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The Global Stratotype Section and Point (GSSP) for the base of the Kimmeridgian Stage (Jurassic System), at Flodigarry, Staffin Bay, Isle of Skye, Scotland, UK

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Following voting by the Kimmeridgian Working Group, the International Subcommission on Jurassic Stratigraphy and the International Commission on Stratigraphy, the Global Stratotype Section and Point (GSSP) for the base of the Kimmeridgian Stage (Jurassic System) was ratified by the executive of the International Union of Geological Sciences. The boundary is placed in the upper part of Bed 35 of the Staffin Shale Formation, 1.25±0.01 m below the base of Bed 36 in block F6 in the foreshore at Flodigarry, Staffin Bay, Isle of Skye, Scotland. The coordinates for the middle part of the two adjacent sections (sections F6N and F6S) are 57°39'39.5"N, 6°14'43.9"W and 57°39'40.5"N, 6°14'45"W; UK National Grid Scheme NG 4687 7139 and NG 4687 7142±5 m. This stratigraphic point coincides with the appearance over a short stratigraphic interval of several new ammonite taxa that delineate the base of the Subboreal ammonite Baylei Zone, the base of the Densicostata Subzone marked by the base of the flodigarriensis horizon, and, independently, the base of the Boreal ammonite Bauhini Zone. The main advantages of this locality are: the presence of a dual ammonite zonation marked by two extensively studied, well-preserved and very abundant groups of ammonites, and their preservation within a continuous section of ~120 m of open marine, fossiliferous, thermally immature mudrocks with no evidence of condensation or stratigraphic gaps. Dinoflagellate cysts, magnetostratigraphy and stable isotope data from the same section provide secondary markers. The stratigraphic point is located 0.17–0.65 m below the boundary interval between the dinoflagellate cyst zones DSJ 26 and DSJ 27 (equivalent to the boundary between subzones c and d of the Scriniodinium crystallinum (=Scr) Zone). The point is located 0.02–0.24 m above the base of reversed magnetozone F3r. This magnetozone probably correlates with marine magnetic anomaly M26r but may correlate to the younger anomaly M25r. The point coin-

cides with a well-marked broad minimum in $\delta^{13}C$ values and a calculated low Sr-isotope value of 0.70687. The section has yielded nannofossils that show that the potential last occurrence of Octopodorhabdus decussatus that marks the lower part of the NJ15 zone occurs about 1.09 m below the boundary. The thermal immaturity and unweathered nature of the strata in the Flodigarry section has permitted a direct Re-Os radio-isotopic age of 154.1±2.2 Ma to be obtained from the mudrocks 0.05 m below the Kimmeridgian GSSP. Sequence stratigraphic analysis indicates that the GSSP lies within the lower part of a highstand system tract. The corresponding stratigraphic level in the Submediterranean-Mediterranean successions is close to the boundary between the Hypselum and Bimammatum ammonite zones. The change in ammonite groups noted at this level provides biostratigraphic markers for further global correlation.

Historical Context

The traditional locality for defining the base of the Upper Jurassic Kimmeridgian Stage was Ringstead Bay, Dorset, UK. It was here that Salfeld (1913) defined the base of the stage according to the original definition by A. d'Orbigny. Salfeld established the boundary based on the lineage of Subboreal ammonites of the family Aulacostephanidae at the place where an older genus *Ringsteadia* was replaced by a younger genus *Pictonia.* This level, which we now recognize to be the base of the Kimmeridge Clay Formation, corresponds to the boundary of the ammonite Subboreal zones of Ringsteadia pseudocordata (=Pseudocordata) Zone, and Pictonia baylei (=Baylei) Zone, and became the 'classical' Oxfordian/Kimmeridgian boundary with which all other zonal schemes have been compared (e.g., Arkell, 1956). The Dorset coast section is, however, unsuitable as the stratotype for the boundary. This is because the strata encompassing the Oxfordian/Kimmeridgian boundary in Dorset consist of strongly contrasting lithologies and contain evidence for condensation and a notable hiatus (Coe, 1995; Williams, 2003; Wright, 2003).

More problematic, and resulting from a poor knowledge of the phylogeny of ammonites of the family Aulacostephanidae in Europe, was an erroneous correlation between the Subboreal ammonite succession from Dorset in NW Europe and the Submediterranean-Mediterranean ammonite succession of central and southern Europe (e.g., Arkell, 1956). As a consequence, since the middle of the 20th century the Oxfordian/Kimmeridgian boundary has been placed at two non-isochronous levels in Europe – at the Pseudocordata/Baylei zonal boundary in the Subboreal province, and at a level corresponding to the boundary of the Subnebrodites planula (=Planula) and the Sutneria platynota (=Platynota) zones in the Submediterranean-Mediterranean provinces. The latter is now known to be about two ammonite zones higher (and about 1.5 Myr younger) than the Subboreal standard (Matyja and Wierzbowski A., 1997; Schweigert and Callomon, 1997; Ogg and Hinnov, 2012; Ogg et al., 2016). This second alternative and stratigraphically higher definition of the Oxfordian/Kimmeridgian boundary at a level resulting from its incorrectly perceived position in the Submediterranean succession cannot be accepted as the base of the Kimmeridgian Stage (Callomon, 2004), because this would neglect all the existing, rigorous and high-resolution correlations of the Oxfordian/Kimmeridgian boundary across the Subboreal and Boreal provinces.

The scientific view of the Kimmeridgian Working Group and the International Subcommission on Jurassic Stratigraphy, is that the traditional placing of the Oxfordian/Kimmeridgian boundary between the highest horizon of *Ringsteadia* and the lowest horizon of *Pictonia* in the Subboreal succession is the best solution. According to the decision of the voting members of the Subcommission taken by a large majority (77%) the base of the Kimmeridgian Stage should be defined at the base of the Baylei ammonite Zone (Morton, 2007), and thus the main task of the Kimmeridgian Working Group was locating a section showing a satisfactory continuous succession of the *Ringsteadia* to *Pictonia* Subboreal ammonites. After considering all the sections with a Subboreal fauna, the Kimmeridgian Working Group found that the only section yielding the Subboreal ammonite fauna, and fulfilling the other requirements for a GSSP, is that at Staffin Bay, Isle of Skye, Scotland. Importantly and uniquely this section *also* contains a full assemblage of Boreal ammonites, thereby further enhancing its correlation potential. The history of the proposal, voting and revisions is given in Appendix 1.

Flodigarry Section of Staffin Bay as the Stratotype for the Oxfordian/Kimmeridgian Boundary

Introduction

The Kimmeridgian is the penultimate stage of the Jurassic. It is well known as a period of accumulation of mudrocks which have been exploited as a hydrocarbon source rock. The Global Stratotype Section and Point (GSSP) for the base of the Kimmeridgian is placed close to the settlement of Flodigarry, Staffin Bay, Isle of Skye, Scotland, UK. The boundary between the Oxfordian and the Kimmeridgian occurs within the Flodigarry Shale Member of the Staffin Shale Formation. The Flodigarry Shale Member consists of ~60 m of dark- to medium-grey siliciclastic claystones and silty claystones with occasional thin beds of limestone, siltstone and, rarely, fine-grained sandstone that make useful lithostratigraphic markers. The strata are interpreted to represent a continuous succession laid down on the continental shelf below storm-wave base. The succession is exposed on the wave-cut platform (Morton and Hudson, 1995), partly restricted to the intertidal zone, and intermittently covered by mobile pebbles and boulders. The boundary is exposed within a series of large and gently rotated fault blocks (Figs. 1–2). The unique position of this exposure, ensures that the boundary is accessible over many tens of metres, has a large preservation potential and is unweathered as it is regularly wave washed. The section is of great stratigraphic importance as shown by the wide variety of studies (e.g., Anderson and Dunham, 1966; Sykes, 1975; Sykes and Callomon, 1979; Birkelund and Callomon, 1985; Wright, 1973, 1989, 2001; Cox, 2001a; Hesketh and Underhill, 2002; Matyja et al., 2004, 2006; Wierzbowski A. et al., 2006, 2016, 2018, and other papers cited therein). The series of large rotated fault blocks in the area are associated with local movement of

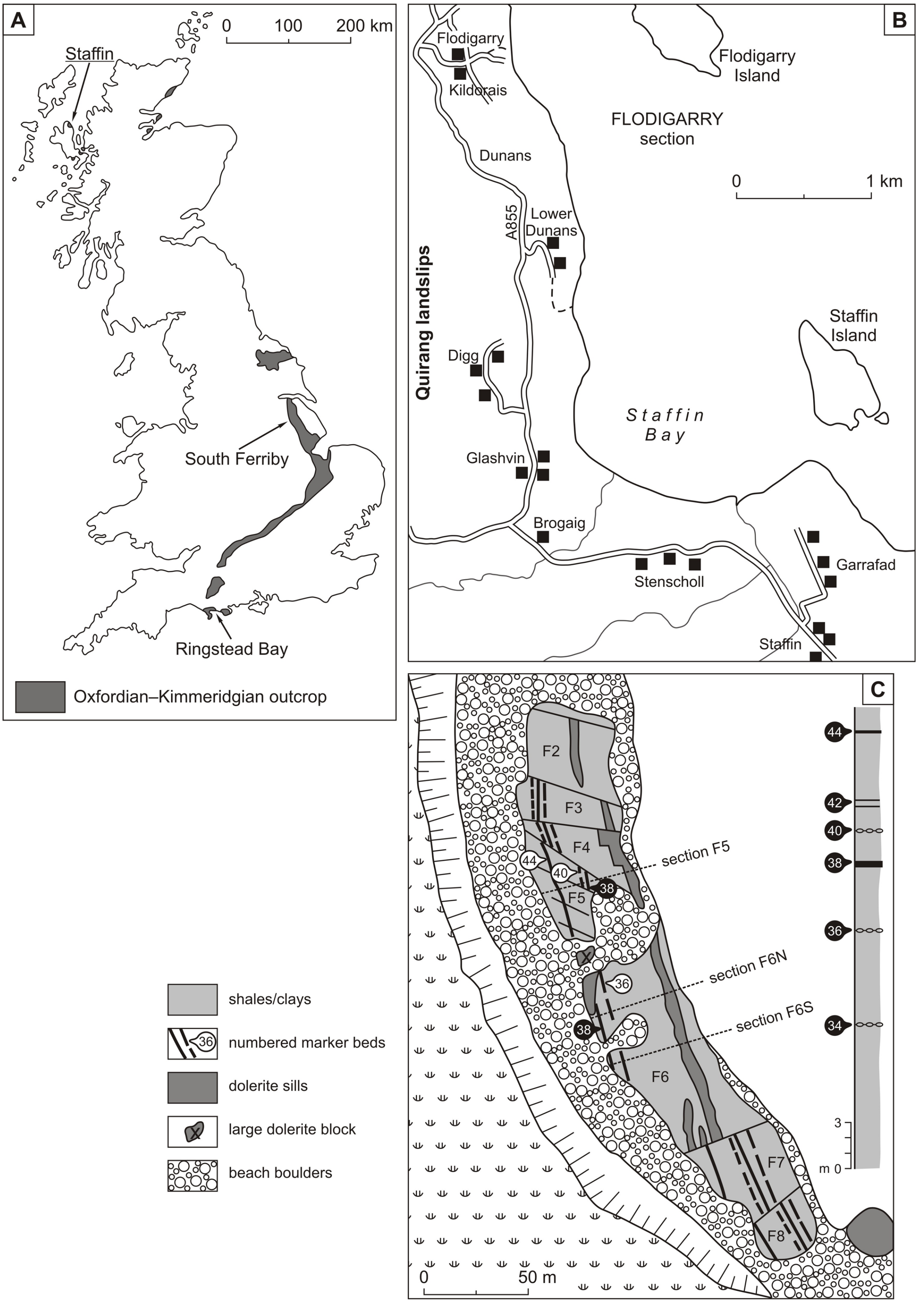

Figure 1. A. Location map for Staffin Bay, Scotland, UK and other UK sections discussed in the text. B: Detail of the Staffin Bay area, including the position of the Flodigarry part of the section shown in part C. C: Geological map of the foreshore at Flodigarry showing the position of the sections studied (after Wierzbowski A. et al., 2006); the generalized section on the right-hand side of Fig. 1C is a composite of sections F6N-S (up to bed 39), and section F5 (beds 39 to 45).

an ancient and stabilized landslip (e.g., Wright, 1989). Distinctive marker beds enable easy correlation between the blocks and these have been mapped in detail (Matyja et al., 2006); Fig. 1). The bedding dips steeply between ~60° and ~80° (Figs. 1–2). Although the

Figure 2. View along the beach at the Flodigarry showing the position of bed 36 and the top of bed 35 where the base Kimmeridgian/ Oxfordian boundary lies: A. General view of the foreshore at Flodigarry; this was taken during the summer when the algae partially covers the rocks. Note the large boulder (arrowed) – which enables the section to be easily located. This boulder is possibly part of a large upstanding in situ dolerite sill; B. View looking north along the beach at Flodigarry showing the marker limestone bed 36 and, on the left-hand side the large boulder shown in A; C. Limestone bed 36 and the top of bed 35.

Jurassic sediments in the area are intruded by occasional Paleocene dolerite sills and dykes, no metamorphic alteration is observed except within about a decimeter of the margins of the intrusions (Thrasher, 1992; Bishop and Abbot, 1995). An organic geochemical study (Lefort et al., 2012) has shown that the organic matter in the uppermost Oxfordian and lowermost Kimmeridgian deposits has very low thermal degradation and is exceptionally well-preserved.

The best sections of the boundary interval (bed 33 up to bed 39) are those denoted F6N and F6S, which are less than 30 m apart within the middle of a rotated fault block F6 (Fig. 1C; Matyja et al., 2006, figs 1–2; Wierzbowski A. et al., 2006, fig. 3; Wierzbowski A. et al., 2018, fig. 2; coordinates for the middle of each section are: F6S: N 57°39′39.5″, W 6°14′43.9″, and F6N: N 57°39′40.5″, W 6°14′45″, UK National Grid Scheme: F6S: NG 4687 7139 ± 5 m and F6N: NG 4686 7142 ± 5 m). Both F6N and F6S are in an area where there has been little cover by present-day beach boulders and pebbles since geological records began. Younger deposits ranging up to bed 45 are well-exposed in the neighbouring block F5 (Fig. 1C). As a whole, the boundary succession is about 35 m thick with the Oxfordian/Kimmeridgian near the middle of the succession (Figs. 2–3). The deposits are very fossiliferous and yield abundant ammonites which, though normally found as flattened impressions, often have nacreous shell present, and the preservation is often excellent, with finest details of ribbing and aperture preserved. Microfossils are also abundant, especially dinoflagellate cyst assemblages. The stratigraphically most important fossils – ammonites and dinoflagellate cysts – are shown in Figs. 4–7 (after Wierzbowski A. et al., 2018; Barski, 2018); these deposits have also yielded nannofossils (Ustinova, 2018; Fig. 8). The stratigraphic distribution of all these fossil groups is discussed in detail below. Other fossil groups are present within the uppermost Oxfordian – lowermost Kimmeridgian succession exposed in Staffin Bay between Flodigarry and Digg (Fig. 1B) but have not yet been studied or published in detail. These include: foraminifers (mostly agglutinated and nodosariids), radiolarians (Gregory, 1989; see also Kelly et al., 2015 in which the unpublished study of Gregory, 1995 on the Jurassic foraminifers and radiolarians of Scotland is cited), brachiopods, bivalves (in the uppermost Oxfordian: *Oxytoma*, *Astarte*, *Lima*, *Pleuromya*, *Pholadomya*; in the lowermost Kimmeridgian: *Oxytoma*, *Astarte*, *Goniomya*, *Pholadomya*, *Neocrassina*, *Nuculana* – see Anderson and Dunham, 1966; Morris, 1968 unpubl., see Cox, 2001a), gastropods (*Dicroloma* and *Procerithium*; Morris, 1968 unpubl., see Cox, 2001a) and belemnites (*Pachyteuthis* and *Cylindroteuthis*).

