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Towards a consistent Oxfordian/Kimmeridgian global boundary: current state of knowledge

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Abstract. New data are presented in relation to the worldwide definition of the Oxfordian/Kimmeridgian boundary, *i.e.* the base of the Kimmeridgian Stage. This data, mostly acquired in the past decade, supports the 2006 proposal to make the uniform boundary of the stages in the Flodigarry section at Staffin Bay on the Isle of Skye, northern Scotland.

This boundary is based on the Subboreal-Boreal ammonite successions, and it is distinguished by the *Pictonia flodigarriensis* horizon at the base of the Subboreal Baylei Zone, and which corresponds precisely to the base of the Boreal Bauhini Zone. The boundary lies in the 0.16 m interval (1.24–1.08 m) below bed 36 in sections F6 at Flodigarry and it is thus proposed as the GSSP for the Oxfordian/Kimmeridgian boundary. This boundary is recognized also by other stratigraphical data – palaeontological, geochemical and palaeomagnetic (including its well documented position close to the boundary between magnetozones F3n, and F3r which is placed in the 0.20 m interval – 1.28 m to 1.48 m below bed 36 – the latter corresponding to marine magnetic anomaly M26r).

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The boundary is clearly recognizable also in other sections of the Subboreal and Boreal areas discussed in the study, including southern England, Pomerania and the Peri-Baltic Syneclise, Russian Platform, Northern Central Siberia, Franz-Josef Land, Barents Sea and Norwegian Sea. It can be recognized also in the Submediterranean-Mediterranean areas of Europe and Asia where it correlates with the boundary between the Hypselum and the Bimmamatum ammonite zones. The changes in ammonite faunas at the boundary of these ammonite zones – mostly of ammonites of the families Aspidoceratidae and Oppeliidae – also enables the recognition of the boundary in the Tethyan and Indo-Pacific areas – such as the central part of the Americas (Cuba, Mexico), southern America, and southern parts of Asia. The climatic and environmental changes near to the Oxfordian/Kimmeridgian boundary discussed in the study relate mostly to the European areas. They show that very unstable environments at the end of the Oxfordian were subsequently replaced by more stable conditions representing a generally warming trend during the earliest Kimmeridgian. The definition of the boundary between the Oxfordian and Kimmeridgian as given in this study results in its wide correlation potential and means that it can be recognized in the different marine successions of the World.

INTRODUCTION

Since the publication of the original proposal for the recognition of the Global Stratotype Section and Point (GSSP) of the base of the Kimmeridgian Stage at the Flodigarry section, Staffin Bay, Isle of Skye, northern Scotland (Matyja *et al.*, 2006; Wierzbowski A. *et al.*, 2006), several years have passed and new data related to that boundary and its correlation potential have appeared. These new data, partly published, but partly announced only as oral presentations during scientific meetings – mostly the 8th Jurassic Congress in Sichuan, China, August 2010, the 1st International Congress on Stratigraphy, Lisbon, July 2013, the 9th Jurassic Congress in Jaipur, India, January 2014, the Meeting of the Kimmeridgian Working Group in Warsaw, Poland, May 2015, and the 2nd International Congress on Stratigraphy, Graz, July 2015 – are summarized below. This work represents progress in knowledge since 2006 in relation to the definition of the Oxfordian/Kimmeridgian boundary, as outlined by the Convenor of the Kimmeridgian Working Group during the Meeting of the Kimmeridgian Working Group in Warsaw, Poland, May 2015, and supplemented and/or commented on by the members the Group in order to provide herein a full basis for voting and a final decision on the matter of the boundary in question.

It should be noted that the base of the Kimmeridgian Stage as defined by Salfeld (1913) is situated at the base of the Kimmeridge Clay Formation at Ringstead Bay, Dorset. It was established on the lineage of the ammonite family Aulacostephanidae, at the level where an older genus *Ringsteadia* was replaced by a younger genus *Pictonia*. This definition produced, however, serious stratigraphical uncertainties which were related to:

(1) Difficulties of stratigraphical correlations because of the limited palaeogeographical distribution of ammonites of the family Aulacostephanidae which are considered as typical of the relatively small Subboreal Province of northern Europe, as well as their marked spatial differentiation (see *e.g.* Sykes and Callomon, 1979; Wierzbowski A., 2010a);

(2) The generally poor knowledge on the phylogenetical transition between the genera *Ringsteadia* and *Pictonia* in the Dorset coast sections as a consequence of a stratigraphical gap at the base of the Kimmeridge Clay Formation (see *e.g.* Matyja *et al.*, 2006; Wright, 2010, text-fig. 8).

The first resulted in the erroneous correlation between the Subboreal succession of NW Europe and the Submediterranean–Mediterranean successions of central and southern Europe in the past (see Arkell, 1956, and earlier papers cited therein – especially Dieterich, 1940). In consequence, the Oxfordian/Kimmeridgian boundary has been placed at two non-isochronous levels in different areas of Europe: one at the boundary of the Pseudocordata Zone (defined by occurrence of the genus *Ringsteadia*) and the Baylei Zone (defined by occurrence of the genus *Pictonia*) in the Subboreal Province, and another at the boundary of the Planula Zone, and the Platynota Zone (or the Silenum Zone) in the Submediterrananean–Mediterranean provinces. The latter is now known to be about two ammonite zones higher (and about 1.5 Myr younger) than the Subboreal Standard (see Ogg and Hinnov, 2012; see also Schweigert and Callomon, 1997; Matyja and Wierzbowski A., 1997; Matyja *et al.*, 2006; Wierzbowski A. *et al.*, 2006; Wierzbowski A. and Matyja, 2014a,b, and other papers cited therein).

The second resulted in generally poor knowledge of the Aulacostephanidae lineage at the transition from the genus *Ringsteadia* to the genus *Pictonia*, which appeared especially troublesome for detailed stratigraphical correlations in this stratigraphical interval. In addition there is an almost total absence of any other ammonites (especially of the family Cardioceratidae) in the Dorset coast sections of southern England.

Studies undertaken at the Flodigarry section at Staffin Bay on the Isle of Skye, northern Scotland (Figs 1–2) demonstrated a continuous succession of Subboreal ammonites across the Oxfordian/Kimmeridgian boundary and revealed the presence of a new assemblage of ammonites, referred to the new species *Pictonia flodigarriensis* Matyja, Wierzbowski et Wright which fills the stratigraphical gap in the am-

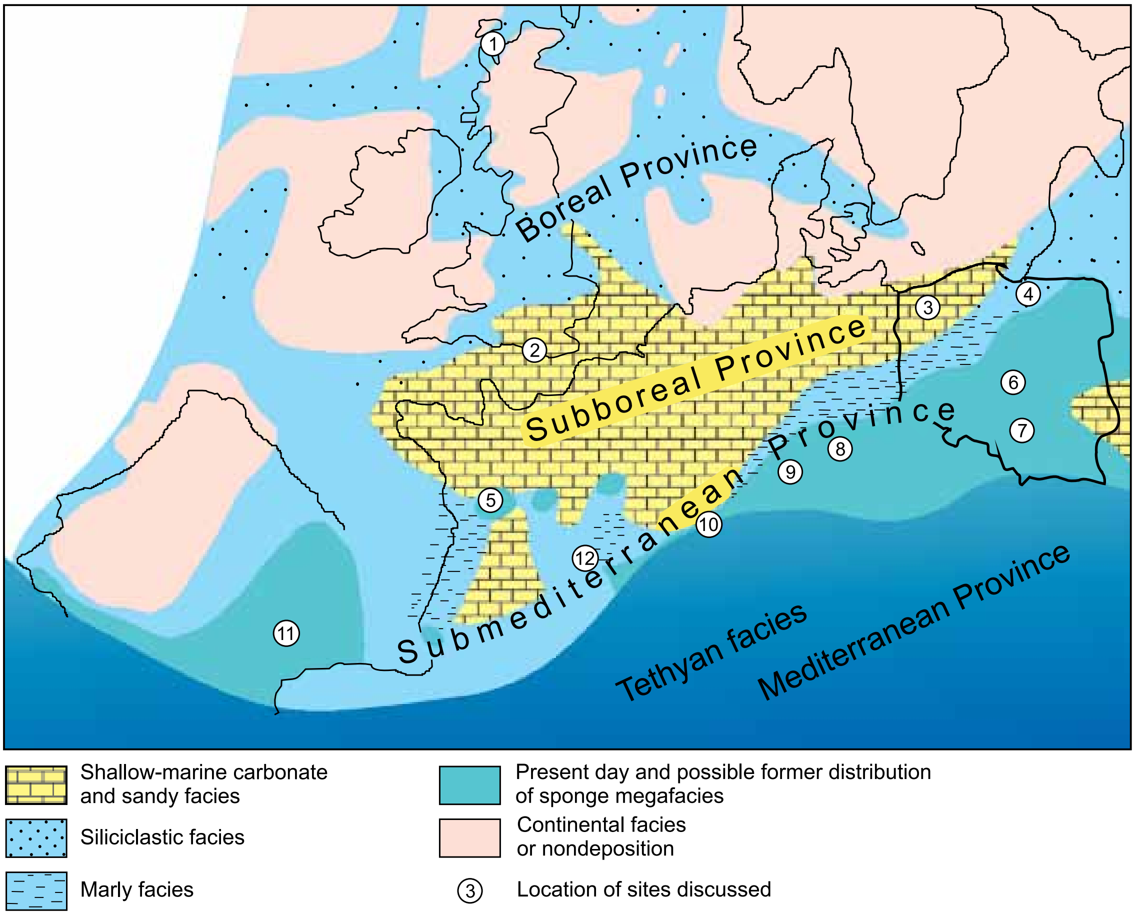
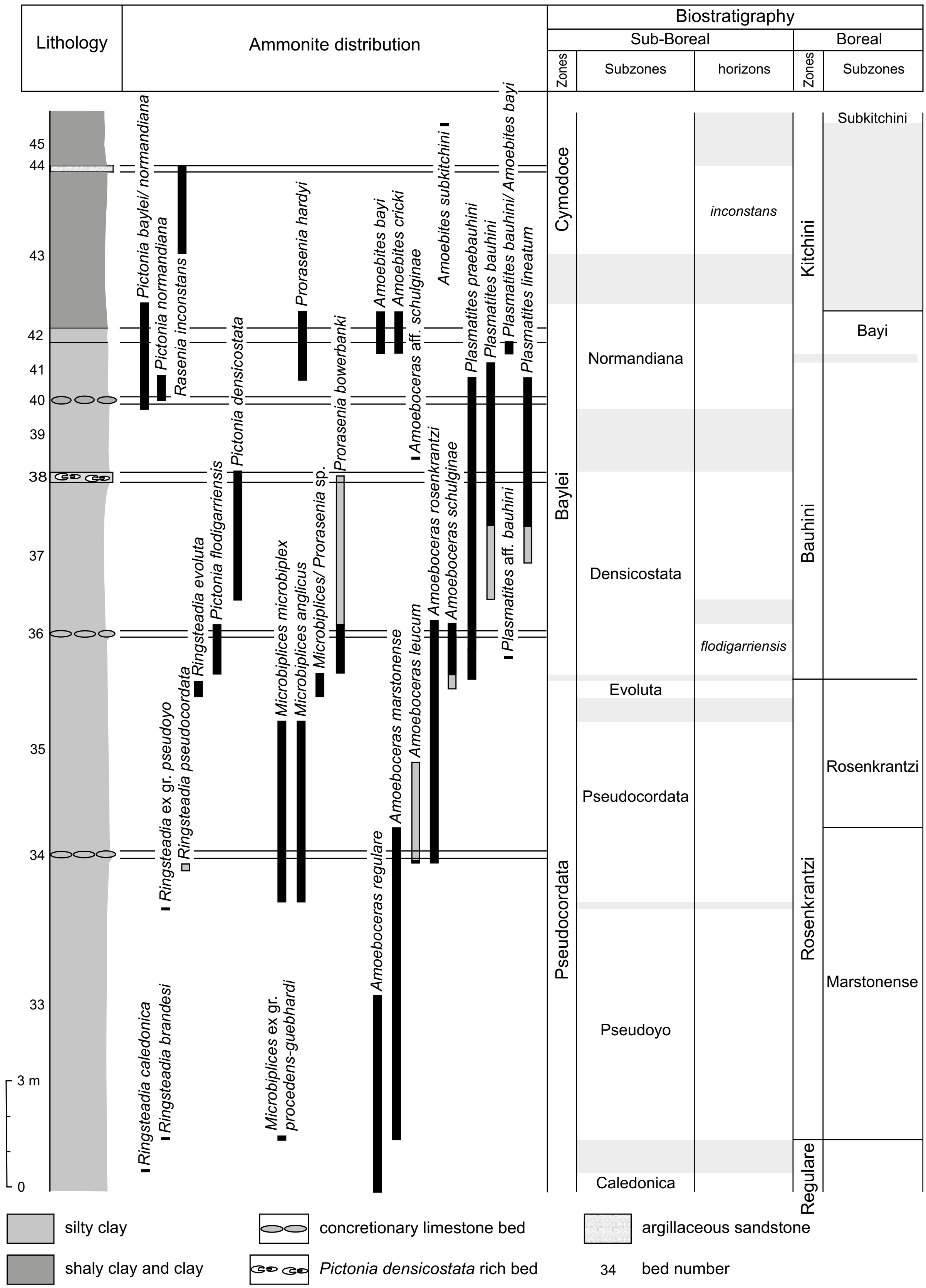


Fig. 1. Location of geological sections discussed in the study placed on a palaeogeographic map of the Middle to Late Oxfordian transition of Europe (after Matyja and Wierzbowski A., 1995)

1 – Staffin Bay, Isle of Skye (Flodigarry section). 2 – Dorset Coast. 3 – Pomerania. 4 – Peri-Baltic Syneclise. 5 – Poitou area. 6 – Wieluń Upland (Katarowa Góra and Bobrowniki sections). 7 – middle part of Polish Jura (Syborowa Góra and Biskupice sections). 8 – Franconian Alb. 9 – Swabian Alb. 10 – northern Switzerland Jura. 11 – Pre-Betic Zone (Fuentelspino de Moya section). 12 – Southeastern France

monite succession at the boundary of the *Ringsteadia* assemblages (Pseudocordata Zone) and the *Pictonia* assemblages (Baylei Zone) in the Dorset coast. In addition, the Flodigarry section shows a continuous succession of ammonites of the family Cardioceratidae of the genus *Amoeboceras* with the older subgenus *Amoeboceras* followed successively by the subgenera *Plasmatites* [with such species as *P. praebauhini* (Salfeld), *P. bauhini* (Oppel) and *P. lineatum* (Quenstedt)] and then by the first *Amoebites* – *A. bayi* Birkelund et Callomon.

On the basis of these new data, the Oxfordian/Kimmeridgian boundary in the Flodigarry section has been defined (Matyja *et al.*, 2006) at the base of the newly recognized horizon of *Pictonia flodigarriensis* treated as the basal horizon of the Baylei Zone and thus the base of the Kimmeridgian. It is marked by the replacement of the Subboreal *Ringsteadia* (M) – *Microbiplices* (m) by *Pictonia* (M) – *Prorasenia* (m). The same level is also marked by the first appearance of Boreal cardioceratids of the subgenus *Plasmatites* which gives independent correlation of the Subboreal boundary in question with the base of the Boreal Bauhini Zone (*i.e.* the boundary between the Rosenkrantzi Zone and the Bauhini Zone of Boreal succession) (see Matyja *et al.*, 2006; Wierzbowski A. *et al.*, 2006). This enlarges very much the correlation potential of the proposed Oxfordian/Kimmeridgian boundary.


Lithology
Ammonite distribution
Biostratigraphy
Sub-Boreal
Boreal
Zones
Subzones
horizons
Zones
Subzones
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44
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Pictonia baylei/ normandiana
Pictonia normandiana
Rasenia inconstans
Pictonia densicostata
Prorasenia hardyi
Prorasenia bowerbanki
Amoebites bayi
Amoebites cricki
Amoeboceras aff. schulginae
Amoebites subkitchini
Plasmatites praebauhini
Plasmatites bauhini
Plasmatites bauhini/ Amoebites bayi
Plasmatites lineatum
Amoebites
Ringsteadia evoluta
Pictonia flodigarriensis
Prorasenia sp.
Microbiplices/ Prorasenia sp.
Microbiplices microbiplex
Microbiplices anglicus
Amoeboceras rosenkrantzi
Amoeboceras schulginae
Plasmatites aff. bauhini
Amoeboceras leucum
Amoeboceras marstonense
Amoeboceras regulare
Ringsteadia ex gr. pseudoyo
Ringsteadia pseudocordata
Ringsteadia caledonica
Ringsteadia brandesi
Microbiplices ex gr. procedens-guebhardi
Cymodoce
Baylei
Pseudocordata
Normandiana
Densicostata
Evoluta
Pseudocordata
Pseudoyo
Caledonica
inconstans
flodigarriensis
Kitchini
Bauhini
Rosenkrantzi
Regulare
Subkitchini
Bayi
Rosenkrantzi
Marstonense
silty clay
shaly clay and clay
concretionary limestone bed
Pictonia densicostata rich bed
argillaceous sandstone
34 bed number

Fig. 2. Distribution of ammonites in the Flodigarry section, Staffin Bay, Isle of Skye – the proposed GSSP of the Oxfordian and Kimmeridgian boundary, and their chronostratigraphical interpretation (after Matyja *et al.*, 2006, slightly modified)

Grey bars are referred to cf. species. Grey blocks in chronostratigrahical column indicate the intervals of uncertain correlation

←

The ammonite stratigraphy which is the basis for recognition of the Oxfordian/Kimmeridgian boundary is based thus on the Subboreal–Boreal ammonite successions studied in the Flodigarry section, Staffin Bay, Isle of Skye (Matyja *et al.*, 2006), proposed, and accepted by the Kimmeridgian Working Group in 2007 as the primary standard (GSSP) of the boundary in question (Wierzbowski A., 2007). The remaining problem (still not formally settled) relates to definition of the base of the Subboreal Baylei Zone – and especially the role of the *P. flodigarriensis* horizon in stratigraphical correlations. On the other hand, this zone is historically, and formally, accepted by both the Kimmeridgian W.G. and the International Subcommisssion on Jurassic Stratigraphy as the lowest zone of the Kimmeridgian Stage (Morton, 2007; Wierzbowski A., 2010b).

