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The Oxfordian/Kimmeridgian stage boundary in Late Jurassic sedimentary rocks of the Swiss Jura range

Reinhart A. Gygi · Alain Morard[1]

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Abstract This paper presents a review of the criteria for and limitations to the definition of a usable long distance correlation scheme for the Oxfordian/Kimmeridgian stage boundary, based on the example of the Late Jurassic of the Swiss Jura range. Two main issues and their stratigraphic consequences are more specifically addressed, namely the interpretation of calcareous oolites in terms of depth of deposition and the dependence of ammonite distribution on the paleoenvironment. Calcareous oolites are not diagnostic for depth of deposition, as demonstrated by the conflict with other detailed sedimentary observations. When the sedimentary record is correctly interpreted in terms of water depth, the distribution of ammonites proves to be dependent on the paleoenvironment. Therefore ammonites cannot be directly used as a time correlation tool in a laterally heterogeneous regional context such as the Swiss Jura range. As a consequence, additional proxies are needed to circumvent the limitations of ammonite biostratigraphy in shallow carbonate platform environments. These proxies can ultimately be calibrated with high-resolution ammonite biostratigraphy in basin setting, which remains the most accurate method for long distance time correlation (provided it is not based on endemic or low diversity assemblages). The analysis of the biostratigraphic and lithostratigraphic schemes for the Swiss Jura range with respect to the position of the Oxfordian/Kimmeridgian boundary leads to the conclusion that the former suggestion of a suitable type section on the slope of Summerhalde (3 km NNW of the city of Schaffhausen) has to be replaced by another section outside Switzerland. Indeed, the Oxfordian/Kimmeridgian boundary in northern Switzerland lies within the Knollen Bed (uppermost part of the Gredingensis Zone) rather than at the base of the Reuchenette, Burghorn and Schwarzbach Formations (boundary between Galar and Platynota Zones with low long distance correlation potential).

Keywords Oxfordian · Kimmeridgian · Ammonite biochronology · Boundary stratotype · Swiss Jura range

Deceased: Reinhart A. Gygi.

Reinhart Adolf Gygi died on 7th November 2014 at the age of 78, shortly after the present manuscript was accepted for publication with minor revisions. As I had helped Dr. Gygi by the electronic submission of the original manuscript, I felt indebted to him to bring his last scientific work through. Therefore, in agreement with the Editorial Office, I integrated the corrections and suggestions of the reviewers, hopefully without denaturing the thoughts of the author. However, two points have been revised somewhat more in depth in order to improve the clarity of the publication and insert it into the broader, updated context of the definition of the Oxfordian/Kimmeridgian boundary by the International Subcommission on Jurassic Stratigraphy: (a) References to alternative views on the correlation between Subboreal and Subtethyan ammonite faunas, as well as related taxonomic works, have been integrated; (b) Fig. 1 has been completely redrawn. Instead of the already published classic lithostratigraphic scheme of Dr. Gygi (see for example Fig. 2 in Gygi 2000b or the more elaborate Fig. 1.5 in Gygi 2012), I developed a representation which permits a clearer straightforward comparison of the successive or alternative interpretations as concerns the position of the Oxfordian/Kimmeridgian boundary, based on the example of the northern Switzerland ammonite succession. Dr. Alain Morard (Swiss Geological Survey—swisstopo), 20th January 2015.

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✉ Alain Morard
alain.morard@swisstopo.ch

[1] Federal Office of Topography swisstopo, Wabern, Switzerland

1 Introduction

Stages were originally defined as mappable units characterized by their lithology and the macrofossil assemblage in them. The obsolete stage Corallien that Gressly (1864, p. 96) re-named Rauracien was called after the hermatypic corals present in it. Gygi (2012) concluded that the maximum water depth to the habitat of hermatypic corals in Oxfordian sediments in northern Switzerland was approximately 20 m. This figure is comparable with the maximal water depth to hermatypic corals in the Recent. Plate-like colonies of living hermatypic corals were found in exceptionally clear water in the Red Sea at the water depth of as much as 160 m (Insalaco in Gygi 2012, p. 130). Large bivalves of the genus *Pholadomya* gave the name to the old stage Pholadomyen of Etallon (1862). The maximal water depth to the habitat of large Oxfordian bivalves of the genus *Pholadomya* was approximately 30 m. Hermatypic corals and infaunal bivalves such as *Pholadomya* are called *facies fossils*.

The Oxfordian and Kimmeridgian stages were conceived in their present form by the international congress "Colloque du Jurassique" held in Luxembourg in 1962 (proceedings published in Maubeuge 1964). The congress defined the two stages based on the succession of the vertical ranges of selected *ammonite taxa*. The modern and *revised* ammonite zones of the Oxfordian and Kimmeridgian stages in northern Switzerland are listed in Gygi (2012, Fig. 1.6 on p. 16). These zones are defined and described in Gygi (2012) from p. 133. The ammonite zones of the Late Oxfordian and Early Kimmeridgian in northern Switzerland are shown in Fig. 1 of the present paper.

The name of the Oxfordian Stage refers to the university city of Oxford in southern England, whereas the Kimmeridgian Stage is named after the village of Kimmeridge on the British south coast. The oldest ammonite zone in the Kimmeridgian of southern England is the Baylei Zone, which is the primary standard for the base of the Kimmeridgian Stage in the Subboreal Faunal Province according to the resolution by the international congress Colloque du Jurassique Luxembourg recommendation published on p. 85 in Maubeuge (1964). Although the zonal index *Pictonia baylei* Salfeld occurs in England, northern Scotland and northern France, it is unsuitable for long distance correlation. Furthermore, it has been repeatedly evidenced that the succession is incomplete in southern England (Arkell 1947, Fig. 16, Wright 2010).