Ammonites

Ammonites are represented both by (i) Aulacostephanidae typical of the Subboreal succession (province) – which makes correlation possible with the Dorset coast sections, although the faunal succession is much more complete at Staffin – and (ii) Cardioceratidae typical of the Boreal succession (province) unknown in Dorset and making independent correlation to the north possible. Both these ammonite groups occur in equal proportions through the whole studied stratigraphic interval. Of 254 specimens of ammonites counted, 131 belonged to family Aulacostephanidae and 123 to family Cardioceratidae. Those specimens which were better preserved and of stratigraphic importance are housed in the collections of the University Museum, Oxford, UK (collection ST600 to ST926; Matyja et al., 2006), and the Geological Faculty Museum of Warsaw University, Poland (collection MWG UW ZI/94/01 to UW ZI/94/01/55; Wierzbowski A. et al., 2018), and are listed in Appendix 2.1 herein: the list shows also the similar proportion of occurrence of Aulacostephanidae (57 specimens) and Cardioceratidae (57 specimens). The occurrences of the specimens most important for stratigraphy are detailed in Appendix 2, because the very short stratigraphic distances between the occurrences makes it impossible to show all of them in Fig. 3. The grey shading shown in the chronostratigraphy column in Figure 3 denotes stratigraphic intervals where, during field work for this proposal, ammonites were not found, but these intervals are either less than 0.50 m thick or well above the GSSP.

The succession of Aulacostephanidae at Flodigarry reveals the presence of very complete ammonite assemblages as shown by the close phylogenetic relationship between the succeeding species and genera. These are indicative of the uppermost Oxfordian (Pseudocordata Zone) (see Matyja et al., 2006; Wierzbowski A. et al., 2018; see also Figs. 3–5 herein; cf. also Wright, 2010; Wierzbowski A., 2022) and include: (1) the assemblage of *Ringsteadia caledonica* Sykes et Callomon (both micro – m, and macroconchs – M), corresponding to the Caledonica Subzone; (2) the assemblage of *R. pseudoyo* Salfeld (M) and an early representative of *Microbiplices* (m), representing the Pseudoyo Subzone; (3) the assemblage of *R. pseudocordata* (Blake et Hudleston) (M) and late representatives of *Microbiplices* (m), including *M. microbiplex* (Quenstedt) and *M. anglicus* Arkell, corresponding to the Pseudocordata Subzone; (4) the assemblage of *R. evoluta* Salfeld (M) and forms transitional between *M. anglicus* and *Prorasenia* (m), representing the Evoluta Subzone. Faunas indicative of the lowermost Kimmeridgian (Baylei Zone) begin with a new ammonite fauna referred to the new species *Pictonia flodigarriensis* Matyja, Wierzbowski et Wright (M) (see Matyja et al., 2006, fig. 5a–c; see also Fig. 4 herein)) and *Prorasenia bowerbanki* Spath (m) along with forms transitional between *Microbiplices* and *Prorasenia* recognized as the *P. flodigarriensis* horizon which fills the stratigraphic gap in the ammonite succession at the boundary of the *Ringsteadia* assemblages and the *Pictonia* assemblages on the Dorset coast. At the base of the Kimmeridgian as defined here, *Pictonia* (*Triozites*) referred to as *P.* (*T.*) cf. *seminudata* (Buckman) (see Wierzbowski A. et al., 2018) also appears. The succeeding assemblages include firstly that of *Pictonia densicostata* Buckman (M) and *Prorasenia bowerbanki* Spath (m) which together with ammonites of the *P. flodigarriensis* horizon comprise the Densicostata Subzone, and secondly that of *P. baylei* Salfeld/ *P. normandiana* Tornquist (M) and *Prorasenia hardyi* Spath (m) recognized as the Normandiana Subzone. The youngest assemblage recognized contains ammonites of the genus *Rasenia* and corresponds to the lowermost part of the Cymodoce Zone – the *Rasenia inconstans* horizon. The complete succession of ammonites representing the particular members of the lineage of the family Aulacostephanidae (e.g., Wierzbowski A. et al., 2018) has led to the interpretation of the zones and subzones (and at least some of the horizons) that have been distinguished as true chronostratigraphic units (Fig. 3).

The boundary between the Pseudocordata Zone and the Baylei Zone, i.e., the boundary between the Subboreal Oxfordian and Kimmeridgian (Fig. 3), is placed at the base of the oldest *Pictonia* assemblage of the *P. flodigarriensis* horizon. In the Flodigarry section, this level lies in the 2 cm thick siliciclastic mudstone interval between the last occurrence of *Ringsteadia* (which is 1.26 m below the base of Bed 36), and the first occurrence of *Pictonia* (which is 1.24 m below the base of Bed 36). [Note all thicknesses are given relative to the base of Bed 36 as this is a prominent marker bed.]

In addition, the Flodigarry section shows a continuous succession

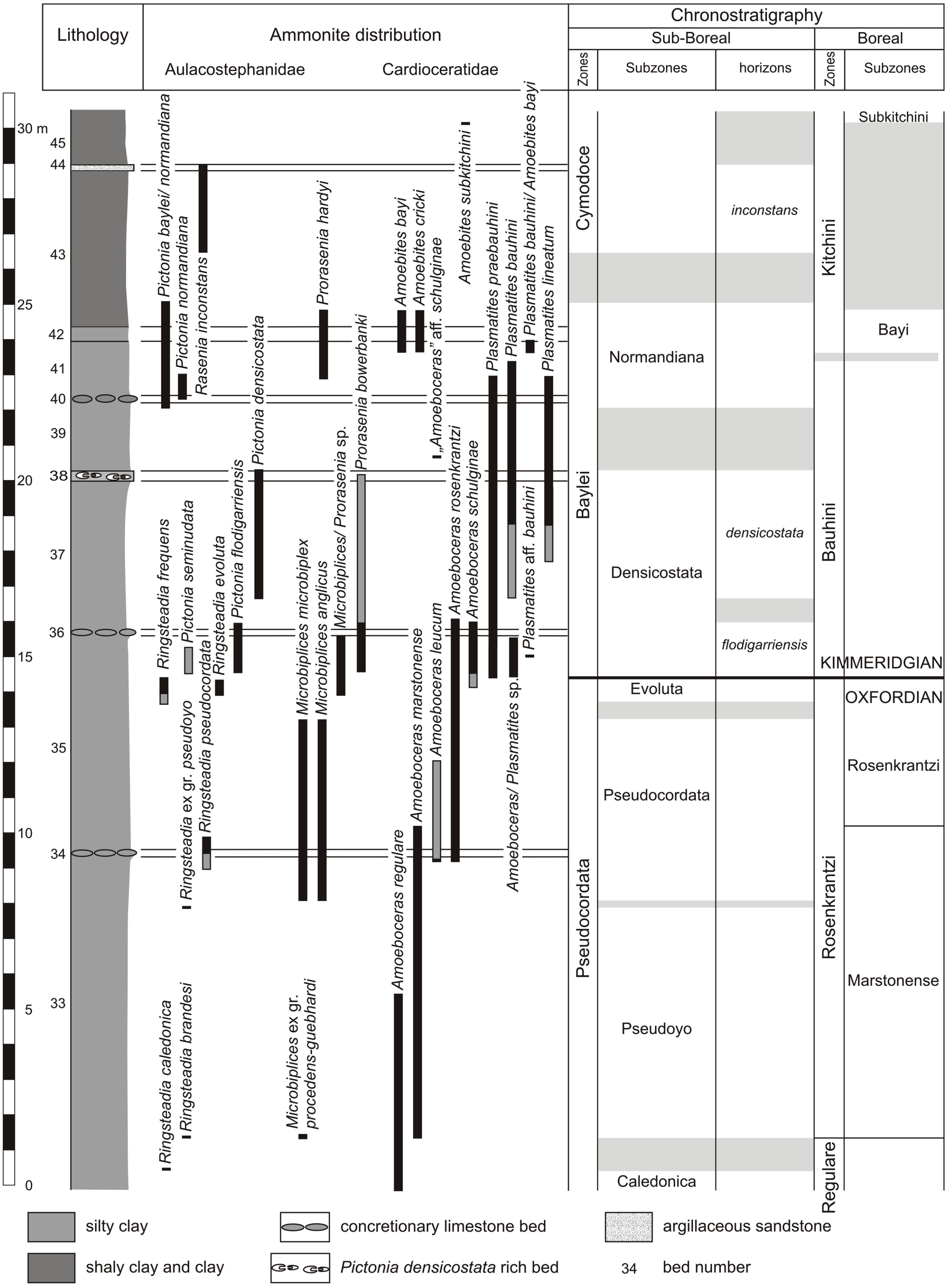

Figure 3. Stratigraphic distribution of ammonites in the Flodigarry section, Staffin Bay, Isle of Skye across the Kimmeridgian GSSP. The ammonites are located to the nearest centimetre. Based on Wierzbowski A. et al. (2018), which is modified from the interpretation of Matyja et al. (2006). Ammonite distribution column – black lines denote the first, last and intervening recorded occurrence of the key species; grey bars denote cf. species; chronostratigraphy column – grey blocks indicate intervals where no ammonites were found during these studies. The stratigraphic height of individual specimens of the most important species are given in Appendix 2.

Figure 4. Pictonia flodigarriensis Matyja, Wierzbowski et Wright – the index species of the flodigarriensis horizon – the lowest faunal horizon of the Baylei Zone at Flodigarry; Flodigarry, paratypes: A and B represent sides of the same specimen (after Wierzbowski A. et al., 2018).

of Boreal ammonites of the family Cardioceratidae of the genera *Amoeboceras*, *Plasmatites* and *Amoebites* with the older genus *Amoeboceras* (of the Amoeboceras rosenkrantzi Zone = Rosenkrantzi Zone with the Amoeboceras marstonense Subzone = Marstonenense Subzone below, and the Amoeboceras rosenkrantzi Subzone = Rosenkrantzi Subzone above) followed successively by the genus *Plasmatites* (of the Plasmatites bauhini Zone = Bauhini Zone), and then by the first *Amoebites* (of the Amoebites kitchini Zone = Kitchini Zone with the Amoebites bayi Subzone = Bayi Subzone below, and the Amoebites subkitchini Subzone = Subkitchini Subzone above). The Oxfordian/Kimmeridgian boundary is marked by the change in Boreal cardioceratids from those of the Rosenkrantzi Zone below, to those of the Bauhini Zone above (Figs 3 and 6). The Boreal Rosenkrantzi Zone spans the stratigraphic range of the last ammonites of the genus *Amoeboceras* correlated with the uppermost Oxfordian. This includes the faunal succession from *A. marstonense* Spath co-occurring with last *A. regulare* Spath below, and is succeeded by the appearance of a younger fauna of *Amoeboceras* with a characteristic rursiradiate ribbing (represented initially by *A. leucum* Spath, but mostly by *A. rosenkrantzi* Spath (and the closely allied *A. schulginae* Mesezhnikov)). The Boreal Bauhini Zone is characterized by the occurrence of small-sized ammonites of the genus *Plasmatites* with such species as *P. bauhini* (Oppel), *P. praebauhini* (Salfeld) and *P. lineatum* (Quenstedt) indicative of the lowermost Kimmeridgian. The first occurrence of the earliest *Plasmatites – P. praebauhini* marks the base of the Bauhini Zone. Along with these first ammonites of the genus *Plasmatites* there appear also forms intermediate between *Amoeboceras rosenkrantzi* and the first *Plasmatites.* These forms show ornamentation of the inner whorls similar to that of *Plasmatites* whereas the ornament on the outer whorl still resembles that of *A. rosenkrantzi* (Wierzbowski A. et al., 2018).

Figure 5. Ammonites of the family Aulacostephanidae from the Staffin Bay sections (after Wierzbowski A. et al., 2018): 1 – Ringsteadia cf. evoluta Salfeld, bed 35 (from 1.5 m below the base of bed 36), Evoluta Subzone, Pseudocordata Zone; 2 – Ringsteadia pseudocordata (Blake et Hudleston), from part of bed 35, Pseudocordata Subzone, Pseudocordata Zone; 3 – Ringsteadia frequens Salfeld, from bed 35, from 1.26 m below the base of bed 36, Evoluta Subzone, Pseudocordata Zone; 4 and 5 – Pictonia (Triozites) cf. seminudata (Buckman), bed 35, from 1.24 m below the base of bed 36, Densicostata Subzone, Baylei Zone; 6 – Pictonia (Triozites) cf. seminudata (Buckman), bed 35, from 0.45 m below the base of bed 36, Densicostata Subzone, Baylei Zone; 7 – Pictonia densicostata Buckman, bed 38, Densicostata Subzone, Baylei Zone; 8 – Pictonia ex gr. normandiana (Tornquist) – baylei Salfeld, bed 41, Normandiana Subzone, Baylei Zone; 9-10 – Prorasenia bowerbanki Spath, 9 – bed 35, from directly below bed 36, 10 – bed 38, Densicostata Subzone, Baylei Zone.