NEW DATA FROM THE STAFFIN BAY (ISLE OF SKYE) SECTIONS

The full description of the section at Flodigarry (Isle of Skye, Staffin Bay) was presented in Wierzbowski A. *et al.* (2006) giving details on its: (1) lithological succession and ammonite biostratigraphy (after Matyja *et al.*, 2006 and earlier papers cited therein), (2) the microfossil biostratigraphy – mostly dinoflagellates (after Riding and Thomas, 1997), and also acritarchs and other non-dinophycean marine palynomorphs (after Stancliffe, 1990), (3) the isotope stratigraphy, especially oxygen and carbon isotopes (after Wierzbowski H., 2004, including new data of this author), and also strontium isotopes (after Jenkyns *et al.*, 2002), and (4) the magnetostratigraphy (new data by M. Hounslow which were combined with the other data from Dorset and South Ferriby of Ogg and Coe, 1997). These data presented the general characteristics of the section, which according to the opinion given (Wierzbowski A. *et al.*, 2006), fulfilled the principal criteria of Remane *et al.* (1996) for definition as a GSSP for the base of the Kimmeridgian Stage. Additional observations obtained after 2006 in the section are detailed below.

AMMONITE BIOSTRATIGRAPHY

Some minor changes were introduced more recently in the biostratigraphical interpretation of the section (Figs 1–2) when compared with the interpretation of Matyja *et al.* (2006, fig. 3) and Wierzbowski A. *et al.* (2006, fig. 4). The oldest ammonites of the Pseudoyo Subzone of the Pseudocordata Zone of the uppermost Oxfordian illustrated in Matyja *et al.* (2006, p. 391, fig. 4a) do not belong to the species *M. microbiplex* (Quenstedt). Instead, they are rather closer to early representatives of the *M. procedens* (Oppenheimer) – *M. guebhardi* (Oppenheimer) group as shown by their fairly dense ribbing on the inner whorls and the lower point of splitting of the ribs (Wierzbowski A. and Matyja, 2014b, p. 60). This observation together with re-interpretation of some forms which had been included previously in *Amoeboceras regulare* Spath as early representatives of *A. marstonense* Spath results in transferring of deposits originally placed in the uppermost part of the Boreal Regulare Zone into the lowest part of the Boreal Rosenkrantzi Zone (Wierzbowski A., Matyja, 2014b, p. 61). These subtle changes in interpretation of the section occur within the uppermost Oxfordian deposits and are shown in Fig. 2. They have no influence on the position of the Oxfordian/Kimmeridgian boundary as originally indicated.

ISOTOPE STRATIGRAPHY

New records of carbon isotope variations in belemnite rostra ($\delta^{13}C_{carb}$) and terrestrial fossil wood debris ($\delta^{13}C_{org}$), as well as the oxygen isotope record ($\delta^{18}O_{carb}$) from the Staffin Bay sections were published by Pearce *et al.* (2005) and Nunn *et al.* (2009). The results show the presence of the highest palaeotemperatures during the Oxfordian–Kimmeridgian boundary interval (Regulare–Baylei chrons) within the whole interval from the base of the Oxfordian up to the lowest Kimmeridgian. This generally confirms the earlier assumption of H. Wierzbowski (in: Wierzbowski A. *et al.* 2006). Analysis of the carbon isotope composition of both marine carbonates and terrestrial organic matter shows the presence of a gradual fall in $\delta^{13}C$ values in the Upper Oxfordian and the lowermost Kimmeridgian.

Rhenium–Osmium ($^{187}Re–^{188}Os$) dating of black shale samples at Flodigarry, Staffin Bay taken from about 1.20–1.40 m below the base of bed 36, yielded an age of 154.1 (+/– 2.2) Ma at the proposed GSSP for the Oxfordian/Kimmeridgian boundary (Selby, 2007). These sampled levels correspond precisely to the base of the Kimmeridgian Stage (Pseudocordata-Baylei zone boundary placed at the base of the *Pictonia flodigarriensis* horizon of the Subboreal subdivision = Rosenkrantzi-Bauhini zone boundary of the Boreal subdivision). It is the first precise radiometric dating of this boundary, which was assumed by Ogg and Hinnov (2012) to correlate with oceanic basalt marine anomaly M26r at 157.3 +/– 3.4 Ma.

MOLECULAR ORGANIC GEOCHEMISTRY

Study of the composition of the soluble organic matter at the Oxfordian/Kimmeridgian boundary in the Flodigarry section, Staffin Bay, shows the exceptional preservation and very low thermal degradation of the organic matter (Lefort *et al.*, 2012). This matter is mostly of continental origin, mainly remains of conifers, and its composition does not change significantly through the section. It should be remembered, however, that the bulk of the samples studied were taken from the Lower Kimmeridgian deposits, and that the lowest part of the succession studied (mostly the lower part of the Bauhini Zone) shows a lesser terrestrial organic matter supply than the higher part of the Lower Kimmeridgian.

MAGNETOSTRATIGRAPHY

Magnetostratigraphic study of the Flodigarry section at Staffin Bay was detailed by M.W. Hounslow and J. Ogg (in: Wierzbowski A. *et al.*, 2006, figs 7–8) who originally indicated that the uppermost Oxfordian was dominated by normal polarity, and the lowermost Kimmeridgian by reverse polarity. The data across the Oxfordian/Kimmeridgian boundary at Flodigarry was combined with magnetostratigraphic data from other U.K. sections (Przybylski *et al.*, 2010) and was interpreted as lying close to the boundary between M27n and M26r chrons of the marine magnetic anomalies sequence (M–sequence). However, the exact level for the change in polarity in the Flodigarry section was not precisely known because of a lack of samples from ca. 1 m interval around the Oxfordian/Kimmeridgian boundary at the top of bed 35. New samples taken from that interval collected by J.K. Wright have been studied by M.W. Hounslow and M. Galvin (Hounslow *et al.*, 2015) and have been combined with the previous data, to show the magnetic polarity across this interval (Fig. 3). Ten of the new samples display reverse polarity, and six normal polarity (for one sample the polarity was uncertain). As in the previous study, the magnetisation components were determined using either straight-line segments (line-fits; Fig. 3) or great circle trends towards the expected Jurassic directions. The mean geomagnetic field direction determined for the new dataset give declination of 4°, and inclination of 50° ($\alpha95=6.5°$, $k=16.8$, $n=16$), giving a palaeopole at latitude, longitude of +64° N, 166° E, similar to that from the previous sample set based on the entire section (Przybylski *et al.*, 2010).

At Flodigarry the base of magnetozone F3n (Fig. 3) is located between 235 cm and 260 cm below the base of bed 36. This interval coincides (within the sampling resolution) with the top of the *R. pseudocordata* Subzone at 234 cm below bed 36. The base of magnetozone F3r (Fig. 3) is located between 128 and 148cm below the base of bed 36, and is now well defined by detailed sampling. The base of the *P. densicostata* Subzone (FAD of *P. flodigarriensis*) is located between 108 cm and 124 cm below bed 36, so these two events are now closer than ~25cm from each other. Assuming that the base of F3r correlates to the base of marine magnetic anomaly M26r, and using the marine magnetic anomaly age scale in Ogg (2012), this equates to an age difference of no more than ~30kyrs. 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 new data indicate that the Evoluta Subzone is dominated by normal polarity, as also demonstrated at the UK South Ferriby and Black Head sections (Fig. 4). The underlying reverse magnetozone F2r, seems to occupy the mid and upper parts of the Pseudocordata Subzone. The polarity in the older parts of the Pseudocordata Zone is only really defined at the Flodigarry sections, so remain somewhat uncertain, considering the wide sample spacing.

CONSERVATION OF THE PROPOSED KIMMERIDGIAN GSSP AT FLODIGARRY

A key part of the guidelines for GSSP selection of Remane *et al.* (1996) concerns its potential for continued use, including safeguarding the reference section for future scientific study, including sampling. Collectively grouped as "*Other requirements*", these criteria effectively relate to the legal heritage status of the site and its on-going or potential sensitive management. Although national conservation systems vary widely – and can even impact negatively on ongoing scientific use of a geological locality – at Flodigarry, a combination of "crown" (effectively public) ownership and a well-established and scientifically informed legal con-

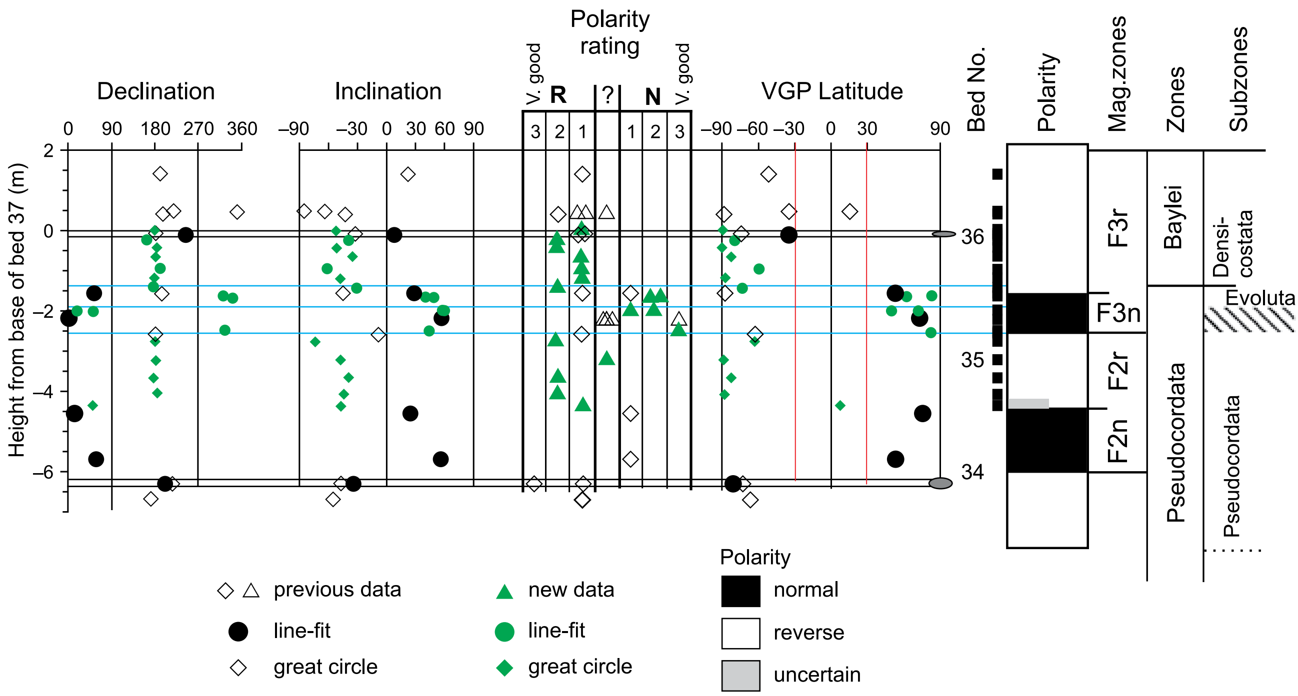


Fig. 3. Summary magnetostratigraphic data across the Oxfordian–Kimmeridgian boundary at Flodigarry, showing the previous and new (in green) data sets

The virtual geomagnetic palaeopole (VGP) was used to determine the VGP latitude (VGP latitude –90 to 0 = reverse polarity; 0 to +90 = normal). Declination, Inclinations are the directions of tilt-corrected specimen characteristic remanence, and show north directed (south), positive (negative) inclination for normal (reverse) polarity. Polarity rating is a qualitative evaluation of the interpreted magnetic polarity shown by individual specimens, ranging from 3 (very good) to poor (1). See Przybylski *et al.* (2010) for further information

servation framework (see Page and Wimbledon, 2006) provides an ideal scenario for safeguarding the candidate GSSP for future scientific study. These criteria are addressed in turn below:

"*Permanently fixed marker*": Despite being a natural foreshore exposure, a permanent marker could still be placed, for instance using an approved, imbedded metal marker, which could be relocated using a GPS reference and metal detector, whatever the beach conditions. The use of this type of buried marker is well established for terrestrial ecological surveys, for instance in woodland.

"*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 public access. Examination of the boundary level requires a falling tide.

"*Free access*": As above, public access rights are guaranteed by Scottish law.

"*Guarantees from the respective authority concerning free access for research and permanent protection of the site*": The area is publically owned and managed on behalf of the Scottish Government by SGRPID (Estates Office, Portree, Isle of Skye, IV51 9DH, Scotland) and protected through the Nature Conservation (Scotland) Act 2004 within the legally designated Trotternish Ridge Site of Special Scientific Interest. Advice concerning protocols and permissions to sample should be directed to: south_highland@snh.gov.uk. For further information about the conservation of natural heritage sites in Scotland see: www.snh.gov.uk.

POSITION OF THE OXFORDIAN/KIMMERIDGIAN BOUNDARY IN OTHER SECTIONS OF THE SUBBOREAL AND BOREAL AREAS

Biostratigraphical correlation of the Subboreal/Boreal succession of the uppermost Oxfordian and lowermost Kimmeridgian of the Flodigarry section with other sections showing similar types of ammonite faunas in northern areas of Europe (Fig. 1) and Asia and adjoining areas of the Arctic (Fig. 8), have been the subject of several papers published recently. The main results of the studies are commented on below.

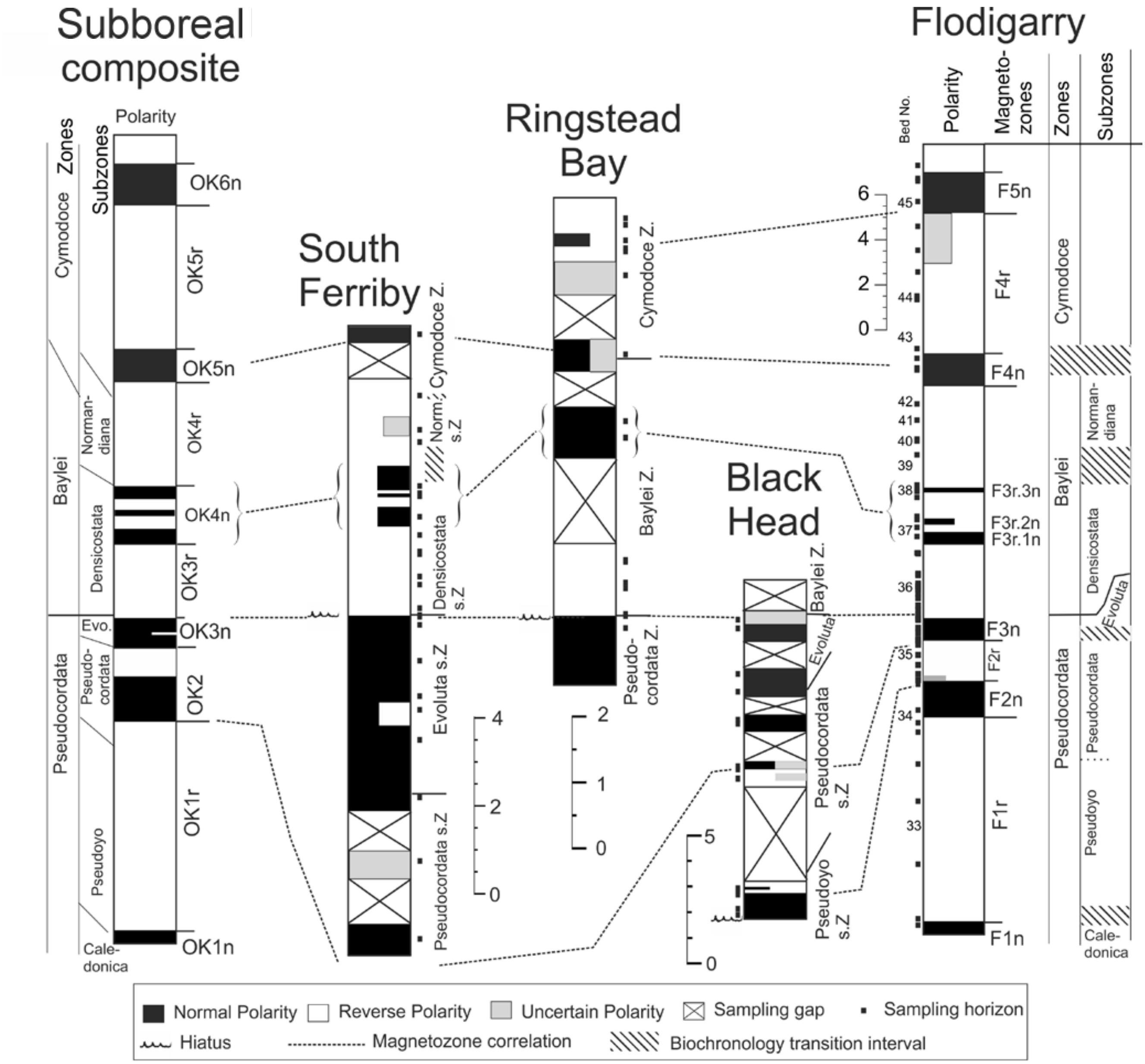


Fig. 4. Summary magnetostratigraphic results from other Boreal–Subboreal sections (see Przybylski *et al.*, 2010, for section data), the proposed GSSP, and the composite magnetic polarity for these sections

SOUTHERN ENGLAND

This is the classical area of the Subboreal Province, and the ammonites occurring here are almost entirely representatives of the family Aulacostephanidae. A recent study of these Subboreal ammonites from southern England – which is their "home area" (Wright, 2010) – generally shows the incompleteness of the succession at the boundary of the Oxfordian and Kimmeridgian, *i.e.* at the boundary of the Pseudocordata Zone and the Baylei Zone. The *P. flodigarriensis* horizon is thus normally missing, but in some basinal sections like that of the central Wessex Basin it seems to be present, but it is normally overstepped by a younger *P. densicostata* horizon typical of the lowermost preserved deposits of the Baylei Zone (the so-called *Inconstans* Bed) in areas such as the Dorset coast and Wiltshire (Wright, 2003). Therefore, the previously supposed local occurrence of an index species, *Pictonia flodigarriensis*, and of the relevant horizon in northern Scotland only – used as an argument against wider recognition of the base of the *P. flodigarriensis* horizon, as a uniform base of the Oxfordian/Kimmeridgian boundary is "not substantiated" (see Wierzbowski 2010b).

POMERANIA AND PERI-BALTIC SYNECLISE

The large quarries of Czarnogłowy (Zarnglaff) in western Pomerania in Poland yielded in the past ammonites of the family Aulacostephanidae described originally by Dohm (1925) and by Wilczyński (1962). The oldest ammonite assemblage consists of representatives of the genus *Vineta* Dohm, 1925, and "*Ringsteadia*" (originally described and often cited thereafter as true representatives of this genus) – but corresponding in fact to the newly established genus *Vielunia* Wierzbowski et Głowniak, 2010 (see Wierzbowski A. *et al.*, 2010). These deposits from Pomerania were traditionally correlated with the Pseudocordata Zone of the Subboreal uppermost Oxfordian (*e.g.* Arkell, 1956). However, both these groups of ammonites, as indicated recently in other areas (Głowniak *et al.*, 2010; Wierzbowski A. *et al.*, 2015 a) co-occur with Boreal ammonites of the subgenus *Plasmatites* indicative of the Boreal Bauhini Zone. Thus, these deposits in Pomerania belong in fact to the lowermost Kimmeridgian, and may be assigned to the Jaekeli Zone (after *Vineta jaekeli* Dohm) (see Dohm, 1925; Wilczyński, 1962) corresponding to a large part of the Subboreal Baylei Zone (possibly except its topmost part).

