A potential stratotype for the Oxfordian/Kimmeridgian boundary: Staffin Bay, Isle of Skye, UK

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ABSTRACT: A coastal exposure of the Staffin Shale Formation at Flodigarry, Staffin Bay, Isle of Skye, Scotland, UK fulfils the criteria for definition as the Global Stratotype Section and Point (GSSP) for the base of the Kimmeridgian Stage (Upper Jurassic). This marine shale succession was deposited during a long-term transgression, and is part of a complete, relatively well-expanded stratigraphic succession. A rich fauna of ammonites above and below the Oxfordian/Kimmeridgian boundary allows recognition of the Evoluta Subzone (Pseudocordata Zone) and Rosenkrantzi Subzone (Rosenkrantzi Zone) of the Subboreal and Boreal uppermost Oxfordian, and the Densicostata Subzone (Baylei Zone) and the Bauhini Zone of the Subboreal and Boreal lowermost Kimmeridgian). A suitable level for the boundary is thus marked by the replacement of the Subboreal *Ringsteadia* (M)/*Microbiplices* (m) by *Pictonia* (M)/*Prorasenia* (m), and by the first appearance of Boreal *Amoeboceras (Plasmatites).* Detailed study of the microfossils reveals an excellent dinoflagellate succession. A variety of stratigraphically important dinoflagellates are found, the assemblages being intermediate in character between Boreal and Subboreal ones. The magnetostratigraphic data, though rather troublesome to extract, shows a polarity pattern which can be confidently correlated to other UK boundary sections. The upper boundary of a normal magnetozone falls at, or very near, the proposed Oxfordian/Kimmeridgian boundary. The $^{87}Sr/^{86}Sr$ ratio at the boundary, based on an analysis of belemnites, lies between 0,70689 and 0,70697, averaging 0.70693. Matching worldwide trends, no distinct change in the ratio is seen across the boundary. A lack of variations in the carbon isotope composition of belemnites across the Oxfordian/Kimmeridgian boundary does not indicate perturbation in the global carbon cycle. However, high $\delta^{13}C$ values and their scatter suggest the influence of local fractionation affecting isotope composition of dissolved inorganic carbon (DIC) in the partly isolated Boreal sea. A fall in the belemnite $\delta^{18}O$ values in the Upper Oxfordian and Lower Kimmeridgian compared to the Mid Oxfordian suggests a slight rise in seawater temperature.

INTRODUCTION

The present document defining a potential Global boundary Stratotype Section and Point (GSSP) for the base of the Kimmeridgian Stage is the introductory presentation prepared for the Kimmeridgian Working Group of the Subcommission on Jurassic Stratigraphy.

HISTORICAL

The traditional locality for the definition of the base of the Kimmeridgian has been Ringstead Bay in Dorset (Fig. 1). It was here that Salfeld (1913) defined the base of the stage by the replacement of the pictoniid ammonite *Ringsteadia* by its descendant *Pictonia.* However, the basal Kimmeridgian is present here in a shallow-water, condensed, shelly, phosphatic facies resting with a notable non-sequence on uppermost Oxfordian strata (Wright 2003 and earlier papers cited therein). The whole succession of strata encompassing the Oxfordian/Kimmeridgian boundary beds, consisting of alternations of ammonite and non-ammonite bearing strata totaling a thickness of 7-8 m, contains at least three non-sequences. All available exposures are poor and frequently covered by land-slipped clay or beach shingle. As such, the sections fail to satisfy many of the principal criteria of Remane *et al.* (1996) for the ideal requirements of a GSSP.

The only other sequence in England which might be considered for GSSP status is that at South Ferriby in Humberside (Fig. 1). However, this section is far from ideal, for, though an excellent section at present, fulfilling many of the criteria of Remane *et al.* (1996), the section being in a working clay pit, long-term preservation cannot be guaranteed once working ceases, and in fact is very unlikely. Thus, the authors feel that the only UK site which fulfills most of the required criteria is that at Staffin in Skye (Figs 1, 2).

GSSP CRITERIA

Geological requirements

a. **Exposure over adequate thickness.**
The Oxfordian/Kimmeridgian boundary is contained within a 25 m continuously exposed section within the Staffin Shale Formation.

b. **Continuous sedimentation.**
There is no evidence of any non-sequences within the section.

c. **Rate of sedimentation.**
The rate of sedimentation is ideal, neither condensed nor too thick, with 3 to 4 ammonite zones being contained within 25 m of strata.

d. **Absence of synsedimentary and tectonic disturbance.**
There is no synsedimentary disturbance. Tectonic disturbance is a minor problem, for the relevant section is contained within several large slipped blocks of shale (F1-F8 in Fig. 3) preserved in the toe of the Quirang landslip (Wright 1989). This does not present any major problems, for distinctive marker bands enable correlation between the 8 major slipped blocks, and the blocks themselves have become completely stabilized, and a wave-cut platform has been cut through them. The dip of the strata is steep ranging between 60° to about 80°.

e. **Absence of metamorphism and strong diagenetic alteration.**
There is no metamorphic or strong diagenetic alteration excepting close to the margins of occasional Early Tertiary sills and dykes.

Biostratigraphical requirements

f. **Abundance and diversity of well-preserved fossils.**
Ammonites are prolific. Bivalves are common (Sykes & Callomon 1979), though they comprise forms adapted to deeper water facies. The sequence has been intensively studied for microfossils. Miospores (largely long-range forms) and dinoflagellate cysts (an excellent dinoflagellate cyst stratigraphy) are abundant at all levels (Riding & Thomas 1997). Acritarchs are also well represented (Stancliff 1990).

g. **Vertical facies changes.**
There are no major changes in facies, only occasional very useful thin limestone and siltstone marker bands in the otherwise continuous silty shale sequence.

h. **Long-range biostratigraphic correlation.**
The sequence has ammonites belonging to both the Sub-Boreal and Boreal faunal provinces, and is ideal for correlating between the provinces.

Other methods

i. **Radioisotopic dating.**
A study directly dating the Oxfordian-Kimmeridgian boundary utilising the Rhenium-Osmium (Re-Os) radiogenic isotope system is currently in progress with promising results (D. Selby, Durham University).

j. **Magnetostratigraphy.**
Preliminary reconnaissance reveals that an excellent magnetostratigraphic record has been retained by the sequence.

k. **Chemostratigraphy.**
Belemnites are common in the sequence, and preliminary work on them reveals an excellent chemostratigraphy.

l. **Regional palaeogeographic context and facies relationships.**
During the boundary interval the area was well connected both to the Boreal Realm and the Subboreal Province, and the use of ammonites as the key correlation tool means that there is no significant facies control of the diagnostic faunas in open marine environments. Similarly, microfossil events are not likely to be controlled by local marine facies, except in a preservation sense.

Other requirements

m. **Permanently fixed marker**.
Due to the nature of the foreshore exposure, a permanent marker cannot be reliably placed; however the production of foreshore maps and measured sections with distinctive marker beds facilitates identification of the boundary.

n. **Accessibility.**
The site is readily accessible on foot along a public right of way from Flodigarry village to the shore, across which there is open access.

o. **Free access.**
As above, access rights exist in Scottish law.

p. **Guarantees from the respective authority concerning free access for research and permanent protection of the site.**
The site is protected under national conservation law, currently the Wildlife and Countryside Act 1981, and lies within the legally designated Trotternish Ridge Site of Special Scientific Interest. Advice concerning protocols and permissions to sample should be directed to Scottish Natural Heritage, Bridge Road, Portree, Isle of Skye, IV51 9ER Scotland.

DESCRIPTION OF THE SECTION

The proposed Global Stratotype Section and Point (GSSP) for the base of the Kimmeridgian Stage is thus located at Staffin Bay, Isle of Skye, UK (Figs 1-3). The boundary between Oxfordian and Kimmeridgian strata occurs within the Staffin Shale Formation (Turner 1966 p. 248), and is exposed in two wave-washed rock platform exposures. That east of Digg is rather small, and covered by seaweed and boulders, and will not be considered further here, as the boundary is particularly well exposed east of Kildorais in Flodigarry district (Fig. 2).