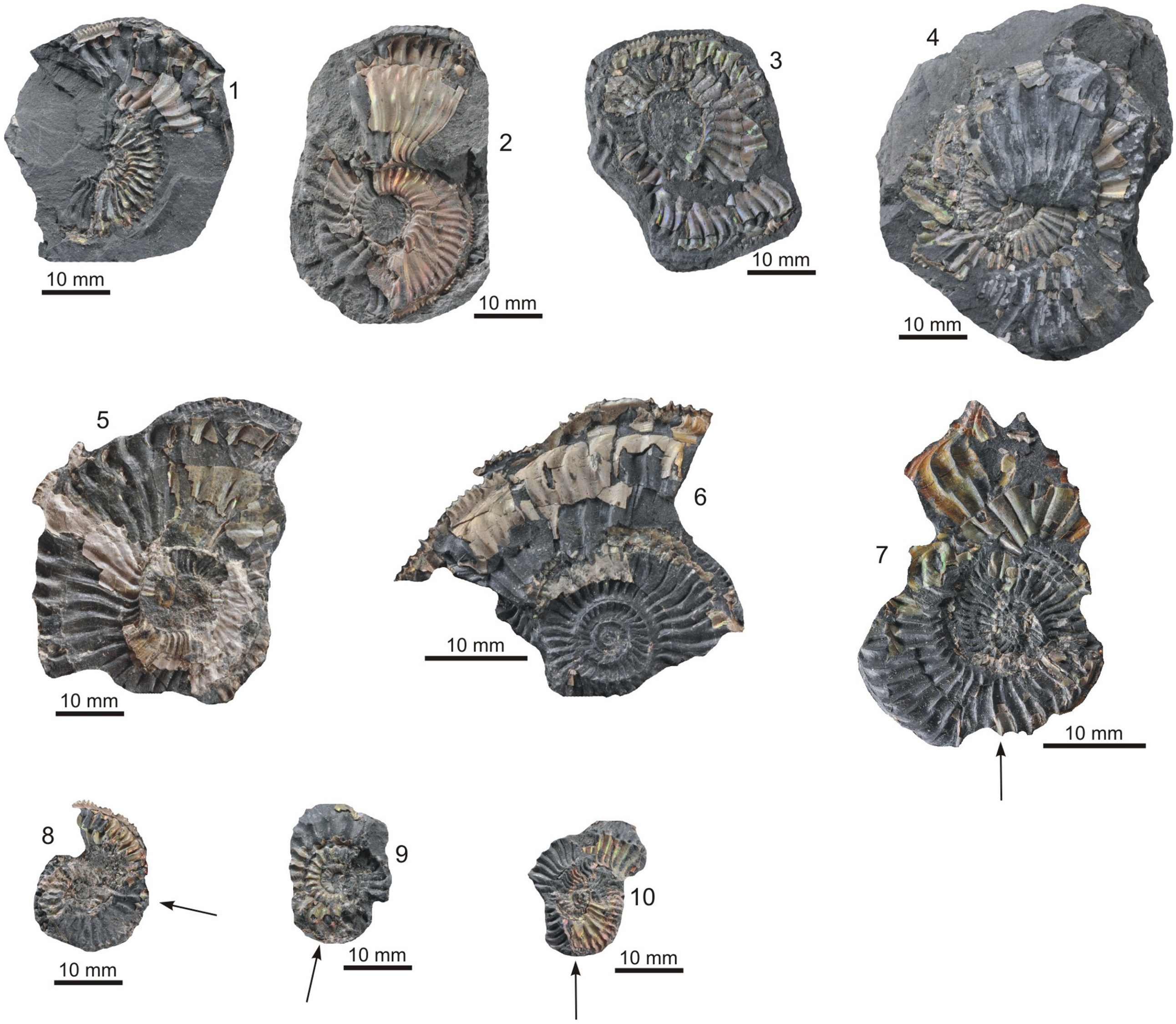

Figure 6. Ammonites of the family Cardioceratidae of the Staffin Bay sections (after Wierzbowski A. et al., 2018): 1 and 2 – Amoeboceras rosenkrantzi Spath, 1– bed 33 (uppermost part), 2 – bed 35 (lowermost part), Marstonense Subzone, Rosenkrantzi Zone; 3 and 4 – Amoeboceras rosenkrantzi Spath, bed 35, from about 1.45 m below the base of bed 36, Rosenkrantzi Subzone, Rosenkrantzi Zone; 5 – Amoeboceras cf. rosenkrantzi Spath, bed 35, from 0.45 m below the base of bed 36, Bauhini Zone, lowermost part; 6 and 7 – Amoeboceras rosenkrantzi Spath – form transitional to Plasmatites praebauhini (Salfeld), 6 – bed 35, from 0.56 m below the base of bed 36, 7 – bed 35, from 117 m below the base of bed 36, Bauhini Zone, lowermost part; 8 – Plasmatites aff. bauhini (Oppel), from 0.60 m below the base of bed 36, Bauhini Zone, lowermost part; 9 and 10 – Plasmatites bauhini (Oppel), bed 41, Bauhini Zone.

In the Flodigarry section this faunal change takes place not higher than 1.17 m below the base of Bed 36 – but it may occur a little lower. This indicates the practically coeval position (within 0.09 m) of the change in the Boreal and Subboreal faunas at the Kimmeridgian GSSP. Similarly, as in the case of the Aulacostephanidae, representatives of the Cardioceratidae also show in the succession studied a continuous phylogenetic record which allows treatment of the zones and subzones as real chronostratigraphic units. The occurrence of Boreal cardioceratids gives independent correlation of the Subboreal boundary in question with the base of the Boreal Bauhini Zone, and greatly enhances the global correlation potential of the Oxfordian/Kimmeridgian boundary.

The phylogeny both of Aulacostephanidae and Cardioceratidae generally shows gradual changes in the morphological development of the particular members of the two ammonite families during the latest Oxfordian and earliest Kimmeridgian (Birkelund and Callomon, 1985), but there are some exceptions when the diversity in particular lineages changed markedly – this is expressed by the rapid evolutionary loss of some forms or the appearance of new forms that are here called – 'evolutionary turnovers'. These are distinct from faunal turnovers which can be a secondary phenomenon resulting from condensation or stratigraphic gaps. Such an evolutionary turnover, originally recognized in the Subboreal ammonite Aulacostephanidae lineage at the boundary of the Pseudocordata Zone and the Baylei Zone, corresponded to the marked evolutionary change from the genus *Ringsteadia* to the genus *Pictonia* and was the basis for recognition of the Oxfordian/Kimmeridgian boundary previously (Salfeld, 1913). The Aulacostephanidae evolutionary turnover corresponds precisely stratigraphically to the evolutionary turnover in the Boreal ammonite Cardioceratidae lineage at the boundary of the Rosenkrantzi Zone and the Bauhini Zone, which represents the marked evolutionary change from the genus *Amoeboceras* to the genus *Plasmatites* (Wierzbowski A., and Smelror, 1993). These evolutionary turnovers were originally observed separately in the Aulacostephanidae lineage in Subboreal areas, and the Cardioceratidae lineage in Boreal areas, but their strictly coeval occurrence has been observed for the first time in both families in the Staffin Bay sections (Matyja et al., 2006). The stratigraphic interval at the Oxfordian/Kimmeridgian boundary thus shows major morphological changes in both ammonite families, which were realized from phylogenetic constraints by heterochrony, and especially by paedomorphosis (Wierzbowski A. et al., 2018; Wierzbowski A., 2022).

Microfossils

Several groups of microfossils from the Staffin Bay succession have been studied (acritarchs and other palynomorphs, foraminifers, nannofossils and radiolarians) – but the most important group for microfossil correlation in this section are the organic-walled dinoflagellate cysts because of the more detailed stratigraphic subdivisions that are available.

The Oxfordian/Kimmeridgian boundary in the Subboreal succession has traditionally been placed near the boundary between the dinoflagellate cyst zones DSJ 26 (corresponding to the Boreal ammonite Rosenkrantzi Zone) and DSJ 27 (corresponding to the Subboreal Baylei Zone) (Poulsen and Riding, 2003), this equates to the boundary of the dinoflagellate cyst subzones c and d of the Scriniodinium crystallinum (=Scr) Zone of Riding and Thomas (1992). This zonal boundary is defined by the last occurrence of *Ctenidodinium ornatum* and the inception of *Senoniasphaera jurassica.*

Riding and Thomas (1997) and references therein from the 1970s investigated the palynomorph assemblage of the mudrock in Staffin Bay and reported a rich and diverse assemblage at Flodigarry (Fig. 7A). Riding and Thomas (1997) described the appearance of three species (*Aldorfia dictyota* subsp. *pyrum*, *Occisucysta balios*, and *Lithodinia mitra*) near and above the base of Bed 37 in the Flodigarry section. The range bases of these three species, as given by Riding and Thomas (1997), were already associated in the literature with the Baylei ammonite Zone in southern England or Germany. Based on the presence of *Occisucysta balios*, Riding and Thomas (1997, p. 73) subdivided the upper part of the Scriniodinium crystallinum (= Scr) Zone in the Flodigarry section into the Scr (b) and Scr (c/d) subzones. Using this evidence, Riding and Thomas (1997) then appear to have correlated the base of the 'Scr (c/d)' subzone with the base of the Kimmeridgian Stage. However, the appearance of the diagnostic species *Occisucysta balios* defines the base of the uppermost Oxfordian DSJ 26 Zone, and hence the equivalent base of the subzone c of the Scriniodinium crystallinum (= Scr) Zone. In addition, this species ranges throughout the Kimmeridgian (Poulsen and Riding, 2003), and thus cannot be used for recognising the boundary between subzones c and d (the Oxfordian and Kimmeridgian boundary). Riding and Thomas (1997) also noted based on their studies of the Flodigarry section that 'the marked maximum level of marine microplankton' recognized near the base of Bed 36 'appears to indicate the position of the J62 maximum flooding surface' from the North Sea and this level was treated by them as corresponding to the base of the Kimmeridgian.

Barski (2018) studied seven samples specifically chosen to span the Oxfordian/Kimmeridgian boundary at Flodigarry and separated from the matrix of ammonites (Appendix 2). These contained an assemblage composed of thirty-one dinoflagellate species, the ten key species of which are shown in Fig. 7B. Some of the species extend many metres below and above the boundary, but three are of stratigraphic significance for placement of the Kimmeridgian GSSP. The inception of *Senoniasphaera jurassica* 0.6 m below the base of Bed 36 (Barski, 2018) indicates the base of subzone d of the Scriniodinium crystallinum (= Scr) Zone of Riding and Thomas (1992), and the corresponding base of the DSJ 27 Zone, and is widely accepted as the dinoflagellate marker for the Baylei ammonite Zone. Furthermore, this first recorded occurrence of *S. jurassica* in the Flodigarry section is within the *P. flodigarrienis* ammonite horizon, representing the lowermost part of the ammonite Baylei Zone. Barski (2018) also reports the lowest occurrence of two individuals of *Perisseiasphaeridium pannonosum* from 0.6 m below the base of Bed 36 which is about 5 m lower than that previously reported by Riding and Thomas (1997) suggesting that this species may also be a useful marker of the boundary interval. In addition, the incoming of the dinoflagellate cyst *Emmetrocysta sarjeanti* just 0.17 m above the Kimmeridgian GSSP (i.e. 1.08 m below the base of Bed 36; Barski, 2018) could provide a third useful secondary marker but due to its low abundance in the samples examined further studies are required to establish whether its first occurrence is lower (Fig. 7B). The deposits of the Flodigarry Shale Member that are relatively rich in skolochorate dinoflagellate cysts (i.e., characterized by presence of distinctive isolated precesses, generally not common in the Boreal areas) appear to be of intermediate Subboreal to Boreal character (Riding and Thomas, 1997), and are worthy of further stratigraphic investigation. Additionally, Chlorophyceae algal blooms were recognized just above the Oxfordian/Kimmeridgian boundary (Barski, 2018; Fig. 7B) and these also may have correlative potential.

Twenty-four samples from the Flodigarry section were investigated for calcareous nannofossil biostratigraphy. The samples were obtained from ammonite specimens precisely located in the succession and are spaced between 0.2 and 4.0 m apart (Fig. 8). Samples were particularly closely spaced around the Oxfordian/Kimmeridgian boundary (11 samples). Smear slides (24 × 24 mm) made with Canada Balsam were examined under an optical microscope with a 1000x magnification. At least 100 fields of view (diameter 0.018 mm) were observed randomly in peripheral and central parts on each slide, to obtain relative abundances and semiquantitative information about nannofossil assemblage composition. The preservation of calcareous nannofossils is generally poor in all the studied samples; coccoliths are usually partially etched and overgrown. Samples 1, 6, 7, 9, 11 were barren of nannofossils (Fig. 8A). The key species are discussed below and illustrated on Fig. 8B.

Calcareous nannofossils are very scarce and poorly preserved in the samples from the lowermost part of the Pseudocordata ammonite subzone, and composed of rare *Cyclagelosphaera margerelii*, *Watznaueria barnesiae*, *W. fossacincta* and *W. britannica*. These species range throughout the studied section and are more common between the uppermost part of the Pseudocordata and the Cymodoce ammonite

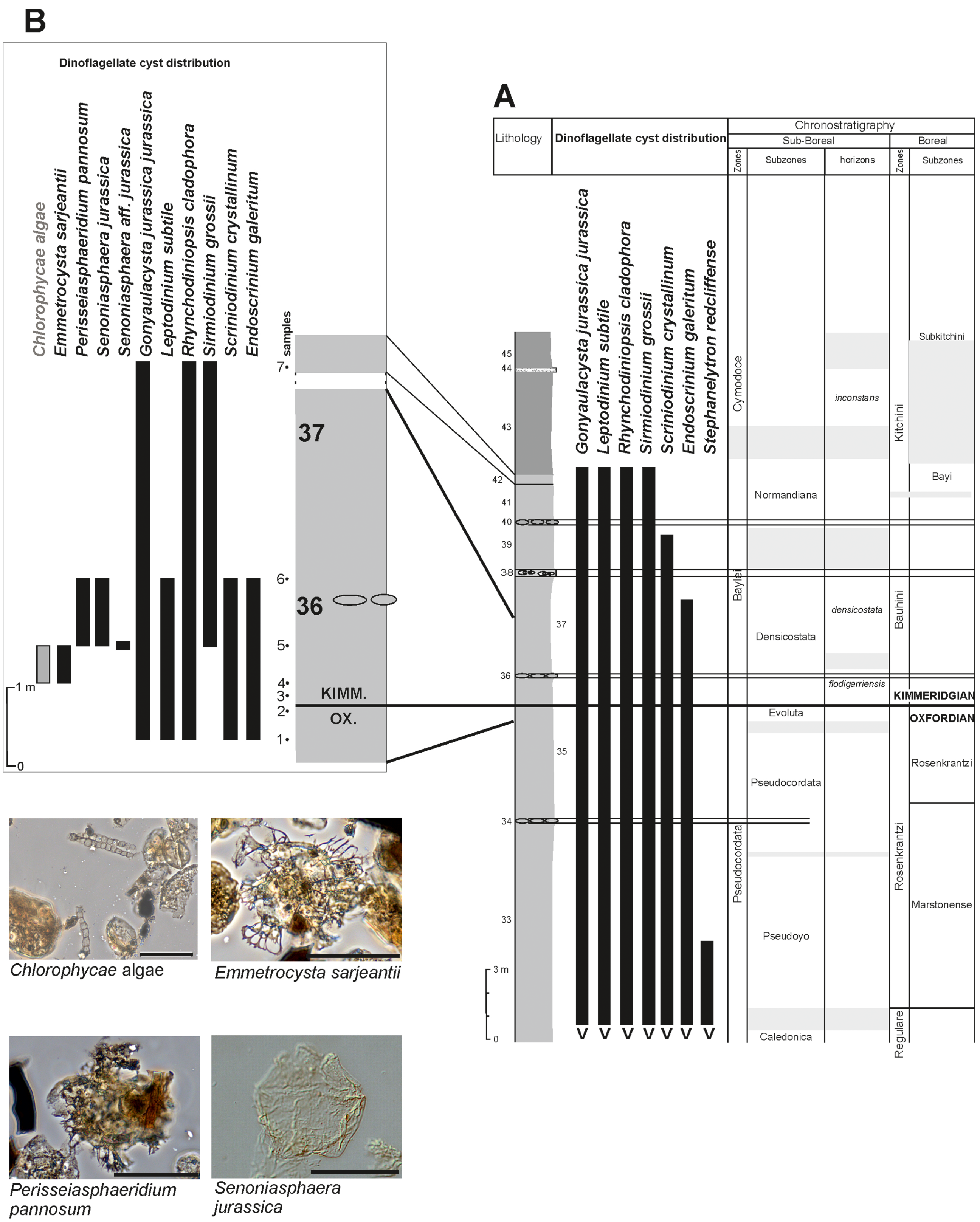

Figure 7. A. The general distribution of the dinoflagellate cysts in the Flodigarry succession (after Riding and Thomas, 1997). B. The Oxfordian/Kimmeridgian boundary part of the stratigraphic column of the Flodigarry section at Staffin Bay, Isle of Skye showing the location of the palynological samples, the incoming of diagnostic dinoflagellate cysts and the specific acme of chlorophyceae algae (after Barski, 2018). Photographs of the four species of stratigraphic significance (see text for details). Scale bar = 50 μm.