Newly published material from boreholes in north-eastern Poland in the area of the Peri-Baltic Syneclise (Wierzbowski A., *et al.*, 2015 a) include the description of a rich collection of ammonites from the Oxfordian and Lower Kimmeridgian including ammonite faunas from the stratigraphical interval at the Oxfordian and Kimmeridgian boundary. The fauna of the uppermost Oxfordian is dominated by Boreal ammonites indicative of the Rosenkrantzi Zone, but including also typical Subboreal ammonites of the Pseudocordata Zone of the genera *Ringsteadia* (M) – *Microbiplices* (m), showing marked similarity to the coeval fauna from southern England. On the other hand, the younger fauna is dominated by Subboreal ammonites of the genera *Vielunia* (M) – *Prorasenia* (m) and *Vineta* (M,m) which may be correlated with the Baylei Zone (or Jaekeli Zone), as it co-occurs with the Boreal ammonites *Amoeboceras* (*Plasmatites*) of the Bauhini Zone. This new assemblage of Subboreal ammonites differs markedly from the coeval assemblage from southern England composed of representatives of the genera *Pictonia* (M) and *Prorasenia* (m). The differences in development of the aulacostephanid faunas during the earliest Kimmeridgian between the NW European areas and NE European areas was related to allopatric speciation within the Aulacostephanidae lineage. This resulted from the development of land-barriers separating NW and NE areas of the Subboreal Province due to the uplift of the London-Brabant Massif and the Ringkøbing-Fyn High (Enay, 1980; Wierzbowski A., 2010a).

Stratigraphical interpretation of the deposits at the Oxfordian/Kimmeridgian boundary is possible also on the basis of the microfossils which have been correlated with the ammonite subdivisions. Especially useful here are the cysts of Dinoflagellata which are commonly recognized over wide areas from southern England, the North Sea, and areas further east – from the Danish Basin, the Fennoscandian Border Zone (Poulsen and Riding, 2003, with earlier papers cited therein) up to the Peri-Baltic Syneclise (Barski *et al.*, 2005). The Oxfordian/Kimmeridgian boundary is placed at the boundary of the dinoflagellate cyst zones DSJ 26 and DSJ 27 or between the subzones c and d of the Scriniodinium crystallinum Zone. The foraminifers and radiolarians which occur in these beds can also be used in stratigraphical correlations (Wierzbowski A. *et al.*, 2015a, with earlier papers cited therein).

The deposits at the Oxfordian/Kimmeridgian boundary of the Peri-Baltic Syneclise of north-eastern Poland show marked differences in thickness and facies ranging from normal pelagic sediments with radiolarian faunas up to strongly condensed deposits associated with stratigraphical hiatuses. The origin of these strongly contrasting deposits was possibly related to tectonic movements during the earliest Kimmeridgian (Wierzbowski A. *et al.*, 2015a). The stratigraphical unconformity recognized is very close in age to the base of the sequence stratigraphic unit interpreted over wider areas of northern Europe, which at least partly seems to be tectonically controlled. Such an unconformity, except in the area of southern England discussed above, is observed in the Danish Basin and the Fennoscandian Border Zone of southern Scandinavia (Nielsen, 2003) and it may occur also on the Russian Platform on its northern edge, close to the Baltic Shield, in the Timan-Pechora Basin and the Mesen Syneclise (Vishnevskaya *et al.*, 1999).

RUSSIAN PLATFORM

Detailed biostratigraphical studies on the Oxfordian/Kimmeridgian boundary were originally presented by Mesehnikov *et al.* (1989) from the Makariev section at Unzha river in the central part of the Moscow Syneclise. This study resulted in recognition of the ammonite succession of the Boreal Oxfordian up to the lowermost Kimmeridgian (Mezehnikov, Kalacheva and Rotkyte *in*: Mesezhnikov *et al.*, 1989) as well as of the relevant foraminiferal zonal scheme (Azbel *in*: Mesezhnikov *et al.*, 1989) for the Russian Platform. The successive studies of the neigbouring section at Mikhalenino resulted in the elaboration of the Subboreal and Boreal ammonite succession at the Oxfordian/Kimmeridgian boundary (Głowniak *et al.*, 2010) which became the basis for the detailed interpretation of the stratigraphical ranges of the forminiferal zones (Ustinova, 2012).

The ammonites occurring at the Oxfordian/Kimmeridgian boundary in the Mikhalenino section are represented by both Subboreal Aulacostephanidae and Boreal Cardioceratidae. The characteristic NW European Subboreal assemblage of *Ringsteadia* and *Microbiplices* is typical of the uppermost Oxfordian Pseudocordata Zone. The overlying Subboreal assemblage composed of representatives of *Vineta*, *Prorasenia* and *Pictonia* is typical of the lowermost Kimmeridgian of north-eastern Europe. However, the latter is different from the NW European representatives of the genus and somewhat similar to the recently established genus *Vielunia*, but more evolute. Nevertheless, the boundary between the Oxfordian and Kimmeridgian is very well marked by the appearance of the Boreal Cardioceratidae – *Amoeboceras* (*Plasmatites*) represented by typical species of the subgenus like *P. praebauhini*, *P. bauhini*, *P. lineatum* – which makes possible very close correlation with the Flodigarry section at Staffin Bay in Skye (Głowniak *et al.*, 2010). Similar data on the stratigraphical distribution of the Subboreal and Boreal ammonites in the sections around Moscow have been recently presented by Rogov (2015a) who shows that an Oxfordian/Kimmeridgian boundary, corresponding closely to that of the standard section on Skye may also be recognized here. Special attention should be paid to the occurrence in the basal part of the Kimmeridgian on the Russian Platform of a new representative of the subgenus *Plasmatites* which is characterized by a strong development of the primary ribs combined with a very weak development of the secondary ribs (Rogov, 2015 a). This form corresponds well to "*Cardioceras*" *zieteni* (Rouiller) as illustrated by Nikitin (1916, pl. 1: 10–13) which seems also close to *Amoeboceras gerassimovi* Mesezhnikov, Kalacheva et Rotkyte as described by Mesehnikov *et al.* (1989, p. 85–86, pl. 26: 3–7) although the latter shows more dense ribbing (Fig. 5: 7–8a, b).

The foraminiferal assemblages typical of the Russian Platform make possible the recognition of two foraminiferal zones in the uppermost Oxfordian and the lowermost Kimmeridgian: the Lenticulina russsiensis – Epistomina uhligi Zone and the Lenticulina kuznetsovae – Epistomina

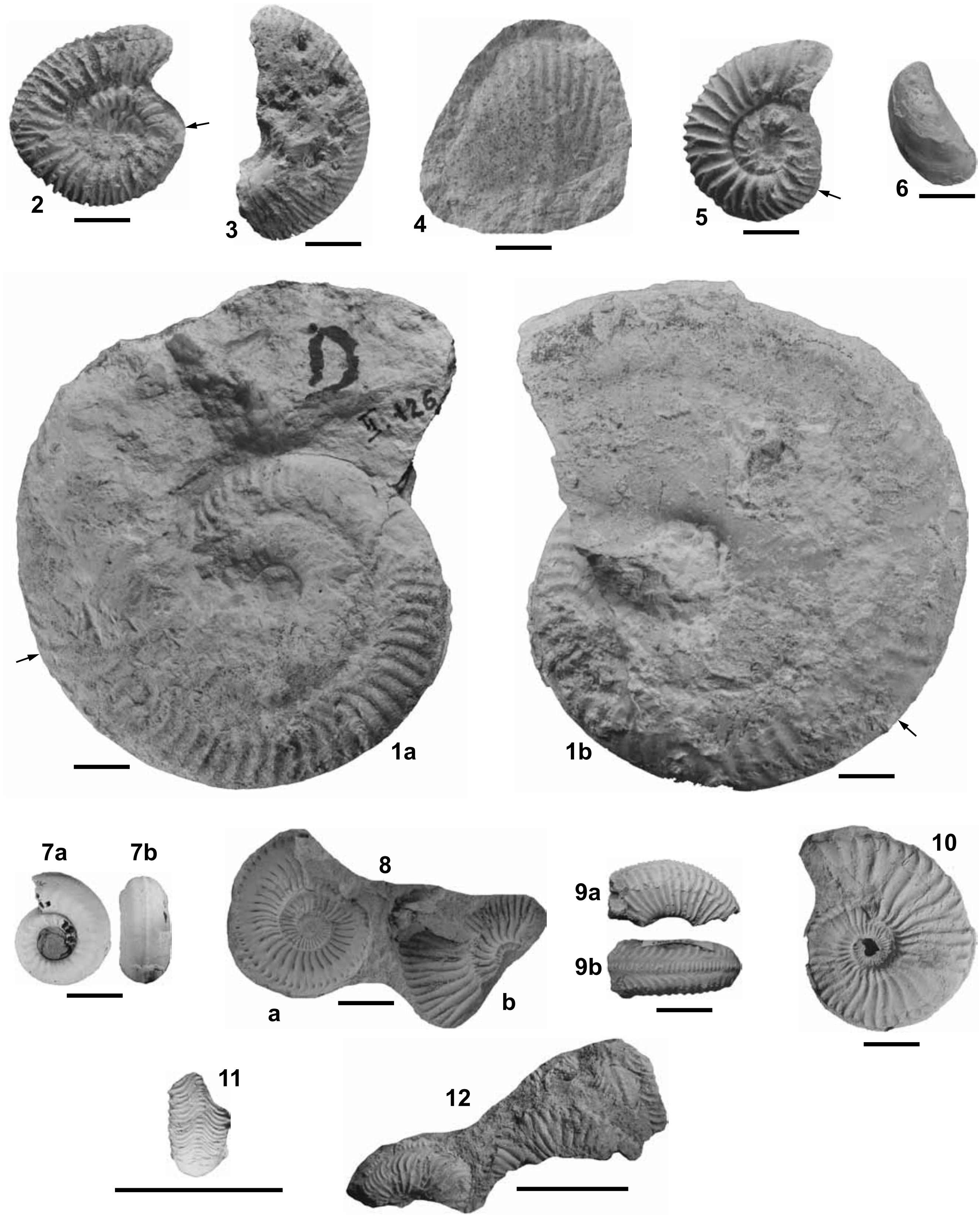
→

Fig. 5. Some newly collected ammonites and bivalves from the Bobrowniki section, Wieluń Upland, central Poland (1–6, cf. Fig. 6) and from Russian Platform (Moscow area), northern Siberia and Franz-Josef Land (Wilczek Land), Russia (7–12)

1a, b – *Ochetoceras marantianum* (d'Orbigny), both sides of a large, fully grown specimen, MUZ PIG 1797.II.126, bed D, Berrense Subzone, Hypselum Zone. 2 – *Vineta* sp., lappeted microconch – closely comparable with microconchs illustrated by Wierzbowski *et al.*, 2010 (pl. 6: 6-7), MUZ PIG 1797.II.100, bed C – uppermost part, at the boundary of the Oxfordian and Kimmeridgian. 3 – aulacostephanid (?*Vineta* sp), macroconch, fragment of the inner whorls of the phragmocone, MUZ PIG 1797.II.118, bed C – uppermost part, at the boundary of the Oxfordian and Kimmeridgian. 4 – aulacostephanid (?*Vineta* sp), macroconch, fragment of the body chamber, MUZ PIG 1797.II.122, bed B – lowermost part, lowermost Kimmeridgian. 5 – *Microbiplices–Prorasenia* trans. form, MUZ PIG 1797.II.100, bed C, uppermost Oxfordian. 6 – *Buchia concentrica* (Sowerby), MUZ PIG 1797.II.112, bed C, uppermost Oxfordian. The phragmocone/body chamber boundary is arrowed.

7a, b – *Amoeboceras* (*Plasmatites*) *zieteni* (Roullier), lateral and ventral side, specimen illustrated by Nikitin (1916, pl. 2: 12), Mnevniki (Moscow), CNIGR Museum, col. 29/5247. 8a, b – a. *Amoeboceras* (*Plasmatites*) *zieteni* (Roullier) transitional to *A. (P.) gerassimovi* Mesezhnikov, Kalacheva et Rotkyte; b. *Vineta* (m) sp., Lipitsy (Kaluga region near Moscow), MK 4761, Geological Institute, Russian Academy of Sciences (RAS), Bauhini Zone – lowermost part. 9a, b – *Amoeboceras* (*Plasmatites*) *praebauhini* (Salfeld), lateral and ventral view, Levaya Boyarka, MK 6970, Geological Institute, Russian Academy of Sciences (RAS), rubble. 10 – *Amoeboceras rosenkrantzi* Spath, Wilczek Land, MK 6843, Geological Institute, Russian Academy of Sciences (RAS). 11 – *Amoeboceras* (*Plasmatites*) sp. – ventral side, Wilczek Land, MK – 6848, Geological Institute of RAS. 12 – *Amoeboceras* (*Plasmatites*) spp., Wilczek Land, MK 6837, Geological Institute of RAS.

Bar scale is 1 cm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praetatariensis Zone (see Azbel and earlier papers cited *in*: Mesehnikov *et al.*, 1989). The boundary between these zones runs somewhat above the basal part of the Kimmeridgian – in the lowermost part of the Bauhini Zone (Ustinova, 2012).

NORTHERN CENTRAL SIBERIA

The northern Siberian sections (Nordvik peninsula, Chernokhrebetnaya river and Levaya Boyarka river sections) were recently discussed by Wierzbowski A. and Rogov (2013) and Nikitenko *et al.* (2015; see also earlier papers cited therein), where also the position of the Oxfordian/Kimmeridgian boundary has been considered. According to Rogov and Wierzbowski A. (2009, pl. 2: 3–4) the base of the Oxfordian/Kimmeridgian boundary in the Nordvik section is defined by the occurrence of representatives of the subgenus *Plasmatites* indicative of the Bauhini Zone. On the other hand, Nikitenko *et al.* (2015, pl. 1: 15–17) illustrated specimens attributed to *Amoeboceras rosenkrantzi* Spath and *Amoeboceras* (*Amoebites*) *bayi* Birkelund et Callomon found nearly at the same level in the section. They argued that their co-occurrence (the former indicative of the Rosenkrantzi Zone of the uppermost Oxfordian, the latter indicative of the basal part of the Kitchini Zone of the lowermost Kimmeridgian) excludes the occurrence of the Bauhini Zone from the section. The specimens attributed to *A. bayi* by Nikitenko *et al.* (2015, pl. 1: 16–17) are poorly characteristic of the species, however, being generally smaller and showing different ornamentation – without the smooth spiral band on the upper part of the whorl-side, and the presence of short but accentuated secondary ribs (*cf.* Birkelund and Callomon, 1985, p. 13–16, pl. 1: 12). It is suggested here, that the specimens attributed to *A. bayi* by Nikitenko *et al.* (2015) cannot be placed in that species; some of the features observable – such as the small size and the type of ornamentation, may even suggest their possible relation with weakly ornamented representatives of the subgenus *Plasmatites*.

Other sections of northern Central Siberia did not yield precise information on the position of the Oxfordian/Kimmeridgian boundary: this occurs possibly within an interval represented by cross-bedded sandstones generally unfossiliferous except in the lowermost part which yielded *Amoeboceras* ex gr. *rosenkrantzi* indicative of the uppermost Oxfordian Rosenkrantzi Zone in the Chernokhrebetnaya section (Aleynikov and Meledina, 1993). The Levaya Boyarka section yielded in its lower part an assemblage of ammonites indicative of the uppermost Oxfordian, including *A. schulginae* Mesezhnikov, known also from the lower part of the Bauhini Zone of the lowermost Kimmeridgian (Mesezhnikov, 1984, and earlier papers cited therein; see also Wierzbowski A. and Rogov, 2013). Recent studies of the Levaya Boyarka and Kheta sections showed, moreover, the presence of the subgenus *Plasmatites*, co-occurring with *A.* aff. *schulginae*, both indicative of the Bauhini Zone of the lowermost Kimmeridgian (Rogov, 2015b, and unpublished data based on new collections 2015; see Fig. 5: 9). These data strongly suggest the possibility of recognition of the Oxfordian/Kimmeridgian boundary in northern Central Siberia as defined in the standard Flodigarry section.

A different opinion on the stratigraphical importance of the Bauhini Zone was given by Nikitenko *et al.* (2013). The authors directly question the possibility of recognition of this zone in the Siberian sections, and consider, moreover, that there are "no sufficient data for the definition" of this zone because of the uncertain status of the subgenus *Plasmatites*, with the problematic species composition of the subgenus, and unclear difference between some *Plasmatites* and early representatives of the subgenus *Amoebites* – especially *A. bayi*. However, the subgenus *Plasmatites* does represent a well defined and closely related assemblage of species as previously indicated by Matyja and Wierzbowski A. (1988). The ammonites of the subgenus occur in a fairly narrow, well defined interval in the *Amoeboceras* succession characterized by the incoming of "small-sized microconchs" (when compared with the underlying and overlying deposits), and are markedly different in many features, including the character of the ventral side of the whorl, from the subgenus *Amoebites* (see Wierzbowski A. and Rogov, 2013, and earlier papers cited therein). Alifirov *et al.* (2016) expressed a similar opinion distinguishing the Bauhini Zone as the basal zone of the Kimmeridgian in Western Siberia.

FRANZ-JOSEF LAND

Wilczek Land has been known for a long time as an area where Oxfordian–Kimmeridgian boundary deposits are exposed (Mesezhnikov and Shulgina, 1982). Among the ammonites described from these deposits, the most stratigraphically important has been the "*Amoeboceras* cf. *ravni*" of Meledina *et al.*, 1979 (pl. 2: 7). This form is very close to ammonites referred to as *A.* aff. *schulginae* by Matyja *et al.* (2006, fig. 6: k–n) from the Flodigarry section at Staffin Bay, and it clearly indicates the presence of the Bauhini Zone. New important ammonite finds were made in 2015 by Nikolay Zverkov (Moscow), who discovered an assemblage composed of *Amoeboceras rosenkrantzi* and *Plasmatites*, both found in a single concretion (Fig. 5: 10–12). This assemblage is indicative of the lowermost part of the Bauhini Zone and correlates precisely with the *P. flodigarriensis* horizon of the basal part of the Baylei Zone.

BARENTS SEA AND NORWEGIAN SEA

Cores drilled in the southwestern Barents Sea and in the northeastern Norwegian Sea revealed the presence of an ammonite succession near the boundary of the Oxfordian and Kimmeridgian (Wierzbowski A. and Smelror, 1993; Wierzbowski A. *et al.*, 2002). The ammonites are mostly Boreal representatives of the genus *Amoeboceras*, especially fully recognized in the cores from the Barents Sea, and with some admixture of Subboreal Aulacostephanidae in the cores from the Norwegian Sea. The Boreal *Amoeboceras* are represented by *A. rosenkrantzi* Spath which is normally typical of the Rosenkrantzi Zone of the uppermost Oxfordian, and representatives of the subgenus *Plasmatites* typical of the Bauhini Zone of the lowermost Kimmeridgian. The latter are known in two successive ammonite assemblages: a lower one composed of *A. (P.) praebauhini* (Salfeld) together with *A. rosenkrantzi* which continues from the underlying uppermost Oxfordian deposits, and a higher one composed of *A. (P.) bauhini* (Oppel) and a form similar to *A. schulginae* Mesezhnikov. This succession corresponds precisely to that of the Boreal *Amoeboceras* as recognized in the standard Flodigarry section at Staffin Bay (Matyja *et al.*, 2006, p. 397).

