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Unlocking paleo-environmental information from Early Cretaceous shelf sediments in the Helvetic Alps: stratigraphy is the key!

Karl B. Föllmi[1*], Stéphane Bodin[1,2], Alexis Godet[1,3], Pascal Linder[1] & Bas van de Schootbrugge[4]

Key words: Cretaceous, Helvetic Alps, northern Tethyan margin, carbonate platform, phosphogenesis, paleoceanographic change

ABSTRACT

The northern alpine Helvetic thrust-and-fold belt includes an Early Cretaceous shallow-water carbonate succession, which was part of an extensive carbonate platform rimming the northern Tethyan margin. The structural architecture of the Helvetic zone allows for the palinspastic reconstruction of proximal-distal transects across the former platform into the outer-shelf realm for distances surpassing 80 km. The Early Cretaceous platform sediments preserved therein provide, therefore, excellent insight into the spatial and temporal evolution of this platform. Furthermore, the presence of ammonites in marker horizons within the Helvetic succession is key to unprecedented time control.

During the life span of the Helvetic platform, carbonate build up and build out occurred along two distinct pathways: we discern between a mode including oligotrophic photozoan communities (latest Tithonian – Late Berriasian; Late Barremian; Early Aptian) and a mode dominated by mesotrophic heterozoan communities (Valanginian – Early Barremian; earliest Aptian; late Early Aptian – Late Aptian). The heterozoan mode was frequently interrupted by incipient platform drowning episodes, which materialized either in an important erosive hiatus, or in the deposition of highly condensed, glauconite- and phosphate-rich intervals (Early Valanginian – Early Hauterivian; late Early – early Late Hauterivian; latest Hauterivian – latest Early Barremian; middle Late Barremian; late Early Aptian – early Late Aptian; and latest Aptian – Early Albian). The photozoan mode is interpreted as essentially oligotrophic, whereas the heterozoan and drowning phases were associated with the input of coarser-grained detrital sediments and a correspondingly increased nutrient load, which were both the consequence of intensified chemical weathering on the continent due to warmer and more humid climate conditions. Their onset is signaled by increases in oceanic phosphorus burial rates and major positive excursions in the stable carbon isotope record. Oceanic anoxic episodes occurred during these latter phases.

The northern Tethyan platform was not only controlled by climatic, environmental and paleoceanographic change, but changes in platform morphology and the composition of carbonate-producing benthic communities also influenced the quality and quantity of dissolved and particulate material exported into adjacent basins.

1. Introduction

1.1 Dedication to Rudolf Trümpy

The here presented synopsis of Early Cretaceous stratigraphy in the Helvetic fold-and-thrust belt includes results both from a long-term research program at the ETH Zürich, which was initiated by Rudolf Trümpy, as well as from research programs at the Universities of Berne, Neuchâtel and Geneva, which were partly created as spin-offs.

Rudolf Trümpy has been a major driving force behind research on the stratigraphy, facies, sedimentology and tectonics in the Helvetic thrust-and-fold belt and in the Alps in general, and his guidance was pervasive and convincing by all means for all of us. We remember very well the numerous visits to small and hidden outcrops deep in the steep, dark and slippery forests of the Helvetic Alps, the evenings spent in alpine cabins and hotels with a glass (or more) of a locally distilled gentian schnaps and a play of poker, followed by early wake-up calls and strenuous marches to the summits of the Helvetic Alps. Rudolf Trümpy always eloquently shared his large experience on the Alps and – most importantly – he taught us not to neglect basic stratigraphic questions, before thinking in

[1] Institut de Géologie, Université de Neuchâtel, rue Emile-Argand 11, 2009 Neuchâtel, Switzerland
[*] karl.foellmi@unine.ch
[2] School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester, M13 9PL, United Kingdom
[3] Neftex Petroleum Consultants Ltd., 115BD Milton Park, Abingdon, Oxfordshire, OX14 4SA, United Kingdom
[4] Institut für Geowissenschaften, Departement für Paläontologie, Johann-Wolfgang-Goethe-Universität, Altenhöfer Allee 1, 60438 Frankfurt am Main, Germany

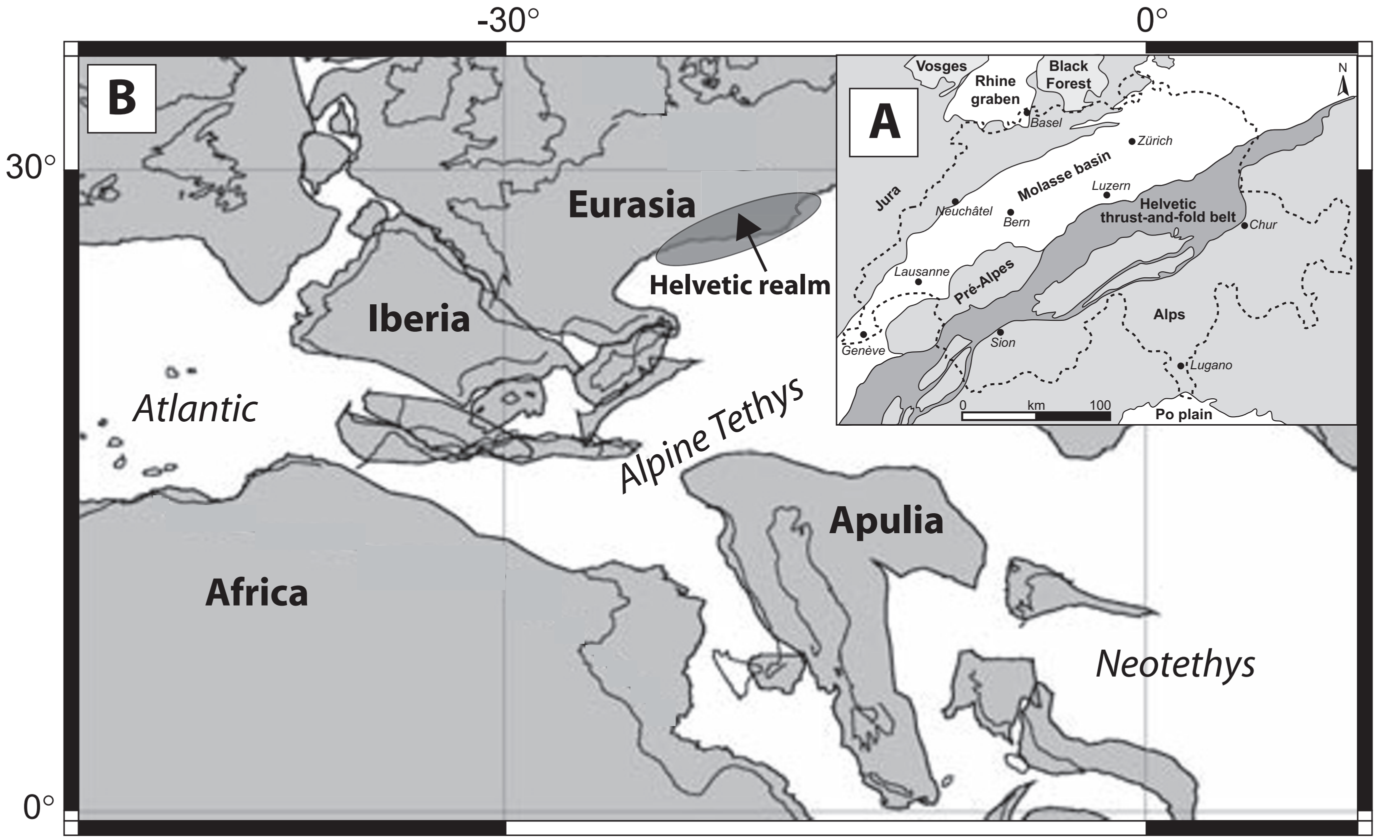

Fig. 1. A. Tectonic overview of Switzerland. The Helvetic fold-and-thrust belt is indicated in dark grey. B. Paleogeographic map of the western part of the Tethyan realm for the Barremian. The Helvetic realm is indicated in dark grey (modified after Bodin et al. 2006a,c).

broader frameworks. It is therefore our pleasure to dedicate this contribution to Rudolf Trümpy, a rigorous and creative geoscientist of great reputation and an excellent teacher.

1.2 Stratigraphy of Early Cretaceous sediments of the Helvetic fold-and-thrust belt

1.2.1 A brief retrospective

One of the true hallmarks of Early Cretaceous platform sediments in the Helvetic fold-and-thrust-belt is the repetitive occurrence of thin and highly condensed, fossiliferous, glauconitic and phosphatic horizons. These levels occur on top of shallow-water carbonates, and are often overlain by deeper water marly sediments, which in their turn transform upwards into to shallow-water carbonates. This regular pattern has attracted the attention of stratigraphers and sedimentologists since the early days of research in the Helvetic realm. Buxtorf (1910) and Arbenz (1919) have described this rhythmical change in sedimentation in detail; Fichter (1934), Carozzi (1951), and Brückner (1951) quantified the trends in the sedimentation pattern by using the presence, different types of ratio, and grain-size distributions of detrital, biogenic and authigenic components as a function of stratigraphy. For all these authors, sea-level and – more in general – climate change were at the origin of these sedimentary cycles.

Heim (1924, 1934, and in Heim & Seitz, 1934) added an important aspect to these interpretations by using a pioneering physical and chemical oceanographic approach. He explained the changes in Helvetic lithologies and especially the formation of the highly condensed phosphate- and glauconite-rich horizons by changes in bottom-current intensity and bottom-water chemistry. Trümpy (e.g., 1980) and his students explored Early Cretaceous Helvetic sediments with regards to their stratigraphy, sedimentology and microfacies, and an important discovery is the interference between paleotectonic structuration of the Helvetic shelf, subsidence pattern, and facies development (e.g., Strasser 1979; Funk 1985). A similar and often complementary approach was followed by René Herb of the University of Berne (e.g., Herb 1976; Ischi 1978; Korner 1978; Schenk 1992).

An important advance in our understanding of Helvetic sedimentation patterns was recently made by Mohr (1992; cf. also Funk et al. 1993; Mohr & Funk 1995) who for the first time used a sequence-stratigraphic approach and established a modern framework for our understanding of the relationships between