zones. Calcareous nannofossils are more abundant and diverse in the samples from the uppermost part of the Pseudocordata ammonite Subzone and in the Evoluta ammonite Subzone interval; here *Watznaueria* dominates, *Zeugrhabdotus erectus* and *Stephanolithion bigotii bigotii*

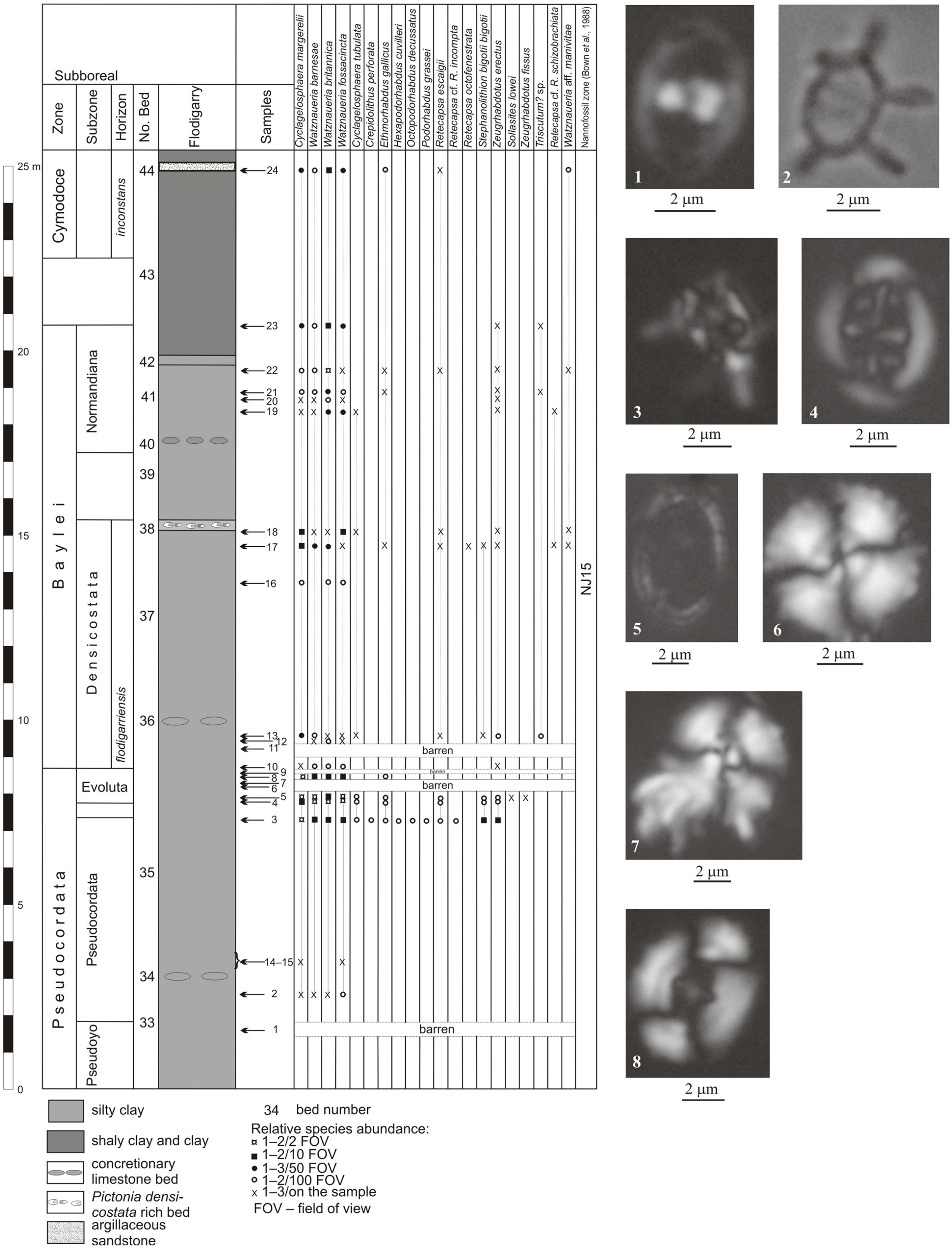

Figure 8. A. Chart showing the distribution and relative abundance of calcareous nannofossils in the Flodigarry section (after Ustinova, 2018) against the Subboreal ammonite zonation and a summary stratigraphic section. White blocks within the ammonite zonation indicate the intervals where no ammonites were recorded in the studies (after Wierzbowski A. et al., 2018). The only evidence for NJ15 is the potential last occurrence of O. decussatus just below the Oxfordian-Kimmeridgian boundary. The last occurrence of this species is taken to indicate the lower part of the nannofossil NJ15 zone (Bown and Cooper, 1998). B. Photographs of selected nannofossils from the Flodigarry section. The location of the samples is shown in Fig. 8A. 1. Zeugrhabdotus erectus, sample 4, pol; 2. Stephanolithion bigotii bigotii, sample 3, tr; 3. Stephanolithion bigotii bigotii, sample 17, pol; 4. Retecapsa escaigii, distal view, sample 4, pol; 5. Ethmorhabdus gallicus, distal view, sample 4, pol; 6. Cyclagelosphaera margerelii, distal view, sample 3, pol; 7. Watznaueria fossacincta, with evidences of overgrowth, distal view, sample 3, pol; 8. Watznaueria britannica, distal view, sample 4, pol.

are common and *Ethmorhabdus gallicus* and *Retecapsa escaigii* are occasionally found. *Crepidolithus perforata*, *Hexapodorhabdus cuvilleri*, *Octopodorhabdus decussatus*, *Podorhabdus grassei* and *Retecapsa incompta* occur occasionally in the upper part of the Pseudocordata Zone. *Sollasites lowei* and *Zeugrhabdotus fissus* are scarce and only recorded in the Evoluta ammonite Subzone. *Retecapsa* cf. *R. schizobrachiata*, and *Watznaueria manivitiae* are only present in the upper part of the Baylei ammonite Zone (Ustinova, 2018).

All of these species are characterized by a very long stratigraphic range, spanning the mid to late Jurassic (at least), and by a wide geographical distribution. This feature and the fact that zonal markers were not recorded in Flodigarry samples makes attribution to a precise nannofossil zone difficult. However, the species *O. decussatus*, which is only recorded in sample 3 (upper part of the Pseudocordata Zone; 2.34 m below the base of bed 36 or 1.09 ± 0.01 m below the base of the boundary; Fig. 8A), was reported by Bown and Cooper (1998) to disappear near the base of the NJ15 zone. This is reported to be a very long zone (mid Oxfordian to uppermost Kimmeridgian), characterized by an evolutionary stasis, and encapsulating the Oxfordian/Kimmeridgian boundary (Bown and Cooper, 1998). If this new record of *O. decussatus* corresponds to its last occurrence datum, it indicates the lower part of the NJ15 zone and is potentially a marker for the Oxfordian/Kimmeridgian boundary.

Magnetostratigraphy

A magnetostratigraphy for the Flodigarry section was constructed by M. W. Hounslow, J. G. Ogg and A. L. Coe based on two sets of samples collected and analyzed independently (Wierzbowski A. et al., 2006, Przybylski et al., 2010b). New and more detailed sampling of the ~ 4 m below the base of Bed 36 across the Oxfordian/Kimmeridgian boundary is combined with these previous data (Fig. 9). Data for all the samples are listed in Appendix 3 along with directional details of the magnetizations. All the data combined pass the DC fold test of Enkin (2003) with the optimum unfolding at 92% (95% confidence interval 48–136% unfolding), and pass the reversal test (See Appendix 3), suggesting the primary nature of the magnetization, as also previously inferred (Wierzbowski A. et al., 2006 and Przybylski et al., 2010b). The new data presented here do not change the palaeomagnetic conclusions for the section presented by Przybylski et al. (2010b).

These magnetostratigraphic results show a predominantly reversed polarity with several short intervals of normal polarity in the uppermost Oxfordian and lowermost Kimmeridgian (Fig. 10). In detail, the uppermost ~0.6 m of the Oxfordian was normal polarity (F3n), and the lowermost Kimmeridgian was reverse polarity (F3r), with the base of the Kimmeridgian as defined by the ammonites in the oldest part of the reversed magnetozone F3r (Fig. 9). The boundary between reverse magnetozone F3r and the top of the underlying normal magnetozone F3n is located between 1.28 m and 1.48 m below the base of Bed 36 (between samples jw9.1 and jw18.1; Appendix 3). The base of the F3r magnetostratigraphic boundary is therefore between 0.02 and 0.24 m below the base of the Baylei Zone, (base of the *P. flodigarriensis* horizon) so the biostratigraphic and magnetostratigraphic events marking the Kimmeridgian GSSP are very close to each other stratigraphically. The occurrence of the ammonite *Ringsteadia frequens* at 1.26 m below the base of bed 36 and the appearance of *Pictonia* (*Triozites*) cf. *seminudata* at 1.24 m below the base of bed 36 constrains the base of magnetozone F3r to the latest Oxfordian. The small uncertainty in the position of the F3n-F3r magnetozone boundary might be reduced with even greater sampling frequency (these friable mudstones are however difficult to sample for magnetostratigraphy), but more importantly it is also likely that there is a transitional interval between the geomagnetic field polarity states, which is often of this approxi-

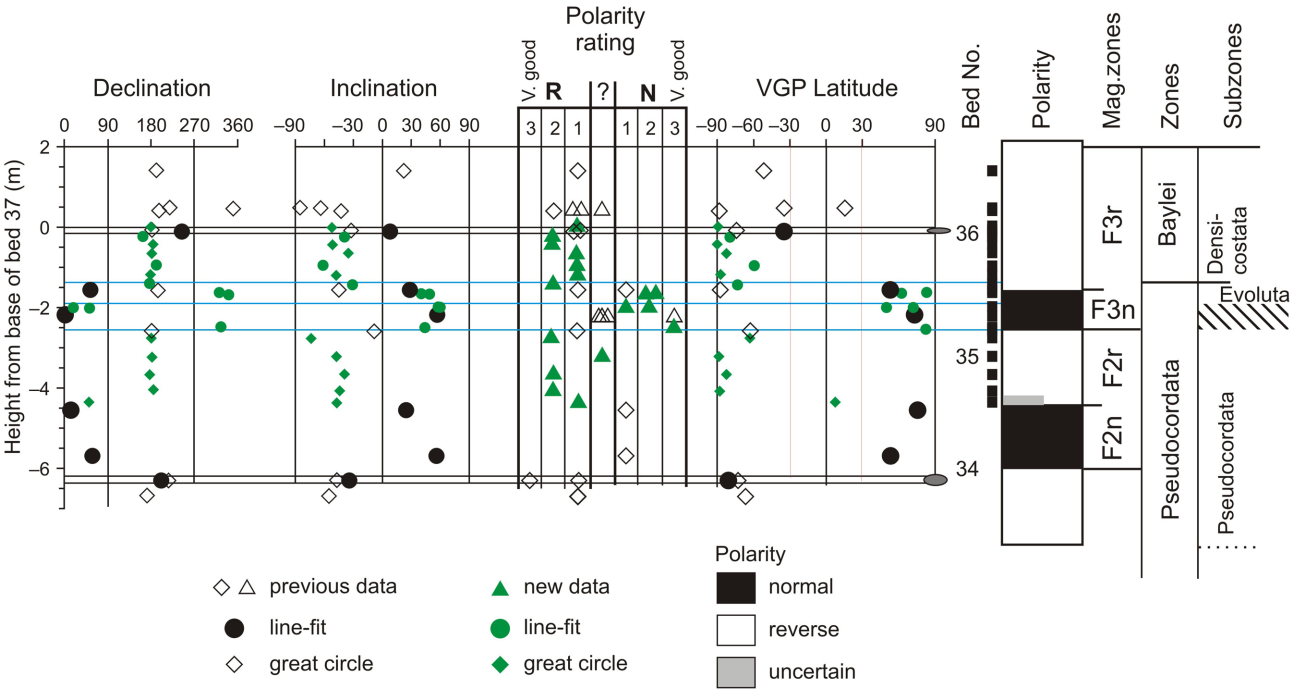

Figure 9. The magnetostratigraphic data across the Kimmeridgian GSSP (from Wierzbowski A. et al., 2016). Further details of the data are included in the supplementary information (Appendix 3).

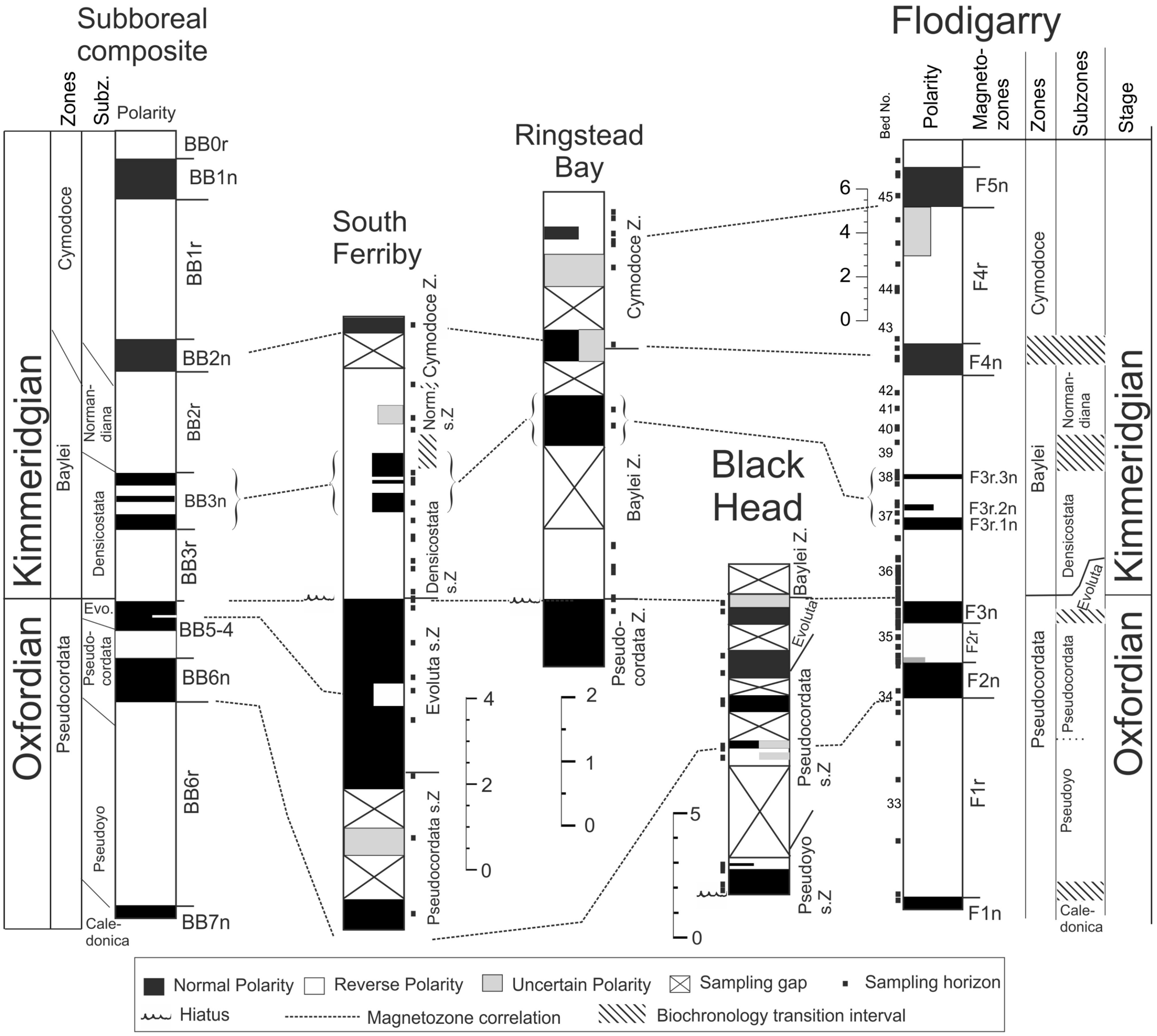

Figure 10. Correlation of UK sections, allowing construction of a Subboreal composite magnetostratigraphy and refinement of some of the details in poorly sampled parts of the Flodigarry section either side of the boundary interval (from Wierzbowski A. et al., 2016). Other section details and chron names (i.e., BB) on the British magnetic polarity composite from Przybylski et al. (2010). Chrons BB4 and BB5 of Przybylski et al. (2010) have been merged into chron BB5-4, since BB4r was based only on a single specimen from the Evoluta Subzone at South Ferriby, Yorkshire, UK.

