sample
FOV – field of view

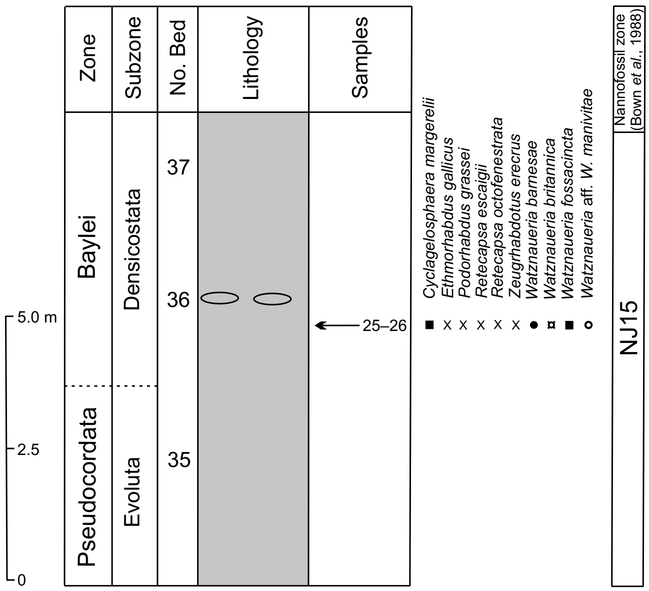


Fig. 3. Distribution of nannofossils in the Digg section (Isle of Skye, northern Scotland)

Samples 14 and 15 (lowermost part of bed 35) of the lower part of the Pseudocordata Subzone of the Pseudocordata Zone yielded: *Cyclagelosphaera margerelii* Noël, *Watznaueria fossacincta* (Black) Bown in Bown and Cooper.

Sample 3 (2.34 m below bed 36), sample 4 (1.9 m below bed 36) and sample 5 (1.8 m below bed 36) – all of them in upper part of bed 35, corresponding to the stratigraphical interval from the topmost part of the Pseudocordata Subzone (sample 3), and the Evoluta Subzone of the Pseudocordata Zone (samples 4, 5), yielded: *Cyclagelosphaera margerelii* Noël (Pl. 1: 12, 13), *C. tubulata* (Grün and Zweili) Cooper (Pl. 1: 14), *Ethmorhabdus gallicus* Noël (Pl. 1: 9), *Retecapsa escaigii* (Noël) Young and Bown (Pl. 1: 5), *Stephanolithion bigotii bigotii* Deflandre (Pl. 1: 3), *Watznaueria barnesae* (Black) Perch-Nielsen (Pl. 1: 16), *W. britannica* (Stradner) Reinhardt (Pl. 1: 17), *W. fossacincta* (Black) Bown in Bown and Cooper (Pl. 1: 18, 19), *Zeugrhabdotus erectus* (Deflandre in Deflandre and Fert) (Pl. 1: 1). Sample 3 also contained *Crepidolithus perforata* (Medd) Grün and Zweili, *Hexapodorhabdus cuvilleri* Noël, *Octopodorhabdus decussatus* (Manivit) Rood *et al.*, *Podorhabdus grassei* Noël (Pl. 1: 11), *Retecapsa* cf. *R. incompta* Bown, while sample 5 additionally contained *Sollasites lowei* (Bukry) Rood *et al.* and *Zeugrhabdotus fissus* Grün and Zweili (Pl. 1: 2).

The stratigraphical interval at the top of the Pseudocordata Zone, representing the topmost part of the Oxfordian (sample 6 – 1.5 m below bed 36; sample 7 – 1.45 m below bed 36) is generally barren, except for sample 8 (1.26 m below bed 36) which yielded: *Cyclagelosphaera margerelii* Noël, *Watznaueria barnesae* (Black) Perch-Nielsen, *W. britannica* (Stradner) Reinhardt, *W. fossacincta* (Black) Bown in Bown and Cooper, and *Ethmorhabdus gallicus* Noël.