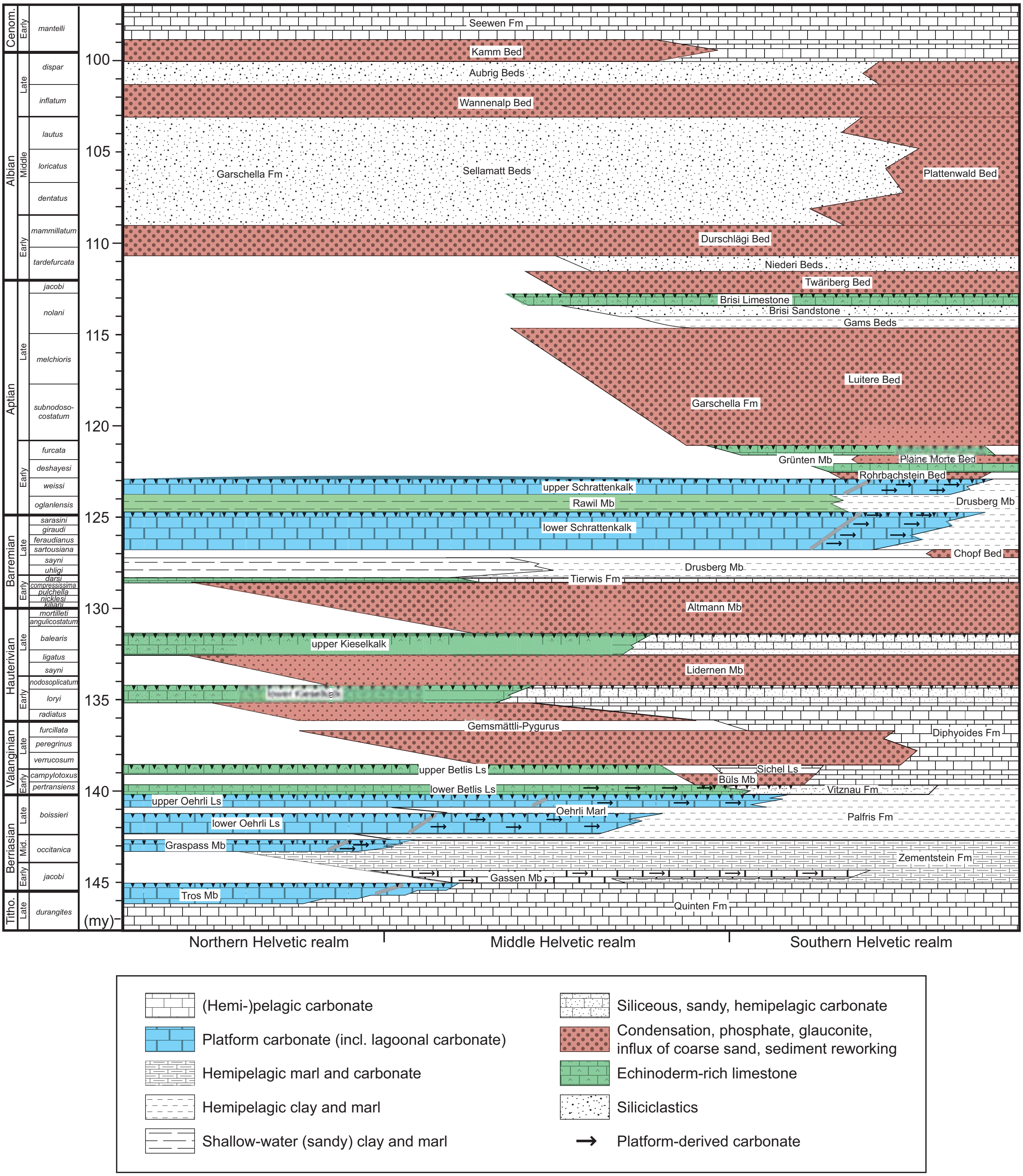

Fig. 2. Time-space diagram of the sedimentary successions of latest Tithonian to Early Cenomanian age present in the Helvetic fold-and-thrust belt. Proximal realms close to the European continent are indicated in the left and more distal areas to the right. The space axis represents approximately 60 km in its totality (modified after Föllmi et al. 2006). Timescale is after Gradstein et al. (2004). Ls = Limestone, Mb = Member, Fm = Formation.

sediment geometries and structures, facies and sea-level change. A further important contribution by the same author was the first-time use of stable-carbon isotope analyses in hemipelagic, distal series of the Helvetic realm. This allowed him to correlate trends in the Helvetic succession with general paleoceanographic change (Mohr 1992; Weissert & Mohr 1996; cf. also Wissler 2001; Hennig-Fischer 2003). At the same time a revival is observed in the use of conventional biostratigraphic methods, which is rigorously combined with modern stratigraphical, sedimentological and geochemical approaches. This approach is very helpful to reconstruct depositional environments and precisely correlate the observed changes in the Helvetic realm with paleoceanographic change (e.g., Wyssling 1986; Ouwehand 1987; Delamette 1988; Delamette et al. 1997; Bodin 2006).

1.2.2 The Early Cretaceous Helvetic succession: an interface between paleoecological and paleoceanographic change

The Helvetic sedimentary archive is of general interest for several reasons: 1) the Helvetic fold-and-thrust belt includes a well-preserved succession of Late Paleozoic to Early Tertiary sediments which are representative of the former southern European margin (Fig. 1). During most of the Mesozoic and Early Tertiary, these sediments accumulated along the northern Tethyan shelf margin, and the successions discussed here document maximally 80 km of the shelf margin along dip, once they are restored in a palinspastic way (Trümpy 1969; Fig. 2); 2) the therein contained latest Jurassic and Early Cretaceous succession documents the life span of the distal part of the northern Tethyan shallow-water carbonate platform, including its arrival by progradation into the Helvetic realm, a series of changes in its carbonate-producing ecology including several incipient drowning phases, and its final demise. Of interest here is that the evolution of the platform was not only influenced by local to regional change, such as relative sea-level variations, changes in the quality and quantity of detrital input, and seawater temperature, but that it was also subjected to global paleoceanographic change and in particular to a series of oceanic anoxic events, which were frequent during the Cretaceous. This interference provides us with the unique possibility to trace the outcome of these extreme events on the ecology of the northern Tethyan shallow-water carbonate-producing organisms; and 3) the presence of age-diagnostic ammonites allows for precise stratigraphic time control and enables correlations of the platform lithostratigraphic units with deeper water successions and the therein preserved paleoceanographic changes.

Here we provide an overview of our present-day state of knowledge with regards to the stratigraphy of the Early Cretaceous Helvetic sediments, and develop several lines of evidence with respect to how the therein documented evolution of the northern Tethyan carbonate platform was influenced by paleoceanographic change, and how this platform may have reciprocally exerted an influence on the chemical properties of the Tethyan basin itself.

2. Stratigraphy

2.1 Overview

The general development of the Early Cretaceous Helvetic succession along a north-south transect as a function of time is shown in Fig. 2. This synthetic diagram combines stratigraphic information from central and eastern Switzerland. The stratigraphic names of the lithological units described here are used in a informal sense, since a more definite hierarchy and corresponding nomenclature is still missing for some of the units. Furthermore, we propose names for two newly discovered phosphate and glauconitic horizons at and near the base of the Garschella Formation (Rohrbachstein and Plaine Morte Beds) and a new name for the formation which includes the Altmann and Drusberg Members, and the Chopf Bed (Tierwis Formation).

In the following, we will summarize essential information on the stratigraphic units shown in Fig. 2 with regards to their distribution, facies, and age, and provide interpretations on geometries and facies development. Our focus will be on the series of condensed phosphate- and glauconite levels, which are marker beds with regards to the stratigraphy and age control in the Early Cretaceous Helvetic succession, and provide valuable information linking paleoceanographic and paleoenvironmental change with phases of change in platform ecology.

2.2 Onset of platform evolution in the Helvetic realm at the Jurassic-Cretaceous boundary and a first phase of photozoan carbonate production during the Berriasian

2.2.1 Quinten Formation (Late Tithonian – Early Berriasian)

During most of the Late Jurassic, the Helvetic shelf represented a pelagic realm, which witnessed the deposition of a several 100 m thick succession of dark and predominantly micritic carbonate. The presence of a shallow-water carbonate platform to the north and northwest in the Jura realm (e.g., Gygi 2000) is only noted by episodic incursions of resedimented platform material, which become more and more abundant towards the Jurassic-Cretaceous boundary (Funk 1990; Mohr 1992a; Mohr and Funk 1995).

Near the Jurassic-Cretaceous boundary, the Jura carbonate platform prograded into the northern, proximal part of the Helvetic shelf and the accumulation of shallow-water carbonates of approximately 60–80 m thickness (Tros Member) documents the arrival of the northern Tethyan carbonate platform into the Helvetic realm. The distribution of sediments within the Tros Member is compatible with an internal platform facies, which developed upwards into a tidally influenced lagoon protected by patch reefs consisting of corals, rudists (e.g., *Diceras*), and sponges (Mohr 1992a). The platform slope towards the outer shelf does not show signs of important steepening and platform resediments are rare. The Tros Member has been interpreted as a highstand systems tract (Fig. 2; Mohr

1992a), and the type of carbonate production is classified as photozoan (Lees & Buller 1972; Föllmi et al. 1994, 2006; James 1997).

Age control for this initial phase of platform sedimentation in the Helvetic realm is obtained by ammonite and calpionellid stratigraphy in correlated outer shelf sediments (Mohr 1992b; Mohr & Funk 1995). The precise age of the onset of platform sedimentation is difficult to determine, but a Late Tithonian age is indicated (*durangites* zone? Mohr 1992a). The termination of this first phase in the evolution of the Helvetic platform is dated as the middle part of the *jacobi* zone (Early Berriasian; Mohr 1992a).

2.2.2 Zementstein Formation (Early to Middle Berriasian)

The sequence boundary between the Tros Member and the overlying sequence (Zementstein Formation; Fig. 2; Diegel 1973; Mohr 1992a) is marked in the platform area itself by brecciated layers, dolomite and brackish to lacustrine facies, and signs of erosion and sediment reworking are abundant. The overlying platform sediments of the Zementstein Formation are merely several dm thick and document an impoverished platform facies (Graspass Member; Arbenz & Müller 1920), which is dominated by the deposition of marine clay-rich sediments containing peloids, miliolids, gastropods and calcarous algae, and brackish-lacustrine sediments rich in charophytes (Mohr 1992a). This succession is interpreted as the highstand systems tract of a second platform sequence, which extends upwards into the Middle Berriasian. The platform margin and the outer shelf area shows a more complete and up to 120 m thick sequence, with an interpreted lowstand systems tract consisting of marl rich in resedimented and partly channelized carbonates (Gassen Member; Hantke in Schindler 1959), and an overlying transgressive and highstand systems tract composed of a regularly bedded alternation of marl and carbonate.

Age control is obtained by calpionellid and ammonite biostratigraphy, and the entire sequence is dated from the middle part of the *jacobi* zone to the middle part of the *occitanica* zone (Mohr 1992a).

2.2.3 Oehrli Formation (Middle to Late Berriasian)

From the Middle Berriasian onward, two phases of substantial platform growth by aggradation and progradation are observed which resulted in the accumulation and preservation of two well comparable highstand systems tracts composed of shallow-water carbonates (lower and upper Oehrli Limestone; Fig. 2). The lower Oehrli Limestone consists of calcareous pack- and grainstone including peloids, green algae (Dasycladaceae), benthic foraminifera, corals and echinoderms, and reaches a maximal thickness of approximately 50 m (Ischi 1978; Burger & Strasser 1981; Burger 1985, 1986; Mohr 1992a; Mohr & Funk 1995). The upper Oehrli Limestone reaches a maximal thickness of approximately 100 m and is comparable in facies to the lower Oehrli Limestone, with as main difference the increased abundance of oolitic grainstone and the presence of small bioherms composed of corals, stromatoporoids and bryozoans. For both units, carbonate production is interpreted as mainly photozoan. A well-preserved succession of shallow-water oolithic carbonate and fine-grained sand in the Vorarlberg Helvetic zone labeled "Oerfla Formation" by Wyssling (1986) is considered to represent a lateral equivalent of the Oehrli Formation. Towards the outer shelf, the Oehrli Formation is completed by its lowstand and transgressive systems tracts, which are composed of hemipelagic marl- and claystone (Oehrli Marl; Palfris Formation; Burger 1985, 1986; Mohr 1992a).

Age control for the evolution of these two sequences is not optimal: calpionellids and ammonites were found only near the base of the lower sequence, indicating the *occitanica* zone (Mohr 1992a). The age of the base of the Vitznau Formation and Büls Beds is Early Valanginian (see below; Pantic & Burger 1981; Kuhn 1996), and an age close to the Berriasian-Valanginian boundary has been arbitrarily proposed for the termination of the sequence of the upper Oehrli Limestone and with that for the end of the first phase of platform carbonate production in a photozoan mode (Burger & Strasser 1981; Mohr 1992a; Mohr and Funk 1995).