mate thickness-scale in sedimentary rocks (Clement, 2004). Therefore, the boundary of magnetozones F3n–F3r provides an ideal secondary marker for the base of the Kimmeridgian in the Flodigarry section and elsewhere. The magnetostratigraphy at Flodigarry combined with data from other UK sections (Fig. 10) can be used to construct a composite Subboreal magnetostratigraphy, with correlations constrained by the ammonite biostratigraphy. The correlation to marine magnetic anomalies is discussed Correlation to the Seafloor.

Isotope Stratigraphy

Results of oxygen and carbon isotope analyses of well-preserved belemnite rostra ($\delta^{13}O_{carb}$, $\delta^{13}C_{carb}$) and carbon isotope analyses of terrestrial organic matter ($\delta^{13}C_{org}$) from the Staffin Bay sections, including the Flodigarry section, were published in Wierzbowski H. (2004), Pearce et al. (2005), Wierzbowski A. et al. (2006), and Nunn et al. (2009). The belemnite isotope data have been calibrated herein according to a revised chronostratigraphy of the Flodigarry section (Fig. 11; cf. Wierzbowski A. et al., 2016; Wierzbowski A. et al., 2018).

Relatively low and variable belemnite $\delta^{18}O$ values (–2.1 to 0.7‰ VPDB) are observed in the uppermost Oxfordian and the lowermost Kimmeridgian (Fig. 11). Overall the data define part of a general decrease in $\delta^{18}O$ values spanning from the uppermost Oxfordian to lowermost Kimmeridgian. Analyses of the belemnite and terrestrial organic matter composition show a gradual overall decrease of $\delta^{13}C$ values in the uppermost Oxfordian (Wierzbowski H., 2004; Pearce et

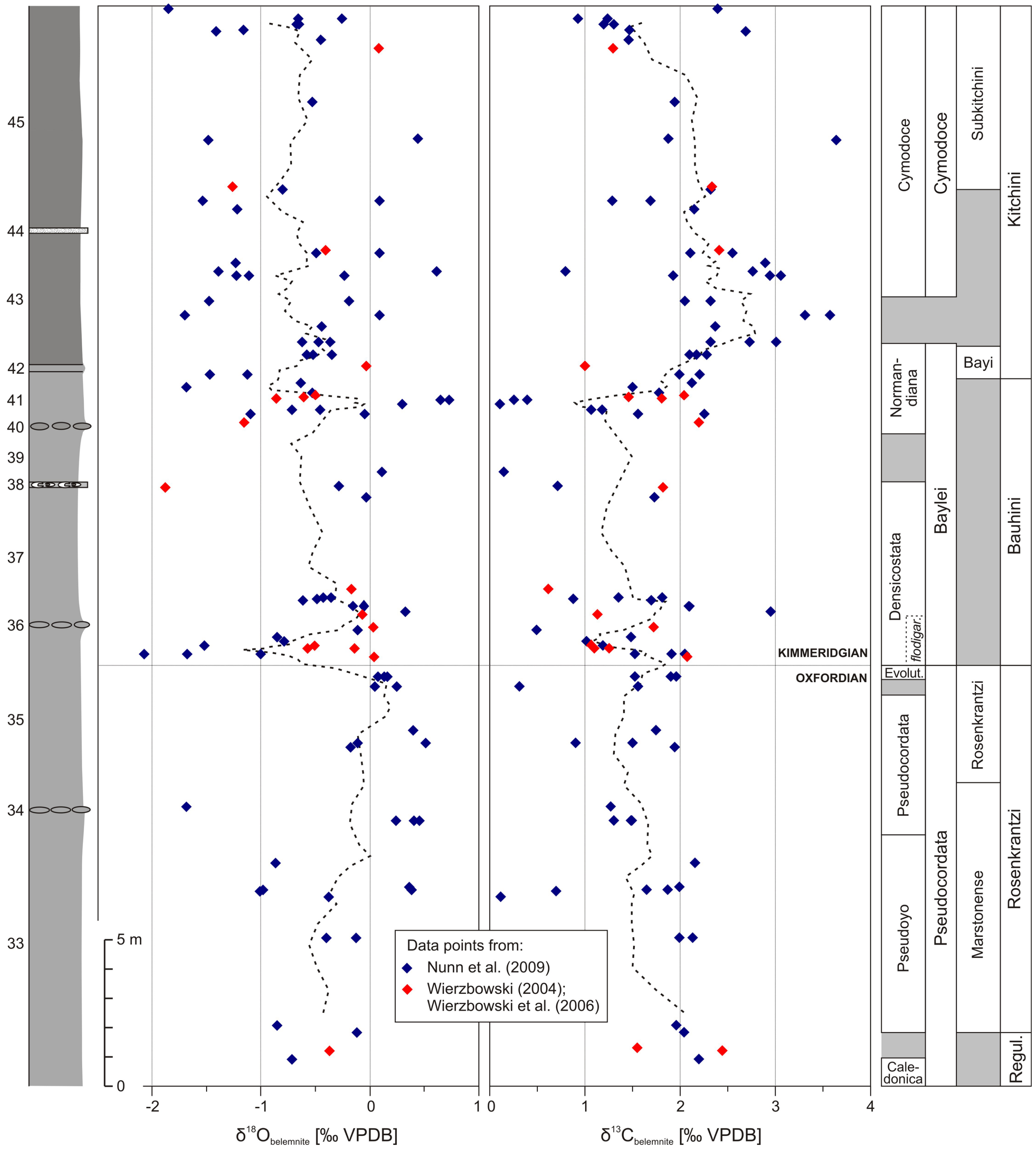

***Figure 11.** $\delta^{18}O$ and $\delta^{13}C$ values of well-preserved belemnite rostra from the Flodigarry section (after Wierzbowski A. et al., 2006; Wierzbowski H., 2006, and Nunn et al., 2009). The dashed lines are 5-point moving averages.*

al., 2005; Wierzbowski A. et al., 2006; Nunn et al., 2009). Low $\delta^{13}C$ values which average ~ 1.5‰ VPDB (range 0.1 to 2.2‰ with one value at 2.9‰ VPDB) occur in the uppermost Oxfordian and lowermost Kimmeridgian. These are followed by an apparently relatively rapid ~1‰ increase in carbon isotope values across the Baylei to Cymodoce zone boundary (Fig. 11). This broad carbon isotope minimum in the uppermost Oxfordian and lowermost Kimmeridgian is likely to be useful for stratigraphic correlation because it occurs after the pronounced uppermost Callovian–middle Oxfordian positive excursion noted in various bioprovinces (Nunn et al., 2009; Wierzbowski H. et al., 2013; Wierzbowski H., 2015). The five-point moving average (Fig. 11) indicates a possible short-term negative excursion in $\delta^{13}C$ values immediately above the Oxfordian–Kimmeridgian boundary, but the current data are highly variable and confirmation of this excursion awaits further high-resolution carbon-isotope studies.

The Kimmeridgian GSSP level is near the base of the gradual increase in the $^{87}Sr/^{86}Sr$ ratios of seawater that occurs after the minimum for the whole of the Mesozoic in the Oxfordian (Wierzbowski H. et al., 2017; McArthur et al., 2020). A mean strontium isotope ratio of *c.* 0.70687 is calculated for the Oxfordian–Kimmeridgian transition, defined according to the revised stratigraphic scheme (Wierzbowski H. et al., 2017). This specific and low Sr-isotope value only occurs twice in the Mesozoic and four times in the Phanerozoic.

Radio-isotopic Dating

Rhenium-Osmium ($^{187}Re - {}^{188}Os$) dating of the organic-rich mudrocks from 1.30 m ±0.1 m below the base of Bed 36 at Flodigarry, i.e., 0.05 m below the Oxfordian/Kimmeridgian boundary interval, yielded an age of 154.1 ± 2.2 Ma (2σ; Selby, 2007). This is the first radio-isotopic date for this boundary that is directly tied to the biostratigraphy (see Correlation of the GSSP Succession for further discussion of the integrated timescale).

Organic Geochemistry

The exceptional preservation and very low thermal degradation of the organic matter in the Flodigarry Shale Member at Flodigarry have been shown by Lefort et al. (2012). The soluble organic matter is characterized by exceptional preservation of hopanids and biomolecules. Preservation of such high quality as this, in deposits of Jurassic age, is very rare worldwide (Lefort et al., 2012). The distribution of *n*-alkanes shows that there is organic matter from both marine and terrestrial sources but that the predominant contribution is continental, consistent with the presence of communicated terrestrial plants.

Sedimentary Facies and Sequence Stratigraphy

The Oxfordian and Kimmeridgian section at Staffin Bay is composed of marine siliciclastic mudrocks rich in fossils and containing subordinate siltstone laminae and thin siltstone beds, organic-rich mudstones, and diagenetic limestone nodules and beds that are no more than a few decimeters thick. These mudrock facies contain no evidence for waves or shallow-marine processes and the fauna indicate open marine conditions throughout the succession. All the facies boundaries are gradational and there is no biostratigraphical or sedimentological evidence for stratigraphical gaps. The siliciclastic mudstones of the Flodigarry Shale Member contain subtle, decimeter-scale sedimentary cycles; the base of each of these is marked by a slightly siltier layer of usually less than 1 cm. Closely spaced cycles are interpreted to represent periods of reduced accommodation space and/or changes in sediment supply whereas widely spaced cycles are interpreted to represent increased accommodation space and maximum flooding. The upper part of Bed 35, including the interval containing the Kimmeridgian GSSP contains no silty beds or any other lithological change such as condensation and is interpreted to fall within the lower part of a highstand systems tract. The wider sequence stratigraphic implications of the position of the Kimmeridgian GSSP are discussed in Climate and Relative Sea-level Change.

Conservation and Access to the GSSP

All the other requirements indicated for the GSSP selection (Remane et al., 1996) are fulfilled, which provides an ideal scenario for safeguarding the GSSP for future scientific studies (Wierzbowski A. et al., 2016). These are: (1) a *permanently fixed marker*: the boundary's location 1.25 ± 0.01 m below the base of Bed 36 which forms a prominent bed is a natural fixed marker (Fig. 2). A further discrete, man-made marker that could be located using GPS reference and metal detector could also be placed if required; (2) good *accessibility* on foot along a 200 m public right of way from a road in the hamlet of Flodigarry to the shore and then 300 m along the shore where the section is well exposed during falling and low tide conditions; (3) *free access* according to rights supported by Scottish law; (4) *guarantees from the respective authority concerning free access for research and permanent protection of the sit*e. The area is publically owned and managed on behalf of the Scottish Government and protected through the Nature Conservation (Scotland) Act 2004 within the legally designated Trotternish Ridge Site of Special Scientific Interest (https://sitelink.nature.scot/site/1566).

Correlation of the GSSP Succession with Other Successions in the World and Global Implications

Biostratigraphic Correlations

The correlation of the GSSP succession with those of the Boreal-Subboreal areas in northern Europe and Asia, and adjoining areas of the Arctic, are summarized below and in detail in Wierzbowski A. et al., 2016).

Aulacostephanid ammonites in southern England (Wessex Basin) — the classical area of the Subboreal Province (Wright, 2010) — generally shows that the ammonite succession in this area is incomplete at the Oxfordian – Kimmeridgian boundary, i.e., the boundary of the Pseudocordata Zone and the Baylei Zone. The *P. flodigarriensis* horizon is normally missing in southern England, however, in some sections like that of the central Wessex Basin it may be present but overstepped by a younger *P. densicostata* horizon. Thus it may be concluded that the full succession of the *Pictonia* ammonites indicative of the lowermost part of the Baylei Zone is recognized only in some of the NW European areas as well as possibly in some adjoining areas of the Arctic (see Birkelund and Callomon, 1985). The great advantage of the Flodigarry section is that it indicates the strictly coeval position of the base of the Baylei Zone, treated as the base of the Kimmeridgian, with that of the Boreal Bauhini Zone. This fact enables correlation (and recognition) of the base of the Kimmeridgian, defined as the base of the Baylei Zone in many sections located in north-eastern parts of the Subboreal Province, and the Boreal Province (Fig. 12). Such as those of Pomerania and the Peri-Baltic Syneclise in northern Poland, the Russian Platform, northern Central Siberia, and Franz-Josef Land, as well as in cores from the Barents Sea and Norwegian Sea (see Wierzbowski A. and Smelror, 1993: Głowniak et al., 2010; Wierzbowski A. and Rogov, 2013; Wierzbowski A. and Matyja, 2014; Wierzbowski A. et al., 2015, 2016; Rogov, 2017).