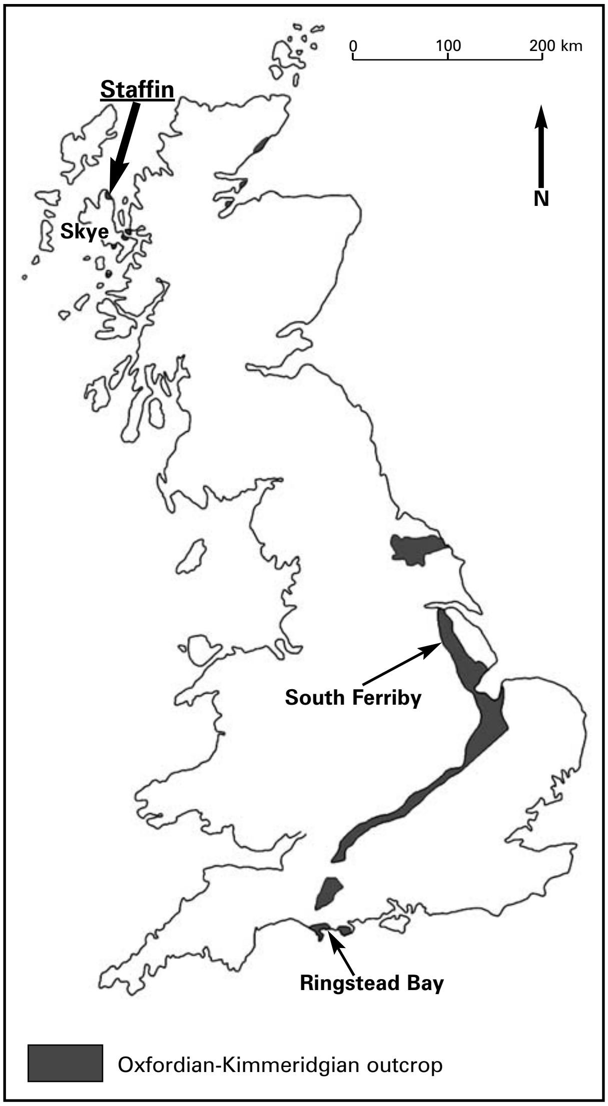

Fig. 1. Map of the U.K. showing Oxfordian-Kimmeridgian outcrop and locations of the exposures discussed.

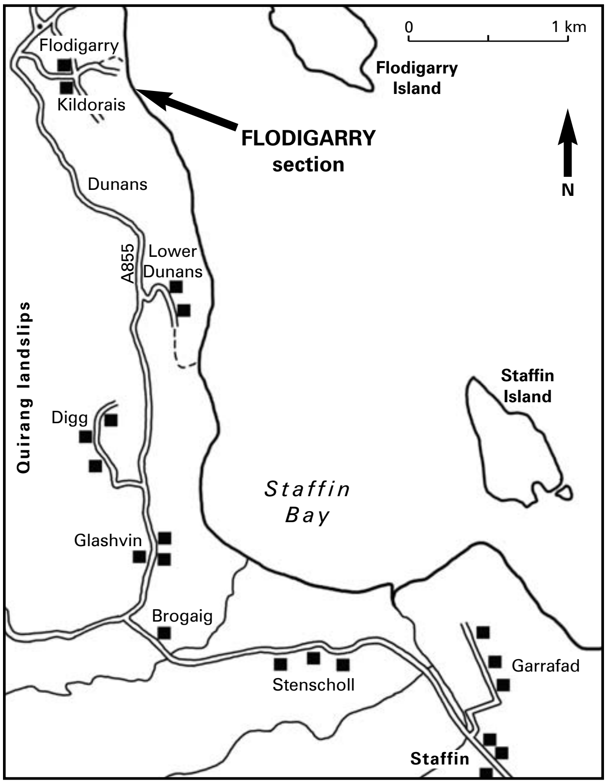

Fig. 2. Locality map of the Staffin Bay area, Isle of Skye; the exposures studied are indicated.

The Staffin Shale has long been known for the richness of its ammonite fauna (Forbes 1851; MacGregor 1934; Anderson & Dunham 1966; Turner 1966; Hudson & Morton 1969; Wright 1973, 1989; Sykes 1975; Sykes & Callomon 1979; Morton & Hudson 1995; Wright 2001). A comprehensive review of the ammonite faunas was given by Sykes & Callomon (1979), and supplemented by Birkelund & Callomon (1985), though the details of the ammonite succession have only recently been established (Matyja *et al.* 2004, 2006).

The Oxfordian-Kimmeridgian boundary succession lies within the Flodigarry Shale Member of the Staffin Shale Formation, and comprises a succession of bituminous and silty shales with the frequent development of limestone lenses and beds. Sykes & Callomon (1979) have shown that this section exhibits the most complete ammonite faunal succession of the Boreal Province, thus spotlighting its potential for boundary definition. As has been noted, the exposure at Flodigarry is the most widespread and shows the Oxfordian/Kimmeridgian boundary to its best advantage, and this is the site which is proposed here for GSSP status.

The rock platform exposures at Flodigarry presented initial problems to stratigraphers in that the Oxfordian-Kimmeridgian succession is exposed in series of wave-cut platform sections cut through several steeply dipping slipped blocks (Wright 1989, figs 5, 6). Accurate correlation between slipped blocks is necessary to establish the complete succession. Currently available maps published by Morton and Hudson (1995) and Wright (2001) are largely based on the preliminary maps of Wright (1973, 1989). With the advent of possible GSSP status, the need for a more accurate map of the exposures was obvious, and the necessary fieldwork was completed by the authors in summer 2001, and a revised map of the Flodigarry exposures is given in Fig. 3.

The stratigraphy of the Flodigarry Shale Member has been set out by Sykes & Callomon (1979), Wright (1989, 2001), Morton & Hudson (1995) and Hesketh & Underhill (2002), and is presented here as measured at Flodigarry, and modified for beds 35-45, by Matyja *et al.* (2004, 2006). The details are as follows:

	thickness (m)
45. Dark grey, poorly fossiliferous clay	seen to 11.0
44. Tough, argillaceous sandstone.	0.17
43. Pale grey clay with occasional ammonites.	4.39
42. Dark, silty clay with abundant ammonites preserved in irridescent calcite.	0.40
41. Pale grey clay.	1.52
40. Band of large limestone concretions.	0.31-0.45
39. Grey, silty clay with crushed ammonites.	1.92
38. Distinctive, hard, black, bituminous, shaley clay with an abundant ammonite fauna.	0.28
37. Grey, silty, blocky clay with abundant ammonites.	4.17
36. Limestone, continuous bed, locally as lens-shaped concretions.	0.20-0.35
35 Medium to dark grey, silty clay, becoming tougher upwards.	6.0
34. Sporadic band of small calcareous concretions about 10 m apart.	0.2
33. Dark, silty, well-laminated clay.	20.0
32. Tough, dark grey, silty clay.	0.95
31. Medium to dark grey, silty clay with numerous bivalves.	6.20
30. Dark grey, glauconitic siltstone.	2.00
29. Yellow to grey, silty sandstone (Digg Siltstone Member)	