2.3 The Valanginian – Early Barremian phase of platform evolution: carbonate production in a heterozoan mode and multiple platform drowning phases

2.3.1 Betlis Formation: lower Betlis Limestone (Early Valanginian)

The switch-over from the deposition of the upper Oehrli Limestone to that of the overlying Betlis Formation near the Berriasian-Valanginian boundary represents a major turning point in the evolution of the Helvetic carbonate platform. The Berriasian photozoan mode of carbonate production is replaced by a heterozoan mode, which is repeatedly interrupted by episodes of incipient drowning (Fig. 2; Föllmi et al. 1994, 2006) and which lasted until the early Late Barremian. The limit between these two carbonate units itself embodies a sequence boundary which on the platform is marked by karstified and iron-stained emersion horizons and perforated hardgrounds (Burger 1985, 1986; Mohr 1992a). Platform sedimentation took up again by the deposition of a thin veneer of sandy marl in distal parts of the platform, which passes into the outer shelf into a maximally 60 m succession of hemipelagic marl including quartz-sand turbidites (Vitznau Formation; Burger & Strasser 1981; Burger 1985, 1986). On top of the thin unit of sandy marl or directly on top of the upper Oehrli Member, a succession of platform carbonates is preserved (lower Betlis Limestone; Fig. 2; Strasser 1979, 1982; Burger & Strasser 1981; Kuhn 1996), which consists of maximally 100 m of a sandy grain- and packstone rich in echinoderms, bryozoans, bivalves, brachiopods, benthic foraminifera, and calcareous algae (Strasser 1979, 1982). The sandy marl layer on the platform may represent a transgressive

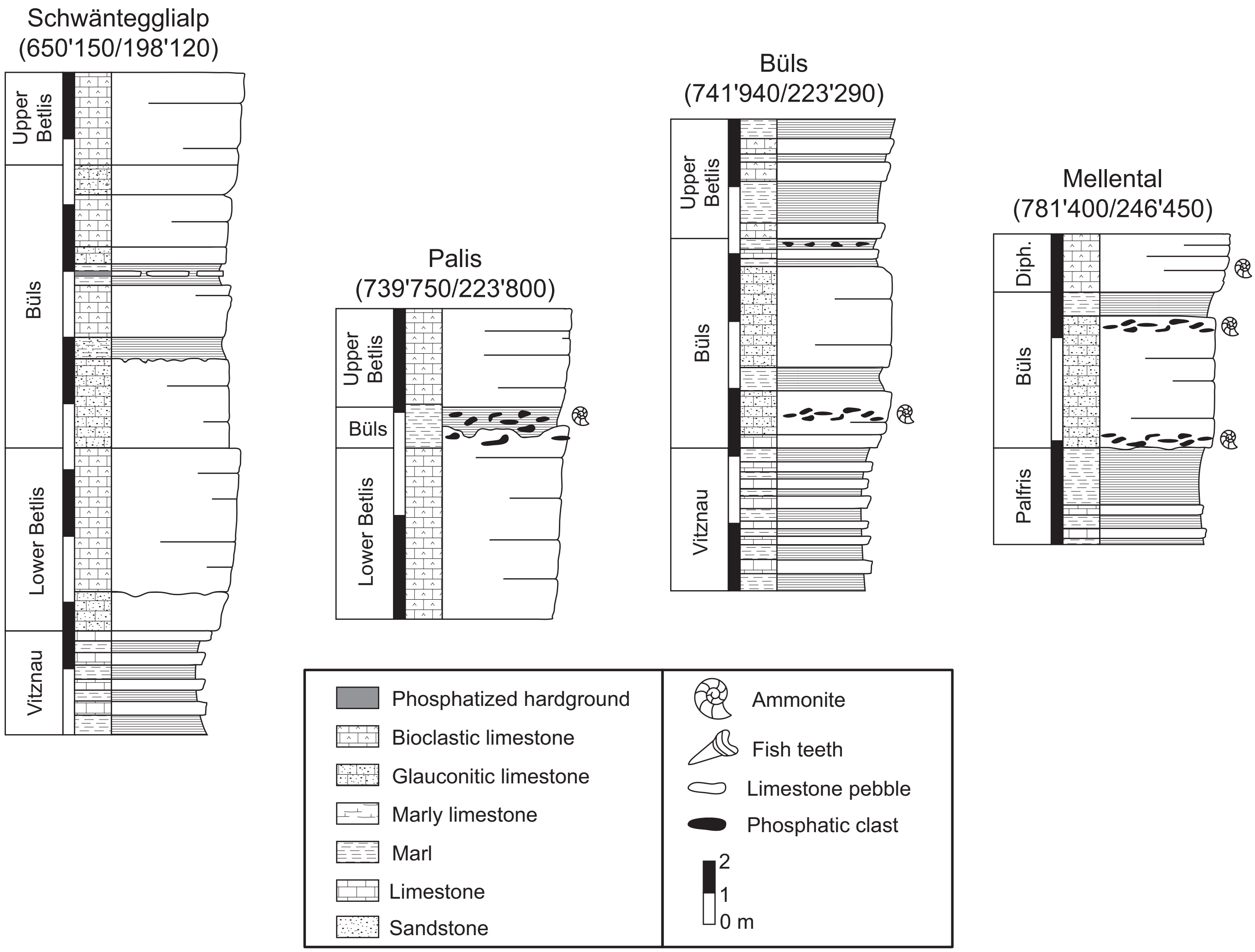

Fig. 3. Detailed lithostratigraphic logs of the Büls Beds in central and eastern Switzerland, and in Vorarlberg (modified after Kuhn 1996 and Wyssling 1986).

systems tract, and the superjacent, prograding carbonates of the lower Betlis Limestone are considered as the expression of a highstand systems tract.

The age of this heterozoan carbonate unit is constrained by the age of the overlying Büls Member and limited to the *pertransiens* zone (Early Valanginian; Kuhn 1996). In distal platform areas where the lower Betlis Limestone progrades over the sandy marl of the Vitznau Formation, a transitional, marly facies has been recognized at the base of the lower Betlis Limestone (Spitzern Limestone; Buxtorf 1910).

2.3.2 Betlis Formation: Büls Member (Early Valanginian)

In distal parts of the platform, the lower Betlis Limestone is overlain by an up to 5 m thick and heterogeneous succession, which consists of sandy, glauconitic, hemipelagic carbonates and marl, which include a discrete level of phosphate nodules or a phosphatized hardground (Fig. 2; Fig. 3). This unit is identified both in different regions in Vorarlberg (Austria), as well as in eastern and central Switzerland (Hauswirth 1913; Heim 1910–1916; Haus 1937; Strasser 1979; Felber and Wyssling 1979) and has been defined as "Büls Beds" by Kuhn (1996). The Büls Member is underlain either by sediments of the Vitznau Formation or of the lower Betlis Limestone (Fig. 2) and overlain by sediments of the hemipelagic Sichel Limestone of the Diphyoides Formation. In the case this latter member is absent, the Büls Member bundle with the overlying Gemsmättli Bed and forms a single phosphate-rich bed (Kuhn 1996). This is the case for example at the type locality of the Gemsmättli Bed in the Pilatus region (Wyssling 1986).

The Büls Member includes the oldest drowning unconformity within the Helvetic platform succession, and documents a first phase of highly reduced carbonate production on the platform (Föllmi et al. 1994, 2006). Its age is constrained by

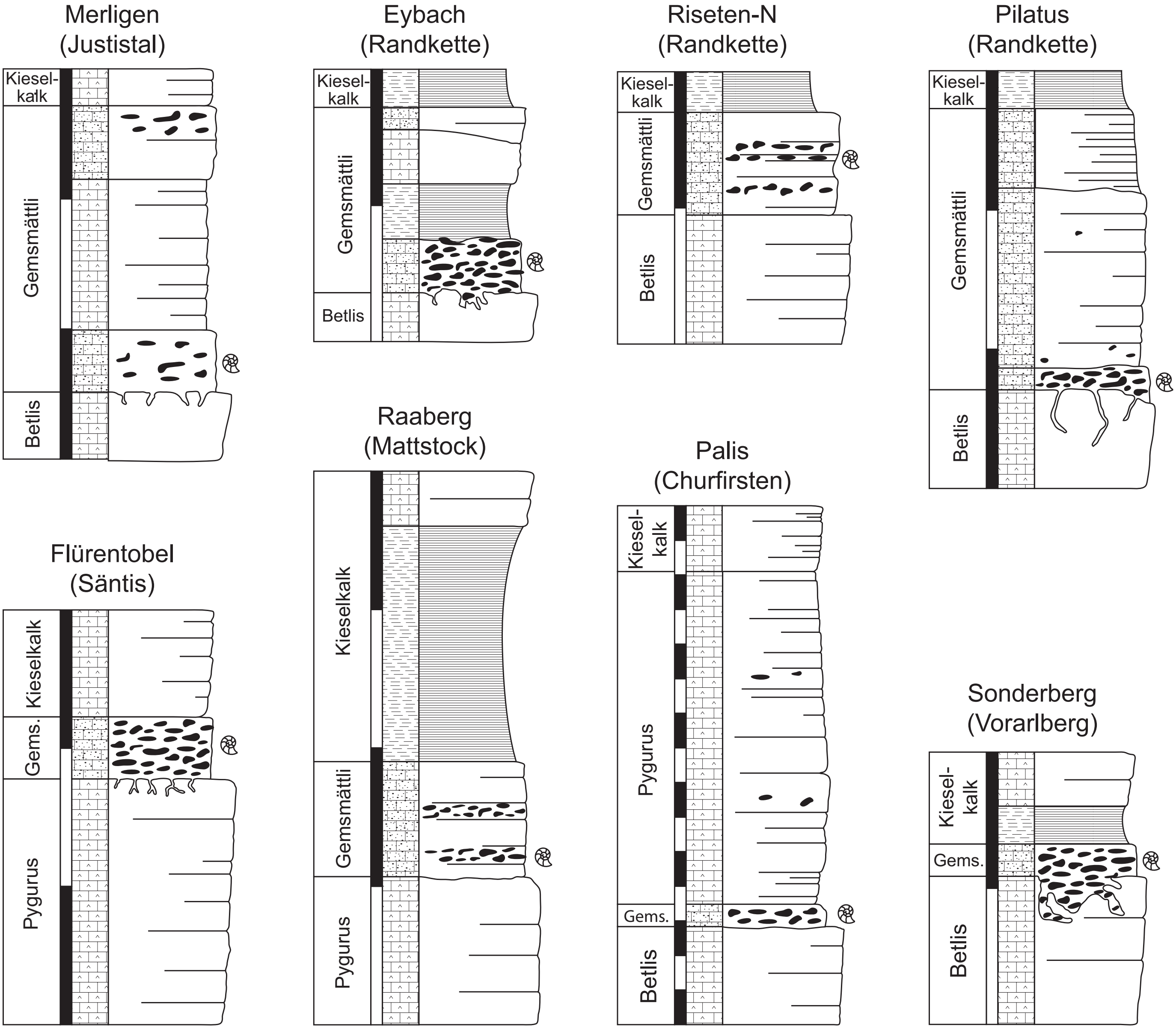

Fig. 4. Detailed lithostratigraphic logs of the Gemsmättli-Pygurus complex in eastern Switzerland and Vorarlberg (modified after Kuhn 1996).

ammonite biostratigraphy in occurrences in Vorarlberg and eastern Switzerland and encompasses the late *pertransiens* and early *campylotoxus* zones (Wyssling 1986; Kuhn 1996).

2.3.3 Betlis Formation: Upper Betlis Limestone (late Early to early Late Valanginian)

Where present on the platform, the upper Betlis Limestone is very similar in facies to the lower Betlis Limestone with the exception of the presence of chert. Its maximal thickness is not yet established but does probably not surpass 20 m. Given their prograding character on top of the Büls Member, the heterozoan carbonates of the upper Betlis Limestone may be interpreted as a highstand systems tract. It is distally replaced by hemipelagic carbonates of the Diphyoides Formation (Fig. 2; Strasser 1979, 1982; Kuhn 1996; Hennig-Fischer 2003). A transitional facies between the upper Betlis Limestone and the Diphyoides Formation has been named Sichel Limestone (Ischi 1978). In central Switzerland, sediments of the upper Betlis Limestone may be absent, and within the Vorarlberg Helvetic zone, sediments of the entire Betlis Formation are widely reduced, relictic or even fully absent (Wyssling 1986).