The Oxfordian/Kimmeridgian boundary is well defined by the

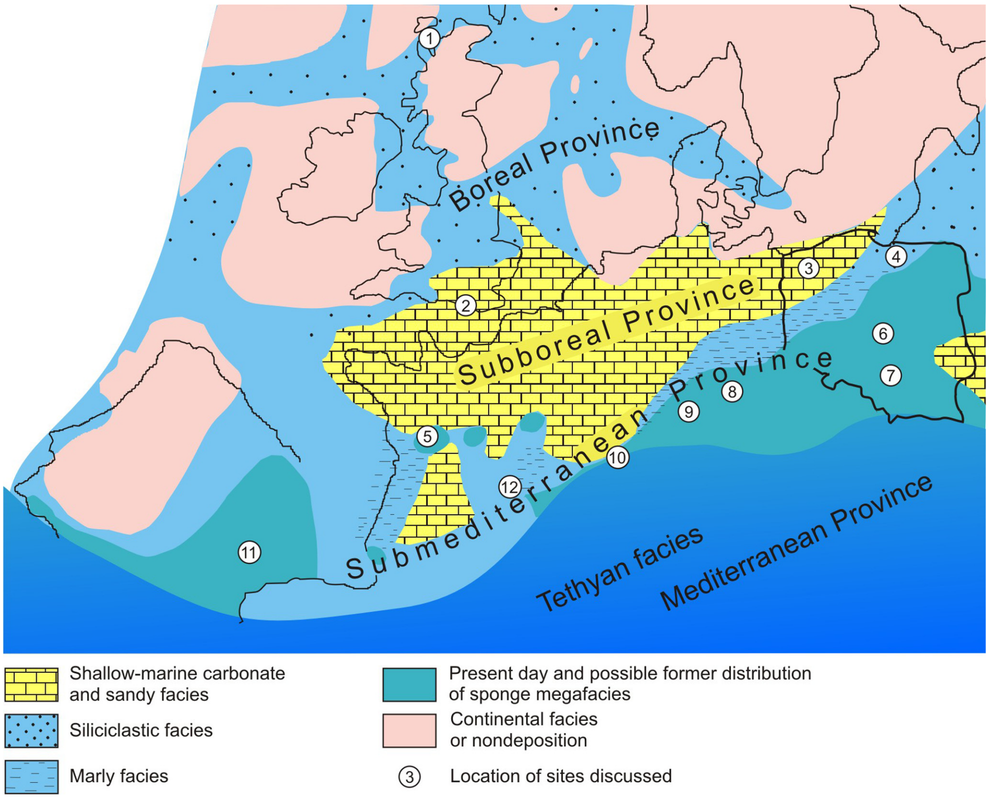

Figure 12. Location of geological sections discussed in the proposal on a palaeogeographic map of the mid to uppermost Oxfordian transition of Europe (after Wierzbowski A. et al., 2016). 1-Staffin Bay, Isle of Skye (Flodigarry section), Scotland; 2-Dorset Coast, England; 3-Pomerania, Germany-Poland; 4-Peri-Baltic Syneclise, Poland-Lithuania-Russia; 5-Poitou area, France; 6-Wieluń Upland (Katarowa Góra and Bobrowniki sections), Poland; 7-middle part of Polish Jura (Syborowa Góra to Biskupice sections), Poland; 8-Franconian Alb, Germany; 9-Swabian Alb, Germany;10-northern Switzerland Jura; 11-Pre-Betic Zone (Fuentelespino de Moya section), Spain; 12-Southeastern France.

replacement of the uppermost Oxfordian Subboreal ammonite assemblage of the Pseudocordata Zone, composed of ammonites of the genus *Ringsteadia* (M) and *Microbiplices* (m), by the new Subboreal ammonite genera of the lowermost Kimmeridgian in the Aulacostephanidae lineage. The Kimmeridgian ammonites, including the ammonites *Pictonia* (M) and *Prorasenia* (m) of the NW European and adjoining Arctic areas, have their strict equivalents in the coeval ammonites *Vineta* (M) and *Vielunia* (M), as well as *Prorasenia* (m) in NE European areas. Some of these ammonites were the basis of distinguishing the local Jaekeli Zone in the past which was originally not precisely defined (Dohm, 1925). The divergence of the Aulacostephanidae lineage into the NW European and the NE European branches was related to allopatric speciation which occurred at the Oxfordian/Kimmeridgian boundary as a consequence of the development of land-barriers separating the particular parts of the Subboreal Province (Enay, 1980; Głowniak et al., 2010; Wierzbowski A. and Matyja, 2014; Wierzbowski A. et al., 2010, 2016; Wierzbowski A., 2022, and earlier papers cited therein).

On the other hand, the assemblages of the Cardioceratidae lineage close to the Oxfordian/Kimmeridgian boundary include the ammonites of the genus *Amoeboceras* which occur throughout the Oxfordian Boreal Rosenkrantzi Zone and within the *flodigarriensis* horizon, and ammonites of the genus *Plasmatites* indicative of the Kimmeridgian Boreal Bauhini Zone. These Cardioceratidae ammonites are widely distributed all over NW and NE Europe, as well as throughout NW Asia (Siberia and the adjoining Arctic archipelagos); thus they occur both in the Boreal province, and large parts of the Subboreal province. These Boreal ammonites are also commonly encountered in some parts of the succession in central Europe together with some Subboreal ammonites (such as *Amoeboceras rosenkrantzi*, and various representatives of the genus *Plasmatites* of the family Cardioceratidae, as well as *Ringsteadia*, *Vielunia*, *Vineta*, and *Microbiplices*, *Prorasenia* of the family Aulacostephanidae) – where they co-occur with Submediterranean and Mediterranean ammonites which permits easy recognition of the Oxfordian/Kimmeridgian boundary in all these areas (Figs. 12 and 13).

These areas include central Poland (especially the Wieluń Upland of the Polish Jura), and also the Franconian Alb and the Swabian Alb in southern Germany, and the Jura Mountains in northern Switzerland. Detailed study of several sections located in these Submediterranean areas clearly indicates that the ammonites characteristic of the Subboreal Upper Oxfordian Pseudocordata Zone such as *Ringsteadia*, *Microbiplices*, and those of the Boreal Rosenkrantzi Zone such as *Amoeboceras* range up into the Submediterranean Euaspidoceras hypselum (=Hypselum) Zone. On the other hand the appearance of the Subboreal *Vielunia*, *Vineta*, *Prorasenia* of the Baylei Zone, and Boreal *Plasmatites* of the Bauhini Zone takes place in the Epipeltoceras bimammatum (=Bimmamatum) Zone (e.g., Schweigert and Callomon, 1997; Schweigert, 2000; Wierzbowski A. et al., 2010, 2016; Jantsche, 2014, and earlier papers cited therein). An example of such a study is shown in Fig. 13, where the detailed distribution of the Sub-

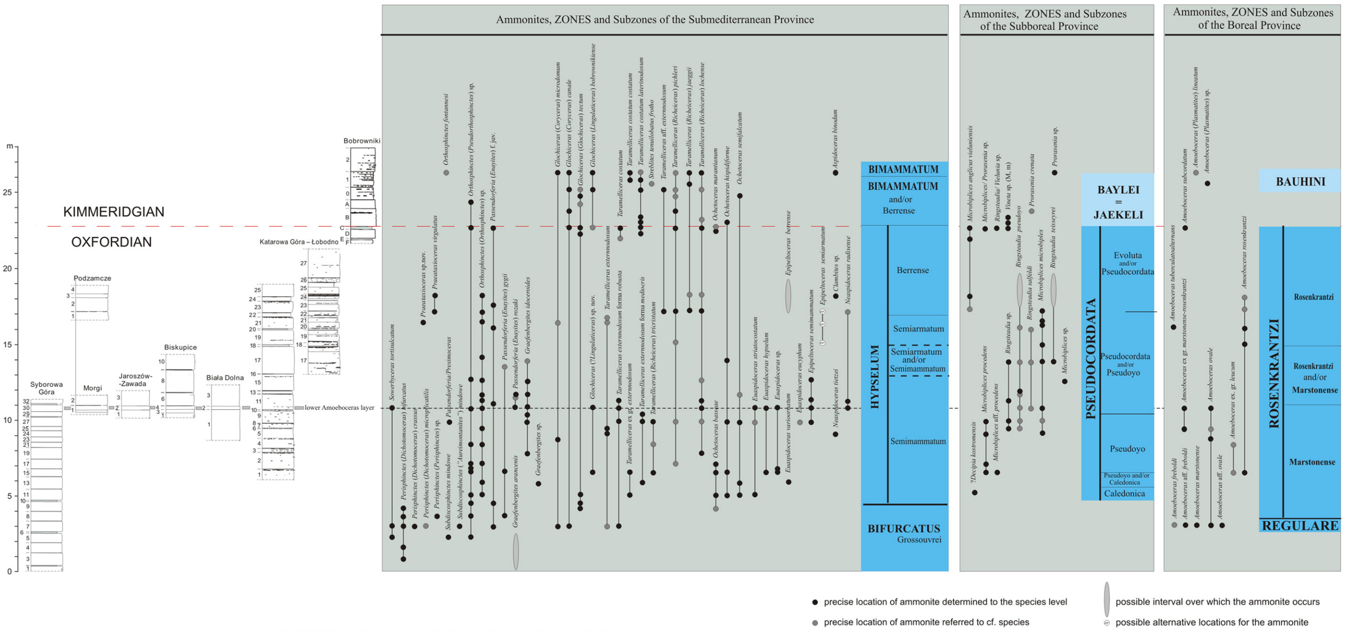

Fig. 13. Distribution of ammonites in the Polish Jura sections (central Poland) and their chronostratigraphical interpretation (after Wierzbowski A., Matyja, 2014; somewhat modified

by Wierzbowski A et al., 2016). The lower Amoeboceras level – the local reference horizon is indicated; dark blue Oxfordian, light blue Kimmeridgian (as referred to the Subboreal and Boreal successions).

Figure 13. Distribution of ammonites in the Polish Jura sections (central Poland) and their chronostratigraphic interpretation (after Wierzbowski A. and Matyja, 2014; somewhat modified by Wierzbowski A. et al., 2016). The lower Amoeboceras level – the local reference horizon is indicated; dark blue Oxfordian, light blue Kimmeridgian (as referred to the Subboreal and Boreal successions).

mediterranean, Subboreal and Boreal ammonites in the Polish Jura sections is shown (after Wierzbowski and Matyja, 2014 supplemented by Wierzbowski A. et al., 2016).

The conclusion of the studies on the ammonite assemblages in these areas (Wierzbowski A. and Matyja, 2014; Wierzbowski A. et al., 2016, and the papers cited therein) is that the boundary of the Oxfordian and Kimmeridgian (as defined on the basis of the Subboreal and Boreal succession in the Flodigarry section on the Isle of Skye at the base of the Subboreal Baylei Zone), and corresponding base of the Boreal Bauhini Zone, lies very close to the boundary between the

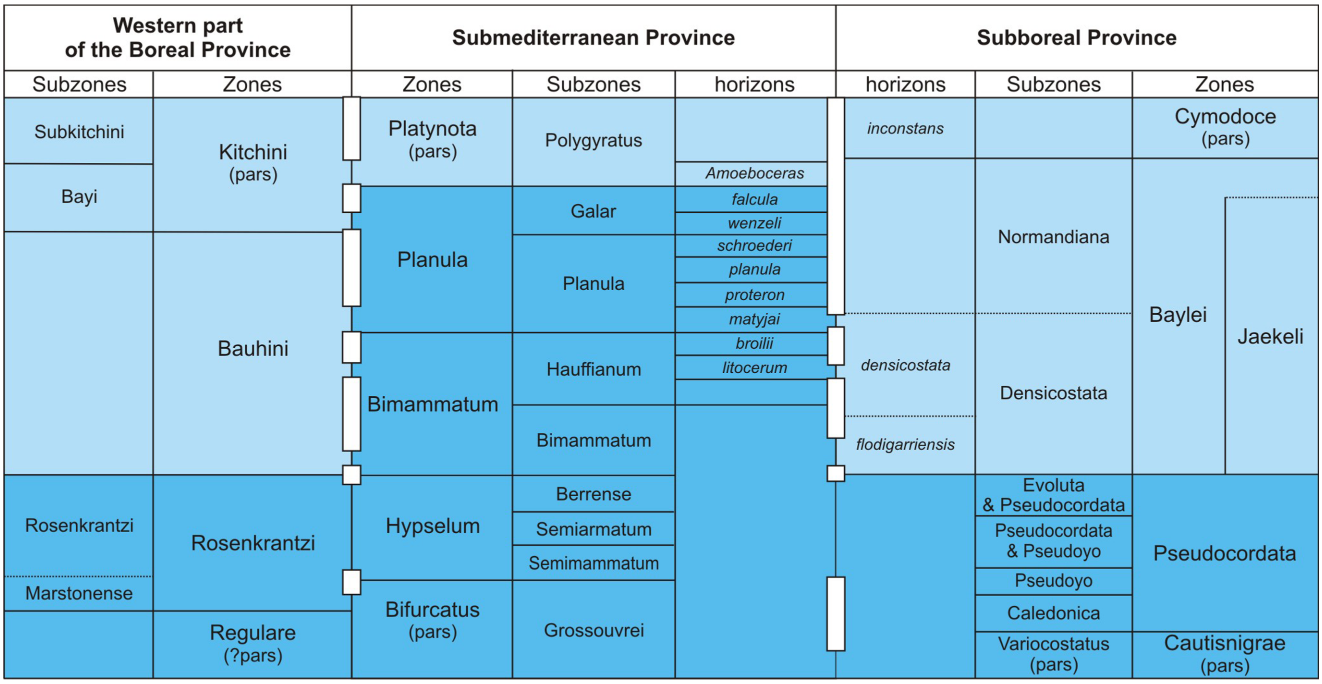

Figure 14. Correlation of the Submediterranean ammonite zonal scheme with the Subboreal and Boreal ammonite zonal schemes across the Oxfordian/Kimmeridgian boundary (after Wierzbowski A. and Matyja, 2014; slightly modified by Wierzbowski A. et al., 2016). White boxes between the zonal schemes indicate uncertain correlation.

Euaspidoceras hypselum (=Hypselum) Zone and the Epipeltoceras bimammatum (=Bimammatum) Zone (treated as independent zones and not as subzones of a more widely treated Bimammatum Zone) in the Submediterranean succession (Fig. 14). The consequence of this correlation is that both the Bimammatum Zone (as distinguished herein with the Bimammatum and Hauffianum subzones) as well as the Subnebrodites planula (=Planula) Zone, included so far into the Submediterranean Oxfordian, becomes part of the lowermost Kimmeridgian succession. This correlation is further supported by dinocysts from cores across the boundary of the Hypselum and Bimammatum ammonite zones from northern Poland. This interval yields Dinoflagellata assemblages indicative of the boundary between the dinocysts zones DSJ26 and DSJ27 (corresponding to the boundary between subzones c and d of the Scriniodinium crystallinum Zone) which correlates with the basal part of the Subboreal Kimmeridgian (Barski et al., 2005).

The placement of the Oxfordian/Kimmeridgian boundary close to the boundary between the Hypselum Zone and the Bimammatum Zone in the Submediterranean-Mediterranean successions has wide biostratigraphic correlation potential because of coeval changes in the associated ammonite faunas (see Wierzbowski A. et al., 2016 where the details on the ammonite distribution which is based for example on newly studied sections from southeastern France and southern Spain (Fuentelspino de Moya section) are given (Fig. 12)). The assemblage of ammonites of Aspidoceratidae composed mostly of *Euaspidoceras – Neaspidoceras* typical of the Hypselum Zone (uppermost Oxfordian) is successively replaced near the boundary with the Bimammatum Zone (lowermost Kimmeridgian) by a new assemblage composed of *Clambites*, and then by *Aspidoceras* and *Physodoceras.* The changes are noted also in other ammonite groups such as Oppeliidae (e.g., appearance of the *Taramelliceras costatum* group) and Passendorferiinae. These changes in the ammonite faunas also make it possible to recognise the Oxfordian/Kimmeridgian boundary in other Tethyan and Indo-Pacific areas, including the central part of the Americas, South America and southern part of Asia (Wierzbowski A. et al., 2016).