Some stratigraphers proposed to define the Oxfordian/Kimmeridgian boundary stratotype in a section in the intertidal zone off the shore of Staffin Bay at Flodigarry, Isle of Skye in northwest Scotland. This section was accepted in 2007 by the Kimmeridgian Working Group of the International Subcommission on Jurassic Stratigraphy as GSSP for the Kimmeridgian. The exact level where the boundary should be drawn is still debated (Wierzbowski 2008, 2010). As this section is difficult to correlate with sections in the Subtethyan and Tethyan Faunal Province on the European Continent, the Kimmeridgian Working Group also agreed that a secondary stratotype needs to be defined for the Subtethyan Province. In our opinion, it is rather the primary boundary stratotype that should be chosen somewhere in the Subtethyan Faunal Province in a section including ammonites of both the Boreal and the Tethyan Faunal Province. As biodiversity of faunas increases from near the geographic poles toward the equator (see below), such a section would also have much more abundant and diverse ammonite assemblages. Schweigert et al. (2002, p. 311) proposed a potential section on Mt. Plettenberg near Schömberg in southern Germany. The section was not published and approved to date. The question of how to delimitate the Oxfordian from the Kimmeridgian Stage on a global scale therefore remains largely open.

Ammonites living in the Late Jurassic in the area where northern Switzerland is at the present time were numerous in marine environments from a minimal water depth of approximately 30 m downward. This is visualized in Gygi (2012, Fig. 4.9 on p. 52). Ammonites were for a long time thought to have been living independently of the environment and mainly of water depth. Ammonites were therefore called *guide fossils* until Scott (1940) documented that the composition of ammonite assemblages in Cretaceous epicontinental sediments in the state of Texas, USA, varied with the depth of deposition of the corresponding sediments (see also Batt 1989 for a more recent review). Scott concluded from this that ammonites lived in close relation to the sea floor and that their mode of life was nectobenthic. The same was concluded from ammonite assemblages in epicontinental sediments of the Late Jurassic in Europe by Ziegler (1967). Ziegler (1963) therefore properly referred to *ammonites as facies fossils*. Data published by Gygi (2012) are ample evidence that ammonite fossils in Late Jurassic strata in northern Switzerland are closely related to the paleoenvironment in their habitat. Mainly *water depth of sedimentation* (Gygi 2012, Fig. 4.9 on p. 52 in) and the *rate of sedimentation* of argillaceous mud (Gygi 2012, p. 199) as well as, to a lesser degree, of calcareous mud in the habitat were critical parameters to explain the abundance and the composition of ammonite assemblages. Gygi (2012, p. 198) concluded that the mode of life of most of the ammonites that were found fossilized in Late Jurassic sediments in northern Switzerland was related to the paleoenvironment close above the sea floor. The mode of life of these ammonites was consequently nectobenthic