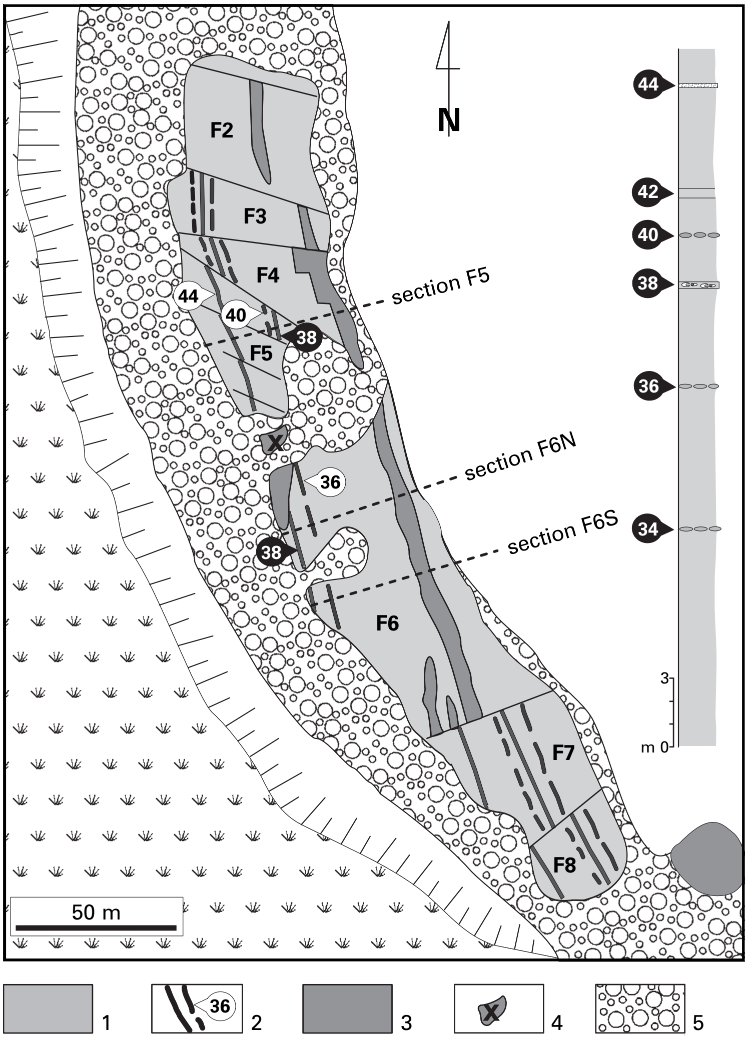

Fig. 3. Geological map of the beach at Flodigarry, Isle of Skye (see also Appendix): 1 – shales/clays, 2 – limestone lenses and beds, 3 – dolerite sills, 4 – large dolerite block, 5 – beach boulders.

APPENDIX – NOTES ON BLOCKS F1 TO F8

F1. Exposes only Upper Oxfordian beds adjacent to the large sill of Point 7. It exposes a succession of grey, poorly fossiliferous shales, baked by the sill. Fragmentary *Amoeboceras* and *Ringsteadia* occur.

F2. Again reveals a thick sequence of Upper Oxfordian grey shale (23 m) with *A. serratum* just above the sill at the base, A. regulare about the middle, and at the top *A. marstonense, Microbiplices* sp. nov., *R. marstonense* and *R. pseudocordata*. Wright (1973, 1989) marked Bed 36 at the top of this sequence. However, there was no sign of concretions amidst the boulders at the top of this section in 2001.

F3 and F4. The fault separating these two blocks has a throw of only 1 m, and the two can be taken together. The bulk of the section is Kimmeridgian in age. Most prominent are limestone concretions of Bed 40, with concretions of Bed 36 indistinctly seen below at the southern end. Bituminous shale Bed 38 is well developed right across the block, very distinctive, and full of *Pictonia* and *A. bauhini*. The section does not quite go high enough to expose Bed 44. Occasional concretions are developed in between Beds 36 and 40.

F5. Again is almost entirely Kimmeridgian in age. Three minor faults cross the outcrop. Muddy siltstone Bed 44 runs distinctly across the block almost to the prominent sill. Above it there is 10 m of fine, grey shale containing *Rasenia inconstans*. 7 m below Bed 44 is the poorly exposed concretion bed 40. Below, beds 38 and 36 are not evident, these levels being covered by boulders.

F6. This is an excellent section, covering the Oxfordian/Kimmeridgian boundary very well. Concretion Bed 36 can be traced along most of it, usually continuous or with lens shaped concretions, but covered by boulders about the middle of this long exposure. There is a well-exposed shale sequence above Bed 36, with good bituminous shale (Bed 38), and possible concretions from Bed 40 amidst boulders. 1.5 to 2 m below Bed 36 is developed hard, black, bituminous shale similar in lithology to Bed 38, and this led Wright (2001) to incorrectly mark Bed 36 as Bed 40 on his map (Wright 2001, figs 5.17 and 5.18). There is a good sequence of fossiliferous clays below, with *Amoeboceras rosenkrantzi* and *Ringsteadia* sp. At 6.5 m below Bed 36 is a sporadic bed of 20 cm diameter concretions regarded as representing Bed 34. At 7.3 m below Bed 36 *A. marstonense* and *Microbiplices* sp. are common. Below is *A. regulare*, with *A. serratum* just above the sill. This persistent sill runs along the seaward margin of F6. At the southern end of the block, sills are developed at higher horizons. *A. koldeweyense* occurs in the shale below the sill. 16.5 m below Bed 36 is a limestone bed, fairly persistent at the southern end of F6, 15-25 cm thick, in a lensoid development.

F7. Has a good development of bed 36, with 30 cm concretions in a continuous band. Bituminous shale 38 is well seen, and Bed 40 is present as a row of frequently developed concretions. 7 m above Bed 40 is a thin, silty band, possibly representing bed 44.

F8. Again has a complete Kimmeridgian succession, with impersistent concretions of Bed 36 seen at low water mark, good Bed 38, good concretions of Bed 40, and the section is completed by 7 m of silty shale with a clear development of argillaceous silt 44 at the top. This section abuts against a slipway.

Beds 32 and older are not accessible at Flodigarry.

The currently proposed boundary between Oxfordian and Kimmeridgian lies in the 0.16 m thick interval – in the topmost part of Bed 35 – between 1.24 m and 1.08 m below marker Bed 36. The detailed studies of the ammonite faunas succession were undertaken in blocks F6 and F5 of the beach outcrops at Flodigarry (Matyja *et al.* 2006; see chapter on Ammonite Biostratigraphy and Fig. 3, and Appendix herein).

AMMONITE BIOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY

The ammonite faunas collected in the Flodigarry sections, and described by Matyja *et al.* (2004, 2006), include successive members of the families Aulacostephanidae and Cardioceratidae, and make possible recognition of both the standard Subboreal and Boreal zones and subzones of Sykes & Callomon (1979) and Birkelund & Callomon