The age of the upper Betlis Limestone is constrained by youngest and oldest ages of ammonites in the underlying Büls Member and overlying Gemsmättli Bed and corresponds to the younger part of the *campylotoxus* zone and the older part of the *verrucosum* zone (Kuhn 1996).

2.3.4 Helvetic Kieselkalk Formation: Gemsmättli-Pygurus Complex (Late Valanginian to Early Hauterivian)

An overall condensed and lithologically highly variable lithological complex – the Gemsmättli-Pygurus Complex (Figs. 2 and 4; Haldimann 1977; Wyssling 1986; Kuhn 1996) documents a second drowning phase of the Helvetic platform. In the proximal platform realm, this phase is merely recorded by a truncation surface which is often impregnated by phosphate and chert. In the distal platform realm, a heterogeneous, up to 30 m thick succession is present which contains condensed sandy, phosphate- and glauconite-rich layers (Gemsmättli Bed and Rahberg Bed; Heim 1910–1916; Funk 1971; Haldimann 1977; Strasser 1979; Wyssling 1986; Kuhn 1996). This unit includes cross-bedded and locally channelized, coarse-grained, sandy carbonates rich in echinoderms (Pygurus Beds; Heim 1905; Pygurus and Palis Beds; Haldimann 1977). In the outer shelf realm beyond the platform margin, the Gemsmättli-Pygurus Complex is progressively replaced by hemipelagic carbonates of the Diphyoides Formation and Sichel Limestone (e.g., Fichter 1934; Kuhn 1996; Hennig-Fischer 2003; Fig. 2).

The Gemsmättli Bed is the dominant and most widely occurring bed within the Gemsmättli-Pygurus Complex. It consists of a nodular phosphatic bed, which is rich in sand and glauconite, and which contain a phosphatized basal hardground in proximal areas. Laterally or upwards, transitions into a predominantly glauconitic sandstone bed are possible. It documents a second, longer lasting, drowning phase of the Helvetic carbonate platform (Fig. 2), which was already heralded by the Büls Member. Carbonate accumulation was minimal during this drowning period and erosion and reworking of pre-existing carbonates may have been important as is indicated by the frequent presence of lithoclasts, irregular hardgrounds, and truncation surfaces (Föllmi et al. 1994, 2006; Kuhn 1996; Weissert et al. 1998). The age of the Gemsmättli Bed is well defined by the occurrence of a rich and highly diversified ammonite fauna (Baumberger & Heim 1907; Heim & Baumberger 1933; Wyssling 1986; Kuhn 1995) and ranges from the *verrucosum* zone to the *radiatus* and locally to the *loryi* zones (Fig. 2). Ammonites from the intervening *furcillata* zone are missing.

The Pygurus Beds embody preserved dunes and waves of relict sediments – mostly reworked from the subjacent Betlis Formation, which were bypassed across the outer-platform realm, partly within channels. Theses bypassing sediments may have been crucial in the fossilization and phosphatisation of suddenly buried ecosystems, in analogy to comparable depositional systems preserved within the Garschella Formation (see below; Föllmi 1989a; 1996).

2.3.5 Helvetic Kieselkalk Formation: Lower Kieselkalk (Early Hauterivian)

The Helvetic Kieselkalk Formation consists of a remarkable and well recognizable succession of dark and siliceous limestone, which reaches a maximal thickness of approximately 550 m in marginal platform areas (Fig. 2; Kaufmann 1867; Heim 1910–1916; Oberholzer 1933; Fichter 1934; Funk 1969, 1971; Wyssling 1986; van de Schootbrugge 2001). It includes two progradational shallowing-upward sequences, which in distal platform areas are divided by the condensed phosphate-rich and/or glauconitic Lidernen Member. The lower Kieselkalk consists of an up to 500 m thick sandy, siliceous grain- to packstone dominated by crinoidal and bryozoan remains in proximal areas and by sponge spicules in distal areas. Sediments of this unit are typically heterozoan and rather coarse in proximal areas, whereas in distal areas fine-grained sediments dominate – especially at the base, where marls and/or micritic carbonates similar to the Diphyoides Formation prevail (Funk 1971; Felber and Wyssling 1979; Wyssling 1986; Kuhn 1996). The presence of channel structures and tempestite deposits is suggestive of a highly dynamic depositional environment in platform and platform slope areas. This is probably also indicated in the eastern, Vorarlberg part of the Helvetic zone, where sediments of the Helvetic Kieselkalk Formation are absent near the platform margin (Wyssling 1986).

The platform carbonate body of the lower Kieselkalk prograding on top of the Gemsmättli-Pygurus Complex probably represents a highstand systems tract, whereas in the outer shelf, the sediments correlated to this member may represent a more complete sequence.

The age of the lower Kieselkalk is well defined by the ages of the under- and overlying condensed and ammonite-rich beds and corresponds to the *loryi* and lower part of the *nodosoplicatum* zones.

2.3.6 Helvetic Kieselkalk Formation: Lidernen Member (late Early to early Late Hauterivian)

In distal platform areas, the top of the lower Kieselkalk is covered by a maximally 12m thick, glauconite and/or phosphate-rich unit – the Lidernen Member -, which signals a further drowning episode in the evolution of the Helvetic carbonate platform (Fig. 2; Fig. 6; Fichter 1934; Schindler 1959; Hantke 1961; Funk 1969; Wyssling 1986; Föllmi et al. 1994, 2006; Lemaire 1994; Kuhn 1996; van de Schootbrugge 2001). This unit is characterized by its heterogeneity, with occurrences of glauconite-rich, sandy gravity-flow deposits being laterally replaced by condensed phosphate-rich beds (Fig. 5).

Good age control for this unit is only possible at its type locality – Liderner Plänggeli SE of Chaiserstock, where a rather well preserved ammonite fauna indicates the *nodosoplicatum*, *sayni* and *ligatus* zones (Hantke 1961; Lemaire 1994; van de Schootbrugge 2001). A few ammonites have been

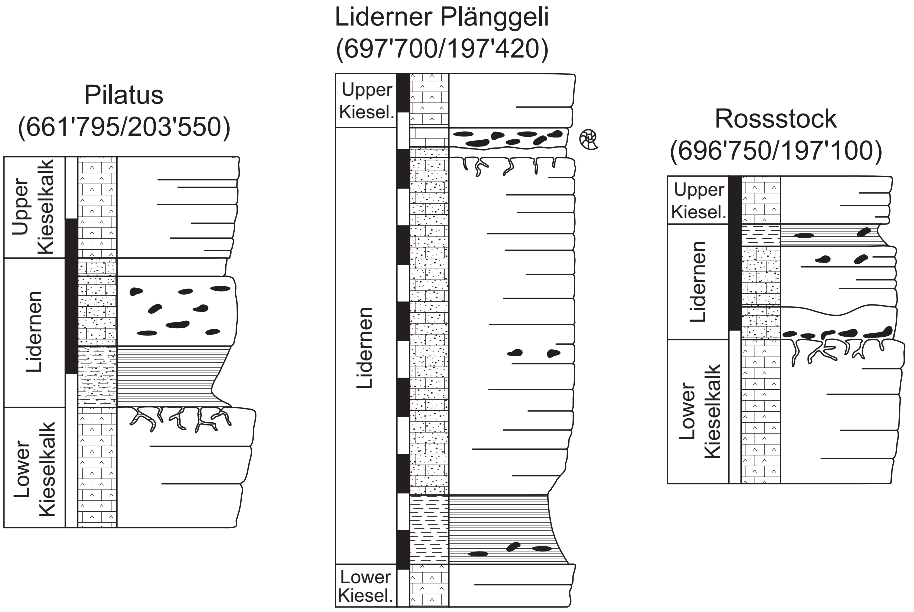

Fig. 5. Detailed lithostratigraphic logs of the Lidernen Beds in central Switzerland (modified after Lemaire 1994; Kuhn 1996; and van de Schootbrugge 2001).

found at other localities (Bauen-Brisen area: Fichter 1934; Hirschau, Vorarlberg: Wyssling 1986), which confirm the age inferred from the type locality.

2.3.7 Helvetic Kieselkalk Formation: Upper Kieselkalk (Late Hauterivian)

The upper Kieselkalk is less thick than its lower counterpart and reaches maximally approximately 50 m (Fig. 2; Funk 1969, 1971; Funk et al. 1993). It is very similar to the lower Kieselkalk with regards to its facies and consists in proximal areas of a coarse grained sandy and siliceous, heterozoan carbonate, which becomes finer grained and more pelagic in the outer shelf area. It displays a well-expressed shallowing upward trend in distal platform areas grading from a fine-grained, marly carbonate at its base into a very coarse crinoidal limestone at its top ("Echinodermen-Breccie" of Kaufmann 1867; see also Funk 1971). The general progradation of shallow-water carbonates shown by the shallowing-upward trend classifies the platform-related part of the upper Kieselkalk as a highstand systems tract.

Its age is well defined by the ammonite biostratigraphy of the underlying Lidernen Member and overlying Altmann Member and is limited to the younger part of the *ligatus* zone and the older part of the following *balearis* zone.

2.3.8 Tierwis Formation: Altmann Member (Late Hauterivian to late Early Barremian)

The name "Tierwis Formation" is proposed here in accordance with the new stratigraphic guidelines published by Remane et al. (2005). The Tierwis Formation includes the Altmann Member, the Drusberg Member and the Chopf Bed. Its type locality is Tierwis in the western Säntis region, WSW of the Säntis (742'970/234'730/2035). Detailed sections are given in Funk (1969), Wissler (2001), and Bodin et al. (2006).

In intermediate and distal parts of the Helvetic platform, the upper Kieselkalk is covered by a thin and highly condensed unit consisting of glauconite- and/or phosphate-rich sandstone and marl (Altmann member; Fig. 2; Fig. 6; Fichter 1934; Funk 1969, 1971; Wyssling 1986; Bodin 2006; Bodin et al. 2006a). It is only in the Säntis and Fluhbrig regions that this unit is more expanded and reaches a thickness of almost 40 m (Oberholzer 1933; Rick 1985; Bodin et al. 2006a). The section at Tierwis in the western Säntis region is mainly composed of heterozoan, partly hemipelagic marl and marly carbonates, which contains a glauconite- and ammonite-rich interval close to its base and a remarkable phosphatic and chert-rich hardground near its top (Funk 1969; Bodin 2006; Bodin et al. 2006a). Bodin et al. (2006a) distinguished three sequences within this section.

The age of the Altmann Member is well constrained by numerous ammonite findings (Fichter 1934; Rick 1985; Wyssling 1986; Bodin 2006; Bodin et al. 2006a) and spans the *balearis* zone to the *darsi* zone (Fig. 2).