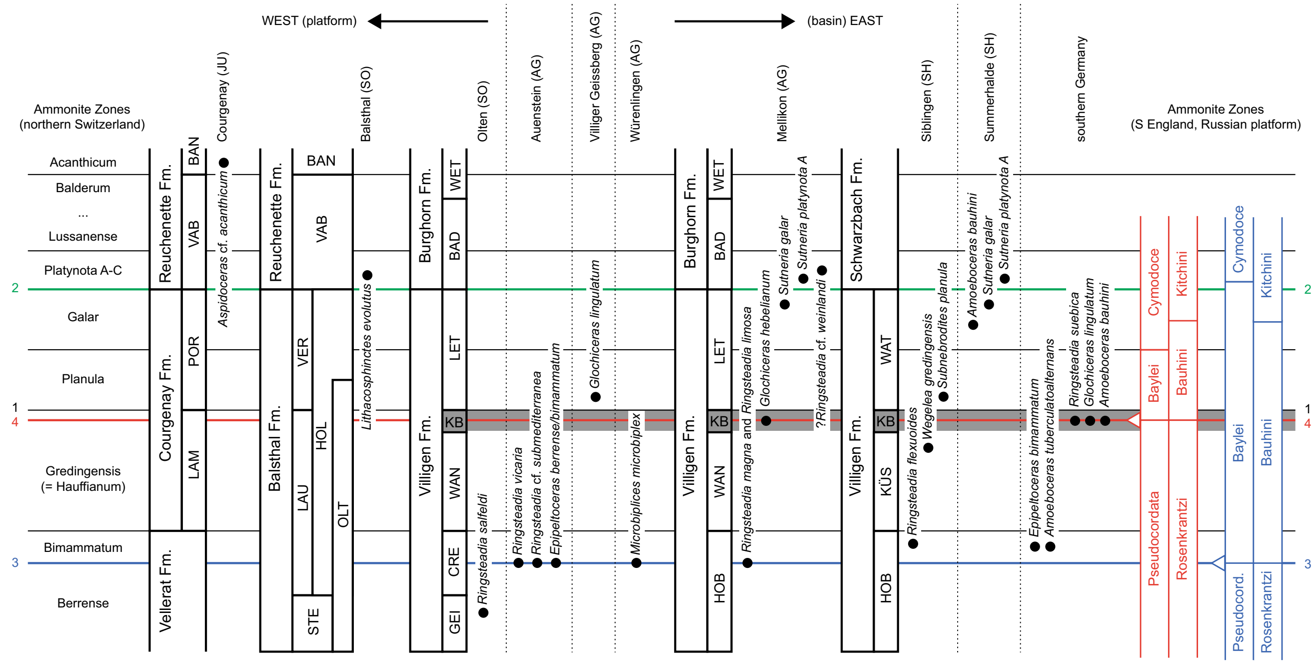

Fig. 1 Position of the Oxfordian/Kimmeridgian boundary in northern Switzerland and southern Germany and alternative correlations with the standard zonation in southern England and the Russian platform according to successive authors (ammonite specimens cited in the text are shown together with the lithostratigraphic succession at the sampling localities): 1. Moesch 1867 (top of Knollen Bed in Aargau) = base of the Subtethyan "Crussolian" sensu Schweigert and Callomon 1997 (top of Bauhini Horizon, whereas the base of the Subboreal Kimmeridgian is correlated with the base of the Bauhini Horizon) 2. (*green*) Heim 1919 (top of Villigen Formation in Solothurn and Schaffhausen) = base of Platynota Zone as defined at the Colloque du Luxembourg (Maubeuge 1964), followed by Atrops (1982), Atrops and Gygi (1990), Gygi (1990) and (2003) = correlation L (Gygi and Persoz 1986) 3. (*blue*) Correlation between the Subtethyan and Subboreal Provinces according to Matyja et al. 2006 (see also Wright 2010 and Wierzbowsky et al. 2010) 4. (*red*) Position of the Oxfordian/Kimmeridgian boundary and correlation proposed in this paper. Abbreviations for Swiss cantons: *AG* Aargau, *JU* Jura, *SH* Schaffhausen, *SO* Solothurn. Abbreviations for lithostratigraphic units: *BAD* Baden Mb., *BAN* Banné Mb., *CRE* Crenularis Mb., *GEI* Geissberg Mb., *HOB* Hornbuck Mb., *HOL* Holzflue Mb., *KB* Knollen Bed, *KÜS* Küssaburg Mb., *LAM* La May Mb., *LET* Letzi Mb., *OLT* Olten Mb., *POR* Porrentruy Mb., *STE* Steinibach Mb., *VAB* Vabenau Mb., *VER* Verena Mb., *WAN* Wangen Mb., *WAT* Wangental Mb., *WET* Wettingen Mb

like that of ammonites in the Cretaceous epicontinental sea in the USA.

The *environment* at the sea floor and especially depth of deposition of an epicontinental sediment can become documented exactly by a *diagnostic sediment* like for instance intertidal stromatolites that were figured by Gygi (2012, Fig. 4.4–4.6). Calcareous ooids in the massive oolite that is the bulk of the Late Jurassic Balsthal Formation (Fig. 1) in the Central Swiss Jura range were accreted on a very widespread sand shoal in sea water less than 6 m deep, according to several authors that are quoted in Gygi (2012, p. 32). These ooids are essentially autochthonous (Gygi 2012, p. 32). The photograph of a Recent sand shoal in the Bahamas where calcareous ooids are in the process of accretion is Fig. 4.7 on p. 50 in Gygi (2012). Common or "normal", more or less autochthonous calcareous oolite rock like that in the Balsthal Formation was distinguished by Gygi (2012, p. 48) from calcareous oolite that was laid down in a small tidal delta like that figured from the uppermost Günsberg Formation in the quarry of La Charuque near Péry in Canton Bern (Gygi 2012, Fig. 5.2 on p. 112). Calcareous ooids in the much larger tidal delta at the basinward margin of the Middle Jurassic carbonate platform of the Hauptrogenstein Formation that is well exposed in the quarries of Oberegg and Unteregg near the village of Auenstein in Canton Aargau were sedimented in water probably up to at least 20 m deep. Gygi (2012, p. 48) concluded from the tidal delta of calcareous ooid sand near Auenstein that calcareous oolite rock in itself is undiagnostic of detailed depth of deposition. The deltaic nature of the marginal part of the carbonate platform of the Hauptrogenstein Formation near Auenstein can be perceived only when the southern wall of the quarries mentioned above is overlooked from a greater distance, like from the northern rim of the quarries.

The Hauptrogenstein Formation in the quarry of Unteregg near Auenstein was interpreted by Gygi (1973, p. 18, and Fig. 3) to be a fossil tidal delta of calcareous ooid sand with the thickness of 60.5 m measured in the western part of the quarry. The delta pinches out entirely below the Aare River east of the eastern end of the quarry of Unteregg. The nearest outcrop east of the Aare River, 1.3 km from the quarry of Unteregg (Gygi 2012, p. 49), is in the quarry of Chalch east of the village of Holderbank in Canton Aargau. There is no trace of Hauptrogenstein in the quarry of Chalch below the early Bathonian Spatkalk Member that is bed no. 3 in section RG 276. Part of this section is represented in Fig. 2 in Mangold and Gygi (1997). Many ammonites in the quarry of Chalch were excavated by R. & S. Gygi from the middle Bathonian iron oolite directly above the Spatkalk Member on August 21, 1991. The specimens were identified by C. Mangold (Lyon) and were figured in Mangold and Gygi (1997). Ample evidence was given by Gygi (1981, 2012, Fig. 4.11 on p. 77) that iron ooids could be *accreted* at times of non-deposition (see Burkhalter 1995) at the surface of calcareous mud in sea water 80–100 m deep in the early Oxfordian Schellenbrücke Bed.

The Late Jurassic, calc-oolitic Balsthal Formation deposited in shallowest water in northwestern Switzerland grades laterally into the well-bedded, micritic limestone of the Villigen Formation that was sedimented in deeper water in Canton Aargau and in even deeper water in Canton Schaffhausen (Gygi 2012, Fig. 1.5). This is a carbonate platform to basin transition. The uppermost part of the Villigen Formation near the city of Schaffhausen with cauliflower pellets of glauconite (such pellets were figured whole and in cross-section in Gygi 2012, Fig. 4.1 A–B on p. 42) was deposited, to conclude from the presence of glauconite according to Gygi (2012, p. 45), at the water depth of at least 100 m. Ammonites are fairly common in the upper Villigen Formation in Canton Schaffhausen mainly because of relatively deep water in their habitat. Few ammonites were found in the upper Villigen Formation from shallower water in Canton Aargau. Probably no ammonites at all were living in the western area where the predominantly calc–oolitic Balsthal Formation was laid down on a carbonate platform in water less than 6 m deep. The very few ammonite casts that *were* found in the Balsthal Formation are assumed to have been moulded from empty shells which surfaced from deeper water after death of the animals within, and then drifted upon the ooid sand shoal and sank there to the sediment surface (see Gygi 1995, Fig. 19 and 20).