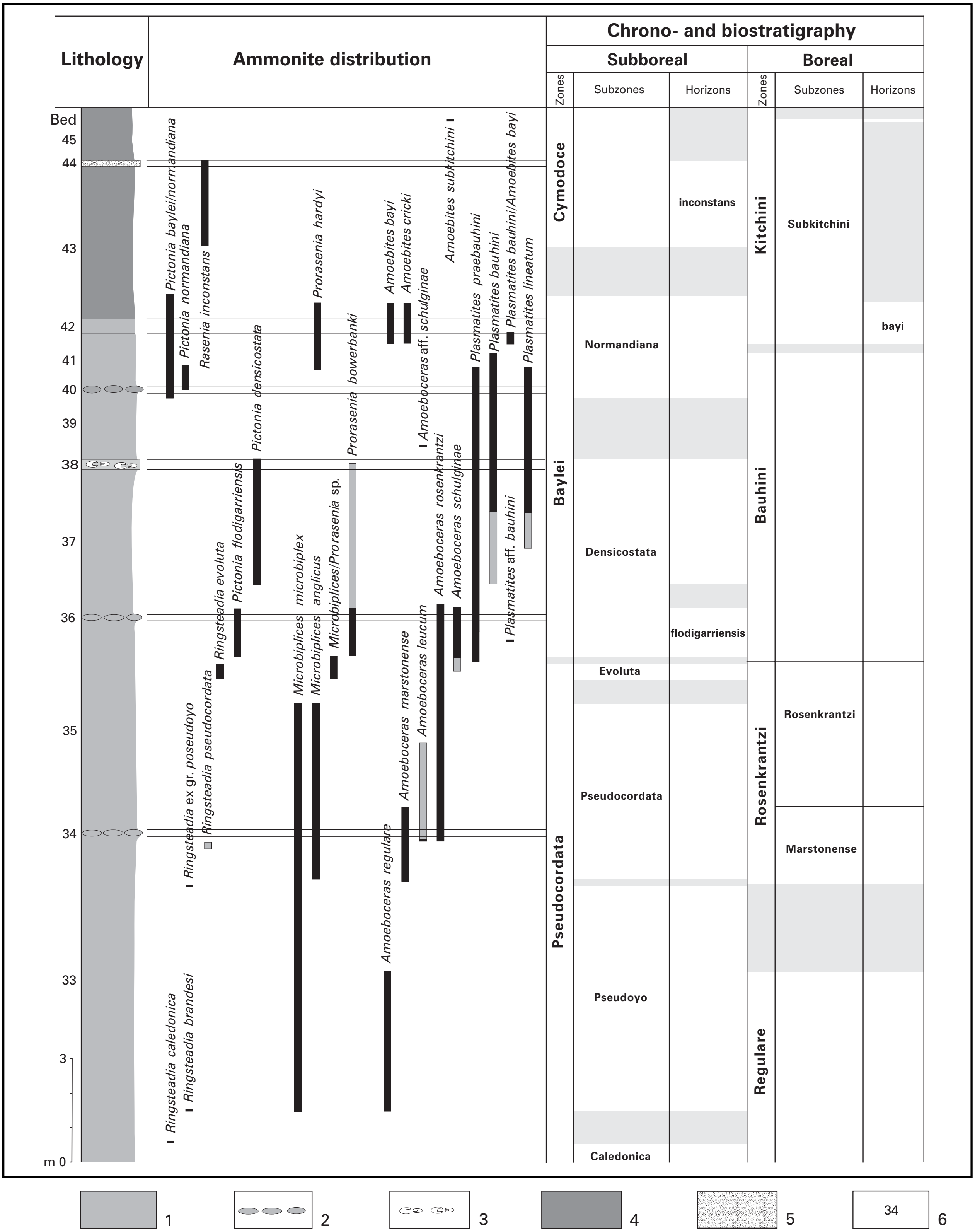

Fig. 4. Ammonite succession and biostratigraphical interpretation of the Flodigarry section. Lithology column: 1 – silty clay, 2 – concrecionary limestone bed, 3 – *Pictonia densicostata* rich bed, 4 – shaly clay and clay, 5 – argillaceous sandstone, 6 – bed number; ammonite distribution column – grey bars are referred to cf. species; stratigraphical column: grey blocks indicate the intervals of uncertain correlation.

(1985), as well as necessitating some modifications to these zonal schemes. The Boreal and Subboreal zonal sequences at Flodigarry are given in Fig. 4.

Subboreal Scheme

The youngest Oxfordian zone, the Pseudocordata Zone, is well represented at Staffin by successive faunas of *Ringsteadia* and its microconch counterpart, mostly *Microbiplices*, and forms transitional between *Microbiplices* and *Prorasenia*.

The oldest fauna of *Ringsteadia*, consisting of *R. caledonica* Sykes & Callomon, is found in Bed 33, 14.72 m below Bed 36. It is indicative of the Caledonica Subzone, the lowest subzone of the Pseudocordata Zone. A fauna with *R. brandesi* Salfeld and *Microbiplices microbiplex* (Quenstedt) found 13.85 m below Bed 36, and specimens of *R. pseudoyo* Salfeld found about 7.5 m below Bed 36, (i.e. still within Bed 33) are characteristic of the Pseudoyo Subzone.

Faunas with *R.* cf *pseudocordata* (Blake & Hudleston) and *M. anglicus* Arkell and *M.* sp. occurring from 7.28 m to 2.34 m below Bed 36 (i.e. from the uppermost part of Bed 33 to the middle part of bed 35) may be treated as indicative of the Pseudocordata Subzone. The youngest subzone of the Pseudocordata Zone, the Evoluta Subzone is also present. It is marked by the occurrence of *R. evoluta* Salfeld together with forms transitional between *Microbiplices* and *Prorasenia* from 1.8 m to 1.24 m below Bed 36.

The boundary between the Pseudocordata Zone and the Baylei Zone, i.e. the boundary between the Subboreal Oxfordian and Kimmeridgian, lies in the 0.16 m thick interval between the last occurrence of *Ringsteadia* (1.24 m below Bed 36) and the first occurrence of *Pictonia* and its microconch counterpart *Prorasenia* (1.08 m below bed 36). This makes the total thickness of the Pseudocordata Zone about 13.5 m.

The total range of the Baylei Zone, as marked by the occurrence of ammonites of the genus *Pictonia* at Flodigarry (see also below), is from 1.08 m below Bed 36 (i.e. from the uppermost part of Bed 35) to 3.73 m below Bed 44 (i.e. to the lowermost part of Bed 43), indicating that the zone is about 10 m thick. *Pictonia flodigarriensis* Matyja, Wierzbowski & Wright and *Prorasenia bowerbanki* Spath occur from 1.08 m below Bed 36 to 0.2 m above Bed 36. *P. densicostata* (Salfeld MS) Buckman is first seen 0.9 m above Bed 36. Prolific *P. densicostata* and *Prorasenia bowerbanki* occur in Bed 38.

The *Pictonia flodigarriensis* – *P. densicostata* (M) – *Prorasenia bowerbanki* (m) assemblage is regarded as indicative of the lower part of the Baylei Zone, distinguished as the Densicostata Subzone (Matyja *et al.* 2006). The Densicostata Subzone ranges from 1.08 m below Bed 36 to between 0.2 m and 1.8 m below Bed 40. The upper part of the Baylei Zone contains *Pictonia baylei* Salfeld/*P. normandiana* Tornquist (M) and *Prorasenia hardyi* Spath (m), and it is distinguished as the Normandiana Subzone (Matyja *et al.* 2006). The Normandiana Subzone ranges from between 1.8 m and 0.2 m below Bed 40 to between 3.73 m and 2.25 m below Bed 44.

The boundary between the Baylei Zone and the Cymodoce Zone in the Subboreal Province occurs at Flodigarry above the last occurrence of *Pictonia*, of the *baylei/normandiana* group, which is about 3.90 m below Bed 44, and the first ocurrence of *Rasenia inconstans* Spath, 2.25 m below bed 44.

Boreal Scheme

The Upper Oxfordian part of the sequence studied contains two zones, the Regulare Zone and the Rosenkrantzi Zone and the Lower Kimmeridgian part again contains two zones, the Bauhini Zone and the Kitchini Zone. The Regulare Zone is characterized by the occurrence of evolute, densely and regularly ribbed *Amoeboceras* of the *A. regulare* group (Sykes & Callomon 1979). Typical representatives are present at Flodigarry from 13.85 m to 9.93 m below Bed 36. The first specimens of *A. marstonense* Spath, indicative of the lower part of the overlying Rosenkrantzi Zone, have been found about 7.50 and 7.28 m below Bed 36. The boundary between the two zones thus lies in this interval, about 6.5 m of the Regulare Zone being present.

The Rosenkrantzi Zone is divided it into two subzones, a lower Marstonense Subzone characterized by the co-occurrence of *A. marstonense* and *A. rosenkrantzi* Spath, and an upper stratigraphic interval containing *A. rosenkrantzi* but below the earliest occurrence of *A. (Plasmatites)* spp. and above the last occurrence of *A. marstonense*, the Rosenkrantzi Subzone (Wright 2003).

The stratigraphic range of *A. marstonense* as recognized here is from about 7.5 m below Bed 36 (i.e. the uppermost part of bed 33) to about 5.25 m below Bed 36 (i.e. the lowermost part of Bed 35). The Marstonense Subzone thus ranges from 7.5 m below Bed 36 to possibly 3.5 m below Bed 36. A horizon with *A. leucum* Spath and typical forms of *A. rosenkrantzi* occurs 6.34 m below Bed 36. The Rosenkrantzi Subzone ranges from about 3.5 m below Bed 36 to 1.65 m below Bed 36, i.e. the minimum thickness of the subzone is thus 2.15 m.

The Bauhini Zone of the lowermost Boreal Kimmeridgian is characterized by the occurrence of small-sized *Amoeboceras* spp. of the subgenus *Plasmatites* (called also the *A. bauhini* group). *A. (P.) praebauhini* (Salfeld) first appears from 1.17 to 1.04 m below Bed 36. It is associated with coarsely ribbed, trituberculate *Amoeboceras* of the group of *A. schulginae* Mesezhnikov from 1.04 m below Bed 36 (possibly 1.44 m below Bed 36) to 0.17 m above Bed 36, and with the last representatives of *A. rosenkrantzi* (up to the lowermost part of Bed 37). The Oxfordian/Kimmeridgian boundary in the Boreal sense thus lies between 1.65 m (last occurrence of *A. rosenkrantzi* without *Plasmatites*) and 1.17 m below Bed 36 (first occurrence of *Plasmatites*), in precisely the same interval of strata where the boundary in the Subboreal sense was deduced to lie (see above). The main part of the Bauhini Zone from the lowest part of Bed 37, continuing up to about 1 m above the base of Bed 41, contains *A. bauhini* (Oppel), *A. praebauhini* and *A. lineatum* (Quenstedt). A thin faunal horizon with numerous *A.* aff. *schulginae* is situated in the middle of the zone. The thickness of the Bauhini Zone is at least 9 m.