OXFORDIAN/KIMMERIDGIAN BOUNDARY IN THE SUBMEDITERRANEAN–MEDITERRANEAN SUCCESSIONS AS A CONSEQUENCE OF CORRELATION WITH THE SUBBOREAL–BOREAL SUCCESSIONS

GENERAL INFORMATION ON THE AMMONITE SUBDIVISION

The Oxfordian/Kimmeridgian boundary interval ranges from the uppermost Bifurcatus Zone (the Grossouvrei Subzone), through the Hypselum Zone up to the Bimammatum Zone of the Submediterranean/Mediterranean zonal scheme. Treating the Hypselum Zone as an independent zone instead as the lower subzone of an extended Bimammatum Zone is justified by the well-defined character of its fauna (*e.g.* Meléndez *et al.*, 2006), as well as for the correlation purposes related to the recognition of a consistent Oxfordian/Kimmeridgian boundary (*e.g.* Wierzbowski A., Matyja, 2014a). The biochronostratigraphical subdivision of the Hypselum Zone is based mostly on ammonites of the genus *Epipeltoceras* (Bonnot *et al.* 2009; see also earlier papers cited therein) in the Poitou area, western France. These authors distinguished three units with the status of ammonite-horizons which have been subsequently treated as independent ammonite subzones (Wierzbowski A., Matyja, 2014a,b): the Semimammatum Subzone, the Semiarmatum Subzone and the Berrense Subzone. Analysis of the ammonite distribution given below is based also on data from the Polish Jura especially the Wieluń Upland (sections at Katarowa Góra and Bobrowniki) published recently (Wierzbowski A., Matyja, 2014b with earlier papers cited therein; see also Fig. 6 herein). In addition, we use data from sections in the Franconian Alb and the Swabian Alb (*e.g.* Schweigert, Callomon, 1997; Jantschke, 2014 with earlier papers cited therein).

The Semimammatum Subzone shows the presence of a characteristic assemblage of aspidoceratids. Besides *Epipeltoceras semimammatum* microconchs, there occurs also *Euaspidoceras* macroconchs, with species like *E. hypselum* (Oppel) which is especially common in this subzone although it ranges higher into the Semiarmatum Subzone. Separation of some of these ammonites from other aspidoceratids such as those of the genus *Clambites* raises, however, some difficulties. It is because the roots of the macroconch genus *Clambites* are in the genus *Euaspidoceras*. Thus, some late representatives of *Euaspidoceras* may be treated as the "hidden" macroconch counterparts of the earliest *Epipeltoceras* microconchs (Bonnot *et al.*, 2009; see also Schweigert, 1995) – and in consequence compared with the genus *Clambites*. This interpretation was used for *Euaspidoceras hypselum* (Oppel) by Schweigert and Callomon (1997) and for *E. striatocostatum* (Dorn) by Wierzbowski A. and Matyja (2014b). The top of the Semimammatum Subzone is also marked by the incoming of a new *Neaspidoceras* fauna such as *N. radisense* (d'Orbigny) which occurs commonly in the Semiarmatum and Berrense subzones (Bonnot *et al.*, 2009; Wierzbowski A., Matyja, 2014b). The Semimammatum Subzone shows also the development of a special assemblage of Mediterranean passendorferiids – grouped around *Graefenbergites idoceroides* (Dorn) (see Schairer, Schlampp, 2003; Wierzbowski A., Matyja, 2014b, and earlier papers cited therein). The Semiarmatum Subzone shows the presence of the first representatives of the genus *Praeataxioceras* which become common [and are represented by *P. virgulatus* (Quenst.)] in the overlying Berrense Subzone (Bonnot *et al.*, 2009; Wierzbowski A., Matyja, 2014b). The topmost part of the Hypselum Zone – the Berrense Subzone – is characterized moreover by the incoming of several new groups of ammonites which are recorded also from the lower part of the Bimammatum Zone. These include some aspidoceratids such as the genus *Clambites* [*C. clambus* (Oppel), *C. schwabi* (Oppel)], but also some oppeliids such as – *Taramelliceras (T.) costatum* (Quenstedt), *Glochiceras (Lingulaticeras) bobrownikiense* Wierzbowski et Główniak, and *T. (Richeiceras) jaeggii*

Quereilhac (Zeiss, 1966; Bonnot *et al.*, 2009; Wierzbowski A., Matyja, 2014b, and earlier papers cited therein).

The Bimammatum Zone is subdivided herein into the Bimammatum Subzone and the Hauffianum Subzone (*e.g.* Wierzbowski *et al.*, 2010), units which are also recognized in all other interpretations of the Bimammatum Zone. The base of the Bimammatum Zone (and the base of the Bimammatum Subzone) is marked by appearance of the very characteristic species *Epipeltoceras bimammatum* (Quenstedt). It is also marked by the occurrence of new groups of aspidoceratids of the genera *Aspidoceras*, *Physodoceras*, *Pseudowaagenia* and *Amoebopeltoceras*, and by an almost total disappearance of the older *Euaspidoceras* species, besides *E. costatum* (Dorn), and the related heavily ornamented *Epaspidoceras* (see *e.g.* Schweigert, 1995; Schweigert, Callomon, 1997; Oloriz *et al.*, 1999; Bonnot *et al.*, 2009; Wierzbowski A., Matyja, 2014b; Jantschke, 2014; Schweigert, Jantschke, 2015, and earlier papers cited therein). A new group of oppeliids – the *Metahaploceras* group – appears in a lower part of the Bimammatum Subzone, but somewhat above its basal part (Wierzbowski A. *et al.*, 2010).

Special attention should be paid to the stratigraphical distribution of the oppeliid species *Ochetoceras marantianum* (d'Orbigny). Its occurrence has been treated as indicative of the Marantianum Zone of de Grossouvre (1896, fide Enay *et al.*, 1971) which has been correlated with the Bimammatum Subzone. It should be remembered, however, that the species in question, although commonly occurring in the base of the Bimammatum Subzone, seems to appear also in the upper part of the Hypselum Zone, mostly in the Berrense Subzone (see *e.g.* Schuler,1965; Zeiss, 1966; Meléndez, 1989; also data given below).

The Bobrowniki section in the Wieluń Upland in central Poland recently yielded specimens closely related to *O. marantianum* from the upper part of bed D, and from bed C which modify somewhat the stratigraphical interpretation of the succession as described by Wierzbowski A. and Matyja (2014b, fig. 2) . The most complete specimen collected is a large, fully grown form which shows rather loosely-spaced concave ribs in the ventrolateral part of the whorl typical of the species, some of them bifurcate very near the well-developed lateral groove (Fig. 5: 1a, b). This last feature differentiates the specimen studied (similarly for other fragmentary preserved specimens from beds D and C) from most representatives of the species in question from the lowermost part of the Bimammatum Subzone (*e.g.* Bonnot *et al.*, 2009, pl. 5: 14–15, 17–18) where the ribs split well above the ventral groove, usually in a markedly higher position. According to that feature, as well as to the fact that the specimens from the Bobrowniki sections are the oldest reported so far representatives of the species in the succession of the Wieluń Upland studied, it may be suggested that they are indicative of the upper part of the Hypselum Zone – the Berrense Subzone (Fig. 6). This changes somewhat the stratigraphical interpretation of the deposits which yielded the ammonites in question, previously referred to by Wierzbowski A. and Matyja (2014b, fig. 2) as representing a loosely-defined interval from the uppermost part of the Hypselum Zone to a lowermost part of the Bimammatum Zone. This interpretation also makes closer correlation possible between the different zonal schemes at the Oxfordian/Kimmeridgian boundary, as discussed below.

CORRELATION BETWEEN SUBMEDITERRANEAN/ MEDITERRANEAN SUCCESSION AND SUBOREAL AND BOREAL SUCCESSIONS

Correlation is possible on the basis of the detailed analysis of the sections in which ammonite faunas indicative of the particular provinces occur together. Such sections are known in the Polish Jura in central Poland, and some other areas of Poland, but also in other areas of Submediterranean Europe such as the Franconian Alb and the Swabian Alb in southern Germany, and northern Switzerland.

The uppermost Oxfordian Subboreal Pseudocordata Zone is subdivided into four subzones: the Caledonica Subzone, the Pseudoyo Subzone, the Pseudocordata Subzone and the Evoluta Subzone (Wright, 2003, 2010, and earlier papers cited therein). The lowest of these subzones has been recognized in the Staffin Bay section (Sykes, Callomon, 1979; Matyja *et al.*, 2006), but for a long time not found in any section elsewhere. However, the species *Ringsteadia caledonica* (Sykes et Callomon) has been discovered recently in cores in the Peri-Baltic Syneclise in northern Poland, represented by both micro and macroconchs, showing a similar type of ornamentation but differing in size and the character of the aperture. This species co-occurs here, as in the Skye section, with Boreal *Amoeboceras* indicative of the upper part of the Boreal Regulare Zone. This assemblage was found between occurrences of the Submediterranean ammonites indicative of the upper part of the Submediterranean Bifurcatus Zone, and a lower part of the Hypselum Zone, respectively (Wierzbowski A. *et al.*, 2015a). Correlations based on the analysis of the oldest Subboreal *Ringsteadia* forms in the Submediterranean succession of central Poland and southern Germany (Wierzbowski A., Matyja, 2014b) gave the same results. Therefore it may be inferred that the base of the Subboreal Pseudocordata Zone (*i.e.* the base of the Caledonica Subzone) occurs in an upper part of the Submediterranean Bifurcatus Zone, whereas the top of the Caledonica Subzone should be placed not very far from the Bifurcatus/Hypselum zonal boundary (Fig. 7). Independently the top of the Boreal Regulare Zone, corresponding to the base of the Boreal Rosenkrantzi Zone, can be placed nearby, but slightly below the top of the Submediterranean Bifurcatus Zone (Wierzbowski A., Matyja, 2014b, and earlier papers cited therein).

The Subboreal Pseudoyo Subzone corresponds to the bulk of the Semimammatum Subzone, representing the lower part of the Submediterranean Hypselum Zone, and the same Subzone corresponds to the lower part of the Boreal Rosenkranzti Zone, mostly the Marstonense Subzone. This interpretation is based on the occurrence in the Semimammatum Subzone of specimens very close to the Subboreal *Ringsteadia pseudoyo* Salfeld together with its microconchs, early representatives of *Microbiplices* of the *M. procedens* (Oppenheimer) group, as well as representatives of Boreal *A. rosenkrantzi* Spath and the closely related small-sized *A. ovale*. The latter may be interpreted as representing a wide spectrum of dwarfed-like and dwarfed forms of the *A. marstonense – A. rosenkranzti* group (see Wierzbowski A., Matyja, 2014a, b, with earlier papers cited therein; see also Matyja, Wierzbowski A., 2000).

The younger assemblage of Subboreal forms found in the Submediterranean succession includes additionally *M. microbiplex* (Quenstedt) which represents a younger *Ringsteadia* microconch , as well as *R. salfeldi* (Dorn) which has the appearance of a more boldly ribbed variant of the Subboreal *R. brandesi* Salfeld, as well as *R. teisseyrei* (Siemiradzki) which is very close to the Subboreal *R. pseudocordata* (Blake et Hudleston) [Wierzbowski A., Matyja (2014a, b); see also Głowniak, Wierzbowski A. (2007), and Wright (2010)]. This assemblage of ammonites indicates the presence of the Subboreal Pseudoyo Subzone and/or the Pseudocordata Subzone (Wright, 2010). Because the ammonites in question were found in a part of the Submediterranean succession which may be correlated with an upper part of the Semimammatum Subzone and the Semiarmatum Subzone of the Hypselum Zone, the Submediterranean interval indicated cannot be younger than some middle parts of the Subboreal Pseudocordata Zone – the Pseudocordata Subzone. The same stratigraphical interval yielded *A. rosenkrantzi* Spath indicative of the Boreal Rosenkrantzi Zone.

The youngest ammonite assemblage of the Subboreal Oxfordian recognized in the Polish Jura, in the stratigraphical interval corresponding to the Submediterranean Berrense Subzone, consists mostly of strongly ornamented representatives of *Microbiplices* which show a marked similarity to the Subboreal species *Microbiplices anglicus* Arkell. They differ only in less evolute coiling and hence are distinguished as the new subspecies *M. anglicus vieluniensis* Wierzbowski et Matyja (see Wierzbowski A, Matyja, 2014b). There occur some specimens in the upper part of the stratigraphical range of this form, however, which show in the inner whorls thicker and somewhat more swollen primary ribs showing a lower point of division of the ribs. These specimens are interpreted as transitional between *Microbiplices* and *Prorasenia* (Fig. 5: 5). Whereas the occurrence of the species *Microbiplices anglicus* indicates the Pseudocordata Subzone, the occurrence of forms transitional between *Microbiplices* and *Prorasenia* is typical of the Evoluta Subzone of the Pseudocordata Zone of the uppermost Subboreal Oxfordian (see Matyja *et al.*, 2006; Wright, 2010). These data indicate that at least most of the Submediterranean Berrense Subzone of the Hypselum Zone may be correlated with the middle and upper parts of the Subboreal Pseudocordata Zone (Fig. 7). The same stratigraphical interval in the Polish Jura sections yielded a few Boreal ammonites such as *Amoeboceras rosenkrantzi* and *A. subcordatum* (d'Orbigny) sensu Salfeld (1916), the latter being closely related to *A. tuberculatoalternans* (Nikitin). The co-occurrence of these forms with the virtual absence of representatives of the subgenus *Plasmatites* is indicative of the upper part of the Boreal Rosenkrantzi Zone (Matyja *et al.*, 2006; Głowniak *et al.*, 2010; Wierzbowski A., Matyja, 2014b).

The topmost part of the deposits attributed to the Subboreal/Boreal uppermost Oxfordian of the Pseudocordata Zone and the Rosenkrantzi Zone in the northern part of the Polish Jura, in the Wieluń Upland (Bobrowniki section) shows the presence of an omission surface well-characterized by geochemical studies (Grabowski *et al.*, 2015; Wierzbowski A. *et al.*, 2015b; see also chapter on environmental and climatic conditions, herein). This omission surface delimits the occurrence of the uppermost Oxfordian Subboreal/Boreal faunal assemblages below from the occurrence of the lowermost Kimmeridgian ones above, and may be correlated with the tectonically enhanced omission surface (interpreted also in terms of sequence stratigraphy) commonly recognized in the Subboreal Province (see Wierzbowski A. *et al.*, 2015a).

Directly at and closely above this omission surface, ammonites of the genus *Vineta* appear in the studied section at Bobrowniki in the Wieluń Upland in central Poland (Fig. 6). The assemblage consists of both fragments of macroconchs, as well as small microconchs (Fig. 5: 2–4). These show a marked similarity to previously illustrated specimens of *Vineta* obtained from younger deposits of the Bobrowniki section attributed to the Bimammatum Zone (Wierzbowski A. *et al.*, 2010, pl. 6: 6–7; pl. 7: 1–3). It should be remembered that the microconchs of *Vineta* closely resemble the much earlier *Microbiplices procedens* which is a microconch of an early representative of the genus *Ringsteadia*, *R. pseudoyo*. The species *R. pseudoyo* is commonly encountered in a lower part of the Pseudocordata Zone, but a similar, although somewhat more evolute variant continues up to the top of the zone in question (Wright, 2010), and such forms possibly gave rise to the genus *Vineta*.

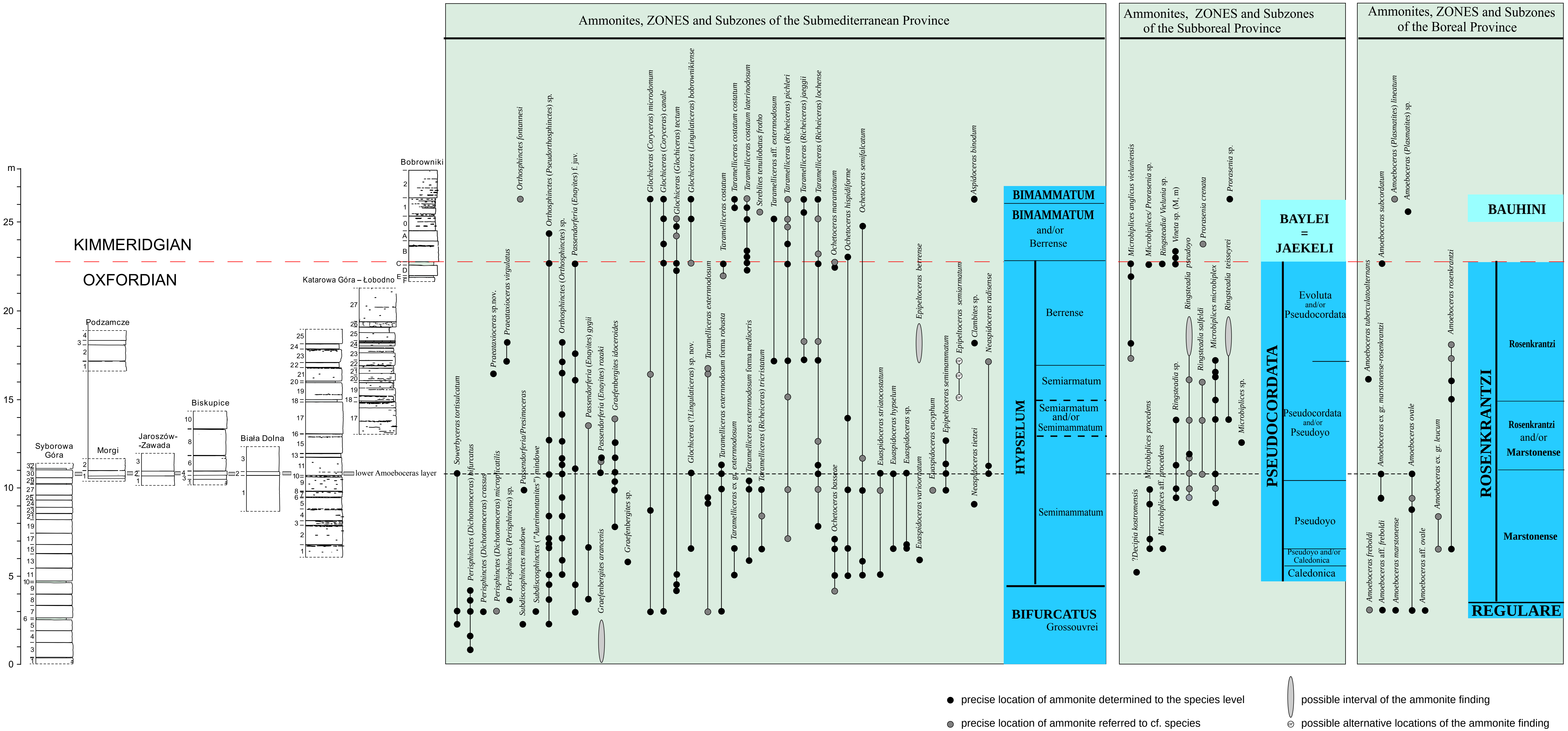


Fig. 6. Distribution of ammonites in the Polish Jura sections (central Poland) and their chronostratigraphical interpretation (after Wierzbowski A., Matyja, 2014b, somewhat modified)