The probability that an empty, entire ammonite shell got preserved as a perfectly formed cast must have been low even in small ammonites like for instance in *Glochiceras* (see Gygi 1991, Pl. 1, Fig. 1) or in *Cardioceras* (Gygi and Marchand 1982, Pl. 8, Fig. 1a, b). Well–preserved ammonite fossils are therefore uncommon compared with microfossils. The potential of ammonites in *regional* time correlation is reduced by the fact that ammonites were dependent on the paleoenvironment, and that they are rare or absent in sediments from very shallow water, except for particular episodes of biogeographical or taphonomic dispersal (Fernández-López and Meléndez 1996). A partial solution of this problem in platform to basin time correlation is possible by first calibrating the vertical variation in the content of the clay mineral kaolinite in sediments from deeper water that are well dated with ammonites, and then using the highs and lows of kaolinite content in these sediments as a tool in correlation of basinal sediments with deposits from very shallow water. This method was successfully used by Gygi and Persoz (1986).

Contrary to the comparative inaccuracy or impossibility of time correlation on a *regional scale* using ammonites that were present or absent in epicontinental sediments depending on the paleoenvironment, *long distance* time correlation by means of Late Jurassic ammonites is the most accurate method. Gygi (2012, p. 150) stated that Gygi and von Hillebrandt (1991) made an *intercontinental* time correlation using the ammonite taxon *Gregoryceras transversarium* (Quenstedt) with the accuracy of ± 0.2 % between Switzerland and Chile in South America. One difficulty in long distance correlation is the pronounced provinciality in ammonites that existed for instance in Late Oxfordian time between northern Switzerland and England. Another trend has to be taken into account in the following text. Biodiversity increases from regions near the geographic poles toward the equator. Ziegler (1967, Fig. 14) documented that the diversity of Late Jurassic hermatypic coral assemblages increased from what is now northern Poland southward to Portugal. Strasser (2007) claimed that he could make precise long distance time correlations based on an "astronomical time scale" using the bedding rhythm of micritic limestone. Gygi (2012, p. 28) documented that this is impracticable.

The lithostratigraphic units of Late Jurassic age in northern Switzerland are described in the annotated index by Gygi (2000b). The chronostratigraphic position of the formations, members, and beds is represented in Fig. 2 of that index. Synonymy lists of older names of the corresponding units are included in Gygi (2000a). The re-named Chestel Member was defined in Gygi (2012). The position of relevant ammonite specimens in the rock where they were collected or excavated from in situ is indicated in the assembled cross-section of Late Jurassic, mainly Oxfordian and early Kimmeridgian sediments between the Swiss Central Jura and Canton Schaffhausen that was published by Gygi (2012, Fig. 1.5 on p. 15). An enlarged equivalent of this figure is the foldout in the pocket at the end of the book. The complete and revised succession of ammonite zones in Oxfordian and Kimmeridgian strata in the Swiss Jura range is shown, as mentioned above, in Gygi (2012, Fig. 1.6 on p. 16). All of these, partially new ammonite zones were defined in Chap. 7.3 in Gygi (2012).

2 History of the Oxfordian/Kimmeridgian boundary in northern Switzerland

The lower boundary of the Kimmeridgian Stage was assumed by Moesch (1867, p. 175) to be in Canton Aargau at the top of what he called on p. 169 Knollenbank or Knollenschicht. This thin, slightly glauconitic marker bed at the base of the Letzi Member is here referred to as *Knollen Bed*. Heim (1919, in the foldout table following p. 506) placed the base of the Kimmeridgian in Canton Solothurn above the top of the calc–oolitic limestone of the Verena Member. He assumed the base of the Kimmeridgian in Canton Schaffhausen to be at the boundary between the micritic, well-bedded "β limestones" (now: Villigen Formation) below and the "Reineckianus–Schichten" above. The obsolete ammonite taxon *reineckianus* is a synonym of what is now *Sutneria platynota* (Reinecke). As mentioned above, the international congress Colloque du Jurassique Luxembourg (Maubeuge 1964) published the following recommendation in the proceedings on p. 85: The base of the Kimmeridgian (in southern Germany) is at the base of the ammonite zone of *Sutneria platynota* (Reinecke). Atrops (1982, p. 331) interpreted the base of the Kimmeridgian Stage in southeastern France corresponding to the congress' recommendation. Atrops and Gygi (1990, p. 6) and Gygi (1990, p. 69) as well as Gygi (2003, Fig. 160, p. 140) placed the stage boundary in excavation RG239 in an old quarry at Summerhalde, 3 km NNW of the city of Schaffhausen at the same level (see also Gygi 2012, p. 18). However, it is nowadays widely agreed that the base of the Kimmeridgian Stage in the Subtethyan Faunal Province is considerably older than the base of the Platynota Zone as evidenced by several authors (Schweigert and Callomon 1997; Wright 2010; Wierzbowsky 2010 and references therein). A revision of the stage boundary in northern Switzerland is therefore also necessary.

3 Relevant ammonite taxa and their vertical succession in northern Switzerland

The oldest *Ringsteadia* that was found to date in the Swiss Jura range is *Ringsteadia salfeldi* Dorn from the upper Geissberg Member near Olten. The specimen was figured by Gygi (1995, Fig. 23). The age of the Geissberg Member is the Berrense Zone according to Gygi (2012, p. 141). Most of the specimens of *Ringsteadia* that were found in the Swiss Jura range are from the glauconitic Crenularis Member directly above the Geissberg Member and from the coeval upper Hornbuck Member. The age of the Crenularis Member is transitional between the Berrense and the Bimammatum Zones (Fig. 1). Moesch (1867, Pl. 2) figured *Ringsteadia vicaria* (Moesch) from the Crenularis Member near the village of Auenstein. This specimen can only have been collected from bed no. 30 with some glauconite in the old quarry near locality Fahr east of Auenstein, where Gygi measured his detailed, unpublished section RG 36. This section is schematically drawn in Gygi (1969, upper section in Pl. 19), and it is listed with coordinates in Gygi (2000a, Table 1 on p. 12). *Ringsteadia* cf. *submediterranea* Wierzbowski (taxon belonging to the genus *Vineta* according to Wierzbowski et al. 2010) was figured by Gygi (2003, Figs. 27–29) from the Crenularis Member in Canton Aargau. Giant *Ringsteadia magna* Gygi and *Ringsteadia limosa* (Quenstedt) (latter taxon belonging to the genus *Vielunia* according to Wierzbowski et al. 2010) of somewhat lesser size were figured by Gygi (2003) from the lower Villigen Formation in section RG 70 near the village of Mellikon in Canton Aargau. This section is figured in Pl. 17 in Gygi (1969). The lower part of the Villigen Formation in section RG 70 with a large sponge bioherm is now attributed to the Hornbuck Member of the late Berrense and the Bimammatum Zones. A specimen of *Ringsteadia flexuoides* (Quenstedt) was found in section RG 279 in bed no. 23 of the Bimammatum Zone in the uppermost Hornbuck Member near Siblingen in Canton Schaffhausen. A photograph of the ammonite is in Gygi (2003, Fig. 30 on p. 41). Section RG 279 (originally RG 82b) is figured in Gygi (1991, Fig. 3 on p. 8).