The appearance of *A. (Amoebites) bayi* Birkelund and Callomon and *A. (A.) cricki* (Salfeld) from 4.99 m below Bed 44 upwards is indicative of the Boreal Kitchini Zone as originally defined by Mesezhnikov (1968; see also Wierzbowski & Smelror 1993). The boundary between the Bauhini and Kitchini zones thus runs through the 0.8 m of strata between 5.7 and 4.99 m below Bed 44.

The occurrence of *A. (Amoebites) bayi* and *A. (A.) cricki* from 4.99 m to 3.91 m below Bed 44 characterizes the lowermost part of the Subkitchini Subzone of the Kitchini Zone – i.e. the *bayi* horizon. The Baylei/Cymodoce zonal boundary is thus considerably higher than the Bauhini/Kitchini zonal boundary. The youngest *A. (A.) subkitchini* Spath in the Flodigarry sections, found 1.57 m above bed 44, is indicative of the higher part of the Subkitchini Subzone (Wierzbowski & Smelror 1993).

The Oxfordian/Kimmeridgian boundary

The problem of the Oxfordian/Kimmeridgian boundary is possibly the most troublesome of all those related to boundaries of the Jurassic stages. This results from the twofold interpretation of the Oxfordian/Kimmeridgian boundary deeply entrenched in the geological literature: the traditional (and primary) definition of the boundary placing it at the base of the Kimmeridge Clay in south Dorset corresponding to the base of the Baylei Zone of the Subboreal zonal scheme (Salfeld 1913); and the boundary definition according to which the base of the Platynota Zone of the Submediterranean zonal scheme is the base of the Kimmeridgian: this interpretation resulted mostly from an erroneous correlation with the primary Subboreal standard. As has been shown rather recently, the two boundaries do not correspond to each other, and the stratigraphic interval between the boundaries covers much of the Upper Oxfordian Substage in the Submediterranean zonal scheme (Schweigert & Callomon 1997, Matyja & Wierzbowski 1997).

Of the two possible positions for the placing of the Oxfordian/Kimmeridgian boundary at Flodigarry listed by Matyja *et al.* (2004, 2006), that situated between the Boreal Bauhini and Kitchini zones matches better the accepted situation of the Oxfordian/Kimmeridgian boundary in the Submediterranean Province corresponding to the boundary between the Planula and Galar subzones. Such a level lies well up in the Subboreal Baylei Zone, and unfortunately would lead to the major part of the sequence of *Pictonia* faunas at Flodigarry being Oxfordian in age, with only the very latest *Pictonia* being Kimmeridgian (Matyja *et al.* 2004, fig. 2). This alternative definition of the Oxfordian/Kimmeridgian Boundary in the Subboreal Province by means of its (incorrectly) perceived position in the Submediterranean Province cannot be accepted as the base of the Kimmeridgian Stage (Callomon 2004). Hence the traditional placing of the Oxfordian/Kimmeridgian boundary between the highest horizon of *Ringsteadia* and the lowest horizon of *Pictonia* seems a better solution, and is easier for general acceptance.

Ever since the first recognition of *Pictonia* as a separate genus by Bayle (1878), and its first monographic description by Tornquist (1896), *Pictonia* has been accepted as a Kimmeridgian ammonite, and Salfeld's (1913) proposal that its first appearance should mark the base of the Kimmeridgian Stage has been accepted by the vast majority of Jurassic workers.

Initially, as the lowest known *Pictonia* horizon was that of *Pictonia densicostata* occurring on the Dorset coast (although as was noted above, a stratigraphical gap occurs there), the situation appeared unequivocal. The discovery of a still older *Pictonia* horizon at Staffin Bay – the *Pictonia flodigarriensis* horizon – brought a new possible interpretation of the Oxfordian/Kimmeridgian boundary, which in the present authors' opinion should be placed at the base of the horizon in question (Matyja *et al.* 2006; see also Matyja *et al.* 2004, where this horizon is distinguished as the *Pictonia* n. sp. horizon). There is in fact only a small difference in height within the succession of ammonite faunas of the genus *Pictonia* at Staffin Bay between the occurrence of the two horizons: the lower horizon (*P. flodigarriensis* horizon at Staffin Bay – covering possibly a stratigraphical gap in the Dorset coast sections), or the higher horizon (*P. densicostata* horizon on the Dorset coast or at Staffin Bay).

The problem of the Oxfordian/Kimmeridgian boundary lies, however, in: selection of a locality based on its quality as the potential GSSP (see discussion above where it was shown that only Staffin Bay fulfils the ICS criteria), correlation potential of each of the two horizons. The *P. flodigarriensis* horizon as the first *Pictonia* horizon contains not only the first ammonites of the genus *Pictonia* (occurring directly above the last representatives of *Ringsteadia*, and showing still some features in common with them in the continuous sequence of deposits), but also the first corresponding microconchs of the genus *Prorasenia* (which replaced here older forms of the *Microbiplices* type). Moreover, as the Staffin Bay sections yield not only aulacostephanids typical of the Subboreal succession, but also Boreal ammonites of the genus *Amoeboceras* (almost completely absent in the Dorset coast sections), it can thus be demonstrated that the *P. flodigarriensis* horizon, treated as the lowest horizon of the Baylei Zone (and thus the base of the Subboreal Kimmeridgian), corresponds also to the base of the Bauhini Zone – the lowest zone of the Boreal Kimmeridgian. Consequently, the Oxfordian/Kimmeridgian boundary, defined in such a manner, is delineated by a wide assemblage of Subboreal and Boreal ammonites, increasing its correlation potential.

The boundary between the Oxfordian and Kimmeridgian placed at the base of the *P. flodigarriensis* horizon can be correlated approximately with the boundary between the Hypselum Subzone and the Bimammatum Subzone in the Submediterranean succession (Matyja & Wierzbowski 2003). The former shares with the Subboreal Pseudocordata Zone and the Boreal Rosenkrantzi Zone such forms as *Ringsteadia* close to the Subboreal *Ringsteadia* species, *Microbiplices* and *Amoeboceras rosenkrantzi*. The latter shares ammonites of the genus *Prorasenia* and the first *Plasmatites*. The ammonite faunas in the Submediterranean succession have yet to be studied in detail; a secondary section for the Oxfordian-Kimmeridgian boundary must eventually be designated here.

MICROFOSSIL BIOSTRATIGRAPHY

A section in the Flodigarry Shale extending from the top of the Serratum Zone to the base of the Cymodoce Zone was sampled and analyzed for pollen and dinoflagellate cysts by Riding & Thomas (1997, fig. 3) and for acritarchs and other non-dinophycean marine palynomorphs by Stancliffe (1990). The majority of the samples produced abundant organic residues rich in both kerogen and palynomorphs. Most samples are dominated by long ranging miospores, particularly bisaccate pollen, with subordinate pteridophytic spores. Marine microplankton are present throughout, with an abundance of dinoflagellate cysts and numerous acritarchs. Newly gathered samples from the Flodigarry section are currently under study, and the results are expected soon.

Dinoflagellates

A plexus of large, thick-walled forms (*Ambonosphaera*, *Atopodimium*, *Glossodinium*, *Gonyaulacysta*, *Sirmiodinium*, *Systematophora* and *Cribroperidinium*) having its inception close to the Middle/Upper Oxfordian boundary, was encountered throughout the succession by Riding & Thomas (1997). The range bases of *Aldorfia dictyota* subsp. *pyrum* (Gitmez 1970) Jan du Chene *et al.* 1986 and *Occisucysta balios* Gitmez 1970 were all observed within the earliest Kimmeridgian

(Baylei Zone). These taxa have inceptions close to the Oxfordian/Kimmeridgian boundary in England. *Scriniodinium inritibile* Riley in Fisher & Riley 1980, which has a range base within the Middle Oxfordian in England, has its inception in the lowermost Kimmeridgian. *Perisseiasphaeridium pannosum* Davey & Williams occurs in the Baylei Zone. In southern England the range base of this species is within the Mutabilis Zone. The top of the Scr dinoflagellate cyst zone is recognisable via the apparent extinction of *Scriniodinium crystallinum* close to the top of the Baylei Zone.

The Oxfordian and Kimmeridgian of the Boreal Realm typically yield low proportions of skolochorate dinoflagellate cysts compared to the Sub-Boreal and Tethyan realms. The Flodigarry Shale Member is relatively rich in skolochorate taxa, and thus appears to be of intermediate Subboreal to Boreal character.