Correlation to the Seafloor M-sequence Anomalies

The pattern of sea floor magnetic anomalies in the Pacific has been the principal source of data to define a geomagnetic polarity timescale (GPTS) through the Late Jurassic (Larson and Hilde, 1975; Channell et al., 1995; Tominaga and Sager, 2010; Malinverno et al., 2012). Older approaches have tended to use single or limited profiles (Channell et al., 1995, 2010), whereas more inclusive approaches have compiled multiple profiles to remove 'anomaly-noise' and build more representative anomaly patterns and block models (Tominaga and Sager, 2010; Malinverno et al., 2012). However, the precise pattern and duration of inferred reversals still has remaining uncertainty, particularly before anomaly M24 (Tominaga and Sager, 2010) where anomaly amplitude decreases and dissimilarity between block-models increase (Fig. 15). The key M-sequence anomaly data for the Kimmeridgian is from the analysis of Tominaga and Sager (2010), based on a composite averaging of many profiles from the Hawaiian, Japanese and Phoenix sea floor segments in the western Pacific. A remaining unresolved difficulty with anomalies prior to M24 is distinguishing real magnetic field reversals from magnetic field intensity variations in the low amplitude anomaly profiles. The seafloor-based geomagnetic polarity-timescales (GPTS) are also hampered by limited direct radio-isotopic age calibration points (only two were used by Tominaga and Sager (2010); 125.0 Ma for anomaly M0 and 155.3 Ma for mid anomaly M26), although other studies have used a slightly wider range of constraints (Malinverno et al., 2012; Ogg, 2012). In Gradstein et al. (2020), the age scale for the Late Jurassic portion of the composite Hawaiian-Japanese M-sequence pattern is largely an estimate based on applying a minor linear increase in spreading rate between; (1) a U-Pb date of 168.7±1.7 Ma on oceanic basalts at ODP Site 801 drilled on marine anomaly M42n (~Bajocian-Bathonian boundary) (Koppers et al., 2003), and (2) an estimated age for the base of the Tithonian, relative to the base of the Aptian, derived from a synthesis of cyclostratigraphic studies spanning the Tithonian through Barremian (Gale et al., 2020).

To evaluate where the base Kimmeridgian may be in the sea-floor anomaly pattern we first used quantitative polarity correlation modeling (Lallier et al., 2013), and secondly, evaluated the two best fitting polarity models to the Kimmeridgian sea floor durations, based on independent dating tools.

We started by correlating the Oxfordian-Kimmeridgian boundary interval portion of the Subboreal polarity composite (Fig. 10) independently to the Hawaiian, Japanese, Phoenix and composite block models of Tominaga and Sager (2010) as shown in Fig. 15. The quantitative method of Lallier et al. (2013) rates various correlation models (out of all possible correlations) with a 'cost', which is based around minimizing the local variation of accumulation (spreading rate for anomalies). The models with the least cost are the better correlations with this method. Since the method handles possible missing magnetozones in the section data, we used a 'gap' parameter of -2, which eliminates correlation models with unrealistically large numbers of missing magnetozones (but some models may still retain missing magnetozones). For example, it is possible that magnetozones may be missing from the lower part of the Subboreal composite (magnetozone F1r at Flodigarry), where sampling density was reduced (Fig. 10). For each of the four Tominaga and Sager (2010) polarity block models (anomaly segments shown in Fig. 15), we considered only the first three correlation models with the lowest cost. This was done for two scenarios, firstly excluding tentative submagnetozone BB4r, and then including BB4r, which gives 12 correlation models with the lowest cost, for each of the two scenarios. These 24 correlation models give seven possible options for the correlation of BB3r with the anomaly patterns, which are tallied in the top panel of Fig. 16a. A larger total tally for a particular anomaly implies a more favored overall correlation option; which in this case indicates anomaly M25r ranks highest (correlation option-A, with 9 out of 24 models with the lowest costs; Fig. 16a). Option-A correlation to the base of the Kimmeridgian is similar to that proposed by Muttoni et al. (2018). The average number of missing anomalies is also shown in the lower panel of Fig. 16a. The raw-cost estimates cannot be directly compared between BB4r-present and BB4r-absent scenarios, so the raw-costs are normalized by the mean-cost in each of the 12 sets of models for each scenario. Thus, allowing the normalized-costs to be compared between the two scenarios. Comparing the mean normalized-cost suggests anomaly M26r is most favored (correlation option–B, blue column in Fig. 16a), but with only 2 out of the 24 models having the least cost. Option-A with M25r is the 2nd least costly (mean normalised cost; blue column

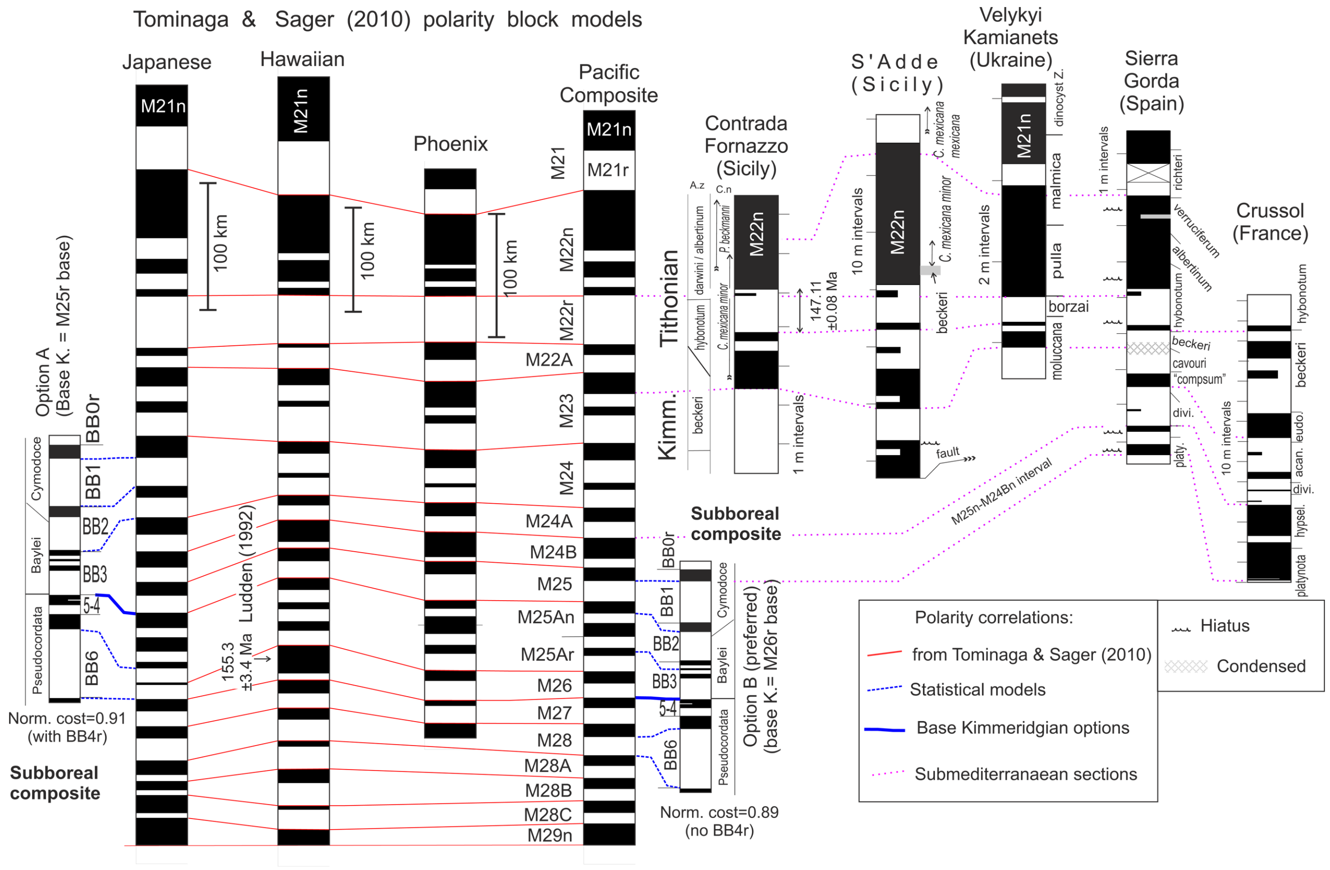

Figure 15. The two options (A and B) for correlation of the magnetostratigraphy from the Subboreal composite to the seafloor magnetic anomalies of Tominaga and Sager (2010). The Pseudocordata/Baylei ammonite zone boundary equates to the Oxfordian/Kimmeridgian boundary GSSP. Radio-isotopic dates are shown with an arrow (see text for details and references). Contrada Fornazzo data from Pavia et al. (2004) (sloping boundary indicates where only a single ammonite mold was recovered); upper part of S'Adde data from Muttoni et al. (2018); Velykyi Kamianets from Grabowski et al. (2019); Sierra Gorda from Ogg et al. (1984); Crussol from Przybylski et al. (2010b) with upward extension through Beckeri and lower Hybonotum zones from Ogg, Coe and Atrops (unpublished; data available at https://www.eaps.purdue.edu/paleomag/download.htm). Mauve dotted correlation lines from the Submediterranean sections are tentative, and are based primarily on visual comparison to the Hawaiian block model. The Divisum Zone in the Crussol reference section is relatively condensed; and an upper portion of the Platynota Zone probably correlates to the lower portion of the Cymodoce Zone of the Subboreal realm through the magnetozone M25n-M24B interval. A.z = ammonite zone, C.n = Calcareous nannofossils. The two correlation models shown are those individual option-A and option-B models with the minimum cost in these two solutions (Norm. cost = normalized cost of best individual model).

in Fig. 16a).

As a result of the issues with the pre-M25 anomaly data, land-based studies of the early-mid Kimmeridgian may hold better promise for constructing a detailed GPTS for this stage interval, and also separating true reversals from paleointensity changes. Option-B is that suggested by Przybylski et al. (2010a, b), Ogg (2012) and Ogg et al., (2012) based on visual pattern-matching of a compilation of over a dozen ammonite-zoned Late Jurassic magnetostratigraphic sections to the Hawaiian polarity block model (with partial guidance from cyclostratigraphy-derived durations of polarity zones). This was also the solution used in Gradstein et al. (2020) for the base of the Kimmeridgian. A representative subset of section data are in Fig. 15, focusing on studies across the Tithonian–Kimmeridgian boundary (Ogg et al., 1984; Muttoni et al., 2018; Grabowski et al., 2019). Statistical correlation Option B is supported by the correlation of the normal-polarity-dominated interval of the Platynota Zone and overlying Hypselocycum Zone, to the normal-polarity-dominated interval M25n-M24Bn. This constrains the reversed-polarity interval of the lowermost Cymodoce Zone to correlate to anomaly M25r, rather than the younger M24r suggested by Option A.

In addition out of all 24 statistical models, Option-B gives the lowest normalized cost (0.89) of any single model, compared to the lowest cost of 0.91 for any single model using Option-A (Fig. 15). For both options A or B, the least costly single-correlation-model is with the Japanese anomaly set alone, rather than the composite. The joint-indication from the two statistical selectors suggests that option-A is perhaps the more likely, and option B less so, but this is just in terms of overall statistical similarity of polarity successions (largest number of model matches; Fig. 16a).

An $^{40}Ar/^{39}Ar$ date of 155. 3±3.4 Ma (1σ) of celadonite veins cored directly from late in sea-floor anomaly M26 (Ludden, 1992), seems rather more consistent with Option-A considering the Re/Os date of 154.1±1.1 Ma (1σ) from Flodigarry, although the large confidence intervals on both make this distinction unclear.

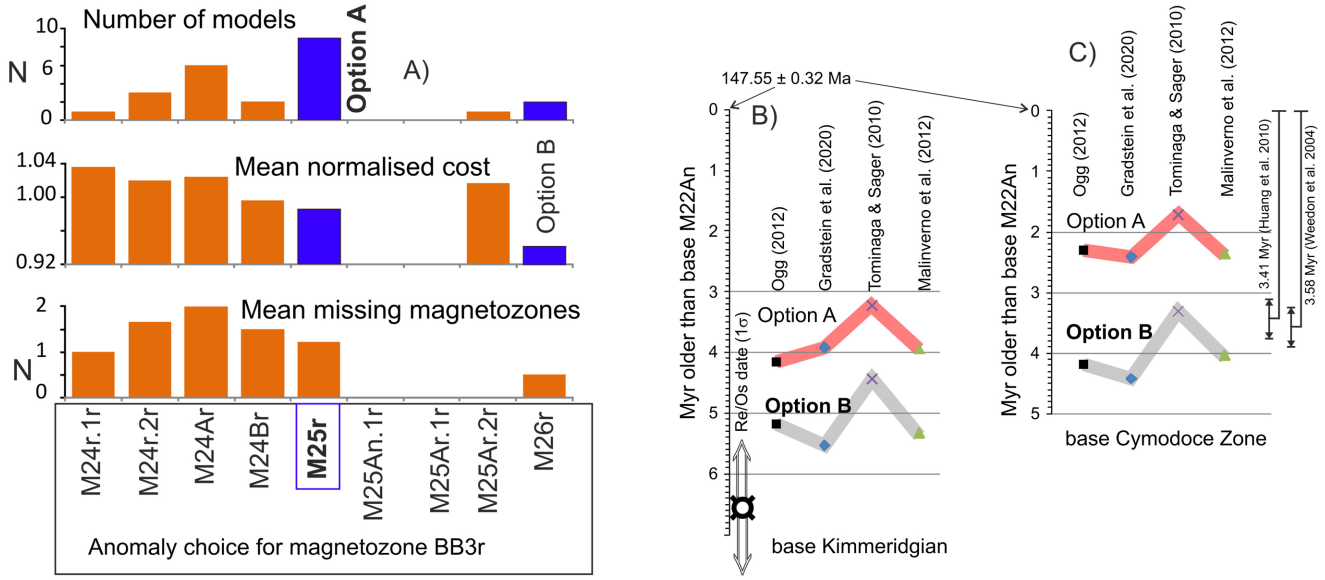

Figure 16. A) Data from statistical correlation of the Subboreal composite to the four sea-floor anomaly block models of Tominaga and Sager (2010), using the method Lallier et al. (2013). The data displays 24 correlation models, the three lowest cost models for each of the four block models in Fig. 15, using the Subboreal composite with and without the presence of the tentative magnetozone BB4r at Flodigarry (Fig. 10). The top panel of A) shows the number of correlation models which equate BB3r to the corresponding anomaly shown at the base. The middle panel shows the mean normalized cost of the N-respective models in the top panel. The bottom panel shows the mean number of missing magnetozones in the respective correlation models. B) Duration from the base of M22An to the base of the Kimmeridgian, using the two correlation options A and B, and the respective age models of magnetic anomaly durations (data for Gradstein et al. (2020) was taken from Timescale Creator v.8). The position of the Re/Os age at Flodigarry and its 1σ range is shown based on the estimated M22An age of 147.55 Ma and the average duration from mid M22r to base of M22An. C) Duration from the base of M22An to the base of the Cymodoce Zone (mid BB2n) using the two correlation options, and the respective age models of magnetic anomaly ages. Also shown (as arrows with 1σ confidence) are the cyclostratigraphic durations from the base of the Tithonian to the base of the Cymodoce Zone (from table 1 in Huang et al., 2010).