Ringsteadia suebica Gygi was figured in Gygi (2000a, Pl. 12, Fig. 1). This is probably the youngest representative of the genus that was found to date on the European Continent. The ammonite is from Mt. Dreifaltigkeitsberg near Spaichingen in southern Germany. The specimen was kept in the Rollier collection in the ETH Zürich and is now on unlimited loan in the Museum of Natural History in Basel. Some fine-grained glauconite in the ammonite cast is evidence that the specimen was collected from the time equivalent of the Swiss Knollen Bed on the slope of Mt. Dreifaltigkeitsberg at a locality that is not exactly known. A specimen of *Glochiceras lingulatum* (Quenstedt) is adhering to the specimen of *Ringsteadia suebica* figured. The oldest specimen of *Glochiceras lingulatum* as figured by Gygi (1991, Pl. 6, Fig. 5) was found in the lowermost Letzi Member of the Planula Zone, 3 m above the Knollen Bed in the rock called Rütifels at the south rim of the table mountain Mt. Villiger Geissberg northwest of the village of Remigen in Canton Aargau. The probably conspecific *Glochiceras hebelianum* (Würtenberger) that is photographed in Gygi (1991, Pl. 7, Fig. 4) is from the Knollen Bed at locality Mösern east of the village of Reckingen on the north, German side of the Rhine River, north of the Swiss village of Mellikon. The vertical range of *Glochiceras lingulatum* is consequently from the uppermost Gredingensis Zone upward (Fig. 1).

Wierzbowski in Atrops et al. (1993, p. 224) claimed that *Ringsteadia* occurs in Poland in the lower Planula Zone. A doubtful *Ringsteadia* cf. *weinlandi* (Fischer) was found in the glauconitic lower Baden Member in bed no. 124 of section RG 70 near Mellikon and was figured in Gygi (2003, Fig. 144 on p. 127).

Ammonites classically attributed to the genus *Ringsteadia* s.l. are well represented in the upper Oxfordian Stage both in southern England and in northern Switzerland. Nevertheless, they cannot be used in detailed time correlation because taxa do not occurr at the same time in both regions on the one hand, and because of pronounced provinciality on the other hand. Indeed, Wierzbowsky et al. (2010) attributed Subtethyan taxa to the genera *Vineta* Dohm and *Vielunia* Wierzbowski and Glowniak. However all species formerly attributed to the genus *Ringsteadia* s.l. have not yet been properly revised. Moreover a substantial time gap has been demonstrated in southern England (Arkell 1947; Wright 2010). All that can be said is that the total vertical range of specimens attributed to the genus *Ringsteadia* s.l. is in northern Switzerland approximately the same as in southern England.

Epipeltoceras bimammatum (Quenstedt) was cited by Moesch (1867, p. 160) to occur in the Crenularis Member near Auenstein. The original specimen was identified by Gygi (2012, p. 73) to be transitional between the taxon *berrense* Favre and *bimammatum* Quenstedt, and it was figured by Gygi (2000a, Pl. 10, Fig. 5). The ammonite was collected, to judge from the lithology of the cast, out of bed no. 31 with abundant pellets of glauconite in the Crenularis Member in Gygi's section RG 36 east of Auenstein. Typical *Epipeltoceras bimammatum* were found only in adjacent southern Germany in the uppermost Hornbuck Member in section RG 74 in the gully of Steiggraben in the township of Geisslingen (section figured in Gygi 1991, Fig. 4) and in section RG 76 at the altitude of approximately 490 m on the north slope of Hornbuck Hill near Riedern am Sand in the township of Erzingen in the German Unterklettgau. An incomplete, but unmistakeable *Epipeltoceras bimammatum* from bed no. 11 of section RG 76 is figured in Gygi (2000a, Pl. 10, Fig. 4). The specimen is associated with a specimen of *Ringsteadia* sp. in bed no. 10 of the same section according to Gygi (1969, Fig. 2 on p. 53).

Microbiplices microbiplex (Quenstedt) was collected out of bed no. 255 in the glauconitic Crenularis Member in the unpublished section RG 65 that was measured by abseiling in the large, former cementstone quarry near Würenlingen in Canton Aargau. The specimen is figured in Gygi (2003, Fig. 35 on p. 45). The diameter of the ammonite cast is 32 mm. Probably conspecific with it are the two *Microbiplices anglicus* Arkell that are figured in Arkell (1935–1948, Pl. LXXVI, Fig. 6–7). The holotype of this taxon is photographed in Arkell's Fig. 7 and has the diameter of 40 mm. It is from the Sandsfoot Grit in Weymouth in southern England. According to Arkell (1935–1948, p. xli and 378), *Microbiplices anglicus* also occurs in the Westbury Ironstone of the *Ringsteadia pseudocordata* Zone and is confined to that zone. The Westbury Ironstone is possibly the time equivalent of the Swiss Crenularis Member with glauconite pellets.