A few samples from uppermost part of bed 35 representing already the lowermost part of the Baylei Zone (the *flodigarriensis* horizon) of the lowermost Kimmeridgian yielded the following nannofossils (sample 10 – 1.08 m below bed 36; sample 12 – 0.40 m below bed 36, and sample 13 (0.30 m below bed 36): *Cyclagelosphaera margerelii* Noël, *Watznaueria barnesae* (Black) Perch-Nielsen, *W. britannica* (Stradner) Reinhardt, *W. fossacincta* (Black) Bown in Bown and Cooper; additionally *Zeugrhabdotus erectus* (Deflandre in Deflandre and Fert) in samples 10 and 13, as well as – *Cyclagelosphaera tubulata* (Grün and Zweili) Cooper, *Retecapsa* (=*Polypodorhabdus*) *escaigii* Noël, *R. octofenestrata* (Bralower in Bralower *et al.*), and *Triscutum?* sp. Sample 11 (0.56 m below bed 36) from this interval appears, however, barren.

Three samples from the upper part of bed 37 (sample 16 – 10.1 m below bed 44; sample 17 – 9.3 m below bed 44, and sample 18 (at the boundary with overlying bed 38) represent the higher parts of the Densicostata Subzone of the Baylei Zone. They yielded: *Cyclagelosphaera margerelii* Noël, *C. tubulata* (Grün and Zweili) Cooper, *Retecapsa escaigii* (Noël) Young and Bown, *Stephanolithion bigotii bigotii* Deflandre (Pl. 1: 4), *Triscutum?* sp., *Watznaueria barnesae* (Black) Perch-Nielsen, *W. britannica* (Stradner) Reinhardt, *W. fossacincta* (Black) Bown in Bown and Cooper, *Zeugrhabdotus erectus* (Deflandre in Deflandre and Fert); sample 17 also contained *Retecapsa octofenestrata* (Bralower in Bralower *et al.*) and *Stephanolithion bigotii bigotii* Deflandre, while the upper part of bed 37 (samples 17, 18) is additionally characterized by the occurrence of *Watznaueria* aff. *manivitae* Bukry.

The nannoplankton from beds 38–40 has not been studied.

Four samples from bed 41 (sample 19 – 5.9 m below bed 44; sample 20 – 5.7 m below bed 44; sample 21 – 5.5 m below bed 44, and sample 22 – 4.9 m below bed 44), corresponding to the Normandiana Subzone of the Baylei Zone, yielded: *Cyclagelosphaera margerelii* Noël, *C. tubulata* (Grün and Zweili) Cooper, *Ethmorhabdus gallicus* Noël, *Retecapsa escaigii* (Noël) Young and Bown, *Retecapsa* cf. *R. schizobrachiata* (Gartner) Grün in Grün and Allemann, *Triscutum?* sp., *Watznaueria barnesae* (Black) Perch-Nielsen, *W. britannica* (Stradner) Reinhardt, *W. fossacincta* (Black) Bown in Bown and Cooper, *Watznaueria* aff. *W. manivitae* Bukry, *Zeugrhabdotus erectus* (Deflandre in Deflandre and Fert).

Sample 23 from lower part of bed 43 (3.73 m below bed 44; Normandiana Subzone, Baylei Zone) yielded: *Cyclagelosphaera margerelii* Noël, *Watznaueria barnesae* (Black) Perch-Nielsen, *W. britannica* (Stradner) Reinhardt, *W. fos-*

sacincta (Black) Bown in Bown and Cooper, *Zeugrhabdotus erectus* (Deflandre in Deflandre and Fert) and *Triscutum?* sp.

The only sample from basal part of bed 44 (sample 24) of the lowermost Cymodoce Zone (*inconstans* horizon) yielded: *Cyclagelosphaera margerelii* Noël, *Watznaueria barnesae* (Black) Perch-Nielsen, *W. britannica* (Stradner) Reinhardt, *W. fossacincta* (Black) Bown in Bown and Cooper, *Ethmorhabdus gallicus* Noël, *Retecapsa escaigii* (Noël) Young and Bown.

Two samples (sample 25 and 26 (from 0.00 to 0.15 m below bed 36) have been studied from the Digg hamlet section (Fig. 2). Both of them came from the lowermost Kimmeridgian (Baylei Zone, Densicostata Subzone, *flodigarriensis* horizon). The nannofossil assemblage includes: *Cyclagelosphaera margerelii* Noël, *Ethmorhabdus gallicus* Noël, *Podorhabdus grassei* Noël, *Retecapsa escaigii* (Noël) Young and Bown, *R. octofenestrata* (Bralower in Bralower *et al.*) (Pl. 1: 6), *Watznaueria barnesae* (Black) Perch-Nielsen, *W. britannica* (Stradner) Reinhardt, *W. fossacincta* (Black) Bown in Bown and Cooper, *Watznaueria* aff. *W. manivitae* Bukry (Pl. 1: 20), *Zeugrhabdotus erectus* (Deflandre in Deflandre and Fert).