The lower Amoeboceras layer – the local reference horizon is indicated; dark blue – Oxfordian, light blue – Kimmeridgian

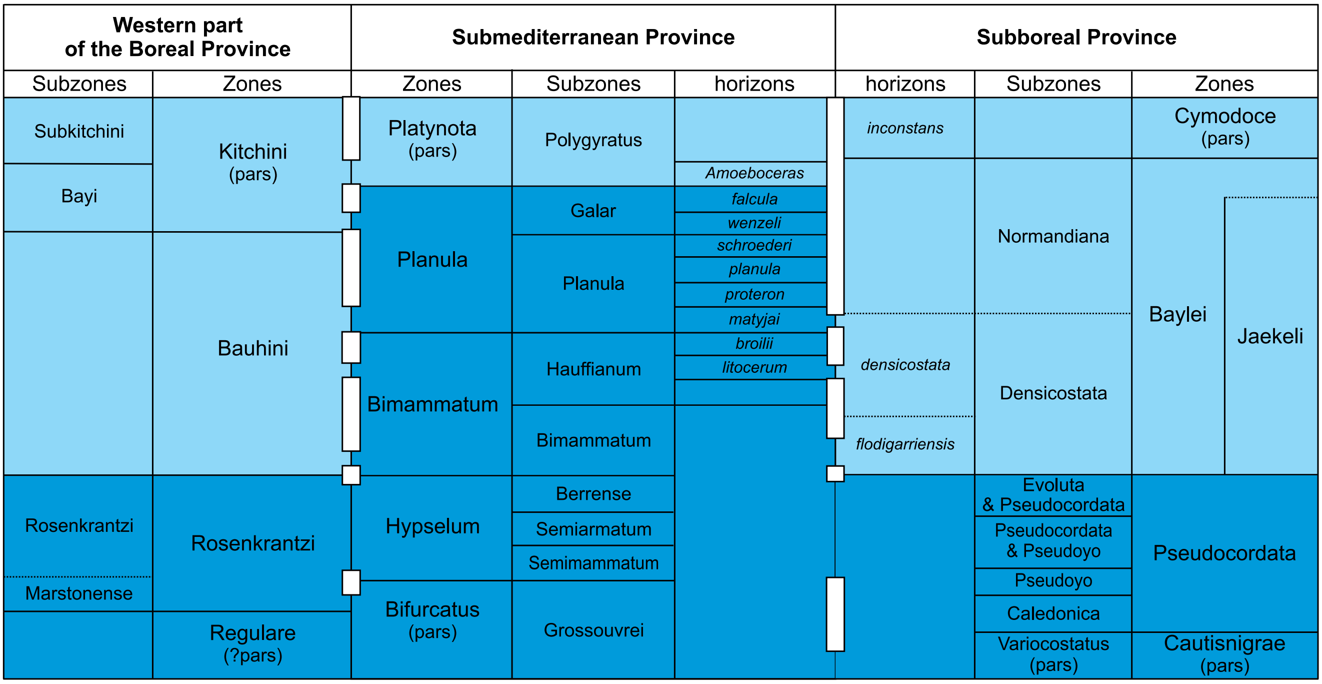


Fig. 7. Correlation of the Submediterranean zonal scheme with the Subboreal and Boreal zonal schemes around the Oxfordian/Kimmeridgian boundary (after Wierzbowski A., Matyja, 2014a, b; slightly modified by Matyja and Wierzbowski, herein)

White blocks indicate the intervals of uncertain correlations; dark blue – Oxfordian, light blue – Kimmeridgian

The occurrence of the genus *Vineta* in north-eastern and central Europe was coeval with the appearance of the genus *Pictonia* in north-western Europe (Wierzbowski A., 2010a; Wierzbowski A. *et al.*, 2015a). Thus, the base of the Baylei Zone of the Subboreal lowermost Kimmeridgian as defined by the appearance of the genus *Pictonia* corresponds to the base of the Jaekeli Zone as defined by the appearance of the genus *Vineta*.

Another group of Subboreal ammonites, *Prorasenia*, appears directly at the base of the Baylei Zone in north-western European areas, including the standard Flodigarry section at Staffin Bay, where it is classified as the microconch of the genus *Pictonia* (Matyja *et al.*, 2006). The oldest representatives of *Prorasenia* are found somewhat higher than the genus *Vineta*, about 1 metre above the omission surface in the studied section at Bobrowniki in the Wieluń Upland of central Poland (Wierzbowski A., Matyja, 2014b). This *Prorasenia* is interpreted as the microconch counterpart of the newly established macroconch genus *Vielunia* typical of the Subboreal areas of the north-eastern and central Europe which may be treated as the "involute analogues of true *Pictonia*" (Wierzbowski A., 1994; see also Wierzbowski A. *et al.*, 2010). It should be noted that the ammonites of the genus *Vielunia* (as well as of the genus *Vineta*) were commonly included in the past to the genus *Ringsteadia* (see *e.g.* Matyja, Wierzbowski A., 1998, and earlier papers cited therein).

Ammonites of the genera *Vineta* and *Vielunia–Prorasenia* are commonly encountered in the Bimammatum Zone (as well as the overlying Planula Zone) in the so-called German-Polish Subprovince of the Submediterranean Province stretching from central Poland, through the Bohemian Massif (where remnants of original cover of the Jurassic deposits with aulacostephanids and cardioceratids are preserved, see Hrbek, 2014; see also Fig. 1 herein), and southern Germany south to the northern Switzerland (Matyja, Wierzbowski A., 1995). In the studied interval of the Bimammatum Subzone a number of forms have been reported which were attributed in many papers to the genus *Ringsteadia*, but which should be transferred nowadays either to the genus *Vineta* or to the genus *Vielunia*.

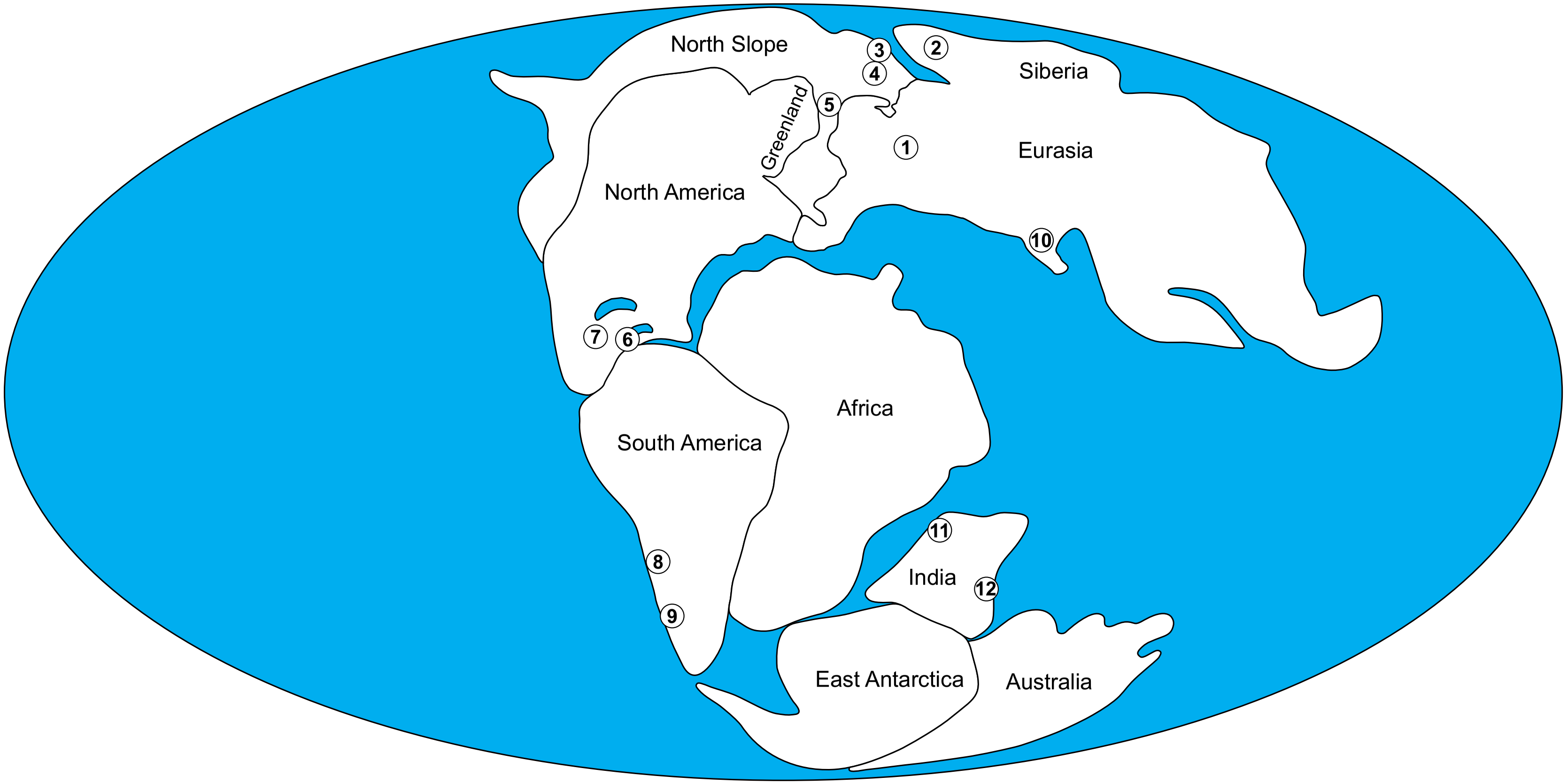


Fig. 8. Location of geological sections outside central and western Europe discussed in the study placed on a global plate tectonic map of the latest Middle Jurassic to Late Jurassic (after Golonka, 2000, simplified)

White – continents – landmass and shallow seas; dark blue – deep ocean basins: 1 – Russian Platform (central part). 2 – northern central Siberia (Taimyr peninsula and Nordvik peninsula). 3 – Franz-Josef Land. 4 – southwestern Barents Sea. 5 – northeastern Norwegian Sea. 6 – Cuba. 7 – Central-east Mexico. 8 – northern Chile. 9 – Argentina: Neuquén-Mendoza basin. 10 – northern Iran. 11 – western India. 12 – Nepal

To the genus *Vineta* belong int. al.: in Poland – specimens originally described as "*Ringsteadia*" *submediterranea* by Wierzbowski A. (1978, pl. 3: 1–3), later transferred to the genus *Vineta* by Wierzbowski A. *et al.* (2010) with its characteristic rapid increase in whorl height; in southern Germany – specimens of "*Ringsteadia flexuoides* (Quenstedt)" of Jantschke (2014, pl. 3: 7; pl. 4: 1) which seem very close to *Vineta submediterranea* (Wierzbowski). The specimens from northern Switzerland, such as some large specimens of "*Ringsteadia*" *magna* of Gygi (2003, figs 31–33) and similar large specimen of "*Ammonites vicarius*" of Moesch (1867, pl. 2: 1a, b), seem close to giant specimens of *Vineta jaekeli* of Dohm (1925, pl. 4: 1. 4–5) – the type species of the genus *Vineta*. All these specimens show generally weak (but poorly recognized) ornamentation of the inner whorls, and completely smooth outer whorls, but differ possibly in a less involute coiling of the inner whorls from *Vineta submediterranea* and its allies (*cf.* Wierzbowski *et al.*, 2010).

To the genera *Vielunia* (M)–*Prorasenia* (m) belong *int. al.*: (1) in Poland – *Vielunia dzalosinensis* Wierzbowski et Głowniak and *Prorasenia crenata* (Quenstedt) representing the dimorphic counterparts and illustrated by Wierzbowski A. *et al.* (2010, pl. 8: 2; pl. 9: 1–4; pl. 10: 1–5; see also older papers cited therein where the representatives of the genus *Vielunia* were compared with the genus *Ringsteadia*); (2) in southern Germany – possibly specimens of *Prorasenia* described by Jantschke (2014, pl. 3: 5–6); (3) in northern Switzerland – a large specimen described to as "*Ringsteadia*" *limosa* (Quenstedt) by Gygi (2003, fig. 25) as well as "*Ringsteadia*" *flexuoides* (Quenstedt) of Gygi (2003, fig. 30) which both seem very close to *V. dzalosinensis*.

Special comments are needed on the taxonomical status of the species "*Ringsteadia*" *flexuoides* (Quenstedt) based on specimens described and illustrated by Quenstedt (1888, pl. 107: 6, 15; see also Ziegler, 1973) from the Bimammatum Zone (Schweigert and Callomon, 1997), and not from the Planula Zone as often given in the past which resulted from the incorrect interpretation of the "*Bimammatumbänke*" Member as the "Weiβjura beta". The specimens most close to those of that species originally described by Quenstedt are those described by Wierzbowski A. (1970, pl. 1: 1–3, pl. 2: 1–2) from the Planula Zone of central Poland. The representatives of this species occur also in Switzerland, such as a large specimen referred to as "*Ringsteadia*" cf. *submediterranea* by Gygi (2003, fig. 27) possibly from the Bimammatum Zone, which shows both the character of coiling as well as the rib density similar to those of "*R.*" *flexuoides*. The true "*Ringsteadia*" *flexuoides* possibly represents a strongly involute species of the genus *Vielunia* as shown by markedly developed secondary ribs with a lower point of rib furcation (Wierzbowski A. *et al.*, 2015 a). The species shows dischizotomous separation of the secondaries – which arise often in triplicate sheaves, and forward-swept ribbing. A similar type of ribbing is shown in *Ringsteadia frequens* Salfeld as revised by Wright (2010) from the topmost part of the Pseudocordata Zone but this is more evolute, especially on the inner whorls. Some similarity may be also observed between *Ringsteadia evoluta* Salfeld from the uppermost Pseudocordata Zone and strongly ornamented representatives of *Vielunia* such as *V. dzalosinensis* and its descendant *V. limosa* (*cf. e.g.* Wierzbowski A., 1970; Wright, 2010). It may be concluded thus that the ammonites of the genus *Vielunia* preserved some features of the latest representatives of the true British *Ringsteadia* which resulted in the past in treatment of all these forms as representing a single group of species.

A different interpretation is possible of the systematic position of the species "*Ringsteadia*" *flexuoides* (Quenstedt). Because this form shows many features in common with older representatives of the genus *Ringsteadia*, it may represent the continuation of the main *Ringsteadia* lineage, and in fact may belong to the genus *Ringsteadia*. Such an interpretation assumes the occurrence of the genus *Ringsteadia* in the earliest Kimmeridgian in the Submediterranean province after its total extinction at the end of the Oxfordian in the Subboreal province. According to this interpretation the genera *Vielunia*, *Vineta* and *Ringsteadia* developed in parallel lineages representing the co-occurring, possibly sympatrically developed genus-rank taxa.

The Bimammatum Subzone in the so-called German-Polish Subprovince of the Submediterranean Province mentioned above also yielded Boreal ammonites. These include mostly representatives of the subgenus *Plasmatites* such as *Amoeboceras* (*P.*) *praebauhini* Salfeld and *A.* (*P.*) *lineatum* (Quenstedt) described and illustrated from the northern part of the Polish Jura of central Poland (Wierzbowski A. *et al.*, 2010, pl. 6: 1–2) as well from southern Germany (Schweigert, 2000, pl. 1: 8; Jantschke, 2014, pl. 1: 3). The occurrence of these ammonites is indicative of the Bauhini Zone of the lowermost Boreal Kimmeridgian. It is worth noting that some ammonites referred to or being close to the Boreal species *Amoeboceras rosenkrantzi* Spath were also discovered in well dated deposits of the Submediterranean Bimammatum Subzone in southern Germany [Schweigert (2000, fig. 2a, b, pl. 1: 7), Jantschke (2014, pl. 1: 4–5)]; and that the deposits of the Bimammatum Subzone in northern Switzerland yielded specimens closely related to *Amoeboceras tuberculatoalternans* (Nikitin) [Atrops *et al.* (1993, pl. 1: 14); Gygi (2000, pl. 10: 3); cf. also Gygi (1969, fig. 2)]. The occurrence of both these species together with *Plasmatites* indicates the lowermost part of the Boreal Bauhini Zone (*cf.* Matyja *et al.*, 2006). The reasoning is as follows: as well as distinguishing the Rosenkrantzi Zone at Flodigarry, *A. rosenkrantzi* and *A. schulginae* (close to *A. tuberculatoalternans*) occur still in the basal Kimmeridgian (*flodigarriensis* horizon), so their presence along with *Plasmatites* indicates the correlation of the Bimammatum Subzone with the lower part of the Baylei Zone.

Conclusion of these discussions is that the boundary of the Oxfordian and Kimmeridgian as defined on the basis of the Subboreal (the boundary between the Pseudocordata and the Baylei/Jaekeli Zone) and the Boreal successions (the boundary between the Rosenkrantzi Zone and the Bauhini Zone) lies very close to the boundary between the Hypselum Zone and the Bimammatum Zone in the Submediterranean succession (Fig. 7).

POSITION OF THE OXFORDIAN/KIMMERIDGIAN BOUNDARY IN OTHER SUBMEDITERRANEAN – MEDITERRANEAN AREAS

The Oxfordian/Kimmeridgian boundary, according to the correlation given above, may be also traced in other Submediterranean and Mediterranean areas where the ammonites of Subboreal/Boreal affiliations are practically unknown or become very rare. The examples discussed relate to the faunal successions in "classic" southern European areas such as southeastern France and the southwestern Iberian Chain and the Prebetic zone of Spain in the west, as well as some areas of central Asia (northern Iran) in the east.