Ammonites of the genus *Amoeboceras* from northern Switzerland were figured by Atrops et al. (1993). They can be used in correlation of sections in northern Switzerland, that are located in the Subtethyan Faunal Province, with sections in the Boreal Faunal Province. A well-preserved specimen of *Amoeboceras tuberculatoalternans* (Nikitin) was found together with *Epipeltoceras bimammatum* (Quenstedt) in the uppermost Hornbuck Member in bed no. 11 of section RG 76 on the north slope of Hornbuck Hill. The *Amoeboceras* is figured in Atrops et al. (1993, Pl. 1, Fig. 14) and it was re-figured by Gygi (2000a, Pl. 10, Fig. 3). According to Atrops et al. (1993, p. 224), the vertical range of *Amoeboceras tuberculatoalternans* in the Boreal Faunal Province extends upward to the base of the Bauhini Zone. Schweigert and Callomon (1997, p. 30) stated that *Amoeboceras bauhini* (Oppel) in southern Germany first appears in a glauconitic bed that can locally be very fossiliferous. This is most probably the time equivalent of the Swiss Knolllen Bed.

Only one specimen of *Amoeboceras bauhini* (Oppel) was found to date in northern Switzerland. The specimen is from bed no. 9 in excavation RG 239 on the slope of locality Summerhalde 3 km NNW of the city of Schaffhausen. Bed no. 9 belongs to the Galar Zone according to Gygi (2003, Fig. 160 on p. 140) and Gygi (2012, Fig. 1.6 on p. 16). This specimen of *Amoeboceras bauhini* is figured in Atrops et al. (1993, Pl. 1, Fig. 19). The perfectly preserved specimen of *Sutneria galar* (Oppel) from bed no. 18 in excavation RG 239 and the excellently preserved specimen of *Sutneria platynota* (Reinecke), morphotype A Schairer, from bed no. 22 of the same excavation were figured in Gygi (2012, Fig. 7.3E and F). The ammonites of the genus *Sutneria* in section RG 239 allow for time correlation with sections in the lower paleolatitudes of the Tethyan Faunal Province.

4 Lithostratigraphy and time correlation

The lithostratigraphic units in northern Switzerland which are dealt with in the present paper and that are shown in Fig. 1 were described by Gygi (2000b). The sediments of the Middle and Late Oxfordian represent a platform to basin transition. The age of the lithostratigraphic units shown in Fig. 1 in the present paper is indicated according to the succession of ammonite zones, based on figured ammonites, that is also represented in Gygi (2012, Fig. 1.6 on p. 16). The Knollen Bed is an excellent marker bed with some glauconite that was traced by the author from the village of Schönenwerd west of the city of Aarau in northern Switzerland over the non-palinspastic distance of 110 km to Ortenberg Hill near the village of Deilingen in southern Germany. Deilingen is 12 km south-southwest of the major town of Balingen in Baden–Württemberg. The glauconitic marker bed could probably be traced from Deilingen further to the east through the Swabian Alb. The Knollen Bed occurs only in sediments from deeper water. Ammonites in this marker bed are in Switzerland uncommon. They are more numerous in southern Germany in the coeval bed in the region around Balingen. The youngest unambiguous *Ringsteadia, Ringsteadia suebica* Gygi, and the first and probably oldest *Amoeboceras bauhini* (Oppel) in southern Germany both occur in the glauconitic marker bed ("*bauhini*-Faunenhorizont" of Schweigert and Callomon 1997) that is time-equivalent with the Swiss Knollen Bed. This does not necessarily mean that the vertical ranges of the two ammonite taxa overlapped. It is possible that the respective vertical ranges touch each other in the thin marker bed that was sedimented at a particularly low rate.

The slightly glauconitic Knollen Bed in northern Switzerland separates the Wangen Member and the Küssaburg Member in the lower Villigen Formation from the Letzi Member and the Wangental Member in the upper part of the formation (Fig. 1). The thickness of the Knollen Bed is at most localities decimeters like in section RG 62 below the rock of Schrannechopf on Mt. Villiger Geissberg above the village of Villigen in Canton Aargau. Detailed section RG 62 is shown in Gygi (1969, Pl. 17). The Knollen Bed in this section is the conspicuous bed nos. 58 and 59. A photograph of the two beds by the author is shown in Gygi et al. (1998, Fig. 12 on p. 539). This easily accessible outcrop of the Knollen Bed is the best one in Switzerland. The Knollen Bed is continuous and very widespread, but it is inconspicuous in most of the other outcrops. Therefore it was mapped neither in Canton Aargau for instance by Mühlberg (1904) nor in Canton Schaffhausen by Schalch (1916). This important marker bed was not mentioned in the explanatory notes (Erläuterungen) to the map sheets of the Geological Atlas of Switzerland 1:25,000, no. 1069/1049 Frick–Laufenburg by Diebold et al. (2006), in no. 1070 Baden by Bitterli–Dreher et al. (2007), nor in no. 1089 Aarau by Jordan et al. (2011).

The rocky head called Schrannechopf is a southward projection of the southern rim of the eastern spur or promontory of the table mountain Mt. Villiger Geissberg with the ruin of Besserstein overlooking the village of Villigen. Schrannechopf is a prominent rock with the coordinates 657.700/264.080. The name of Schrannechopf is not shown on the map Landeskarte 1:25,000, no. 1070 Baden. The word Schrannechopf can only be read from Grundbuchplan Villigen at the scale of 1:5,000. The outcrop of bed nos. 58 and 59 in section RG 62 directly below Schrannechopf is at the elevation of 525 m. The outcrop is a few meters above the road leading from Villigen upward to Mt. Villiger Geissberg. The conspicuous two beds no. 58 and 59 of the Knollen Bed in section RG 62 are described in Gygi (1969, p. 62). Detailed section RG 62 was assembled from overlapping partial sections that are exposed on both sides of the small valley south of Schrannechopf. The procedure of measuring and assembling section RG 62 is described in Gygi (1969, pp. 61–62), and mainly in Gygi (2012, p. 28).