CONCLUSIONS

The nannofossils from the Staffin Bay sections remained up to present poorly known. A study of the Upper Callovian and Lower Oxfordian calcareous nannofossils of Staffin Bay was presented by Hamilton (1978), but the younger nannofossil assemblages have not been studied so far in detail. The present study is thus the first devoted to the Upper Oxfordian and Lower Kimmeridgian nannofossils of this area.

The studied interval can be compared to the nannofossil zone NJ15 of the northern European zonation (Bown *et al*., 1988); this zone spans the wide stratigraphical interval from the Middle Oxfordian to the uppermost Kimmeridgian. The boundaries of this zone are defined from last occurrence of *Stephanolithion bigotii maximum*, to the first occurrence of *Stephanolithion brevispinus*. It is characterized by the presence of *Watznaueria britannica* (dominate), *Axopodorhabdus cylindratus*, *Biscutum dubium*, *Cyclagelosphaera margerelii*, *Ethmorhabdus gallicus*, *Retecapsa escaigii*, *Stephanolithion bigotii bigotii*, *Staurolithus stradneri*, *Zeugrhabdotus erectus* (Bown *et al*., 1988). NJ15 zone is subdivided into two subzones: NJ15a and NJ15b, whose boundary is defined by LO of *Lotharingius crucicentralis*. First occurrences of this long-ranging species are known from the Toarcian, but its last records are strongly diachronous in Boreal/Subboreal vs. Tethyan/Submediterranean successions, as the latter are dated by the Middle Oxfordian (Plicatilis Chron, see de Kaenel *et al*., 1996). The same problem appears with the event chosen for definition of the base of NJ15 zone, as LO of the *Stephanolithion bigotii maximum* is also diachronous (de Kaenel *et al*., 1996, tab. 8). The upper subzone is named after *Hexapodorhabdus cuvillieri*, although the both FO and LO of this species lies outside the subzone NJ15b (de Kaenel *et al.*, 1996; Bown, Cooper, 1998). Although the taxon is only rarely encountered in the material studied, there is no doubt, however, that, as based also on the ammonite correlation, the whole stratigraphical interval from the base of ammonite Pseudocordata Zone upwards should be correlated already with NJ15b nannofossil subzone.

It should be noted that the last occurrences of some nannofossil taxa in the Skye section slightly differ from those reported by Bown *et al.* (1988). For example, LO of *C. perforata* in the studied section lies in the Upper Oxfordian, although this taxon ranges up to the top of the Lower Kimmeridgian Baylei Zone in other sections in the northern European areas. This may, however, result from the generally small number of specimens in the samples studied. On the other hand, *Triscutum* sp., which has been considered as crossing the Oxfordian/Kimmeridgian boundary in the Tethyan areas only, here ranges up to the Baylei/Cymodoce boundary beds of the Subboreal-Boreal areas. Some contradictions concerning the range of this genus should be also taken into account: although Bown *et al.* (1988) have indicated the LO of *Triscutum* in the uppermost Oxfordian for Boreal/Subboreal areas, in their figure 3 the LO of this genus is shown at the top of the Pectinatus Zone, *i.e.* in the Lower Tithonian (at the Lower/Middle Volgian boundary). Worth noting is also the occurrence of the many barren samples directly below the Oxfordian/Kimmeridgian boundary. A similar feature is observed near this boundary in the distribution of the cysts of Dinoflagellata (Barski, 2018), and it is an open question whether this phenomenon may have resulted from changes in sea-current activity at the Oxfordian/Kimmeridgian boundary (*cf*. Wierzbowski *et al.*, 2016).