Acritarchs

Acritarchs are common throughout the upper part of the Skye sequence (Stancliffe 1990) excepting the Serratum Zone. Most species of acritarch cross the Oxfordian/Kimmeridgian boundary. One species which is not known from the Lower Oxfordian of Dorset and which only appears at Staffin close to the Oxfordian/Kimmeridgian boundary is *Leiofusa jurassica*.

ISOTOPE STRATIGRAPHY

Carbon isotopes

In theory, the carbon isotope curve of marine carbonates has great potential as a high-resolution stratigraphic tool when characterized by distinctive shape and form. However, the uppermost Oxfordian – lowermost Kimmeridgian $\delta^{13}C$ values from Staffin Bay, measured from well preserved belemnite rostra (Figs 5-6) are significantly scattered (from 0.6 to 2.4‰ VPDB; Vienna Pee Dee Belemnite) and 1-2.5‰ higher in comparison with Submediterranean values (cf. Wierzbowski 2004). This is probably due to the incorporation of ancient dissolved inorganic carbon (DIC) having high $\delta^{13}C$ values into belemnite rostra, and to brief variations in the isotopic composition of DIC, that took place in the moderately shallow Boreal sea in Scotland. The high $\delta^{13}C$ values of DIC, and the variations, may in turn be linked to the enhanced bioproductivity and burial of organic matter occurring in the partly isolated basin (cf. Wierzbowski 2004). In addition, a lack of carbonate sedimentation in the Boreal sea did not enable the long-term stabilization of the $\delta^{13}C$ values of DIC.

The Oxfordian carbon isotope values from the Staffin Bay sections become increasingly more negative in the upper-most Middle and lowermost Upper Oxfordian after the maximum of the mid-

Sample	Position (bed/meters above the base)	Mn [ppm]	Fe [ppm]	Sr [ppm]	$\delta^{18}O$ (‰) VPDB	$\delta^{13}C$ (‰) VPDB
izo 173*	bed 45/ 6.1 m	73	207	1031	0.08	1.30
izo 175*	bed 45/ 1.4 m	81	184	1180	-1.26	2.34
izo 183*	bed 43/ 3.79 m	37	112	1137	-0.41	2.41
izo 218	bed 42/ 0.25 m	47	159	1126	-0.03	1.00
izo 220	bed 41/ 0.77 m	12	51	1051	-0.50	2.04
izo 165*	bed 41/ 0.76 m	52	225	1105	-0.61	1.46
izo 221	bed 41/ 0.66 m	21	66	1062	-0.86	1.80
izo 219	bed 41/ 0 m	15	37	1237	-1.15	2.20
izo 174*	bed 38/ 0.15 m	90	205	1120	-1.88	1.82
izo 181*	bed 37/ 1.1 m	96	167	1164	-0.17	0.62
izo 166*	bed 37/ 0.25 m	60	161	1087	-0.07	1.13
izo 158*	bed 35/ 6 m	30	175	1200	0.03	1.72
izo 171*	bed 35/ 5.4 m	85	171	1076	-0.51	1.07
izo 179*	bed 35/ 5.3 m	25	200	1100	-0.57	1.26
izo 169*	bed 35/ 5.3 m	6	40	1370	-0.14	1.10
izo 163*	bed 35/ 4.5 m	25	86	1109	0.04	2.07
izo 182*	bed 33/ 11.9 m	145	305	1270	-1.39	1.55
izo 217	bed 33/ 11.7 m	46	110	1017	-0.37	2.44
izo 216	bed 33/ 8.7 m	50	136	992	0.33	1.94
izo 184*	bed 32/ 0.48 m	60	156	1130	0.21	3.00

Fig. 5. Position and geochemical data for studied, non-luminescent belemnite rostra from the Staffin Bay sections; * – data from Wierzbowski 2004.

Oxfordian positive excursion, which falls in the Densiplicatum Zone (the highest $\delta^{13}C$ values oscillate between 3 and 4.7‰ VPDB; Wierzbowski 2004). The lowest $\delta^{13}C$ values are reached at the boundary between the Oxfordian and Kimmeridgian (Pseudocordata and Baylei zones; 0.6-2.4‰ VPDB; Fig. 5). However, the results collected from underlying and overlying zones are only slightly higher (1.3-3.0‰ VPDB; Fig. 5). This suggests a lack of major perturbation in the global carbon cycle at the Oxfordian/Kimmeridgian boundary.

Despite high and scattered $\delta^{13}C$ values, the Oxfordian – Early Kimmeridgian $\delta^{13}C$ trend for the Staffin Bay sections resembles the more compact belemnite trend recognized from the Submediterranean Province (the Middle Oxfordian maximum falls here in the Arkelli Subzone of the Plicatilis Zone; Wierzbowski 2002). This is evidence that the carbon isotope record from the Staffin Bay sections reflects global changes, albeit with the superimposition of local fractionation factors.

The change in sediment type in NW Europe over the Oxfordian Stage was from carbonate shelf and ramp sedimentation (Corallian Group – Mid Oxfordian) to thick, bituminous shale sedimentation (Upper Oxfordian – Kimmeridgian). Bituminous shales preferentially incorporate C^{12} into oceanic sediments, leading to a rise in $\delta^{13}C$ values of DIC in sea-water (e.g. Toarcian Anoxic Event; Jenkyns *et al.* 2002). Thus, anoxic events, of which the Kimmeridgian of NW Europe was certainly one, may have led to a positive carbon isotope excursion (Jenkyns *et al.* 2002). However, the part-isolation of northern seas possibly resulted in the restriction of organic rich sedimentation and high $\delta^{13}C$ values of DIC to these regions, preventing a global rise in carbonate $\delta^{13}C$ values. Otherwise, a global fall in carbonate $\delta^{13}C$ values is observed in the Upper Oxfordian .

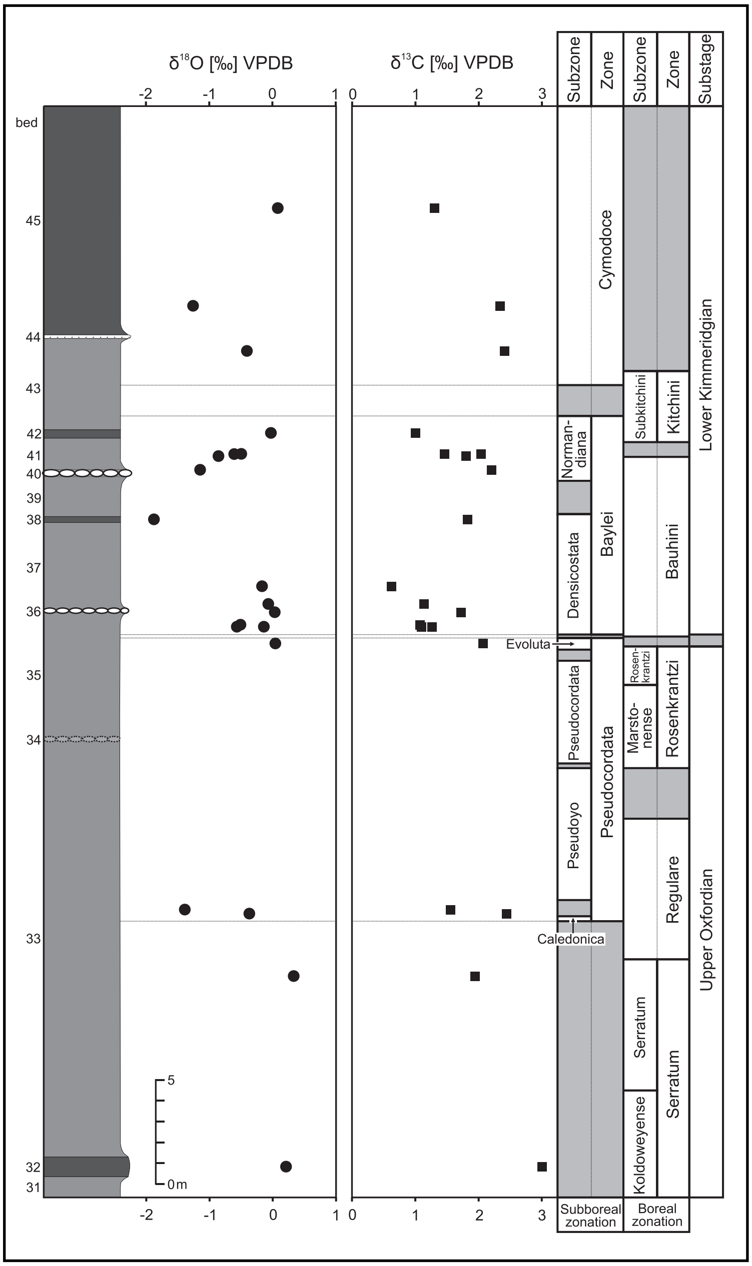

Fig. 6. The record of the Oxfordian/Kimmeridgian $\delta^{18}O$ and $\delta^{13}C$ values measured from well preserved belemnite rostra in the Flodigarry section (for details see Fig. 5).