The accuracy in combining partial sections into section RG 62 was checked in the cliff 400 m northeast of section RG 62 on the north slope of Mt. Geissberg. This was done by descending down the cliff on the rope with a device that is figured in Gygi (2000a, Fig. 4). Thereby section RG 63 was measured in detail. It can be read from the upper assembled section in Gygi (1969, Pl. 19) that the overlapping parts of sections RG 62 and 63 compare well. Combination of partial sections into section RG 62 could thereby be corroborated. Gygi (1969, p. 71) noted that Mühlberg (1904 and 1905, p. 507) confounded the Knollen Bed in section RG 62 at the elevation of 525 m below Schrannechopf with the Crenularis Member. The Crenularis Member in this section did not occur to Mühlberg. The member is well exposed further down along the road at the elevation of 510 m in normal, glauconitic facies in bed nos. 31–37 of section RG 62. No time equivalent of the Knollen Bed can be discerned in the west in Canton Solothurn in the shallow-water facies of the calcareous oolite of the Holzflue Member in the Balsthal Formation, for instance in section RG 438 in Balsthal (Gygi 2000a, Pl. 44). Further to the west, the boundary between the La May Member and the Laufen Member below and the Porrentruy Member and the Verena Member above is probably coeval with the top of the Knollen Bed.

The upper boundary of the predominantly calc–oolitic and mostly massive Balsthal Formation from shallowest water in the west and of the well-bedded, micritic Villigen Formation from deeper water in the east in Canton Aargau and Canton Schaffhausen is conspicuous. The only exception to this is, according to Gygi (2012, p. 19), in the region of Balsthal, Canton Solothurn, in the atypical bed no. 49 in the type section RG 438 of the Balsthal Formation that is shown in Gygi (2000a, Pl. 44). The dip of the Villigen Formation and that of the Schwarzbach Formation directly above near the city of Schaffhausen is very slight or subhorizontal. The limestone of the Villigen Formation weathers there in an escarpment on both flanks of the valley in which the village of Hemmental is located 5 km northwest of the city of Schaffhausen. Marl of the Schwarzbach Formation above the clear-cut upper boundary of the limestone of the Villigen Formation levels off in a slightly inclined plateau on the sides of the valley near Hemmental.

The vertical boundary in Canton Schaffhausen between the Villigen Formation below and the Schwarzbach Formation above could be drawn precisely in excavation RG 239 that was made in 1974 on the slope of locality Summerhalde near the city of Schaffhausen (Gygi 2003, Fig. 160 on p. 140). The formation boundary in section RG 239 is at the top of bed no. 17. This lithostratigraphic boundary almost coincides with the biostratigraphic boundary between the Galar and the Platynota Zones situated *within* bed no. 20 in this section. The index ammonites of the two zones are shown in Gygi (2000a, Pl. 13, Figs. 2–3). In Canton Aargau, in section RG 70 near Mellikon, the corresponding lithostratigraphic boundary between the Letzi Member below and the Baden Member above, was dated by Gygi (1969, Pl. 17) with the ammonites *Sutneria galar* (Oppel) and *Sutneria platynota* (Reinecke). *Sutneria galar* (Oppel) from section RG 70 was figured by Gygi (2003, Fig. 64 on p. 64) and *Sutneria platynota* (Reinecke), morphotype A Schairer, from the same section was figured by Gygi (2003, Fig. 159a on p. 139). Judging from these ammonites, the top of the Villigen Formation in the eastern deeper water region is isochronous between Canton Aargau and Canton Schaffhausen.

The coeval vertical lithostratigraphic boundary between the Balsthal Formation below and the Reuchenette Formation above in the western, shallow-water region is equally clear-cut except, as mentioned above, in the area around Balsthal. The upper boundary of the Balsthal Formation in the landmark rock of Rouge Pertuis north of the village of Undervelier in Canton Jura is conspicuous when seen from a distance. A corresponding photograph of the rock is in Gygi (2000a, Fig. 38 on p. 65) and in Gygi (2012, Fig. 1.7 on p. 19). The well-defined lithostratigraphic boundary between the massive Holzflue Member (Balsthal Formation) below and the well-bedded Vabenau Member above (lowermost Reuchenette Formation) crops out above the village of Rumisberg in Canton Bern on the south side of the summit of Mt. Rüttelhorn. This conspicuous lithostratigraphic boundary is visualized in the detailed section RG 440 of Mt. Rüttelhorn (Gygi 2000a, Pl. 43). The Vabenau Member was defined by Comment et al. (2011) based on a section from the locality L'Alombre aux Vaches (section RG 341), 2.5 km southwest of Courgenay. Gygi (2012 p. 20) defined the Paulin Member only 1 km further to the SW (section RG 350, also type section of the Courgenay Formation, see below) for the same lithostratigraphic succession. *As both units are identical, only the former name should be retained (i.e. the Paulin Member is a junior synonym of the Vabenau Member)[A. Morard].*

Approximate time equivalence of the vertical boundary between the Balsthal Formation below and the Reuchenette Formation above in the region of Balsthal is indicated by the ammonite that was found by Martin (1984) in his section no. 18 in Innere Klus that later became Gygi's section RG 439. F. Atrops (Lyon, France) identified the ammonite to be *Lithacosphinctes evolutus* (Quenstedt). The specimen is figured in Gygi (1995, Fig. 19 on p. 40). Persoz in Gygi and Persoz (1986, Pl. 1B) drew his correlation L at the base of the Reuchenette Formation and of the Baden Member. Gygi calibrated correlation L biochronologically with ammonites in section RG 70 near Mellikon in Canton Aargau. This is represented in Gygi and Persoz (1986, Fig. 14 on p. 435). Part of the abundant ammonites that were collected in section RG 70 is figured in Gygi (2000a and 2003). Some of these ammonites are mentioned in Gygi (1969, Pl. 17). Correlation L is characterized by a sharp upward drop in the content of the clay mineral kaolinite from limestone in the uppermost Letzi Member with *Sutneria galar* (Oppel) into marly limestone of the lower Baden Member above with abundant glauconite and *Sutneria platynota* (Reinecke).