2.3.9 Tierwis Formation: Drusberg Member (early Late Barremian to Early Aptian)

With the sediments of the Drusberg Member (Fig. 2; Heim 1910–1916; Oberholzer 1933, Fichter 1934; Lienert 1965; Briegel 1972; Felber & Wyssling 1979; Bollinger 1988; Schenk 1992), a period of transition is documented in which the Helvetic platform returned to a mode of photozoan platform production. On the platform, the Drusberg Member consists of an up to 50 m thick marl-limestone alternation, which stratigraphically develops from a marl-dominated basal interval (missing in proximal areas) to a predominantly calcareous interval in the middle and

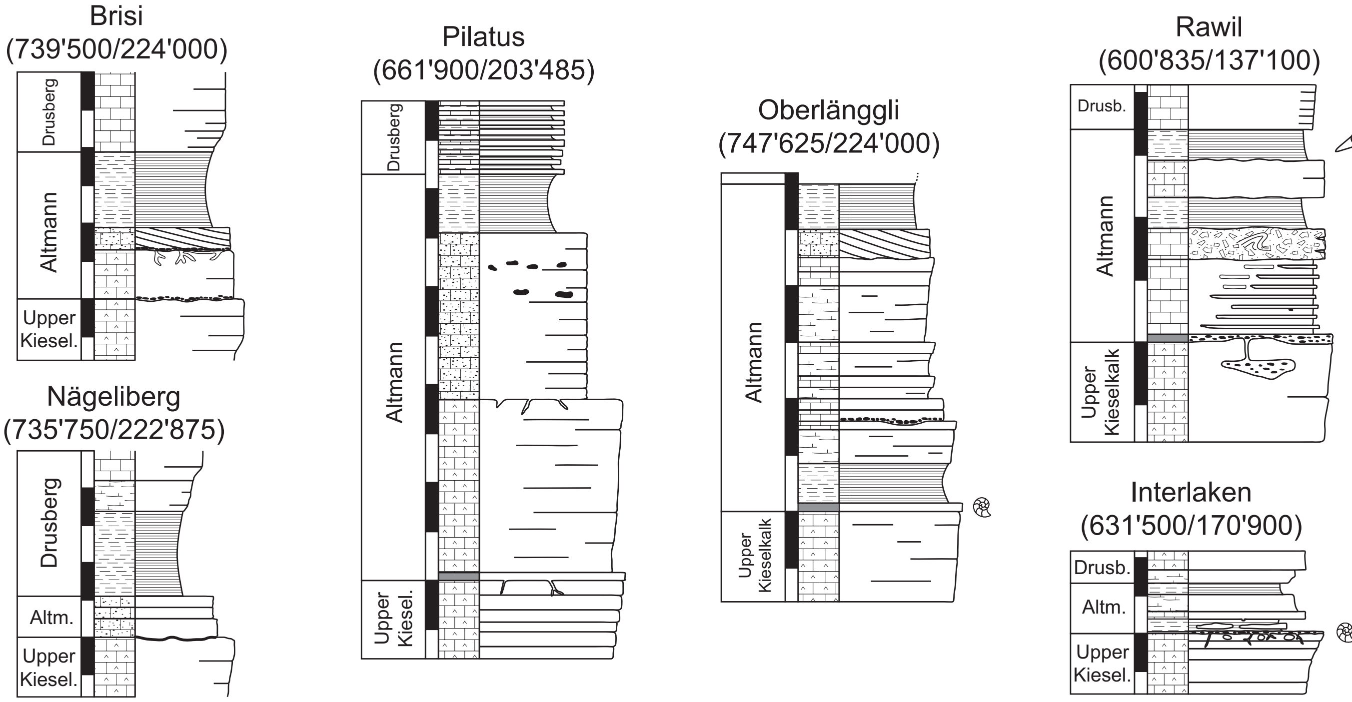

Fig. 6. Detailed lithostratigraphic logs of the Altmann Member in central Switzerland (modified after Bodin et al. 2006a).

a marly interval regularly intercalated with limestone beds near the top (Heim 1910–1916; Fichter 1934; Bodin et al. 2006a,b). In proximal areas, the carbonates usually include dense oyster layers, and sporadically coral and sponge fragments (e.g., Oberholzer 1933). The preserved microfauna consists of peloids, benthic foraminifera, sponge spicules, fragments of crinoids and bivalves. Bodin et al. (2006a) identified the lower marly and middle calcareous intervals of the Drusberg Member on the platform as a highstand systems tract and the overlying marl-limestone alternation as transgressive systems tract.

In the outer shelf realm beyond the carbonate platform, the Drusberg Member encompasses an up to 350 m thick succession consisting of regular marl-limestone alternations (Heim & Baumberger 1933; Briegel 1972; Bollinger 1988). This succession is the distal equivalent of the Drusberg Member and of the overlying Schrattenkalk Formation on the platform (the latter was baptized “Hurst Beds” by Briegel 1971). A thin glauconite- and phosphate-containing bed (Chopf Bed) marks the boundary between both platform equivalents (Fig. 2).

Ammonite biostratigraphy within the underlying Altmann Member and the overlying Chopf Bed allows for the attribution of an age for the platform-type Drusberg Member, which spans the time between the *darsi* and *sartousiana* zones. The outer-shelf sediments of the Tierwis Formation are dated from the *darsi* to the *weissi* zone, where the top age is a minimal age obtained by ammonite stratigraphy in the overlying Grünten Member (see below).

2.3.10 Tierwis Formation: Chopf Bed (middle Late Barremian)

In platform margin areas, the lower part of the Drusberg Member (equivalent to the Drusberg Member on the platform) is separated from the upper part of the Drusberg Member (equivalent to the Schrattenkalk Formation on the platform: “Hurst Beds” of Briegel 1972) by an up to 4 m thick, glauconitic and phosphate-containing carbonate unit rich in echinoderms and intraclasts (Chopf Bed of Briegel 1972; Bodin et al. 2006b; Fig. 2; Fig. 7). This succession has been identified in Vorarlberg (Heim and Baumberger 1933; Bollinger 1988), eastern Switzerland (Heim 1910–1916; Oberholzer 1933; Lienert 1965; Briegel 1972; Wissler et al. 2003; Bodin et al. 2006b), and central Switzerland (Fichter 1934; Staeger 1944). Bodin et al. (2006b) interpreted this unit as the equivalent of a maximum flooding surface, which in its prolongation towards the platform would separate the upper part of the Drusberg Member (interpreted as a transgressive systems tract) from the overlying lower Schrattenkalk (interpreted as a highstand systems tract; see below).

The age of the Chopf Bed has recently been determined based on a newly discovered ammonite fauna at the type locality near Alvier, which indicates the younger part of the *sayni* zone and the older part of the following *sartousiana* zone (Bodin et al. 2006b).

2.4 A second phase of photozoan carbonate production in the Helvetic realm during the Late Barremian – Early Aptian interrupted by a short phase of heterozoan carbonate production in the earliest Aptian

2.4.1 Schrattenkalk Formation: Lower Schrattenkalk Member (late Late Barremian to earliest Aptian)

The presence of reworked and transported coral debris in proximal occurrences of the Drusberg Member indicates the progressive inclusion of photozoan elements in an otherwise heterozoan carbonate production in areas north and northwest to the Helvetic realm. The transition of the Drusberg Member to the Schrattenkalk Formation signals the return of platform carbonate production to the Helvetic realm by progradation (Fig. 2; Heim 1910–1916; Oberholzer 1933; Fichter 1934; Lienert 1965; Bollinger 1988; Schenk 1992) and the start of shallow-water carbonate deposition in a typical Urgonian, photozoan facies. The Helvetic, Urgonian-type sediments pile up in a locally over 200 m thick succession and form the steep and resistant, bright rock cliffs barren of vegetation, which are so typical for proximal and intermediate parts of the Helvetic zone.

The lower Schrattenkalk reaches a maximal thickness of over 100 m and is composed of carbonate pack- and grainstone rich in ooids, peloids, benthic foraminifera (e.g., miliolids, orbitolinids), green algae, rudists (e.g., *Requienia*), bryozoans, brachiopods, bivalves, echinoderms and corals. This unit is characterized by a strong progradational trend (Fig. 2) and by a rather rapid transition (within a few kilometers; Fichter 1934; Bollinger 1988) into the outer shelf marls and marl-limestone alternations of the Tierwis Formation. The entire succession is considered as a second-order systems tract, which may form one single sequence with the underlying Drusberg Member and the Chopf Bed (Funk et al. 1993). It is not excluded that third-order sequence-stratigraphic subdivisions may be present within the lower Schrattenkalk, as is the case in the Vercors area (Arnaud et al. 1998).

The age of the lower Schrattenkalk is indicated by the ammonite fauna of the Chopf Bed and by orbitolinids in the overlying Rawil Member (see below) and can be constrained as *sartousiana* to *oglanlensis* zones. A diachrony of its base along a proximal-distal axis is highly probable and due to the progradational character of this unit.

2.4.2 Schrattenkalk Formation: Rawil Member (earliest Aptian)

The deposition of the Urgonian lithological unit was interrupted by a phase of increased input of detrital material and the temporary disappearance of photozoan carbonate producting organisms such as corals and rudists near the Barremian-Aptian boundary. This short heterozoan phase led to the deposition of a heterogeneous, up to 40 m thick succession of marly carbonates and silty or sandy marls, which were traditionally named "lower Orbitolina Beds" (Fig. 2; Heim 1910–1916; Oberholzer 1933; Fichter 1934; Lienert 1965). Schenk (1992) introduced the name "Rawil Beds" for the occurrences of this lithological unit in the southern part of the Bernese Swiss Alps. She reserved this lithostratigraphic term for distal, several tens of meters thick and internally well differentiated occurrences, whereas the sandy and calcareous occurrences in more proximal areas were still considered as "lower Orbitolina Beds". Her definition is extended here to all Helvetic occurrences.

The Rawil Member frequently shows layers of pack- and grainstone rich in orbitolinids and is locally enriched in echinoids, gastropods, brachiopods, and bivalves. Variegated paleosols containing wood fragments occur in the region of Lopper (NE of Pilatus) and Tierwis (western part of the Säntis). The sequence stratigraphic context of this member is not clear yet, but the entire succession may represent a transgressive systems tract (Funk et al. 1993).

The age of the Rawil Member has been identified as earliest Aptian (*oglanlensis* to early *weissi* zones), based on orbitolinids and on correlations with occurrences in the Vercors realm (Bollinger 1988; Schenk 1992; Arnaud et al. 1998; Arnaud-Vanneau et al. 1976).

2.4.3 Schrattenkalk Formation: Upper Schrattenkalk (Early Aptian)

The facies of the upper Schrattenkalk is similar to that of the lower Schrattenkalk, with as main difference the frequent occurrence of small patch reefs in its upper part in the outer zone of the platform (Fig. 2; Heim 1910–1916; Oberholzer 1933; Fichter 1934; Lienert 1965; Gebhardt 1983; Bollinger 1988; Schenk 1992). These reefs are composed of corals, rudists, stromatoporoids and chaetetids and separate an inner, lagoonal environment from an outer platform margin environment (e.g. Bollinger 1988; Linder et al. 2006). This maximally 100 m thick unit shows an overall shallowing upward trend and is interpreted as the highstand systems tract of a stratigraphic sequence which started with the Rawil Member (e.g., Funk et al. 1993).

Ammonites from the overlying Grünten Member constrain the minimal age of the upper Schrattenkalk to an age near the boundary between the *weissi* and the *deshayesi* zones (Linder et al. 2006) and the deposition of this entire member is essentially limited to the *weissi* zone.