Although the correlation of the studied nannofossil succession, which is typical of the northern European areas, with that recognized in the Tethyan areas is so far difficult, the potential importance of the boundary between the Tethyan zones NJT 13 and NJT 14 for the future recognition of the Oxfordian/Kimmeridgian boundary as discussed herein is worth noting (*cf.* Ogg, Hinnov, 2012, fig. 26.10). The boundary of these zones was defined by Casellato (2010) by FO of the Tethyan species *Faviconus multicolumnatus* and *M. quadratus* in the succession of the southern Alps in northern Italy. This succession is unfortunately poorly defined by ammonites, nevertheless the boundary of NJT 13 and NJT 14 zones is possibly close to the ammonite Bimammatum Zone, as follows from its position in the La Villedieu succession indicated by de Kaenel *et al*., 1996 (tab. 8). It should be remembered that the base of this Submediterranean ammonite zone is very close to that of the Oxfordian/Kimmeridgian boundary in the Subboreal/Boreal successions as accepted herein (see Wierzbowski *et al.*, 2016). The occurrence of a large number of nannofossil taxa in common between the Tethyan succession and the succession studied here, although not unequivocally diagnostic for the NJT 14 zone, but generally associated with those diagnostic for that zone (see Casellato, 2010) is remarkable. The list include such taxa as *Cyclagelosphaera margerelii* Noël, *Watznaueria barnesae* (Black) Perch-Nielsen, *Watznaueria britannica* (Stradner) Reinhardt, *Watznaueria fossacincta* (Black) Bown in Bown and Cooper, *Zeugrhabdotus erectus* (Deflandre in Deflandre and Fert) and *Cyclagelosphaera tubulata* (Grün and Zweili) Cooper. The detailed correlation between the northern European and the Tethyan nannofossil zonations, and their calibration to ammonite zonations appear thus an especially challenging subject of study for the future.

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Appendix 1

IDENTIFIED NANNOFOSSIL TAXA

Crepidolithus perforata (Medd, 1979) Grün and Zweili, 1980
Cyclagelosphaera margerelii Noël, 1965
Cyclagelosphaera tubulata (Grün and Zweili, 1980) Cooper, 1987
Ethmorhabdus gallicus Noël, 1965
Hexapodorhabdus cuvilleri Noël, 1965
Octopodorhabdus decussatus (Manivit, 1961) Rood *et al.*, 1971
Podorhabdus grassei Noël, 1965
Retecapsa escaigii (Noël, 1965) Young and Bown 2014
Retecapsa cf. *R. incompta* Bown, 1987
Retecapsa octofenestrata (Bralower *in* Bralower *et al.*, 1989) Bown *in* Bown and Cooper, 1998
Retecapsa cf. *R. schizobrachiata* (Gartner, 1968) Grün *in* Grün and Allemann, 1975
Sollasites lowei (Bukry, 1969) Rood *et al.*, 1971
Stephanolithion bigotii bigotii Deflandre, 1939
Triscutum? sp. Dockerill, 1887
Watznaueria barnesae (Black, 1959) Perch-Nielsen, 1968
Watznaueria britannica (Stradner, 1963) Reinhardt, 1964
Watznaueria fossacincta (Black, 1971) Bown *in* Bown and Cooper, 1989
Watznaueria aff. *W. manivitae* Bukry, 1973
Zeugrhabdotus erectus (Deflandre *in* Deflandre and Fert, 1954) Reinhardt, 1965
Zeugrhabdotus fissus Grün and Zweili, 1980

PLATE 1

Calcareous nannoplankton from the Flodigarry and Digg sections (Isle of Skye, northern Scotland)

Fig. 1. *Zeugrhabdotus erectus*, distal view, sample 4, pol

Fig. 2. *Zeugrhabdotus fissus*, distal view, sample 5, pol

Fig. 3. *Stephanolithion bigotii bigotii*, distal view, sample 3, tr

Fig. 4. *Stephanolithion bigotii bigotii*, distal view, sample 17, pol

Fig. 5. *Retecapsa escaigii*, distal view, sample 4, pol

Fig. 6. *Retecapsa octofenestrata*, distal view, sample 26, pol

Fig. 7. *Retecapsa* cf. *R. schizobrachiata*, distal view, sample 17, pol

Fig. 8. *Triscutum?* sp., distal view, sample 13, pol

Fig. 9. *Ethmorhabdus gallicus*, distal view, sample 4, pol

Fig. 10. *Octopodorhabdus decussatus*, distal view, sample 3, tr

Fig. 11. *Podorhabdus grassei*, distal view, sample 3, pol

Fig. 12. *Cyclagelosphaera margerelii*, distal view, sample 4, pol

Fig. 13. *Cyclagelosphaera margerelii*, with secondary changes, distal view, sample 3, pol