SOUTHEASTERN FRANCE

The boundary interval between Oxfordian and Kimmeridgian is well represented throughout the basin of southeastern France (Subalpine chains), and in its southern (Provençal margin) and western margins (Ardèche margin). The area shows well-exposed, thick and continuous natural sections which yield numerous ammonite faunas of the Hypselum Zone and Bimammatum Subzone (of the Bimammatum Zone) as well as of the underlying and overlying Bifurcatus Zone and the Hauffianum Subzone, respectively, collected over many years by F. Atrops (collections preserved in Lyon University). The litho- and biostratigraphic characteristics of the successions are given in some regional synthesis (Atrops, 1984, 1994; Atrops *et al.*, 1989), but there are only a few detailed studies on particular sections and ammonites, such as the unpublished theses of Duong (1974) and that of Lhamyani (1985) on the Provençal margin. In advance of some future publication showing detailed descriptions of the main sections and ammonites, some general data summarizing the general knowledge on the ammonite succession at the Oxfordian/Kimmeridgian boundary in southeastern France are given below. Everywhere, the lower boundary of the Bimammatum Zone, treated as the base of the Kimmeridgian in the Submediterranean–Mediterranean subdivisions, is well characterised by the first appearance of the index-species *Epipeltoceras bimammatum* (Quenstedt). The most fossiliferous sections are located in the Provence and Ardèche margins, whereas in the basin the best known reference section is that at Châteauneuf-d'Oze (Hautes-Alpes) in the Subalpine chains (Atrops, 1982, 1994).

In the Ardèche region, two different types of facies successions are recognized. The marginal "Ardèche" facies is the best represented showing the common stratigraphic gap at the Upper Callovian–Lower Oxfordian junction (reference sections near Les Vans), and the presence of the "Grumeleux" facies in the Plicatilis Zone of the Middle Oxfordian up to the Bifurcatus Zone of the lowermost part of the Upper Oxfordian. In some areas, however, a transition from the marginal to the basinal facies can be observed, and it becomes quite rapid, towards the east. The basinal succession is characterized (for example in the Crussol and Le Chénier sections near La Voulte) by the appearance of the "Terres Noires" facies (Lower Oxfordian with pyritic ammonites), by the successive reduction of the importance of the "Grumeleux" levels, as well as by development of a thick succession of deposits from the Plicatilis Zone to the Bifurcatus Zone. From the Bimammatum Zone, however, these differences tend to disappear. The facies and thicknesses in both types of successions become very similar which allows the precise lithological correlations even between distant sections.

The reference sections of the "Ardèche" facies zone are located near Les Vans (Ardèche). The Bifurcatus Zone (18 m in thickness) shows a dominantly marly development with rare "Grumeleux" calcareous banks (Chanabier Beds; Dromart, 1986), and it yields the successive species of the genus *Dichotomoceras* characteristic of different levels of the zone. The still younger deposits of the Hypselum Zone (24 m in thickness) are well characterized by the occurrence of *Epipeltoceras semimammatum* (Quenstedt), in a hard calcareous level ("Brown Banks", 1.5 m thick) at the base of the zone. This lithological unit is a good reference level in the whole of the southeastern France basin and its margins. The younger deposit interval consist of soft intercalated marls and marly limestones ("Joyeuse Beds"), generally with few ammonites. The "Grumeleux" intercalations practically disappear here.

Still higher, however, a change in lithology is observed and the deposits become evidently more calcareous. These deposits form spectacular cliffs of the Upper Jurassic rocks well seen in the landscape (the "Pouzin Limestones" Formation, Atrops and Elmi, 1984). The ammonites are much more numerous, allowing recognition of the Bimammatum and Hauffianum subzones as well as the Planula Zone in this thick and continuous calcareous succession. A subdivision into three units well characterized by their lithology and fauna can be easily made. The lower unit (a lower cliff, 8 m in thickness) provides the first representatives of the true *E. bimammatum*, associated with the first, but always rare, representatives of the *Aspidoceras* (*Aspidoceras*) *atavum* (Oppel) group. This unit is separated from the upper one (composed of much thicker and hard limestones – 65 m in thickness) by a more soft calcareous unit (9–10 m in thickness) representing the so-called "*Praeataxioceras* interval" (Atrops, 1984) – very rich in ammonites. The ammonites *Praeataxioceras* of the *virgulatus* group are here dominant; on the other hand they co-occur with *E. bimammatum* (Atrops, 1994, pl. 4: 9), and commonly occurring *Taramelliceras costatum* (Quenstedt). The species *E. bimammatum* disappears at the top of the "*Praeataxioceras* interval". It is worth noting that *E. bimammatum* occurs here continuously through a 10 m thick interval, allowing precise analysis of its morphological variation during the Bimammatum Zone (different successive chronological subspecies?; studies in progress by F. Atrops).

Above the last occurrence of *Epipeltoceras bimammatum* and below the first appearance of *Taramelliceras hauffianum* (Oppel), there exists an interval of limestone 10 m thick, which yields mainly *Orthosphinctes*, *Taramelliceras* of the *costatum* group and different species of *Metahaploceras*. A similar interval without *E. bimammatum* and *T. hauffianum* is recognized in Germany, where it was referred to as (except its upper part) the *tizianiformis* horizon (Schweigert and Callomon, 1997). The name, after "*Perisphinctes*" *tizianiformis* (Choffat), is not appropriate, however, to characterize this interval, because the type-specimen of Choffat's species comes from deposits dated to the Plicatilis Zone of Portugal, and thus it is much older than the interval in question (Meléndez *et al.*, 2006, with earlier papers cited therein). The proper systematic interpretation of the *Orthosphinctes* ammonites discussed above needs additional study (in progress), and they are provisionally referred to as *Orthosphinctes* aff. *tiziani* (Oppel). The occurrence of *T. hauffianum*, in the 3.5 m thick deposits overlying the interval discussed, characterizes the Hauffianum Subzone. The total thickness of the deposits of the "Ardèche" facies, corresponding to the Hypselum, Bimammatum and Planula zones, attains 55 metres.

The 'Terres Noires" facies succession is well recognized in the reference section at Crussol in Ardèche. The succession is thick, continuous and rich in ammonites in all levels from the Bifurcatus Zone up to the Tithonian Hybonotum Zone. The Bifurcatus Zone is represented by well-exposed monotonous marls with rare limestone beds c. 50 m thick, and locally encountered intercalations of the "Grumeleux" facies. The successive species of *Dichotomoceras* enable recognition of the Stenocycloides and the Grossouvrei Subzones. The younger, dominantly marly deposits belong to the Hypselum Zone (54 m). These deposits begin with a thick (3.5 m) brown limestone bed, and the whole Hypselum Zone is much thicker here than in the "Ardèche" facies succession at Les Vans (54 m instead of 24 m). A lower part of the zone belongs to the Semimammatum Subzone – with *E. semimammatum* found up to 16 m from the base. The Bimammatum Zone begins at the base of the massive cliff of the "Pouzin Limestone" Formation, as in the "Ardèche" facies area. The species *E. bimammatum* occurs at different levels in a more soft part of the succession which corresponds to the "*Praeataxioceras* interval" (11 m in thickness). This interval is characterized by the common occurrence of *Praeataxioceras virgulatus* (Quenstedt) together with *Taramelliceras costatum* (Quenstedt) and *E. bimammatum* ranging up to the top of this interval. The first T. *hauffianum* appears about 18 m higher than the highest *E. bimammatum*, and it co-occurs with common ammonites of the *Metahaploceras* group. The latter are rare in the interval of 18 m below and in the Bimammatum Zone. Of the ammonites of the genus *Ochetoceras* – the species *Ochetoceras marantianum* (d'Orbigny) occurs only in the Hauffianum Subzone, whereas the species *Ochetoceras semifalcatum* (Oppel) occurs only in the Bimammatum Subzone. The first representatives of *Subnebrodites*, close to the *S. planula* group, appear just above the last *T. hauffianum*. The Planula Zone (including the Galar Subzone) attains nearly the same thickness both in the Crussol (51 m) and Les Vans (53 m) sections. The Hypselum–Bimammatum zone interval (89 m) is thicker in Crussol than in Les Vans (55 m).

In the Dauphinois basin itself (Subalpine Chains), the basinal deposits are well exposed in the southern Subalpine chains (Diois, Baronnies, Dévoluy). The reference sections are Châteauneuf-d'Oze (Atrops, 1982, 1984, 1994) and Saint-Geniez (Atrops, 1982). The upper part of the "Terres Noires" Formation (Lower Oxfordian and lower part of the Middle Oxfordian) is well developed here. The Châteauneuf-d'Oze section (South of Dévoluy) is continuous from the Upper Oxfordian Hypselum Zone to the Acanthicum Zone of the Kimmeridgian. A detailed stratigraphic study by Atrops (1982), has been supplemented by micropaleontological, sedimentological and geochemical data, but the magnetostratigraphical study by J.Ogg gave no results. The lower part of the section, dominantly calcareous (70 m), is dated to the Hypselum, Bimammatum (with Hauffianum Subzone) and Planula zones (Atrops, 1982, 1994). The ammonites here are less numerous than in Ardèche (Les Vans and Crussol sections), but the "*Praeataxioceras* interval" (6,5 m in thickness), with many ammonites of the Bimammatum Zone, is also well recognized here. These include:

E. bimammatum, *E. treptense* (Atrops, 1994, pl. 4: 10), *T. costatum*, *Orthosphinctes* aff. *tiziani* (Atrops, 1994, pl. 2: 4) and abundant *Praeataxioceras*: *Praeataxioceras virgulatus* (Quenstedt) microconch (Atrops, 1982 pl. 19: 3) and *Praeataxioceras ? suevicum* (Siemiradzki) macroconch (Atrops, 1982, pl. 19: 1). Above this assemblage some rare ammonites are present: *T. hauffianum* and a primitive *Subnebrodites* of the *S. proteron* group (Atrops, 1994, pl. 1: 1) which characterize the Hauffianum Subzone and the Planula Zone.

The Saint-Geniez (Baronnies) section (Atrops, 1994) shows some unusual features which makes it distinct from the successions normally recognized in the Subalpine basin from the Hypselum Zone up to the Upper Kimmeridgian. These are, most of all, the reduced thickness (only 25 m for the interval Bimammatum–Planula, instead of 70 m in the Châteauneuf-d'Oze section), and the presence of the "Grumeleux" facies. The Saint-Geniez area might be interpreted as representing a relatively shallow shoal area. The lower part of the section (7 m), has yielded, in a 3 m interval, a rich assemblage of ammonites characterizing the Bimammatum Subzone of the Bimammatum Zone: *Epipeltoceras bimammatum*, *E. treptense*, *Taramelliceras costatum*, *Orthosphinctes* aff. *tiziani* and *Praeataxioceras virgulatus*. Higher, the deposits become more hard and massive, ranging from the Hauffianum Subzone (9 m) to the Planula Zone (8 m). As in Les Vans and Crussol sections, the ammonites *Orthosphinctes tiziani* and *Taramelliceras* (*Metahaploceras*) are frequent, particularly in the Hauffianum Subzone.

In Provence, on the southern margin of the Dauphinois basin (Haute-Provence Subalpine chains, Castellane arch), the transitional area between the platform deposits (Provençal Platform) and basinal deposits (including the "Terres Noires" of the Lower Oxfordian and the base of the Middle Oxfordian) is well developed. This area includes the most fossiliferous sections, from the Bifurcatus Zone to the Bimammatum Zone (Duong, 1974; Lhamyani, 1985; Atrops *et al.*, 1989). Higher, in the sections, the ammonites become rare, and the Hauffianum Subzone and the Planula Zones are more difficult to recognize within the compact calcareous succession. As in the "Ardèche" facies zone, the succession shows important stratigraphical gaps (Upper Callovian, Lower Oxfordian, base of the Middle Oxfordian) and is characterized by the presence of the "Grumeleux" facies. The thicknesses of the deposits are much smaller than in Ardèche; the interval from the Transversarium to the Bimammatum zones attains only 11 m in maximum thickness.

The whole area around Castellane has many sections which are very fossiliferous, and generally of smaller thickness (Le Teillon, Chabrières, and others) (Duong, 1974; Lhamyani, 1985; Atrops, 1994). In the Teillon section, the Bifurcatus Zone with 5 m thickness is well characterized by numerous *Dichotomoceras*. Just above, *E. semimammatum* occurs in the reference hard "Brown Bank" (0.65 m thick). The interval Hypselum–Bimammatum (6 m in thickness) shows the classical faunal sequence from *E. semimammatum*, to *E. berrense*, and to *E. bimammatum*. In the Chabrières section, the deposits are still thinner (2.80 m for the Bifurcatus Zone, 2.30 m for the Hypselum Zone). The Hypselum Zone is characterized by numerous *Euaspidoceras* with *E. hypselum* at the top of the zone. The succession of the *Epipeltoceras* species is also very clear: *E. semimammatum* (Quenstedt), *E. semiarmatum* (Quenstedt), *E. berrense* (Favre). Just above, the boundary of the Bimammatum Zone is indicated by the presence of *E. bimammatum* morphotype alpha (Bonnot *et al.*, 2009) which is followed, immediately at the base of the "Rauracian" cliff, by typical *E. bimammatum*, showing a more advanced morphology. This section is very important for studying in detail the boundary between the Hypselum and the Bimammatum zones.

In conclusion, in southeastern France, there are many reference sections showing a full development of the Bimammatum Zone. The best are located in Ardèche (Les Vans and Crussol sections) showing a complete succession of the *Epipeltoceras* of the *bimammatum* group. The appearance of index-species is particularly important for recognizing the base of the zone, and thus establishing the boundary between the Oxfordian and Kimmeridgian. The Trept section (Enay, 1962, 1966), near Lyon, is also a good section for stratigraphical study: the Hypselum and Bimammatum zones attain here about 17 m in thickness (5 m of the Bimammatum Zone), and present a well recognized succession of *Epipeltoceras*. The ammonite faunas in southeastern France are clearly of Submediterranean – Mediterranean character, and those of Subboreal/Boreal affinity occur very rarely (no reported Boreal *Amoeboceras* in the Bimammatum Zone, and very rare specimens in the Hypselum Zone and the Hauffianum Subzone–Planula Zone interval).

NEW SECTIONS FROM THE THE SOUTHWESTERN IBERIAN RANGE AND PRE-BETIC ZONE OF SPAIN

The Oxfordian–Kimmeridgian Submediterranean–Mediterranean ammonite successions in the southwestern Iberian Range and the Pre-Betic Zone of Spain were the subject of several studies (*e.g.* Meléndez, 1989; Olóriz and Rodríguez-Tovar, 1993; Olóriz *et al.*, 1999) and can be considered as representative of the southern Submediterranean region. A study of the Fuentelespino de Moya sections in the westernmost part of the Castilla – La Mancha region, currently being undertaken, concentrates mostly on the succession of the Upper Oxfordian and basal Kimmeridgian as interpreted herein. The full description of the section and its ammonites will be published elsewhere, but some preliminary data by B.A. Matyja, F. Olóriz and A. Wierzbowski are presented herein. The section is of wider importance because it shows a full succession of the Mediterranean–Submediterranean ammonites which may be compared with those described above from Submediterranean sections yielding also Boreal and Subboreal ammonites.

The Bifurcatus Zone is well characterized by the occurrence of the ammonites *Perisphinctes* (*Dichotomoceras*) spp. together with fairly common oppeliids – mostly *Ochetoceras* represented by *O. basseae* (Fradin), and *O. hispidiforme* (Fontannes). The base of the zone is marked by the common occurrence of *Larcheria*. The top of the zone is marked by the disappearance of *Dichotomoceras*, and the first ammonites appearing above are Passendorferiinae especially of the genus *Graefenbergites*, possibly belonging to *G. idoceratoides* (Dorn) which indicates the base of the Hypselum Zone. This zone is characterized by the occurrence of oppeliids, mostly *Ochetoceras*, as in the underlying Bifurcatus Zone deposits, but associated with very numerous aspidoceratids – including *Euaspidoceras* (which appears already in the uppermost part of the Bifurcatus Zone together with *Mirosphinctes*), *Neaspidoceras*, and associated representatives of the genus *Epipeltoceras*. The latter enables recognition of the Semimammatum Subzone (with *E. semimammatum*), the Semiarmatum Subzone (with *E. semiarmatum*) and the Berrense Subzone (with *E. berrense*). The top of the Berrense Subzone is marked by the appearance of forms transitional between *E. berrense* and *E. bimammatum*. The detailed ranges of some ammonite groups in the Hypselum Zone, as recognized in the Fuentelespino de Moya sections, are very similar to those described previously in other areas in Europe of the Submediterranean Province (see *e.g.* Bonnot *et al.*, 2009; Wierzbowski A., Matyja, 2014b), and the results shown below are important for more general stratigraphical correlations: (1) *Euaspidoceras* commonly occurs in the lower part of the Hypselum Zone; (2) *Neaspidoceras* is recorded somewhat higher, at the top of the Semimammatum Subzone; (3) the oppeliids become very common in the upper part of the Hypselum Zone, in the Berrense Subzone, and are represented by both small, weakly ornamented forms of the *Taramelliceras* (*Richeiceras*) group and more heavy ornamented forms *T.* (*Taramelliceras*) *costatum* (Quenstedt); (4) the first representatives of *Ochetoceras marantianum* (d'Orbigny) occur in the uppermost part of the Berrense Subzone.

Some of these observations are important for stratigraphical interpretation of the Oxfordian/Kimmeridgian boundary in other sections studied in more northerly areas of the Submediterranean Province which do not yield the aspidoceratids important for stratigraphical subdivision of the Hypselum Zone. For example in the Wieluń Upland, central Poland, the co-occurrence of the first representatives of *Taramelliceras costatum* (Quenstedt) and *Ochetoceras marantianum* (d'Orbigny) may be treated as indicative of the upper part of the Berrense Subzone (see Figs 5–6). The observations given above shed also some light on the stratigraphical position of the Oxfordian/Kimmeridgian boundary in extra-European areas, as discussed below.

NORTHERN IRAN

Upper Jurassic ammonite successions of Submediterranean–Mediterranean character occur mainly in northern Iran (Seyed-Emami, Schairer, 2010 and references therein): (1) Alborz Mountains (Dalichai and Lar formations), northern Iran; (2) Binalud Range (Dalichai Formation), northeastern Iran; and (3) Koppeh-Dagh (Chaman-Bid and Mozduran formations), northermost East Iran (palaeogeographically related to the southern Russian Platform). Oxfordian–Kimmeridgian successions are known also from the Tabas Block of Central Iran (Schairer *et al.*, 2003; Wilmsen *et al.*, 2009, and references therein). Ammonites have rarely been described from stratigraphically controlled, bed-by-bed sampling, and the summary given below refers to more recent papers based on such successions.

In northern East Alborz there is at least one section, in the region of Rostam-Kola, which has yielded a small, but controlled ammonite collection of the Hypselum-Bimammatum zones, described by Parent *et al.* (2012). The ammonite succession, from below, consists of the three successive ammonite-assemblages: (1) *Passendorferia ariniensis* Meléndez and *Passendorferia uptonioides* (Enay), indicating the upper Bifurcatus to lower Hypselum zone interval; (2) *Passendorferia gygii* (Brochwicz-Lewiński et Różak) and *Orthosphinctes* sp. B, indicating almost certainly the upper Hypselum to lower Bimammatum zone interval; and (3) *Orthosphinctes* sp. A (in isolation), as well as several specimens from the top of the section closely resembling *Orthosphinctes tiziani* (Oppel) of the Bimammatum Zone.