Oxygen isotopes

There is no obvious general trend in Oxfordian $\delta^{18}O$ values, measured from well-preserved belemnite rostra in the Staffin Bay section (Wierzbowski 2004, fig. 4). All values are significantly scattered from -1.9 to +0.8% VPDB. However, results obtained from the Upper Oxfordian and the Lower Kimmeridgian (total range from -1.9 to +0.3‰ VPDB; average value: -0.5‰ VPDB, n=20; see Figs 5-6) are slightly lower than in the Middle Oxfordian (total range from -0.6 to +0.8% VPDB; average value 0.0% VPDB, n=9). This may indicate a rise in average sea-water temperaturse of about 2°C from +11.6°C in the Middle Oxfordian to +13.7°C in the Late Oxfordian and the Early Kimmeridgian (the temperatures were calculated by using Friedman and O'Neil's 1977 equation: the assumption was that the $\delta^{18}O$ value of non-glacial seawater amounted to -1% VSMOW; Vienna Standard Mean Ocean Water). However, the absolute temperatures might be slightly overestimated due to decreased salinity of the Boreal sea in Scotland (cf. Wierzbowski 2004).

Strontium isotopes

The Upper Oxfordian and Lower Kimmeridgian Substages lie within a slowly ascending part of the global strontium isotope curve, so that no significant difference would be expected around the Oxfordian/Kimmeridgian boundary. Based on analyses of belemnites, $^{87}Sr/^{86}Sr$ ratios between 0,70689 and 0,70697, averaging 0.70693 were given for the boundary in the Staffin Bay section by Jenkyns *et al.* (2002). However, these authors report a wide scatter of the Oxfordian-Kimmeridgian $^{87}Sr/^{86}Sr$ ratios measured up to present. This hampers estimation of the average trend.

MAGNETOSTRATIGRAPHY

Palaeomagnetic methodology, behaviour and directions

Samples for magnetostratigraphy were collected in two batches. A set of 35 horizons were sampled by two of us, A.L.C. and J.O., using conventional paleomagnetic drilling apparatus, from Points 2 and 7 of Wright (1989). These single specimens from each horizon were measured at Oxford University (UK) using a 2G magnetometer, and progressive thermal demagnetization through 310°C or higher depending on monitored magnetic behaviour. A further set of 9 horizons were sampled from Point 7 of Wright (1989), using oriented hand samples collected by J.K.W. Multiple (2-4) specimens from these horizons were measured at CEMP (Lancaster University, UK) using a CCL GM400 3-axis cryogenic magnetometer. Specimens from these hand samples were subjected to stepwise thermal demagnetization using a Magnetic Measurements Ltd thermal demagnetizer using temperatures up to 240°C. Beyond this temperature, specimens were subject to alternating field (AF) demagnetization using a Molspin tumbling demagnetizer, due to large increases in magnetic susceptibility (pyrite decomposition and clay dehydration?) starting about this temperature.

In general, the sets of specimens display two components of magnetization, a low temperature (up to 150-250°C) B-component, with an in situ direction of 049°, +50° (α_{95}=8.3°, k=6.7, n=51). This component is probably of Brunhes age (since 0.7 Ma), mostly acquired before the (tilted) beds were affected by land-slippage. A second much weaker component Ch is of dual polarity direction (normal mean 032°, 43°, α_{95}=10.5°, k=12.5, n=17), and has a northerly downwards or southerly upwards directed magnetization interpreted as a Late Jurassic magnetization. Many of the specimens do not display the Ch component clearly, but are dominated by great circle paths towards either of the dual polarity Ch directions. Demagnetization diagrams are available from M.W.H.

A combined great circle mean (McFadden & McElhinney 1988) gives an overall mean direction of 017°, 45° (α_{95}=6.6°, k=10.7, n=48), giving a virtual geomagnetic pole at 57°N, 146°E (dp/dm=5.3/8.4). This is some 16 degrees equatorwards from the mean European 150 Ma poles of Torsvik *et al.* (2001) [75°N, 148°E], and Besse & Courtillot (1991) [72°N, 150°E]. The reverse and normal polarity great circle combined means pass the McFadden & McElhinny (1990) reversal test with class Rc (critical α_{95}=20, observed α=16). An Enkin (2003) DC fold test, using the horizon mean directions from 19 horizons, indicates the best solution is at 89% unfolding with 95% confidence of ±35% which indicates an acceptable pre-tilting magnetization. In contrast, the McFadden (1998) fold test gives a best solution at 25% unfolding, and an unrealistic net shallow magnetization. However, the data are not well suited to this later fold test, since the number of points are few and most have similar dip directions with a range of bedding dips from 84° to 43°.

Overall the magnetostratigraphy is dominated by reverse polarity, with normal polarity