2.5 The last phase of platform evolution during the late Early and Late Aptian: carbonate production in a heterozoan mode and multiple platform drowning phases

2.5.1 Garschella Formation: Grünten Member (middle to late Early Aptian)

Sediments of the Grünten Member (formerly named "upper Orbitolina Beds"; Fig. 2; Heim 1919; Fichter 1934; Schaub 1936; Bentz 1948; Hantke 1961; Schenk 1992; Wissler 2001;

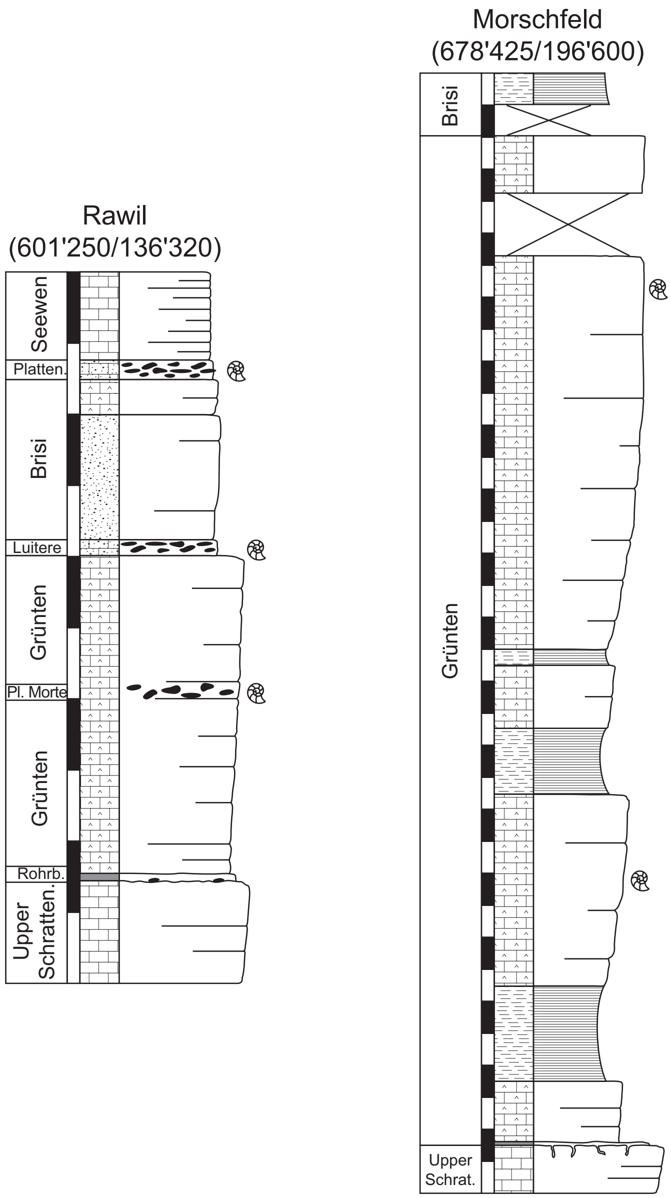

Fig. 7. Detailed lithostratigraphic logs of the Grünten Member in central Switzerland (modified after Linder et al. 2006).

Wissler et al. 2003; Linder et al. 2006) are of special interest because they document the termination of photozoan, Urgonian-type carbonate production on the Helvetic platform and a renewed change towards a phase of heterozoan platform carbonate production, which was interrupted by several drowning phases. The Grünten Member has recently been included into the Garschella Formation as a basal member (Linder et al. 2006). Its occurrences are limited to the distal Helvetic zone in Allgäu, Vorarlberg and central Switzerland (Fig. 2; Fichter 1934; Schaub 1936; Bentz 1948; Hantke 1961; Gebhardt 1983; Bollinger 1988; Linder et al. 2006).

In platform-margin areas where sediments of this member are preserved, the top of the upper Schrattenkalk is sharply defined and marked by erosion (e.g., Gainon 2001; Hüsser 2005; Gigandet 2005; Linder et al. 2006). In the Rawil area, this surface is locally phosphatized (Fig. 8; Gainon 2001), and in the Grünten, Fronalpstock and Niederbauen areas, a cm-thin to less than a meter thick layer of glauconite-containing calcarenite rich in echinoderm debris covers the same surface (Gigandet 2005; Hüsser 2005; Linder et al. 2006). We propose to name this unit Rohrbachstein Bed or surface in the case only a phosphatized surface is present, and as type locality we define the outcrop of the Grünten Member north of the "Col de la Plaine Morte" and west of the Rohrbachstein mountain (Rawil area; Schaub 1936; Gainon 2001; Linder et al. 2006; 601'250/136'320/2540). The Rohrbachstein surface or bed is interpreted as the result of a drowning phase. In outer shelf areas beyond the carbonate platform, the Grünten Member rests directly on top of the Tierwis Formation and the drowning unconformity is less conspicuous.

The lower part of the Grünten Member overlying the Rohrbachstein Bed consists of a quartz- and glauconite-containing marl or marly carbonate, which is rich in echinodermal debris and reworked and partly micritized Schrattenkalk extraclasts. This unit is limited to the southern areas within the Helvetic realm and reaches a maximum thickness of about 15 m. In the Rawil area, the lower part of the Grünten Member is covered by a thin, nodular glauconite- and phosphate-containing layer, in which sparse phosphate particles occur. The limestone nodules are peripherically phosphatized. For this bed we propose the name Plaine Morte Bed (Fig. 2, Fig. 8; Gainon 2001), with as type locality the same outcrop as described above for the Rohrbachstein Bed. The Plaine Morte Bed signals again an episode of platform drowning.

The upper part of the Grünten Member is composed of an up to 20 m thick succession of sand-bearing crinoidal carbonate, which may contain chert nodules and discrete levels of orbitolinid pack- and grainstone. In the Fronalpstock area this unit is topped by an oolitic grainstone (Gigandet 2005).

The carbonates preserved in the Grünten Member are a good example of heterozoan carbonate production. The Rohrbachstein Bed and the lower, marly, carbonate unit of the Grünten Member may represent transgressive and highstand systems tracts, whereas the Plaine Morte Bed and the overlying carbonate unit displaying a shallowing-upward trend may be equally interpreted as transgressive and highstand systems tracts.

With regards to its age, based on ammonite stratigraphy, the Grünten Member encompasses the *deshayesi* zone and the early part of the *furcata* zone, (Gainon 2001; Linder et al. 2006). Earliest Aptian ages (*oglanlensis* zone) proposed by Heim (1919) and Gebhardt (1983) are too old and cannot be accepted here (cf. Linder et al. 2006 for more detailed information). The "Mittagspitz Formation", which was defined by Felber & Wyssling (1979) for sandy and marly carbonates and

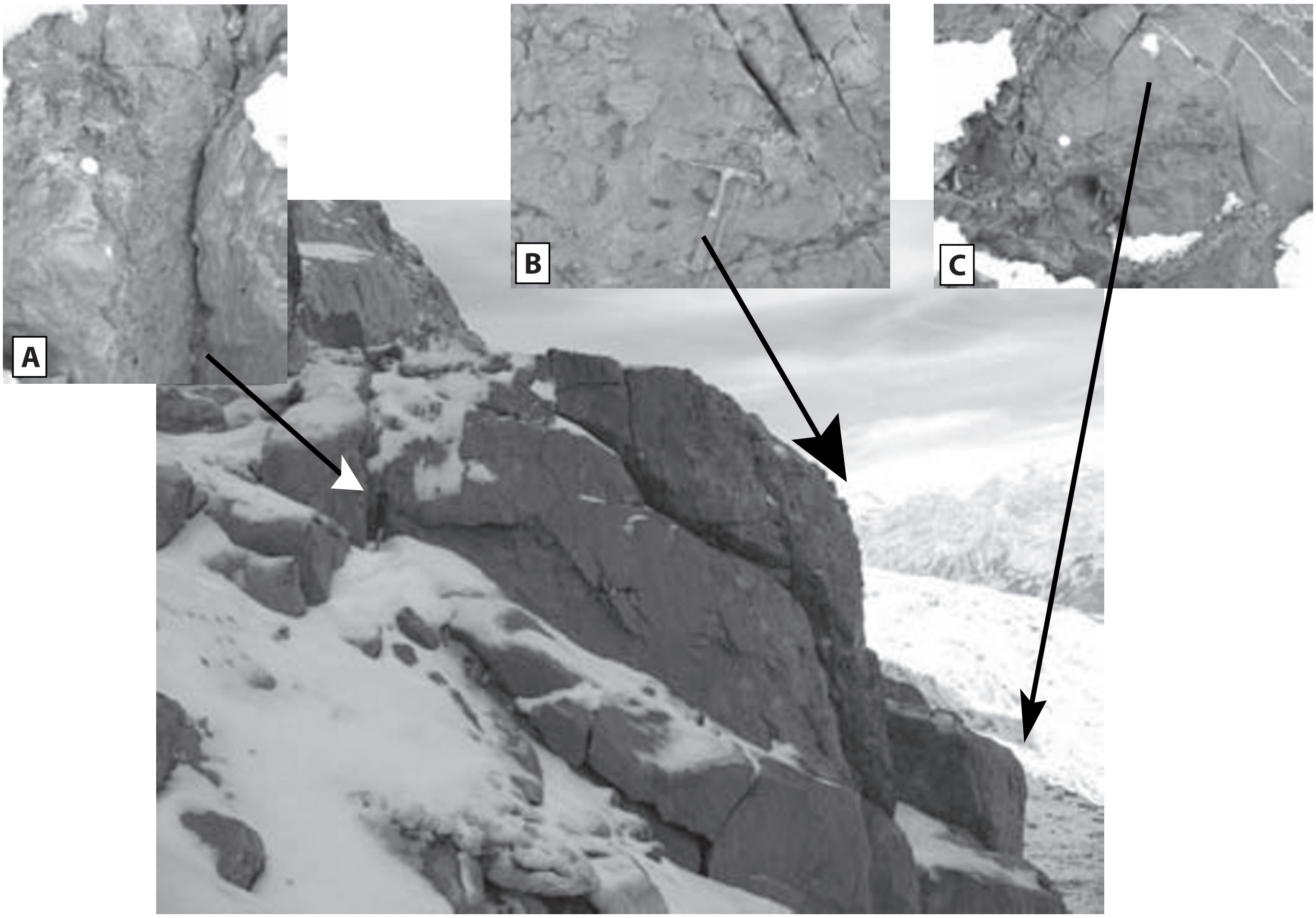

Fig. 8. Upper Schrattenkalk Member and overlying sediments of the Grünten Member in the Rawil area (Schaub 1936; Gainon 2001). The contact surface between the two members (inset A) is marked by local phosphate-rich patches and phosphatized coral remains (Linder et al. 2006) and is considered a drowning surface (Rohrbachstein Bed in Fig. 2); inset B shows the Plaine Morte Bed, which consists of a nodular bed where the nodules are peripherically phosphatized; inset C shows the Luitere Bed which follows on top of the Grünten beds. It consists of an up to 50 cm thick sandy and glauconitic bed containing numerous phosphate particles and nodules (e.g., Föllmi et al. 1994, 2006; Linder et al. 2006).

marls containing partly channelized resediments on top of the Drusberg Member in distal parts of the Vorarlberg Helvetic zone is considered here as a younger (partial?) synonym of the Grünten Member (cf. Bollinger 1988; Linder et al. 2006).

2.5.2 Garschella Formation: Brisi Member: Luitere Bed (late Early to Late Aptian)

The Luitere Bed is composed of a highly condensed phosphatic and glauconite-rich layer, which appears in distal parts of the platform realm and in the outer shelf area (basal bed of the Brisi member; Garschella Formation; Fig. 2; Jacob & Tobler 1906; Ganz 1912; Heim & Seitz 1934; Fichter 1934; Schaub 1936; Föllmi 1986, 1989a; Föllmi & Ouwehand 1987; Ouwehand 1987; Delamette 1988; Delamette et al. 1997). In regions where the Grünten Member is missing, the Luitere Bed may directly rest on top of the upper Schrattenkalk. In proximal platform areas, this unit is missing and the upper Schrattenkalk is directly covered by higher units of the Garschella Formation which become progressively younger to the north, thereby marking a hiatus which envelops more and more time (Föllmi & Ouwehand 1987; Ouwehand 1987). In distal areas of the Vorarlberg Helvetic zone and in Grünten (Allgäu) the Luitere Bed and the older Plaine Morte Bed are unified into one single phosphate bed (Linder et al. 2006).

The Luitere Bed represents a major drowning unconformity, which documents a long-lasting total stop in platform carbonate production accompanied by erosion of the top of the Schrattenkalk Formation in proximal platform areas. Ammonite biostratigraphy indicates that the deposition of the Luitere Bed started in the *furcata* zone and ended near the boundary between the *melchioris* and *nolani* zones (Rick 1985;

Föllmi 1986, 1989b; Delamette et al. 1997). Where the Luitere Bed is unified with the Plaine Morte Bed, the maximal age corresponds to the *deshayesi* zone (Linder et al. 2006).