From an outcrop in a region of the eastern Alborz/northern Binalud Mountains, Seyed-Emami and Schairer (2010, 2011) have described two ammonite-assemblages which also seem to range from the Bifurcatus-Hypselum zones through the base of the Bimammatum Zone. The lower assemblage (Seyed-Emami, Schairer, 2011) consists of *Perisphinctes* (*Dichotomoceras*) *crassus* Enay/*Perisphinctes* (*Dichotomoceras*) *bifurcatoides* Enay, *Taramelliceras* aff. *costatum* (Quenstedt), *Ochetoceras semifalcatum* (Oppel), *Ochetoceras* cf. *marantianum* (d'Orbigny), and *Euaspidoceras* cf. *striatocostatum* (Dorn). From the known stratigraphic ranges of most of the species cited it can be assumed that this assemblage corresponds to the upper Bifurcatus–

lower Hypselum zone interval of the Upper Oxfordian. The upper assemblage (Seyed-Emami, Schairer 2010) does include some similar forms but the assemblage is significantly different and younger, including also: *T. costatum*, *O.* aff. *marantianum*, *O.* aff. *tiziani*, *Praeataxioceras* sp. (microconch), *Epipeltoceras bimammatum* (Quenstedt), *Euaspidoceras* cf. *striatocostatum*, and *Physodoceras wulfbachense* Schweigert et Callomon. The occurrence of *E. bimammatum* and *Physodoceras* is indicative of the Bimammatum Zone, and the assemblage thus corresponds already to the lowermost Kimmeridgian as accepted herein.

OXFORDIAN/KIMMERIDGIAN BOUNDARY IN OTHER TETHYAN AND INDO-PACIFIC AREAS

The key criteria for recognition and definition of the boundary are best documented in Europe, so that only a few other areas have yielded data that merit discussion, including (Fig. 8) the territory of the middle part of the Americas (mostly Cuba and Mexico), the Southern America (Chile and Argentina), and some parts of southern Asia – including western India (Kachchh Basin) and Nepal (Spiti Shales).

CENTRAL AMERICA (CUBA, MEXICO)

The celebrated Upper Oxfordian ammonite assemblages of western Cuba were studied in detail by Wierzbowski A. (1976), Myczyński (1976), Kutek *et al.* 1976 (and earlier papers cited therein). An older assemblage includes closely related perisphinctids ("Cuban" genera – such as *Vinalesphinctes*, *Cubasphinctes* and so-called "Cuban *Discosphinctes*"), some oppeliids – *Cubaochetoceras* and *Ochetoceras* along with *Glochiceras*, and some *Euaspidoceras*. It was correlated with parts of the Transversarium Zone (uppermost Middle Oxfordian), and of the Bifurcatus Zone (lowermost Upper Oxfordian) by Wierzbowski A. (1976), or only with the Bifurcatus Zone (Myczyński *et al.*, 1998).

The perisphinctid ammonites cited, corresponding to the subfamily Vinalesphinctinae Meléndez et Myczyński, are interpreted as having their roots in the European subfamily Prososphinctinae Głowniak. These forms colonized the Caribbean province during the Middle and early Late Oxfordian with the opening of a new east-west marine connection between the Mediterranean Tethys and the Central Atlantic area – the so-called Hispanic Corridor. Here they developed in partly isolated environments under environmental stress conditions (Meléndez *et al.*, 1988; Olóriz *et al.*, 2003; Głowniak, 2012). The palaeobiogeographic changes in the Mexico–Caribbean area were related also to development of a deep sea-way between the proto-Gulf of Mexico and the Central North Atlantic basin already during Middle Oxfordian (*e.g.* Cobiella-Reguera, Olóriz, 2009).

Younger ammonite assemblages in western Cuba are composed almost entirely of aspidoceratids. Two sequential assemblages may be distinguished (Myczyński, 1976; see also Myczyński *et al.*, 1998): a lower one dominated by *Euaspidoceras* and *Mirosphinctes*, and an upper one composed mostly of *Cubaspidoceras* and *Mirosphinctes*. There are also some oppeliids – *Ochetoceras* and *Glochiceras*, and very rare perisphinctids. With reference to possible derivation of the ammonite assemblages from Tethyan ones, it should be noticed that *Epipeltoceras* (as well as their possible dimorphic counterparts – *Clambites* and some related *Euaspidoceras*, see Bonot *et al.*, 2009; Wierzbowski A., Matyja, 2014b) are for palaeoecological reasons absent in Cuba, as in other extra-European areas). A consequence of this observation may be that Cuban *Euaspidoceras* and *Cubaspidoceras* (macroconchs) and related *Mirosphinctes* (microconchs) represent a separate phylogenetic lineage from that of Mediterranean *Clambites* and *Epipeltoceras*. The lineage of ammonites *Euaspidoceras* and *Neaspidoceras* (similar and related to *Cubaspidoceras* – which possibly represent a highly specialized segment of the lineage) but mostly without *Mirosphinctes* from the Hypselum Zone in Europe (although some ammonites of this genus are reported from Spain and Portugal – see Myczyński *et al.*, 1998, and earlier papers cited therein) may be thus treated as a possible counterpart of the Cuban lineage in question. According to observations from the European sections given above it may be concluded that a lower Cuban ammonite assemblage dominated by *Euaspidoceras* may be correlated with the similar assemblage in Europe recognized in a lower part of the Hypselum Zone; on the other hand an upper assemblage with *Cubaspidoceras* may be correlated with the assemblage with common *Neaspidoceras* occurring in the middle and upper parts of the Hypselum Zone. It should be also remembered that the Cuban perisphinctid referred to as *Perisphinctes* (?*Otosphinctes*) *wierzbowskii* by Myczyński (1976, pl. 11: 6a, b) seems very close to an early representative of the genus *Praeataxioceras* which is transitional to an older passendorferiid genus *Graefenbergites* as described by Wierzbowski A. and Matyja (2014b, pl. 7: 5; see also similar form illustrated by Bonnot *et al.* 2009, pl. 1: 7a, b) from the middle part of the Hypselum Zone in Europe.

The youngest ammonite found in the Cuban succession, well above the youngest *Mirosphinctes*, is an oppeliid of the genus *Metahaploceras* (Myczyński, 1994, pl. 1: 4–6; Myczyński *et al.*, 1998) indicating the Bimammatum Zone (lowermost Kimmeridgian). This ammonite occurrence underlies the appearance of a sedimentary breccia and subsequent shallow-carbonate deposits in the Jurassic succession of western Cuba interpreted as a consequence of tectonic uplift at the Oxfordian/Kimmeridgian boundary (Pszczółkowski, 1999; Cobiella-Reguera, Olóriz, 2009, with earlier papers cited therein).

The ammonite assemblages of the Upper Oxfordian and lowermost Kimmeridgian in Mexico were discussed recently by Villaseñor *et al.* (2012, with earlier papers cited therein). Several ammonite assemblages can be distinguished in central-east Mexico including one with *Vinalephinctes* attributed to the Bifurcatus Zone, and a directly younger one with *Euaspidoceras* and *Praeataxioceras* attributed to a lower part of the Bimammatum Zone *sensu lato* (López-Palomino in Villaseñor *et al.*, 2012), *i.e.* corresponding mostly to the Hypselum Zone. The occurrence of *Praeataxioceras* together with *Metahaploceras* in the Sierra Madre sections indicates the Bimammatum Zone and possibly the Planula Zone of the lowermost Kimmeridgian (Myczyński *et al.*, 1998). The youngest ammonites recorded in the carbonates of the Zuolaga Group in Mexico, as well as in their lateral equivalents in the southern United States (Smackover Fm., and its lateral equivalents), indicate the presence of the Bimammatum Zone, and locally even possibly the upper part of the Bimammatum Zone and/or a lower part of the Planula Zone (Olóriz *et al.*, 2003; Villaseñor *et al.*, 2012).

A widespread regional unconformity occurs across the northern rim of the Gulf of Mexico, at the top of the deposits of the shallow carbonate shelf system discussed above. The overlying deposits are mixed carbonate-fine siliciclastic rhythmites which yielded ammonites of the upper Platynota to lower Hypselocyclum zones of the Lower Kimmeridgian. These data indicate that the hiatus with non-deposition, and erosion, prevailed during shallowing trends at the Oxfordian–Kimmeridgian boundary interval over wide areas of Cuba, north-central Mexico and the northern rim of the Mexican Gulf basin (Olóriz *et al.*, 2003; Cobiella-Reguera, Olóriz, 2009).

SOUTH AMERICA (CHILE AND ARGENTINA)

Several ammonite assemblages from the Oxfordian of northern Chile were described by Gygi and Hillebrandt (1991). The assemblages with *Gregoryceras* corresponding to the Transversarium Zone and lowermost Bifurcatus Zone contains in its upper part also some representatives of *Vinalesphinctes* as well as *Perisphinctes* (*Dichotomoceras*) and forms referred to as *Subdiscosphinctes* – closely comparable with “Cuban *Discosphinctes*”. The younger assemblage is composed dominantly of aspidoceratids (*Euaspidoceras*, *Cubaspidoceras*, *Mirosphinctes*) and possibly *Praeataxioceras* (see Myczyński *et al.*, 1998) indicating the presence of the Hypselum Zone. Still higher there occur perisphinctid ammonites attributed to such European genera/subgenera as *Orthosphinctes–Lithacosphinctes*, including also a form referred to as “*Idoceras* cf. *neogaeum* Burckhardt” by Gygi and Hillebrandt (1991) which is possibly *Geyssantia* according to Myczyński *et al.* (1998). This assemblage may thus be attributed to the Bimammatum Zone, *i.e.* to the lowermost Kimmeridgian (*cf.* Meléndez, 1989; Myczyński *et al.*, 1998).

Relevant ammonite assemblages have been described recently by Parent (2006) from the Neuquén-Mendoza basin of Argentina. The stratigraphical interval correlated with the upper Bifurcatus and lower Bimammatum (*i.e.* the Hypselum Zone) yielded fairly common aspidoceratids: *Euaspidoceras* with its microconch *Mirosphinctes* and corresponding to the Tarapacaenense Zone. The younger assemblage, dominated by ammonites compared to the *Orthosphinctes–Lithacosphinctes* group, corresponds to the Desertorum Zone, and is correlated with the Bimammatum and Planula zones (see Parent, 2006, and earlier papers cited therein), *i.e.* the lowermost Kimmeridgian according to classification accepted herein. Several of the studied sections of the Neuquén-Mendoza Basin yielded also some ammonites attributed to the subfamily Vinalesphinctinae and referred to as *Vinalesphinctes*, *Subvinalesphinctes* and *Cubasphinctes* from Lower Oxfordian deposits. This observation differs markedly from the distribution of these genera in other areas of the Americas – especially in the Cuban–Mexico areas where they are known from much younger deposits. According to Parent and Garrido (2015, p. 212) this observation strongly suggests that the Vinalesphinctinae “originated in the Andean region, expanded through the Caribbean (Cuba and Mexico) region during the early Middle Oxfordian, and developed up to the Late Middle Oxfordian in both domains”. This hypothesis is in contradiction with those of Meléndez *et al.* (1988) and Głowniak (2012), as shown above, and additional studies should be undertaken to solve this problem.

WESTERN INDIA

Recent studies in the Kachchh Basin yielded new observations on the ammonite succession at the Oxfordian/Kimmeridgian boundary. The ammonites of the Upper Oxfordian are especially common in the Bifurcatus Zone – mostly its lower part (Stenocycloides Subzone) where numerous specimens of *Perisphinctes*, especially of the subgenus *Dichotomoceras*, many of them close to European forms, are encountered (Pandey *et al.*, 2012, with earlier papers cited therein). Ammonites from the upper part of the zone (the Grossouvrei Subzone) are much less common, and a general stratigraphical hiatus covering the uppermost

Oxfordian and a large part of the Lower Kimmeridgian is present in large areas of the Katchchh Basin (Pandey *et al.*, 2013, with earlier papers cited therein). The only area where this stratigraphical gap is most reduced is north-eastern part of the basin – the so called Wagad Uplift. Studies in that area (Rai *et al.*, 2015) based on nannofossils and dinoflagellate cysts also suggests condensation and reworking in the stratigraphical interval across the Oxfordian/Kimmeridgian boundary. The stratigraphical gaps in the Katchchh Basin discussed above may be related with one of the episodes of rifting during formation of the Malagasy Gulf related to break up of Gondwana, possibly responsible also for changes in temperature of sea-water (Alberti *et al.*, 2012).

NEPAL (SPITI SHALES)

New studies of the ammonite faunas from the Thakkola area in central Nepal showed the presence of a few specimens of aspidoceratid species which could be important for wider correlations. These include: *Neaspidoceras* cf. *tietzei* (Neumayr) together with *Perisphinctes* (*Perisphinctes*) of early Late Oxfordian age (in beds with mayaitids), and along with Indo-SW Pacific perisphinctids (*Sulaites*, *Praekossmatia*). The overlying assemblage with *Paraboliceras* (and the last mayaitids) yielded in its lower part a form referred to as *Clambites* sp. indet./ cf. *spathi* Collignon which suggests an Early Kimmeridgian age (see Enay, 2009). These data shed some light on the stratigraphical correlation between the "classical" Mediterranean ammonite faunas and those of Indo-SW Pacific areas (Enay, Cariou, 1997).

CLIMATIC AND ENVIRONMENTAL CHANGES AT THE OXFORDIAN/KIMMERIDGIAN BOUNDARY

The general changes in climatic/environmental conditions across at the Oxfordian/Kimmeridgian boundary have been the subject of several palaeontological and geochemical papers published recently. The comments given below mostly relate to the European areas.

Abbink *et al.* (2001) analyzed the sporomorph assemblages from boreholes in the southern North Sea, *i.e.* from the area generally corresponding to the Subboreal–Boreal province transition. They showed that the general trend of aridification and warming of the climate which had begun in the Middle Oxfordian was "briefly interrupted in the latest Oxfordian–earliest Kimmeridgian interval by a cooling" especially well pronounced during the late Regulare and Rosenkrantzi chrons of the latest Oxfordian, and successively followed by a warming near the Oxfordian/Kimmeridgian boundary (Abbink *et al.*, 2001, p. 241, fig. 12).

The changes in composition of the ammonite and microfossil faunas in the boreholes of the Peri-Baltic Syneclise in northern Poland show the mixed character of the assemblages corresponding to the uppermost Oxfordian and lowermost Kimmeridgian (Wierzbowski *et al.*, 2015, figs 10–11). The uppermost Oxfordian (Rosenkrantzi, Hypselum and Pseudocordata zones) is characterized by a marked increase in the number of Boreal ammonites interpreted as a renewal of the Boreal Spread reported from earlier, in the Lower and lowermost part of the Middle Oxfordian; on the other hand, the lowermost Kimmeridgian is characterized by a dominance of the Subboreal ammonites.

These changes in faunal assemblages in the northern European areas are well correlated with changes in the depositional environments. The latest Oxfordian marked the decline of shallow-water carbonate and sandy deposits of the British Corallian, whereas the beginning of the Kimmeridgian showed the appearance of a younger Pomerania shallow water carbonate platform. It seems highly probable that the changes in environmental conditions were stimulated to some degree by the tectonic movements which occurred at the Oxfordian/Kimmeridgian boundary in wide areas of northern Europe. These phenomena are reported from Dorset and southern England and the North Sea through the Danish Basin and the Fennoscandian Border Zone of southern Scandinavia, the peri-Baltic Syneclise, and possibly even farther east up to the northern edge of the Russian Platform – the Timan-Pechora Basin (Wierzbowski A. *et al.*, 2015 with earlier papers cited therein). The related stratigraphic unconformity is also interpreted in terms of the sequence-stratigraphical scheme, and these tectonic phenomena may have stimulated the changes in the Subboreal ammonite (Aulacostephanidae) lineage resulting in the appearance of two separate branches – that of *Pictonia* in NW Europe, and another of *Vineta* and *Vielunia* in NE Europe (see Enay, 1980; Wierzbowski A., 2010 a; Wierzbowski A. *et al.*, 2015, and earlier papers cited therein).

Seawater paleotemperatures, and variations in carbon isotope composition in the Middle Russian Sea and in the peri-Tethyan basins of central Europe, corresponding mostly to the northern areas of the Submediterranean province, were discussed recently by Wierzbowski H. *et al.* (2013) and Wierzbowski H. (2015). The $\delta^{18}O$ values of belemnite rostra and brachiopod shells decrease from the top of the Middle Oxfordian up to the Early Kimmeridgian. The decrease may have resulted from an increase in sea-water temperature and local effects related to the shallowing of the basins studied. The data obtained from central European basins are, however, unusually scattered in the uppermost

Oxfordian (uppermost Bifurcatus Zone and the Hypselum Zone up to the boundary with the Kimmeridgian) – which may suggest unstable environmental conditions in those times and areas. Despite the effects of local bathymetry changes and salinity variations, the isotope studies show a world-wide long-term warming trend during the Late Oxfordian–Early Kimmeridgian, which is observed not only in various European basins but also in Arctic and Indo – Malagasian basins (cf. Zakharov *et al.* 2005; Nunn *et al.*, 2009; Žak *et al.*, 2011; Alberti *et al.* 2012; Arabas, 2016, in press).

The $\delta^{13}C$ values of marine carbonate fossils from the peri-Tethyan sections show a general decrease after the Middle Oxfordian, and the lowest carbon isotope values correspond to the stratigraphical interval of the uppermost Oxfordian from the uppermost part of the Bifurcatus Zone and in the Hypselum Zone. The data may show the high level of nutrients and increased productivity of sea water at the Oxfordian–Kimmeridgian boundary interval in the peri-Tethyan basins studied (Wierzbowski H., 2015, figs 9–10). Broadly similar trends of decreasing carbon isotope values at the Oxfordian–Kimmeridgian boundary are reported from Boreal and Mediterranean sections of Europe, although the absolute $\delta^{13}C$ values of marine carbonates vary probably because of changes in the chemistry of the local seawater and the varied origins of carbonates studied (Bartolini *et al.*, 1996; Morettini *et al.*, 2002; Nunn *et al.*, 2009; Wierzbowski *et al.*, 2013; Coimbra *et al.*, 2014; Jach *et al.*, 2014; Arabas, 2016, in press).