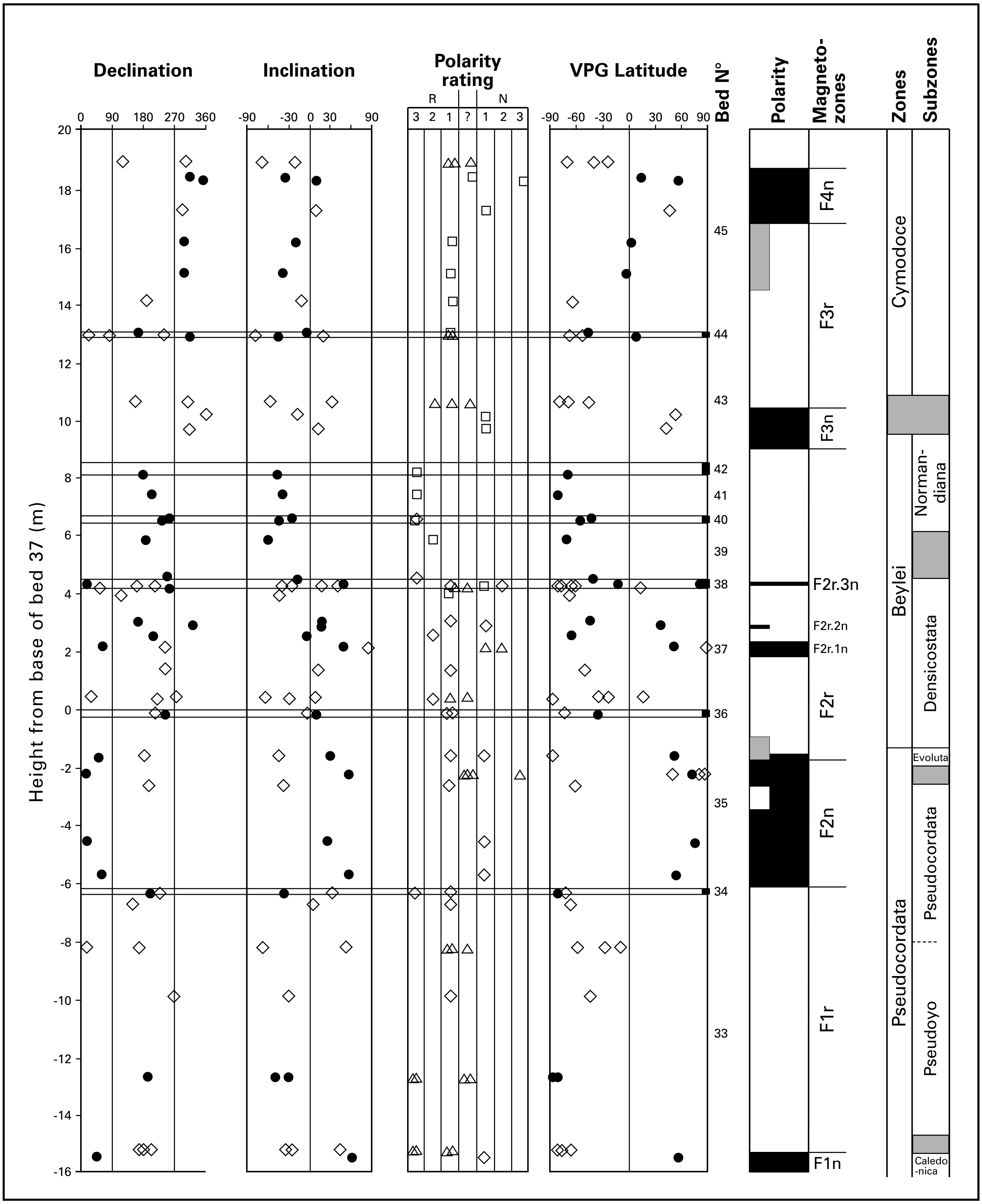

Fig. 7. Specimen-based magnetostratigraphic data from Flodigarry. In the declination, inclination and virtual geomagnetic pole (VPG) latitude columns, filled symbols indicate the line-fit data, unfilled symbols the interpreted great circle data. Great circle declination and inclination data are "ends" of great circle trends. Great circle data in VGP latitude columns is the point on each specimen great circle which contributes to the combined site mean direction. Polarity rating: 3 – highest quality, 1 – lowest quality, ? – no polarity assignment made. Different symbols in polarity rating plot relate to section and sample collections. Hatched boundaries between chronozones indicate the uncertainty in location of the chronozone boundary.

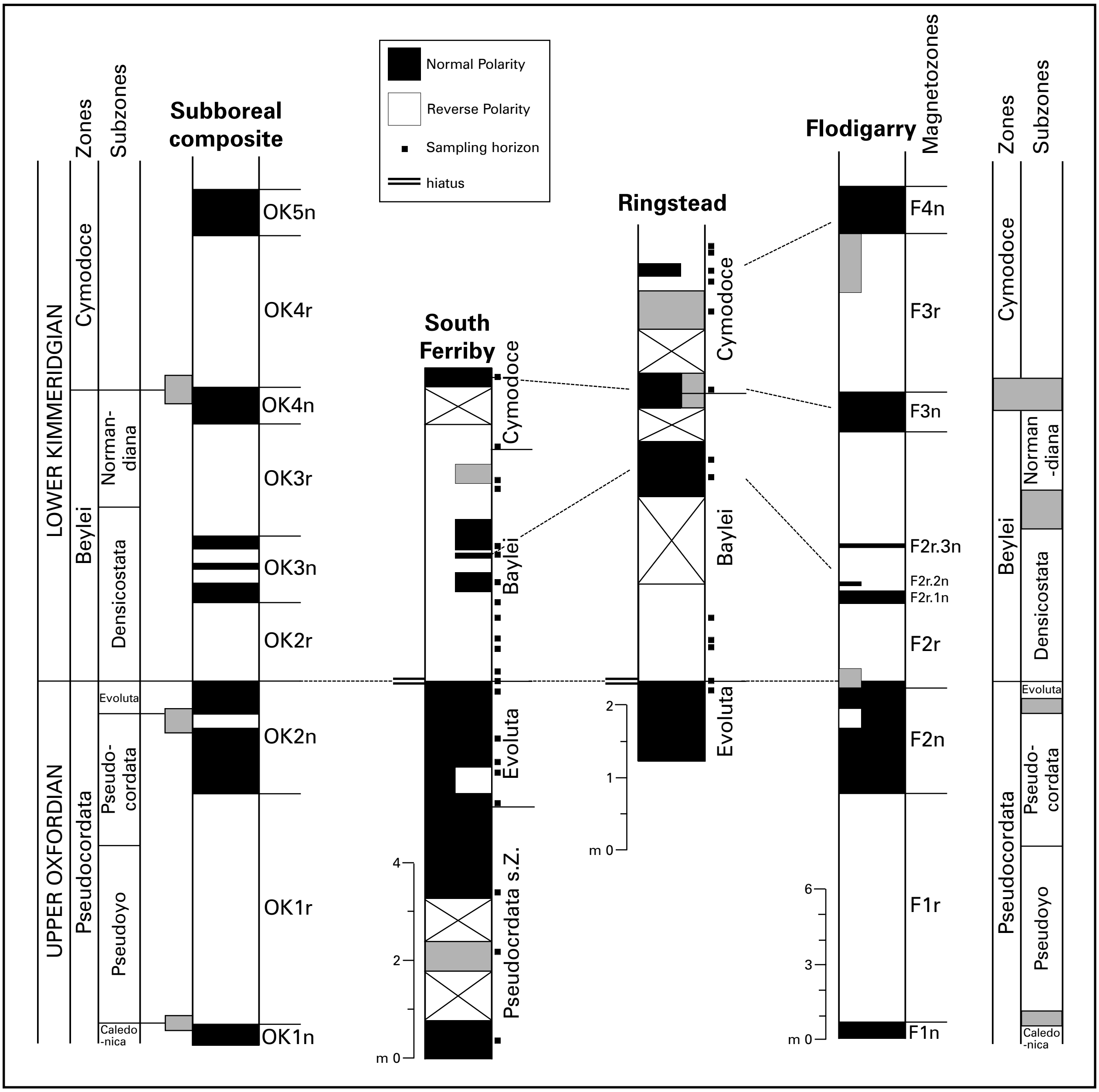

Fig. 8. Magnetostratigraphic data from the Subboreal region, and the Sub-Boreal composite suggested here, based on integration of bio- and magnetostratigraphic data from South Ferriby (Humberside, U.K.), Ringstead Bay (Dorset, U.K.) and Flodigarry. Ringstead and South Ferriby data from Ogg and Coe (1997). Grey blocks in left and right side columns indicate the uncertainty in locations of the boundaries.

magnetozones F2n, F2r.3n, F3n and F4n defined by sampling at two or more horizons (Fig. 7). Magnetozone F2r.3n is apparently restricted to bed 38, being defined by multiple sampling, to start within 6-8 cm of the base of the bed (Fig. 7). The unusual lithology of this bed may be indicative of some condensation.

The magnetostratigraphic data from Flodigarry can be combined with unpublished data from South Ferriby and Ringstead Bay (Ogg & Coe 1997), to produce a Sub-Boreal composite (Fig. 8). In all three sections the boundary between the Pseudocordata and Baylei Zones occurs at or just above a N-R transition (i.e. top of F2n, OK2n). The magnetozones F2r.1n, F2r.2n and F2r.3n within the Baylei Zone appear to represent a more substantive normal magnetozone at Ringstead and South Ferriby than at Flodigarry (Fig. 8).

This is probably due to insufficient sampling density over this interval at Flodigarry. The more detailed sampling at South Ferriby appears to confirm the three reverse submagnetozones within this predominantly normal polarity interval (i.e. OK3n).

Conclusions re the Staffin magnetostratigraphy

The majority of samples spanning this Oxfordian/Kimmeridgian boundary sequence at Flodigarry yielded reasonable palaeomagnetic data, and the polarity pattern is consistent with the expected frequency of magnetic reversals obtained from coeval sections. Magnetic sulphides in these dark mudstones may carry a significant component of the palaeomagnetic signal. The base of the Baylei Zone, the traditional placement of the base of the Kimmeridgian in the Subboreal ammonite zonation, is reversed polarity, with normal polarity characterizing the underlying uppermost Pseudocordata Zone.

SUMMARY AND CONCLUSIONS

The coastal exposure at Flodygarry, Isle of Skye, fulfils the principal criteria of Remane *et al.* (1996) for definition as GSSP for the base of the Kimmeridgian Stage. The section is well exposed, relatively thick, lacks any major hiatus, has not been subject to synsedimentary disturbance and has been subject to only minor, faulted disturbance. It contains an abundance of well-preserved marine fossils, and does not show abrupt facies changes. Three distinctive marker beds are of great assistance for stratigraphic location within the section. The best candidate level for the boundary is at the base of the Baylei/Bauhini zones, as characterized by the replacement of *Ringsteadia*/*Microbiplices* by *Pictonia*/*Prorasenia*, and by the incoming of *Plasmatites.*

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