2.5.3 Garschella Formation: Brisi Member: Gams Beds, Brisi Sandstone and Brisi Limestone (Late Aptian)

Following the long-lasting drowning episode documented by the Luitere Bed, sedimentation processes took up again in outer shelf areas by the deposition of a coarsening- and shallowing-upward succession which starts with a dark and fine-grained, glauconite-containing mud and marl evolving upward into a more and more sandy and often heavily bioturbated marl (Gams Beds: Fig. 2; Heim 1910–1916; Ganz 1912; Heim & Seitz 1934; Föllmi & Ouwehand 1987). The maximal thickness of this unit is approximately 50 m. The Gams Beds show an upward transition to a coarse-grained and bioturbated sandstone (Brisi Sandstone: Fig. 2; Heim 1910–1916; Ganz 1912; Heim & Seitz 1934; Föllmi & Ouwehand 1987), which onlaps in proximal directions onto the platform area. This detrital unit of maximally 50 m thickness documents a highly dynamic depositional environment, with frequent storm- and current-related structures (mesoscale cross-bedding, hummocky cross stratification). In the Vorarlberg area, this unit can be composed of several deepening-upward parasequences (Föllmi 1986). Towards the top the Brisi Sandstone grades into a calcareous unit rich in crinoidal and bryozoan remains, which contains both coarse quartz sand and glauconite as well as significant amounts of micritized extraclasts reworked from underlying Schrattenkalk Formation (Brisi Limestone: Fig. 2; Heim 1910–1916; Ganz 1912; Heim & Seitz 1934; Fichter 1934; Föllmi & Ouwehand 1987). This unit continues the onlap onto the platform already initiated by the Brisi Sandstone and may in northern realms directly cover the platform sediments of the Schrattenkalk Formation. At the same time a progradational trend is obvious and deposition of this shallow-water carbonate unit extended well into the outer shelf realm. The Gams Beds are considered to represent a lowstand systems tract, which is followed by an onlapping transgressive systems tract – the Brisi Sandstone. The superjacent Brisi Limestone appears to embody a highstand systems tract (e.g., Funk et al. 1993).

The heterozoan Brisi Limestone is the youngest shallow-water carbonate unit present on the Helvetic carbonate platform. The overlying condensed and phosphate- and glauconite-rich Twäriberg Bed indicates a further and final drowning phase during the latest Aptian, which signals the termination of platform growth across this particular part of the northern Tethyan margin.

The age of the Gams and Brisi Beds can only be determined by the ages of the underlying Luitere Bed (youngest age: *nolani* zone) and the overlying Twäriberg Bed (or Klaus Beds; oldest age: *jacobi* zone; cf. Föllmi 1986; Föllmi & Ouwehand 1987). It is therefore likely that these units were deposited during the younger part of the *nolani* and older part of the following *jacobi* zones.

2.5.4 Garschella Formation: Selun Member: Twäriberg Bed (latest Aptian to earliest Albian): Final platform drowning episode

In distal, outer platform areas, the top surface of the Brisi Limestone is covered by a thin veneer of condensed and fossiliferous, glauconite- and phosphate-rich sediments, which may also be restricted to infills in surface incisions (Twäriberg Bed; Fig. 2; Ganz 1912; Föllmi 1986, 1989; Föllmi & Ouwehand 1987; Ouwehand 1987). In outer-shelf areas of the Vorarlberg Helvetic realm, this formation is replaced by a resediment – the Klaus and Rankweil Beds containing sediments of the Twäriberg Bed, Brisi Limestone and older sediments (Föllmi 1986; Föllmi & Ouwehand 1987).

The Twäriberg Bed documents a further and final drowning phase in the history of the Helvetic carbonate platform. Ammonites indicate the *jacobi* and the overlying *tardefurcata* zones, which suggests that the termination of platform growth coincides with the *jacobi* zone.

2.6 The period following the final platform drowning phase in the latest Aptian: continuing condensation and phosphogenesis followed by progressive installation of pelagic conditions in the Helvetic realm

Following the final drowning phase near the Aptian-Albian boundary, further phases of condensation and phosphogenesis are observed, notably during the later part of the *tardefurcata* zone and the *mammillatum* zone (Durschlägi Bed; Fig. 2; Ganz 1912; Föllmi 1986; Föllmi & Ouwehand 1987), during the *inflatum* zone (Wannenalp Bed; Fig. 2; Ganz 1912; Föllmi & Ouwehand 1987), and during the *dispar* zone and earliest Cenomanian (Kamm Bed; Fig. 2; Heim & Seitz 1934; Föllmi & Ouwehand 1987). In distal areas, theses beds unify into one single condensed and phosphatic bed – the Plattenwald Bed (Fig. 2; Heim & Seitz 1934; Föllmi 1987; Föllmi & Ouwehand 1987). In the intervening periods, sandstone and sandy hemipelagic carbonates and marls were deposited (Niederi, Sellamatt and Aubrig Beds; Fig. 2; Föllmi & Ouwehand 1987). All condensed and phosphatic beds are well dated by ammonite biostratigraphy. They and the intervening non-condensed beds are all part of the Garschella Formation.

The glauconite and phosphate-rich sediments of the Garschella Formation are overlain by pelagic carbonates of the Seewen Formation, which in the northern part of the Helvetic zone follows on top of the Kamm Bed and has a oldest age corresponding to the Early Cenomanian. In southern parts, the Seewen Formation lies directly on top of the Aubrig or Plattenwald beds and there, its stratigraphic age may well correspond to the *dispar* zone (Fig. 2). In a zone following the former platform margin, Seewen sediments of latest Albian and Cenomanian age are missing, which indicates a continuation of condensation processes related to the deposition of the Plattenwald Bed well into the Turonian (Föllmi 1986, 1989a).

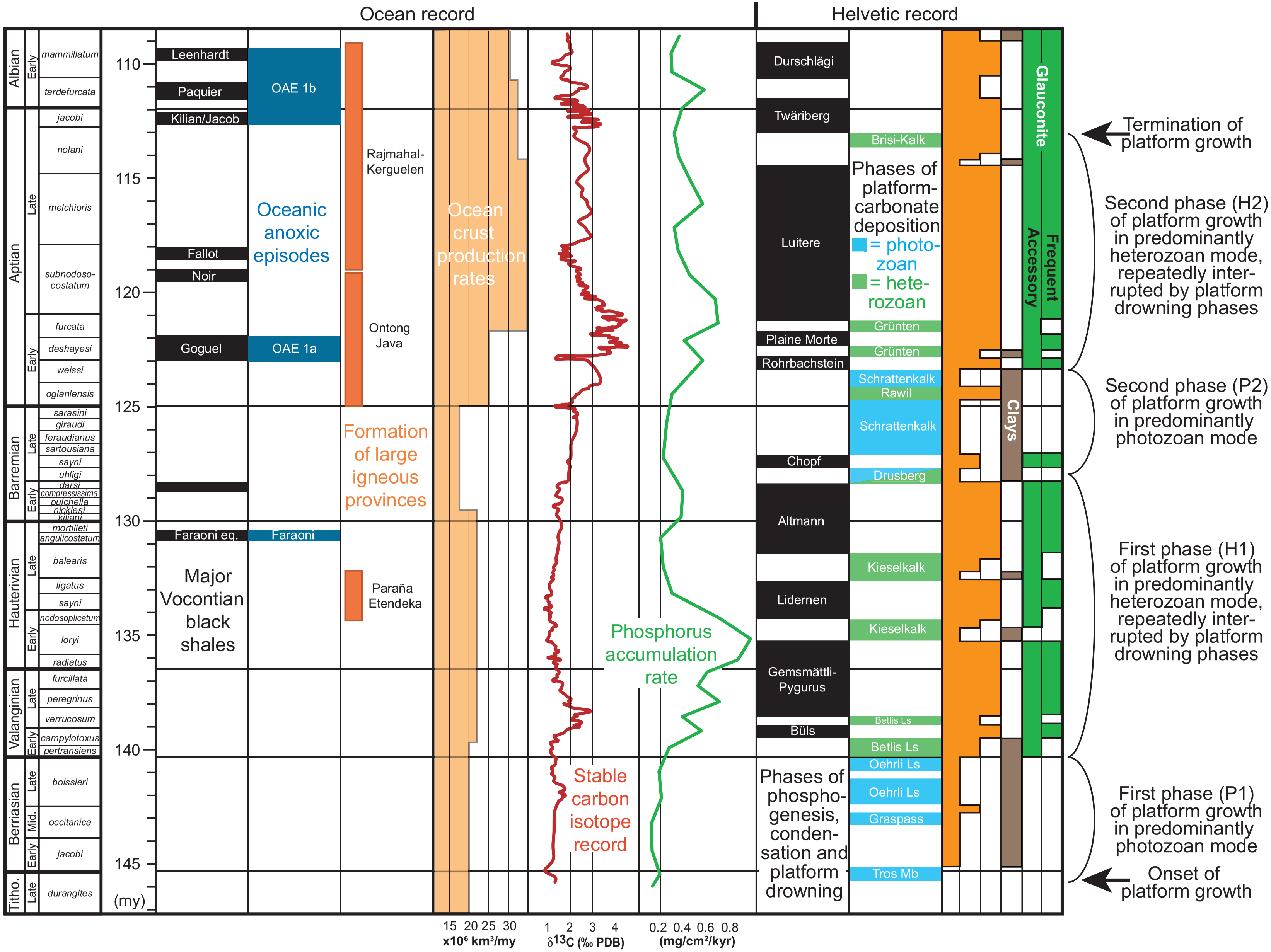

Fig. 9. Synthesis diagram showing general paleoceanographic and paleoenvironmental trends ("ocean record") correlated with temporal trends in Helvetic platform growth. Vocontian anoxic records after Bréhéret (1997); ocean anoxic events after Leckie et al. (2002) and Erba et al. (2004); large igneous provinces after Courtillot & Renne (2003); ocean-crust production after Larson (1991); stable carbon isotopes after Emmanuel & Renard (1993), Hennig et al. (1999), van de Schootbrugge et al. (2000), Herrle et al. (2004), Godet et al. (2006) and Föllmi et al. (2006) (compare also Wissler et al., 2002; Duchamp-Alphonse et al., 2006); ocean phosphorus accumulation rates after Föllmi (1995); time scale after Gradstein et al. (2004). Note that with alternative time scales, such as with those recently published by Fiet et al. (2006) and Sprovieri et al. (2006), the emplacement and correlation of the large igneous provinces (dated by radiogenic isotopes) would correspondingly shift.

3. Interpretation of the evolution of the Early Cretaceous Helvetic carbonate platform in the context of paleoceanographic and paleoenvironmental change

3.1 General trends in Early Cretaceous platform sedimentation pattern

The evolution of the Early Cretaceous carbonate platform of the Helvetic realm passed essentially through two different types of functioning, which are summarized in Fig. 9. The first type of platform development consisted in carbonate production in a photozoan mode – a mode in which the platform ecosystem included photosynthetic organisms (such as green algae) or metazoa which may have contained photosymbionts (corals). These ecosystems favored the growth of patch reefs composed of corals, rudists, stromatoporoids and chaetetids, and influenced as such the morphology of the platform, in inducing a distally rimmed platform morphology (especially in the case of the Tros Member, the upper Oehrli Limestone, and upper Schrattenkalk; Read 1985; Bollinger 1988; Mohr 1992; Linder et al. 2006). The presence of oolitic shoals and carbonate sand bodies may have added to this effect. This has led to a separation of an inner lagoonal environment from an outer platform-margin environment. Of interest here is also the observation that carbonates produced in this mode included an important aragonitic component (Godet et al. 2006; Föllmi et al. 2006).

During the development of the Helvetic platform in the photozoan mode, the deposition of clay-rich successions became important in the outer shelf (Zementstein Formation, Palfris Formation and Drusberg Member), whereas detrital material in the form of quartz grains is sparse and mostly very fine grained. Glauconite is rare and occurs only in discrete layers (e.g., Lienert 1965); phosphates and phosphatized materials are absent on a macroscopic scale (Fig. 9).