Detailed studies of the uppermost Oxfordian deposits (Hypselum Zone) and the lowermost Kimmeridgian in two sections (Katarowa Góra and Bobrowniki) in the Wieluń Upland in central Poland enable correlation between the long-term and short-term fluctuations in the faunal assemblages and in the magnetic and the geochemical data (presented by Grabowski *et al.*, 2015; Wierzbowski A. *et al.*, 2015b, during the 2nd International Congress on Stratigraphy, Graz, July 2015, but the full results will be given elsewhere). The deposits studied consist of bedded limestones and marls of the sponge megafacies of the deep neritic northern Tethyan shelf (Fig. 1). The ammonite faunas occurring here are mostly of Submediterranean character, but Boreal ammonites (Cardioceratidae: *Amoeboceras*) and bivalves (*Buchia*) as well as Subboreal ammonites (Aulacostephanidae) become quite common at some levels (Fig. 9A, B). Longer term, as well as shorter term, variations in the faunal assemblages may be recognized. The former are especially evident and are discussed below. A prominent maximum of occurrence of the colder-water Boreal–Subboreal faunas is observed in the middle of the lower part of the succession (about 6–7 m thick) of the Hypselum Zone of the uppermost Oxfordian in the Katarowa Góra section of the Wieluń Upland – around the "*Amoeboceras* layer" [containing over 70% Boreal cardioceratids (see Fig. 9A and Fig. 10 interval I)]. Another interval, similar in thickness and displaying an increase (but a weaker one) in the number of Boreal–Subboreal faunal elements, is recognized in the upper part of the Hypselum Zone (interval II in Fig. 10). The older deposits corresponding to the upper part of the Bifurcatus Zone of the Upper Oxfordian show another marked increase in Boreal *Amoeboceras* ammonites (Wierzbowski A., Matyja, 2014b; see also Fig. 9A). The deposits of the Hypselum Zone studied in the Wieluń Upland show the occurrence of radiolarian faunas , mostly of Tethyan origin but representatives of the Boreal *Paravicingula* assemblage do occur in the "*Amoeboceras* layer".

The occurrence of Boreal–Subboreal ammonite assemblages in the Hypselum Zone of the uppermost Oxfordian could be related to activity of the marine currents which brought additionally nutrient-rich waters and which enabled the development of the radiolarian assemblages. The action of marine currents along the existing sea-ways between the northern and southern areas of Europe may have been stimulated by the contrasted climate changes during the latest Oxfordian. The content of non-carbonate material in the studied sections of the Wieluń Upland is very low. The content of Al and Rb typically varies between 0.04–0.15%. and 0.5–2.0 ppm respectively (Fig. 10). A relatively higher input of terrigenous material is observed only in the intervals rich in Boreal and Subboreal ammonites (*e.g.* the "*Amoeboceras* layer") which occur in the lower and upper parts of the Hypselum Zone (intervals I and II in Fig. 10). These intervals reveal also relatively higher values of the anhysteretic remanent magnetization (ARM – proxy of fine grained magnetite of presumably detrital origin) as well as the Th/U and P/Al ratios, which points to oxic conditions of the bottom water and increased accumulation of biogenic phosphorus, most probably related to enhanced productivity. These geochemical observations are in good agreement with the palaeoecological observations.

A marked change in faunal assemblages is observed in the upper part of the succession of the Wieluń Upland (Bobrowniki section); *i.e.* in the lowermost Kimmeridgian (Bimammatum Zone). This change corresponds to the decline of colder-water Boreal–Subboreal faunas, and the dominance of warmer-water Submediterranean ammonites (Oppeliidae) (see Fig. 9B). Their dominance follows mostly a well developed, tectonically enhanced omission surface (interval III in the Fig. 10; see also Wierzbowski *et al.*, 2015a) – that is recognized at the Oxfordian/Kimmeridgian boundary over vast areas of northern Europe – delimiting there two environmentally contrasted faunal assemblages. The dominant oppeliids are mostly small-sized nekto-pelagic forms whose occurrence along with the Tethyan radiolar-

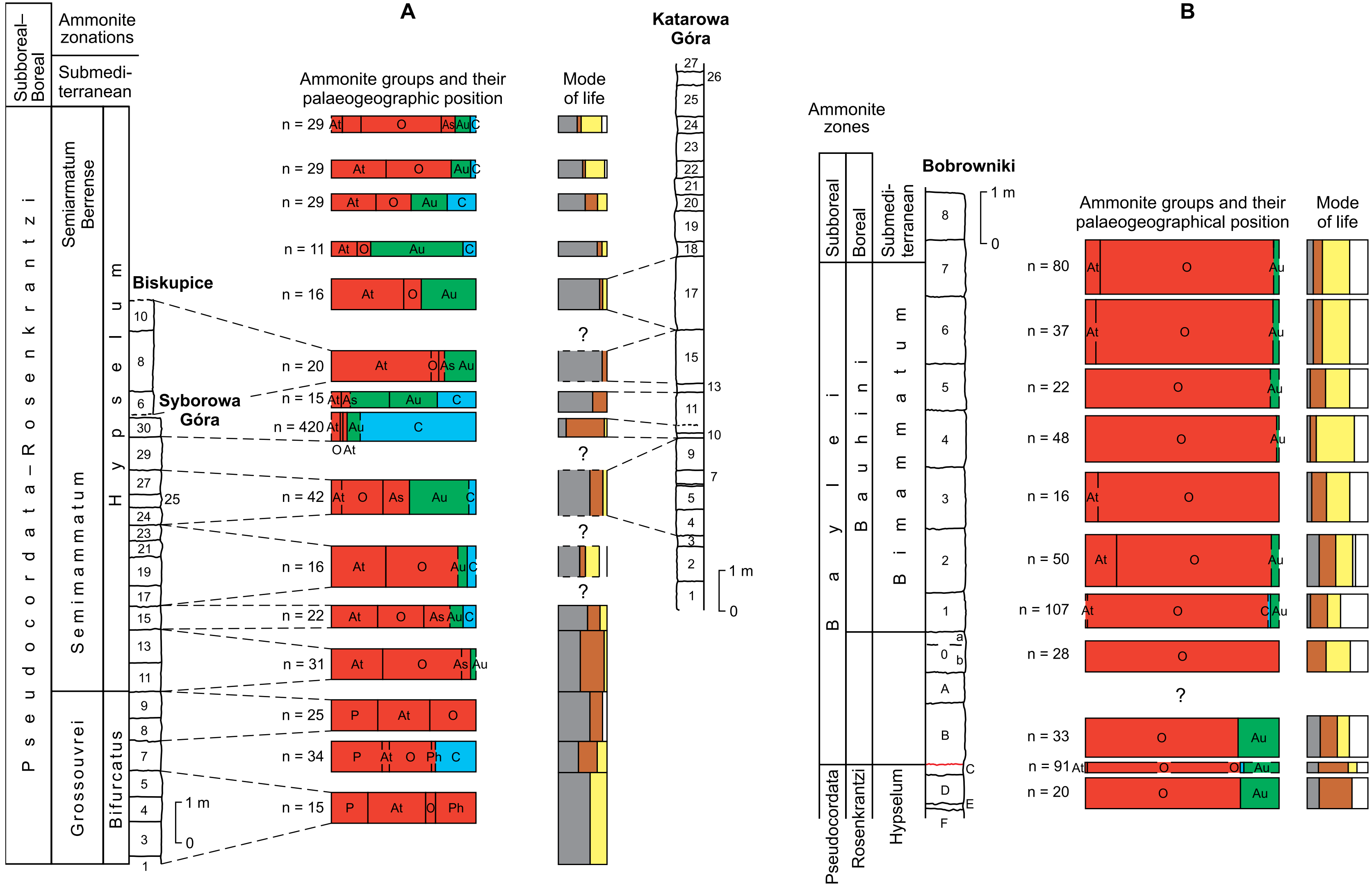
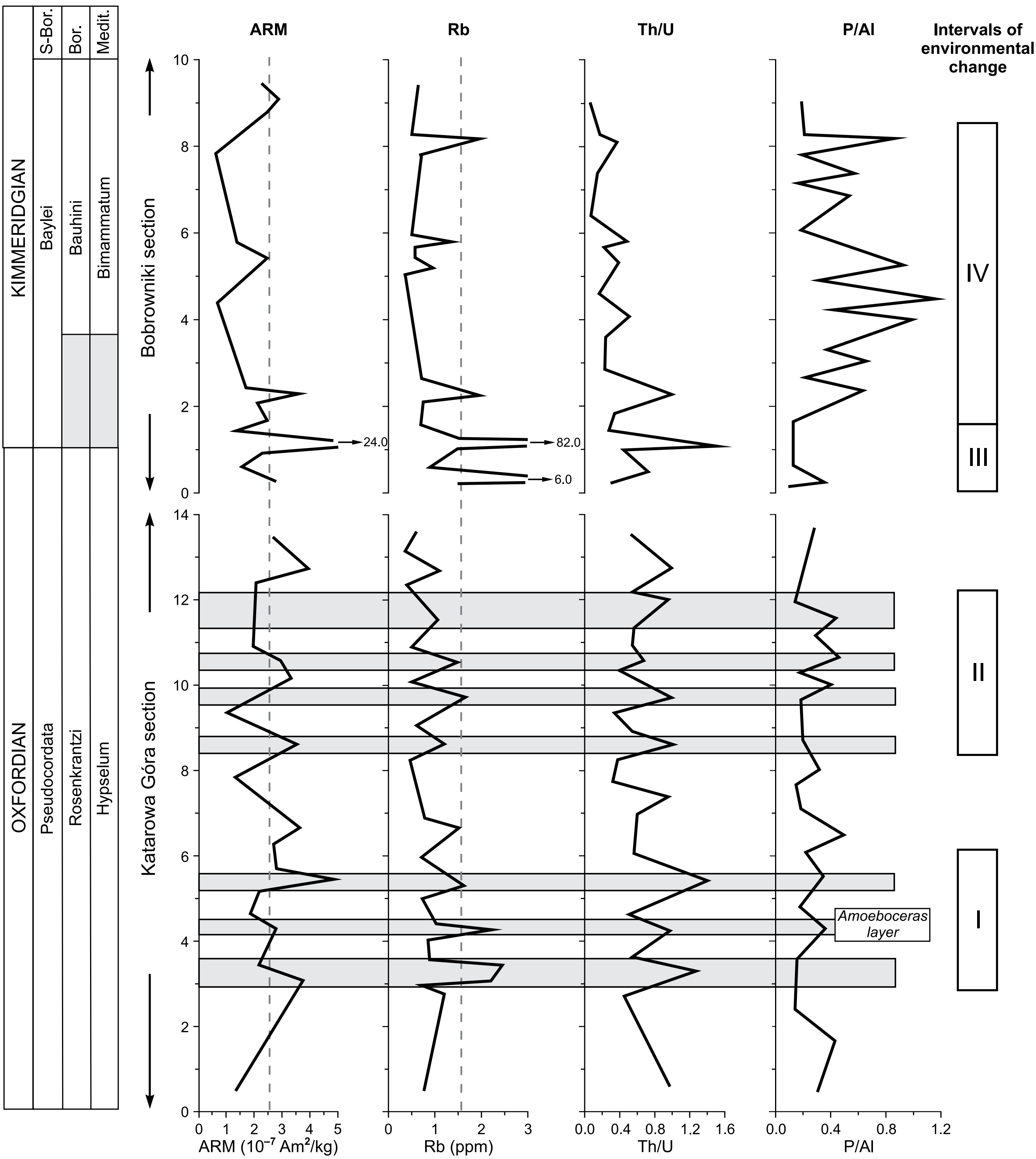


Fig. 9. Frequencies of occurrence of ammonites in the uppermost Oxfordian and lowermost Kimmeridgian in the sections of the Polish Jura (central Poland) studied

A – uppermost Oxfordian at Syborowa Góra, Biskupice and Katarowa sections. B – uppermost Oxfordian and lowermost Kimmeridgian at Bobrowniki section (omission surface at the Oxfordian/Kimmeridgian boundary is shown in red)

Ammonite groups and their palaeogeographic position: red – Mediterranean and Submediterranean (Ph – Phylloceratidae, P – Perisphinctidae, At – Ataxioceratidae and Passendorferiinae, As – Aspidoceratidae, O – Oppeliidae); green – Subboreal (Au – Aulcostephanidae); blue – Boreal (C – Cardioceratidae); mode of life: gray – bentho-nektonic (perisphinctids and aulacostephanids); brown – nekto-benthic (heavy-ornamented Oppeliidae, Cardioceratidae); yellow – nekto-pelagic (Phylloceratidae, small Oppeliidae: *Richeiceras*, *Metahaploceras*, *Coryceras*), white – nekto-benthic and/or nekto-pelagic



KIMMERIDGIAN
OXFORDIAN
S-Bor.
Bor.
Medit.
Baylei
Bauhini
Bimammatum
Pseudocordata
Rosenkrantzi
Hypselum
Bobrowniki section
Katarowa Góra section
ARM
Rb
Th/U
P/Al
Intervals of environmental change
24.0
82.0
6.0
IV
III
II
I
Amoeboceras layer
ARM (10−7 Am2/kg)
Rb (ppm)
Th/U
P/Al

ians indicates the presence of nutrient-rich waters. Within the part of the Wieluń Upland succession discussed a gradual decrease in detrital influx is observed, which is interrupted temporarily only at the Oxfordian/Kimmeridgian boundary, represented by the omission surface, showing an extremely high content of terrigenous elements and magnetic minerals. The upper part of the succession discussed (interval IV in the Fig. 10) is characterized however by generally lower values of magnetic indices and stepwise oxygen depletion of bottom water (decrease of Th/U ratio), when compared with its lower, uppermost Oxfordian part. The productivity index (P/Al) reveals in interval IV higher variations and attains its maximum values. These phenomena might be related to a diminished mixing of seawater when compared with the lower part of the succession studied and an increase in carbonate production either as a result of the long term warming trend, which is documented on the basis of belemnite $\delta^{18}O$ ratios, or the local shallowing of the Polish Jura basin. The abrupt changes in ammonite assemblages are, however, not mirrored in variations in the $\delta^{18}O$ values of nekto-benthic belemnite rostra and benthic brachiopod shells, although the discussed intervals are characterized by scattered $\delta^{18}O$ values, which may indicate an environmental instability (*cf.* Wierzbowski H., 2015).

Summarizing the observations given – the transition from the Oxfordian to the Kimmeridgian (corresponding to the boundary accepted herein) show marked climatic and environmental fluctuations as observed in the vast areas of the Boreal–Subboreal and the Submediterranean basins in Europe and the adjoining Arctic basins. Very unstable conditions of the latest Oxfordian (Pseudocordata–Rosenkrantzi–Hypselum chrons) may have resulted from changes in sea-current activity and short-term cooling of the sea water (possibly in several successive episodes) in some marine basins. Tectonic phenomena additionally modified the palaeogeography in northern Europe (Subboreal Province) at the Oxfordian/Kimmeridgian boundary (see Wierzbowski *et al.*, 2015a, and earlier papers cited therein) and possibly stimulated the climatic changes. A general warming trend observed in the earliest Kimmeridgian (Baylei–Bauhini–Bimammatum chrons) both in the Submediterranean province, especially in its northern areas, but also in the Subboreal–Boreal provinces, has been well proved by stable isotopes and palaeontological data (*e.g.* Abbink *et al.*, 2001; Nunn *et al.*, 2009; Wierzbowski H. *et al.*, 2013; Wierzbowski A. *et al.*, 2015a; Wierzbowski H., 2015). A good example of the latter is the spectacular appearance of small-sized *Plasmatites* at the base of the Boreal Kimmeridgian over wide areas (including the "deep" Arctic) possibly representing the mature paedomorphic (neotenic) forms whose occurrence has been most probably controlled by environmental factors (Wierzbowski A., Rogov, 2013).

The climatic and environmental fluctuations during latest Oxfordian – earliest Kimmeridgian resulted also in changes in the other ammonite groups. The extinction of the genus *Perisphinctes* and the whole subfamily Perisphinctinae in the Submediterranean–Mediterranean provinces, and also in the Indo-Malagasian Province (to the decline of the Mayaitidae), at the Bifurcatus/Hypselum boundary, can be related to the beginning of such fluctuations. Of a similar character might be the disappearance of ammonites of the subfamily Vinalesphinctinae approximately at the same level in the Andean and Caribbean provinces of the Americas. These can also have been stimulated by tectonic phenomena reported from both margins of the Central North Atlantic basin and Western Tethys (Olóriz *et al.*, 2003, and the references therein), as well as from the Malagasy Gulf of the Indo-Malagasian areas (Alberti *et al.*, 2012, and the references therein). On the other hand, successive renewal of ammonite faunas took place during latest Oxfordian, resulting in the appearance of a new ammonite family (Ataxioceratidae) and new groups of ammonites of the families Aspidoceratidae and Oppeliidae at the boundary interval between the Oxfordian and Kimmmeridgian.

←

Fig. 10. Selected magnetic and geochemical element data from the Katarowa Góra and Bobrowniki sections (Wieluń Upland, central Poland) representing the stratigraphical interval at the Oxfordian/Kimmeridgian boundary (the Hypselum Zone – the Bimammatum Zone interval): anhysteretic remanent magnetization (ARM), Rb, Th/U and P/Al

ARM is a rock magnetic proxy for the presence of fine grained magnetite (most probably of detrital origin). Rb is a lithogenic element very well correlated with Al (r = 0.95), quantifying detrital input in the sections. Th/U ratio is applied as a redox sensitive parameter, while the P/Al ratio reflects changes in biogenic phosphorus accumulation related to productivity changes. I, II, III. IV – characteristic intervals of environmental change. Grey stripes: marly limestone horizons where there is the common occurrence of Boreal and Subboreal ammonite species. Note the long term decrease of detrital input and deterioration in oxic conditions. Intervals I and II represent periods of frequent excursion of Boreal and Subboreal ammonites, marked by increased detrital input (maxima of ARM, Rb) and relatively better bottom water oxygenation, manifested by peaks of the Th/U ratio. Most of the peaks correlate with increased productivity proxies (P/Al). Interval III contains the omission surface related to the very large increase of detrital proxies and maximum Th/U ratio. Interval IV is dominated by extremely low detrital input, poor oxygenation of bottom water and large increase of biogenic productivity shown by the common occurrence of small nekto-pelagic Oppeliidae

CONCLUSIONS

The data discussed show that the base of the Subboreal Baylei Zone (placed at the base of the *flodigarriensis* horizon) and the corresponding base of the Boreal Bauhini Zone may be correlated with a narrow stratigraphic interval at the boundary of the Hypselum and Bimmmatum ammonite zones of the Submediterranean/Mediterranean succession, and can be recognized as a perfect candidate for the Oxfordian/Kimmeridgian boundary with a large correlation potential. The boundary is also defined by methods other than palaeontological, including palaeomagnetic, climatic and geochemical data. Such a definition of this boundary in question results in its wide correlation potential and means that it can be recognized in the different marine successions of the World. The changes are likely to be recognizable in terrestrial successions as well. Thus, strongly recommended by us, is the formal recognition of the base of the *flodigarriensis* horizon at the base of the Baylei Zone [placed in the 0.16 m interval (1.24–1.08 m) below bed 36 in sections F6 in the Flodigarry section; see Matyja *et al.*, 2006, figs 2–3; Wierzbowski *et al.*, 2006, figs 3–4] at Staffin Bay on the Isle of Skye, northern Scotland, as the level and site of the Global Stratotype Section and Point (GSSP) for the Oxfordian/ Kimmeridgian boundary, and the base of the Kimmeridgian Stage.

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