The same, probably coeval upward drop in kaolinite content is conspicuous as well in the shallow-water facies of section RG 307 in the quarry of La Charuque near the village of Péry in Canton Bern. Persoz labeled this section "Reuchenette" in Fig. 10 on pp. 428–429 in Gygi and Persoz (1986). Detailed section RG 307 is represented in Gygi (2000a, Pl. 22). The abrupt upward drop in kaolinite content is attenuated between Péry and section RG 315 in Pichoux Gorge near the village of Sornetan in Canton Bern. Detailed section RG 315 is shown in Gygi (2000a, Pl. 21). This section is closer to ancient land in the northwest which is shown in Gygi (1992, Fig. 1, and 2012, Fig. 1.2). The upward drop in kaolinite content is even less pronounced in the more proximal section no. 4 in Fig. 10 by Persoz in Gygi and Persoz (1986). This is the detailed section RG 350 that was measured in 1981 along the forest road called Chemin Paulin near Courgenay in Canton Jura. Gygi (2000b, p. 129) designated section RG 350 as the type section of the Courgenay Formation. It was measured bed by bed and shown in Gygi (2000a, Pl. 19). A specimen of *Aspidoceras* cf. *acanthicum* (Nr. J30714, Basel Museum of Natural History, illustrated in Gygi 1995 Fig. 17/4) was collected from the Banné Member by A. and H. Zbinden, which dates therefore from the Acanthicum Zone. P. R. Vail and A. L. Coe elaborated sequence stratigraphy in northern Switzerland based on Gygi's detailed sections. Their result was published in Gygi et al. (1998, Fig. 2). Sequence stratigraphy confirmed that the top of the Villigen, Balsthal, and Courgenay Formation is isochronous.

It is obvious for instance from the rock of Rouge Pertuis near Undervelier in Canton Jura or from Mt. Rüttelhorn above Rumisberg in Canton Bern, why Swiss geologists mapping in Canton Jura, Bern, and Solothurn traditionally drew the Oxfordian/Kimmeridgian stage boundary at the base of the Vabenau Member in the lowermost Reuchenette Formation. The corresponding stage boundary in Canton Aargau was drawn to date at the base of the Baden Member in the lower Burghorn Formation, and in Canton Schaffhausen at the base of the Schwarzbach Formation. Gygi (2012, p. 21) therefore suggested that the major excavation RG 239 that was made in 1974 on the slope of Summerhalde above an old quarry beside the road leading from the city of Schaffhausen to the village of Hemmental would be a suitable type section of the Oxfordian/Kimmeridgian stage boundary on the European Continent. Section RG 239 was figured by Gygi (2003, Fig. 160 on p. 140). Approximately thousand well-preserved ammonites were collected bed by bed in excavation RG 239. Out of these, about 600 specimens are prepared. The ammonites prepared were studied by F. Atrops (Lyon, France) during a total of 4 weeks in the Museum of Natural History in Basel, where all of the macrofossils collected in excavation RG 239 are stored. Atrops did not publish as yet the relevant ammonites from the excavation.

5 Conclusion

It follows from this study that ammonites alone are insufficient in *regional* time correlation in northern Switzerland, because varying paleoenvironments were the cause of presence or absence of ammonites in the rocks in that region. This is documented by some rock types like for instance calcareous oolite, whether sedimented normally or shed into a tidal delta. Ammonites were not living in environments where *calcareous* ooids were *accreted* in sea water less than 6 m deep, or where such ooids were sedimented in tidal deltas in somewhat deeper water. Conversely, the work by Gygi (1981 and 2012, Fig. 4.11 on p. 77) is unambiguous evidence that *ferriferous* ooids could be *accreted* at times of near non-deposition (see Burkhalter 1995) at the surface of mudgrade, argillaceous or calcareous sediment laid down at the much greater water depth of as much as between 80 and 100 m. An instructive example of this is the Schellenbrücke Bed of early Oxfordian age in Canton Aargau (see Gygi 1981, Figs. 2 and 3). Ammonites in the Schellenbrücke Bed, which were fossilized in the matrix of calcareous mud including ferriferous ooids that was laid down in relatively deep water, are abundant and often perfectly preserved. Many of these ammonites were figured by Gygi and Marchand (1982).

Ammonites of the genus *Ringsteadia* s.l. that were found in situ in the Villigen Formation are coeval with the ammonites *Epipeltoceras berrense* (Favre) and *Epipeltoceras bimammatum* (Quenstedt). According to our interpretation (red correlation scheme in Fig. 1), the Berrense and the Bimammatum Zones in the sense of Gygi (2012, Fig. 1.6) are coeval with the zone of *Ringsteadia pseudocordata* as it was conceived in southern England by Gradstein et al. (2012, Fig. 26.8 on p. 749). *Ringsteadia suebica* Gygi, the youngest species of the genus on the European continent, from the time equivalent of the Knollen Bed at the top of the Küssaburg Member on the slope of Dreifaltigkeitsberg near Spaichingen in southern Germany, indicates that the major part of the Swiss Gredingensis Zone is time-equivalent with the uppermost part of the English Pseudocordata Zone. Therefore it is concluded that the base of the Kimmeridgian Stage in northern Switzerland is situated within the thin, glauconitic marker bed of the Knollen Bed. However, it should be noted that several authors (Matyja et al. 2006, Wright 2010; Wierzbowski et al. 2010) consider Subtethyan taxa classically attributed to *Ringstaedia* s.l. to be younger than Subboreal representatives of this genus. Consequently they correlate the base of the Subboreal Baylei Zone and the base of the Boreal Bauhini Zone with the base of our Bimammatum Zone (blue correlation scheme in Fig. 1). In that case, the Oxfordian/Kimmeridgian boundary would lie further down in the Villigen Formation, namely within the Hornbuck Member, respectively within the Letzi Member in slightly more proximal settings.

Anyhow, although ammonites are comparatively abundant in the lowermost Wangental Member of the Planula Zone in section RG 82c in the abandoned quarry in Churz Tal in Siblingen (Gygi 1969, Pl. 16), this section is not suited as boundary stratotype because ammonites are too few in the Küssaburg Member and in the Knollen Bed. The same would apply at the boundary between the Berrense and Bimammatum Zones around Auenstein. In conclusion an Oxfordian/Kimmeridgian boundary stratotype with sufficient ammonites in the boundary beds should be found outside Switzerland on the European Continent.

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