Two photozoan phases are discerned during the life time of the Helvetic platform, which are dated as latest Tithonian to latest Berriasian (phase P1) and Late Barremian to the early part of the Early Aptian (phase P2, which was interrupted by a brief phase of heterozoan carbonate production preserved in sediments of the Rawil Member; Fig. 9).

A second mode of platform development is characterized by heterozoan carbonate production, with a clear dominance of crinoidal biostromes in the inner part of the platform (e.g., Betlis and Kieselkalk Formations, Grünten Member and Brisi Limestone). They were accompanied by bryozoans, brachiopods, echinoids, and thick-shelled bivalves. Siliceous sponges dominated the external platform, and hermatypic reefs were generally absent. The platform morphology showed less relief and was ramp-like (e.g., Read 1985). Platform-derived carbonates may have been transported along long distances into the outer shelf. Carbonate-producing platform ecosystems in this mode were predominantly respiring and probably lacked a major photosynthetic component. Carbonate production was essentially calcitic (high Mg; e.g., Wefer & Berger 1991).

The heterozoan carbonates of the Helvetic platform are commonly rich in quartz- and glauconite grains. Clay-rich deposits in the outer shelf are rare, and pelagic carbonate may prevail (e.g., Diphyoides Formation, distal equivalents of the lower Kieselkalk).

In contrast to photozoan platform development, the heterozoan mode of platform growth was repeatedly interrupted by episodes during which platform carbonate production came to an almost complete standstill, and already deposited carbonates were subjected to erosion and strong reworking. These platform drowning episodes were marked by the development of an erosional hiatus in proximal platform areas, whereas in distal platform regions strongly condensed, phosphatic, glauconite- and quartz-rich beds were deposited (e.g., Schlager, 1981; Föllmi et al. 1994).

Two main phases of heterozoan platform development accompanied by platform drowning episodes are distinguished, which are dated as Early Valanginian to Early Barremian (phase H1) and late Early Aptian to latest Aptian (phase H2). The final platform drowning episode took place during the latest Aptian. A minor phase of heterozoan platform developement occurred in the earliest Aptian (Rawil Member).

3.2 Correlation of general trends in Early Cretaceous platform growth with general paleo-environmental and paleoceanographic change

Bréhéret & Delamette (1989) were amongst the first to point out that a temporal correlation and genetic link is present between the Helvetic condensed and phosphate-rich beds and organic-rich horizons in the outer-shelf and basinal Tethyan realm (e.g., Vocontian Trough, Apulian realm; Fig. 9). Indeed, a coarse correlation is possible for a selection of condensed beds but albeit not (yet?) for all. The basal part of the Büls-Gemsmättli-Pygurus complex is correlated to the globally recognized Valanginian positive excursion in the $\delta^{13}C$ record (e.g., Lini et al. 1992; Erba et al. 2004), even if the Büls Member itself predates this event. The onset of the Altmann Member is coarsely correlated to the Faraoni anoxic event; although also here, a slight diachroneity in the onset of both episodes is present. The Rohrbachstein-Plaine Morte-Luitere complex is partly correlated with oceanic anoxic event (OAE) 1a and its follow-ups (Noir and Fallot; Fig. 9; Wissler et al., 2003), but also here, the Rohrbachstein episode predates the onset of OAE1a. The exact time equivalent of OAE1a is located within the phosphatic Plaine Morte Bed. The final drowning event of the Helvetic platform appears to coincide with the onset of OAE1b. Albian phosphorite beds in the Helvetic zone are almost all correlated to Vocontian episodes of increased black-shale deposition (Bréhéret & Delamette 1989). However, the drowning episode documented by the Lidernen Beds has not found a major anoxic counterpart so far.

With the recent arrival of more complete and higher-resolution carbon-isotope data sets, our rather optimistic correlation of the Early Cretaceous drowning episodes with $\delta^{13}C$

positive excursions can only partly be maintained (Föllmi et al. 1994). It is now clear that not every drowning episode is correlated with a specific carbon excursion (Fig. 9; van de Schootbrugge et al. 2003; Godet et al. 2006), but that more in general, the onset of each phase of heterozoan carbonate production (H1 and H2) is correlated with a major positive carbon isotope excursion (Fig. 9). Also here, the onset of both phases slightly predates both excursions.

A rather good correlation exists between increases in oceanic phosphorus burial rates during the Early Cretaceous and the onset of both major phases of heterozoan carbonate accumulation and platform drowning (H1 and H2; Föllmi et al. 2006). Younger drowning episodes within each phase (H1 and H2), such as the oldest sediments within the Altmann Member are less well correlated with positive excursions in oceanic phosphorus burial (e.g., Bodin et al. 2006c).

3.3 The influence of general paleoenvironmental and paleoceanographic change on Helvetic platform development

Even if not every change within the evolution of the Helvetic carbonate platform is correlated to a corresponding paleoceanographic event, it can be stated that the general changes in carbonate production are positively linked with global change during the Early Cretaceous. The two photozoan phases (P1 and P2) are positively correlated with phases of low input rates of coarse-grained detritus and higher input rates of clay-sized material, to generally low rates of phosphorus burial and to the absence of major OAE's. The two periods are interpreted as predominantly oligotrophic (possible exception are the sediments of the Rawil Member).

The two phases of carbonate deposition in a heterozoan mode and frequent platform drowning (H1 and H2) are correlated to periods of increased coarse-grained detrital input, glauconite and phosphate authigenesis, increased phosphorus burial, and their onsets are marked by a major positive excursion in stable carbon-isotope records. Furthermore, these periods are characterized by the episodic occurrence of oceanic anoxic conditions, generally elevated oceanic crust production (Larson 1991), and by the formation of large igneous provinces (Courtillot & Rennes 2003).

The increase in coarse-grained detrital and phosphorus input is an indication of increased chemical weathering on the continent, which may have been related to global warming (Weissert 1990; Föllmi 1995; Wortmann et al. 2004). Potential inductors of global warming are the important flood-basalt events and the identified phases of globally increased seafloor spreading by the increased release of primordial CO_2 to the atmosphere (e.g., Arthur et al. 1985).

The heterozoan mode of carbonate production is interpreted as mesotrophic. The drowning episodes are considered to have resulted from eutrophic conditions, related to the increased upwelling of colder, nutrient-rich waters (Föllmi et al. 1994, 2006; van de Schootbrugge et al. 2000).

The offset in timing between the onset of the two heterozoan-drowning periods (H1 and H2) and the positive excursions in the stable-carbon isotope record may indicate that the ecology of the Helvetic platform system was quite sensitive to global paleoenvironmental change in general and reacted in close response to it, whereas the oceanic stable-carbon isotope system and – in tandem – the widespread deposition of organic-rich sediments had a longer response time. Similar observations have been made in other ecosystems such as in pelagic nannoplankton ("nannoconid crises"; Erba 1994; Erba & Tremolada 2004), and for OAE2 (Late Cenomanian, Mort et al. 2007). The prolonged durations of phases H1 and H2 relative to the positive excursions within the stable carbon-isotope and phosphorus burial records are also an indicator that these phases were rather persistent and may have been buffered in one way or another, once they unfolded on the Helvetic platform.

3.4 The influence of the Helvetic carbonate platform on the chemistry of the Tethyan basin

The Helvetic platform was part of a large and impressive shallow-water platform system that constituted the northern Tethyan margin along a distance of at least 2500km (e.g., Kilian 1907; Golonka 2004). This platform interacted actively with adjacent basins, in that it was not only passively influenced by paleoenvironmental and paleoceanographic change, but it also influenced the outer shelf and basinal environment itself.

A first interface was defined by its morphology and by the temporal changes therein. During times of photozoan carbonate production, the platform was predominantly distally rimmed, according to facies distributions and sedimentological features (e.g., Föllmi et al. 2006; Linder et al. 2006), and the belt of patch reefs, oolitic shoals and carbonate sand bodies functioned as a filter, which fractionated fluxes of dissolved and particulate material. For example, a fractionation can be observed with regards to kaolinite distributions along a platform – outer shelf – basin transect. This phyllosilicate mineral is preferentially retained on the platform during times of photozoan carbonate production. We also postulate fractionation patterns with regards to the export of dissolved organic and inorganic carbon (DOC and DIC), derived from the platform and the adjacent continent (Föllmi et al. 2006).

During times of heterozoan carbonate production, the subtle changes in facies distributions along bathymetric transects and the width of the belt in which carbonate exportation occurred suggest that the platform morphology resembled a homoclinal ramp, which was more transparent with regards to fluxes from the platform and the continent to the outer shelf and the Tethyan basin (Bodin et al. 2006a).

The type and composition of the platform ecosystem and changes therein influenced not only the quality and quantity of carbonate sediment accumulated on the platform itself, but also of those exported into the outer shelf and basin. Reboulet et al. (2003) observed, for instance, that Valanginian hemipelagic carbonates in the Vocontian Trough contain an important component of platform-derived material. A link between platform carbonate export and hemipelagic carbonate accumulation is also suggested by the observation that times of major platform drowning, such as in the Late Valanginian and Late Aptian, are times of minimal carbonate deposition in the Vocontian Trough (Bréhéret 1997; Duchamp-Alphonse 2006). To this we add that the mineralogical composition of platform-derived carbonate material may have changed as well: during times of photozoan platform development, aragonite producers were important members of the carbonate-producing benthic community, whereas during times of heterozoan platform development, the platform ecosystem consisted predominantly of calcite producers. Inclusion of aragonite and changes in the aragonite/calcite ratio of exported carbonate probably had an influence on the carbonate carbon cycle in the adjacent outer shelf and basin, in that aragonite may more readily dissolve and influence oceanic DIC budgets. We also postulated that this phenomenon – together with changes in the quality and quantity of exported DOC – may have had an effect on the stable carbon-isotope record of the adjacent basin (Godet et al. 2006; Föllmi et al. 2006).

4. Conclusions

During the last 25 years, relevant biostratigraphic age information has been obtained from a row of new ammonite discoveries in the Early Cretaceous sedimentary succession of the Helvetic thrust and fold belt, which allow us to propose a chronostratigraphic scheme of unprecedented accuracy. This stratigraphic precision permits us to propose precise correlations with paleoceanographic and paleoenvironmental data sets of the same time, which were obtained in well-dated basinal sequences, and to compare the evolution of the Helvetic shallow-water carbonate platform succession with coeval paleoenvironmental and paleoceanographic change.

The evolution of the Helvetic platform started in the latest Jurassic and passed through two different modes of build up: the first mode consisted in carbonate deposition in a photozoan mode and is observed during the period between the latest Jurassic and the Late Berriasian, and between the Late Barremian and Early Aptian. The second mode encompassed carbonate production in a heterozoan mode, which was frequently interrupted by incipient platform drowning phases, and occurred during the periods between the Early Valanginian and Early Barremian, the earliest Aptian, and late Early Aptian to latest Aptian. Shallow-water production on the Helvetic platform stopped during the latestmost Aptian.

The unfolding of these two phases was driven by paleoceanographic and paleoenvironmental change. The photozoan phases coincide predominantly with oligotrophic conditions, whereas the mesotrophic heterozoan phases are associated with warmer and probably more humid periods, in which continental weathering rates increased. This led to the increased input of coarse-grained detritus and nutrients into the platform realm, and with that to changes in the carbonate producing ecosystems towards heterozoan, suspension-feeding and respiring communities or even to the temporary disappearance of carbonate-producing organisms. The heterozoan phases are accompanied by oceanic anoxic events in the deeper basins and their ultimate cause is to be sought in increases in atmospheric greenhouse conditions induced by intensified oceanic spreading and increased volcanic activity.

The northern Tethyan carbonate platform itself influenced the deeper basinal environment by changes in its filtering, throughput, and output capacities of dissolved and particulate material related to changes in its morphology and carbonate-producing ecosystems.

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