We also evaluated which one of these two models best-fitted the likely age duration of the Kimmeridgian. The position of the base of the Tithonian is currently undecided; but most place this at the base of the Hybonoticeras hybonotum (=Hybonotum) Zone. Based on ammonoid and magnetostratigraphic data section from Spanish sections (Ogg et al., 1984), and unpublished data from Crussol and the Kimmeridge Clay sections (Ogg, Coe, Przybylski, Atrops), a proxy used here for the Kimmeridgian-Tithonian boundary is the base of anomaly M22An (as in Ogg, 2012; Ogg et al., 2012; Casellato and Erba, 2020). However, this position is not universally accepted, with some placing the base Tithonian within the older M23n (Pavia et al., 2004; as shown in Fig. 15), or younger within the lower part or base of M22n (Muttoni et al., 2018; Grabowski et al., 2019).

A U-Pb date on ash bed LY-5 (147.112 ±0.078 Ma) from the Tordillo Formation (Aguirre-Urreta et al., 2019; Lena et al., 2019), most likely corresponds to a part of anomaly M22r (Martínez et al., 2018) within the lowest Tithonian (Lena et al., 2019) (Fig. 15).

Using the base of M22An as a proxy for the base of the Tithonian and four age models of the anomaly pattern (Tominaga and Sager, 2010; Malinverno et al., 2012; Ogg, 2012; Gradstein et al., 2020), we can estimate the duration of the Kimmeridgian based on the Option A and Option B correlation models. These four anomaly-age models give a mean duration from mid M22r to the base of M22An of 0.45±0.01 Myr, (1*σ*), which when combined with the correlations options provide an estimate of Kimmeridgian durations shown in Fig. 16b. Using the date on ash bed LY-5 an independent mean age estimate for the base of M22An is 147.55 Ma (±0.32 Ma, 1σ uncertainty from M22r duration and LY-5 placement in M22r). This age difference from the Re/Os date of 154.1±1.1 Ma (1σ) from Flodigarry indicates the base Kimmeridgian is ca. 6.55 Myr older than the base of M22An, suggesting that Option B fits these estimates better (Fig. 16b).

Lastly, cyclostratigraphic constraints from time-series analysis for the duration from the base of the Tithonian (Pectinatites elegans ammonite Zone) to base Cymodoce Zone, suggests a minimum duration of 3.58 or 3.41 Myr for this interval (Weedon et al., 2004; Huang et al., 2010). Option A and Option B place the base of the Cymodoce Zone at around M24r.1n and M25An.1n respectively (Fig. 15). Both cyclostratigraphic durations (with uncertainty derived from the estimated age of M22An) for this interval are more compatible with Option B and less compatible with the Option A correlation (Fig. 16c). Using the Option B correlation, mean durations (from anomaly models) and an anchor to ash bed LY-5, provides an independent age estimate of the base of the Kimmeridgian of 152.22±0.32 Ma (1σ). This is within the 2σ confidence interval (151.9 to 156.3 Ma) on the Re/Os data from Flodigarry. However, these age and duration estimates are strongly dependent on the correct placement of the base of the Tithonian and placement of LY-5 in the anomaly pattern. If the base Tithonian were near the base of M22n, the same duration-based arguments would tend to support Option-A instead.

Therefore the statistical correlation models and the Kimmeridgian duration estimates give somewhat conflicting conclusions. Using durations and the Submediterranean magnetostratigraphic data, suggests the base of the Kimmeridgian is near the base of M26r, but alternatively the statistical models suggest near the base of M25r if the base of the Tithonian were near the base of M22n. A definitive correlation to the M-sequence marine magnetic anomalies awaits an improved interpretation of the pre-M24 anomaly pattern, better anomaly dating and future verification of the full late Oxfordian-Kimmeridgian-early Tithonian magnetic polarity pattern from land-based studies.

Climate and Relative Sea-level Change

General changes in climatic and environmental conditions across the Oxfordian/Kimmeridgian boundary transition have been the subject of several palaeontological and geochemical studies and are summarized by Wierzbowski A. et al. (2016). The comments below mostly relate to the European areas.

Abbink et al. (2001) analyzed the sporomorph assemblages from boreholes in the southern North Sea and identified a general trend of aridification and warming of the climate, which began in the mid Oxfordian and was briefly interrupted in the latest Oxfordian interval by a cooling. Abbink et al. (2001) inferred that the cooling is pronounced during the Boreal late Regulare and Rosenkrantzi chrons (i.e., the Subboreal Pseudocordata Chron) of the latest Oxfordian and was followed by warming near the Oxfordian/Kimmeridgian boundary. This climatic change is supported by changes in the composition of the ammonite faunas in the Subboreal and northern Submediterranean areas (such as the Peri-Baltic Syneclise (northern Poland), and Polish Jura (central Poland)), with the more common occurrence of the cooler Boreal elements during the latest Oxfordian, and a marked increase in Subboreal and Submediterranean elements during the earliest Kimmeridgian (Wierzbowski A. et al., 2016, also Wierzbowski A. and Matyja, 2014; Wierzbowski A. et al., 2015).

The uppermost Oxfordian–lowermost Kimmeridgian overall decrease in $\delta^{18}O$ values of belemnite rostra and brachiopod shells observed in the Boreal, Subboreal and Submediterranean province is interpreted as a temperature rise and/or freshening of local seawater (Nunn et al., 2009; Wierzbowski H. et al., 2013, 2018; Wierzbowski H., 2015; see also Wierzbowski A. et al., 2016). Scattered $\delta^{18}O$ values in the latest Oxfordian may, however, suggest unstable environmental conditions at that time in the Polish areas. This is in agreement with palaeontological data from the Wieluń Upland (central Poland), which shows marked fluctuations in the ammonite assemblages which are composed of various proportions of Boreal, Subboreal and Submediterranean-Mediterranean ammonites and radiolarians (see Wierzbowski A. et al., 2016, figs 9-10). A rise in global temperature would have also driven a rise in eustatic sea-level. This fits with sedimentological evidence for an overall increase in relative sea-level in the latest Oxfordian and earliest Kimmeridgian at Flodigarry and in Dorset (Coe, 1995). At Ringstead Bay and Black Head, Dorset and South Ferriby, Humberside the interval either side of the correlated base Kimmeridgian is condensed as shown by several lines of evidence including abundant fauna, phosphate nodules, boring and encrustation (Coe, 1995; Wright, 2003; Williams, 2003; Cox, 2001b). The boundary at these locations is interpreted as a maximum flooding surface. This interpretation is further supported by the magnetostratigraphy at these locations (Fig. 10) and the absence of the *P. flodigarriensis* horizon in Dorset, but its possible presence in other areas of the Wessex Basin as described earlier in Biostratigraphic Correlations. In the Peri-Baltic Syneclise of north-eastern Poland (Wierzbowski et al., 2015, fig. 15) and at Bobrowniki in the Wieluń Upland of central Poland (Wierzbowski et al., 2016, fig. 6, reproduced here as Fig. 13) the correlated base of the Kimmeridgian, recognized on the basis of ammonites, is also interpreted as a maximum flooding surface. In the Swiss Jura the new ammonite correlation of the Oxfordian-Kimmeridgian within the Submediterranean-Mediterranean Province (Fig. 14) indicates that the boundary is likely to lie near the base of the highstand systems tract immediately overlying the Effingen Member (Gygi et al., 1998). This highstand systems tract also marks a longer-term change to widespread carbonate platforms in the Jura, Pomerania of northern Germany and north-western Poland, as well as a marked progradation of carbonate platforms in central Poland (Gygi et al., 1998; Wierzbowski A. et al., 2015, 2016 and references therein). The coincidence of the stratigraphical level of the Kimmeridgian GSSP in the lowermost part of a highstand systems tract places it in the most ideal position sequence stratigraphically for ensuring both completeness of the marine stratigraphic record and global correlation.

The presence of an interval with low $\delta^{13}C$ values in the uppermost Oxfordian and lowermost Kimmeridgian in the Flodigarry section (Fig. 11; Nunn et al., 2009; Wierzbowski H. et al., 2013; Wierzbowski H., 2015) may be linked to the influx of organic carbon from deep oceanic and/or terrestrial sources. It could indicate a higher level of nutrients in seawater and a well-mixed state of the water column. High productivity of marine basins may be related to the configuration of ocean currents which brought nutrient-rich waters and caused radiolarian blooms (cf. Wierzbowski A. et al., 2016). The blooms of charophytic algae directly above the Oxfordian/Kimmeridgian boundary in the Flodigarry section in Scotland are also inferred to be associated with the increased eutrophication (Barski, 2018). The correlation between the negative shift shown in $\delta^{13}C_{organic}$ in the Staffin Bay sections in Scotland (Nunn et al., 2009) and the $\delta^{13}C_{carbonate}$ values from the Submediterranean Province (Wierzbowski H., 2015) suggest that the observed variations represent NW European and possibly global phenomena.

Summary

The base of the Kimmeridgian is placed at the stratigraphic level of the first appearance of the Subboreal ammonite taxa that define the *P. flodigarriensis* horizon, namely *Pictonia flodigarriensis, Prorasenia bowerbanki and Pictonia (Triozites)* at 1.25 ±0.01 m below the top of Bed 35 in section F6 at Flodigarry, Isle of Skye, Scotland (NG 4687 7140). Furthermore, this level and location was agreed as a Global Stratotype Section and Point because of the co-existence of ammonite faunas (in roughly equal numbers) from two provinces as demonstrated by the observation that the base of the *P. flodigarriensis* horizon is within 0.09 m of the first occurrence of Boreal genus *Plasmatites*. This level also marks a transition in other Boreal and Subboreal ammonite species (Fig. 17). Further secondary markers are the lower part of reversed-polarity magnetozone F3r (probably marine magnetic anomaly M26r or possibly M25r), the base of dinoflagellate cyst zone DSJ 27, a broad minimum in $\delta^{13}C$ averaging 1.5 per mil VPDB, the calculated Sr isotope value of 0.70687 and a Re-Os age of 154.1 ±2.2 Ma (2σ) (Fig. 16).

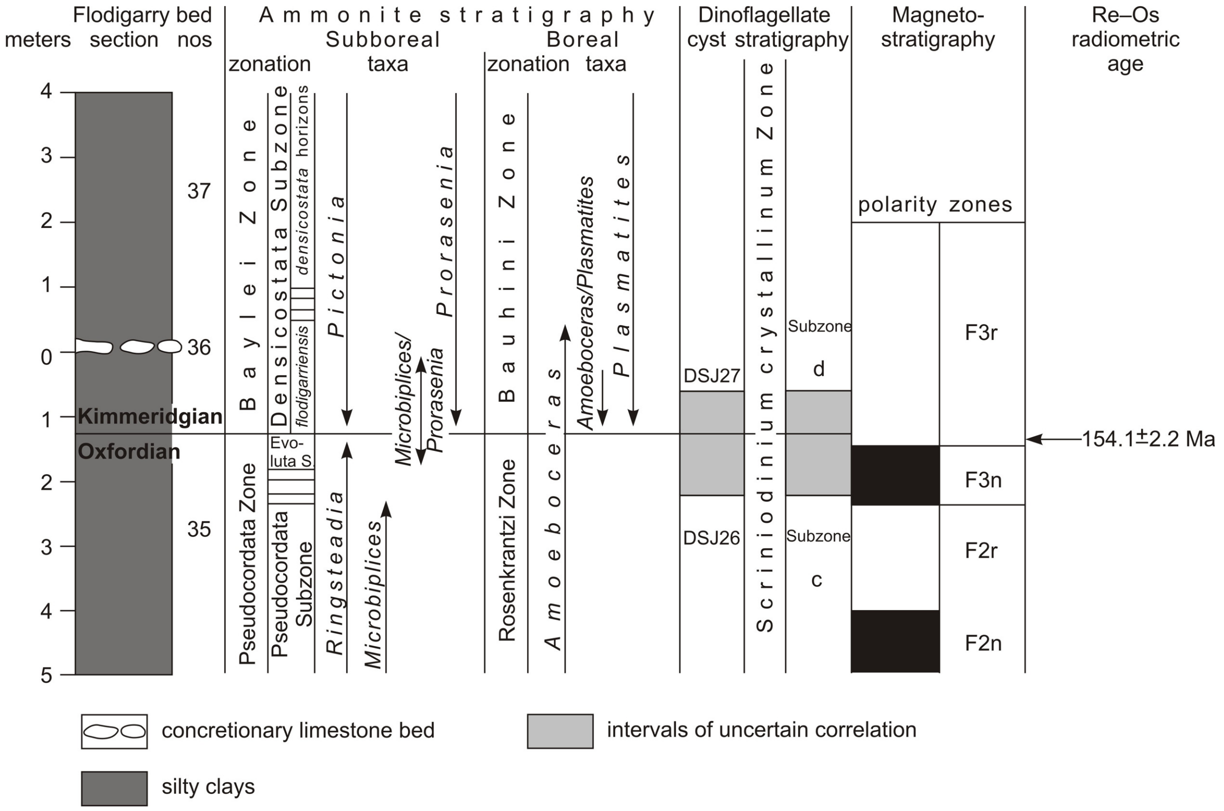

Figure 17. Summary diagram of the biostratigraphic and magnetostratigraphic criteria for placing the Oxfordian/Kimmeridgian boundary in the Flodigarry section, Staffin Bay, Isle of Skye (from the left): ammonite stratigraphy – Subboreal and Boreal zonations (ranges of the genus rank taxa are only indicated – after Matyja et al., 2006; Wierzbowski A., et al. 2018); dinoflagellate cyst stratigraphy (after Barski, 2018); magnetostratigraphy (after Hounslow in Wierzbowski A. et al., 2018, and new data herein). The position of the samples for the Re-Os radioisotopic age (after Selby, 2007) are also shown. The boundary is interpreted to be within the lower part of a highstand systems tract.

The base of the Subboreal Baylei Zone (placed at the base of the *Pictonia flodigarriensis* horizon) and the corresponding base of the Boreal Bauhini Zone, as defined at the Flodigarry section, is correlated with a narrow stratigraphic interval at the boundary of the Hypselum and Bimammatum ammonite zones of the Submediterranean-Mediterranean successions. This ammonite correlation together with the secondary markers provides a multi-stratigraphical, global correlation basis for the base of the Kimmeridgian.

Future Work

This study demonstrates the Kimmeridgian GSSP has the potential for a wide range of further stratigraphic studies including:

1. Foraminifers and radiolarians
2. High stratigraphic resolution studies of calcareous nannofossils and palynomorphs.
3. Other macrofossil groups which may be important for stratigraphy (belemnites), and for reconstruction of the environment (bivalves, gastropods, brachiopods, trace fossils);
4. Geochemical studies including elemental concentrations and radiogenic isotope tracers such as rhenium, molybdenum, uranium across the boundary interval and organic geochemistry of the uppermost Oxfordian to complement previous studies.

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