Fig. 14. *Cyclagelosphaera tubulata*, distal view, sample 4, pol

Fig. 15. *Cyclagelosphaera tubulata*, distal view, sample 3, pol

Fig. 16. *Watznaueria barnesae*, distal view, sample 4, pol

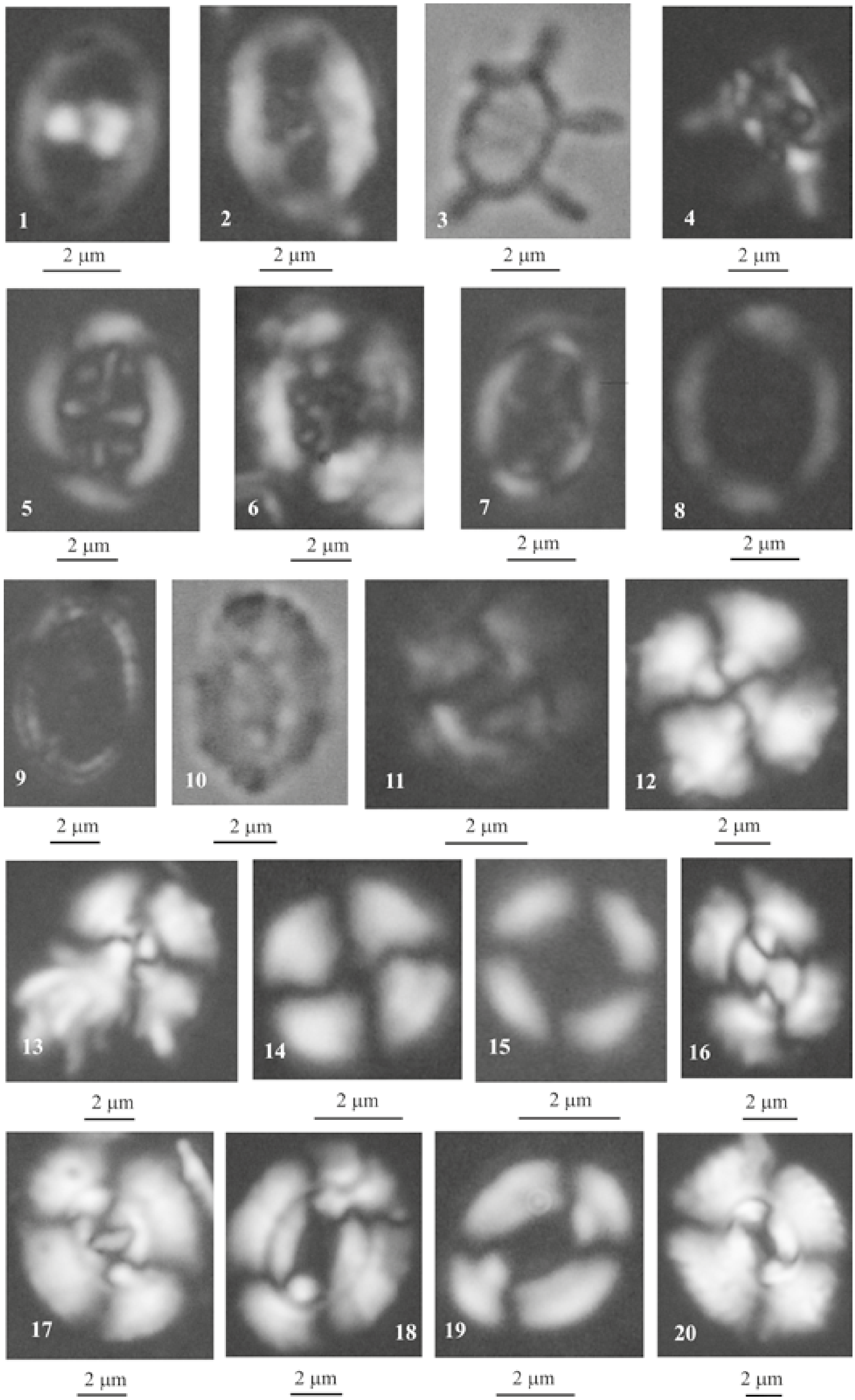
Fig. 17. *Watznaueria britannica*, distal view, sample 3, pol

Fig. 18. *Watznaueria fossacincta*, distal view, sample 4, pol

Fig. 19. *Watznaueria fossacincta*, distal view, sample 5

Fig. 20. *Watznaueria* aff. *manivitae*, distal view, sample 25

All illustrations are light micrographs. Abbreviations "pol" and "tr" denote polarized and transmitted light, respectively



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