Evolution of the northern Tethyan Helvetic Platform during the late Berriasian and early Valanginian

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ABSTRACT

The Early Cretaceous period is characterized by widespread carbonate production in tropical and subtropical epicontinental seas, which was modulated by changes in sea-level, detrital and nutrient fluxes, and the global carbon cycle. As a result, carbonate platforms were sensitive recorders of environmental change, which often anticipated global environmental perturbations. A good example is provided by the northern Tethyan carbonate platform, which is presently preserved in the central European Helvetic Alps. There, the latest early to late Valanginian Weissert episode of global change, which is defined by the first important positive shift in δ¹³C records of the Cretaceous, is expressed by a prolonged, stepwise drowning phase. In this contribution, a detailed reconstruction of palaeoenvironmental change before and during the Weissert episode is provided based on three representative sections of the Helvetic platform. The sections are placed along a deepening transect and correlated by means of ammonite and microfossil biostratigraphy, sequence stratigraphy and δ¹³C chemostratigraphy. In a first phase of palaeoenvironmental change during the latest Berriasian, photozoan carbonate production was stopped by a major and hitherto undetected drowning episode, which was followed by a phase of renewed carbonate production by heterozoan biota. This phase was linked to major sea-level rise, a change to a more humid climate and strong regional subsidence associated with tectonic block tilting. During the Valanginian, the circulation of nutrient-enriched sea waters prevented a return to oligotrophic conditions and two further drowning episodes occurred, which are both documented by condensed phosphate-rich beds and dated as middle early Valanginian and late Valanginian to early Hauterivian. The exact causes of the three-step deterioration in carbonate production are not established but a link to episodic volcanic activity is likely, eventually related to the formation of the Paraná-Etendeka large igneous province.

INTRODUCTION

The Early Cretaceous was characterized by generally high pCO₂ levels and correspondingly reinforced greenhouse conditions, which were favourable to important carbonate production in tropical and subtropical shallow-water settings (Hay, 2008). During this time interval, carbonate deposition was modulated and in certain regions episodically interrupted by global sea-level change, changes in the global carbon cycle and corresponding pH and pCO₂ in sea water, which were often related to phases of major volcanic activity, and changes in detrital and nutrient flux rates. The resulting carbonate deposits represent first-order archives of palaeoclimate and palaeoenvironmental change, which recorded and often anticipated global perturbations (Föllmi et al., 1994, 2006; Weissert et al., 1998; Huck et al., 2011).

During the Early Cretaceous, a first episode of major palaeoenvironmental change occurred during the latest
early to the late Valanginian (Weissert episode), which is defined by the first important carbon-isotope excursion (CIE) of the Cretaceous. The mechanisms leading to this episode are likely to be sought in increased volcanic and hydrothermal activity, which – depending on which time scale is used – may be attributed to the formation of the Paranà-Etendeka Large Igneous Province (Lini et al., 1992; Erba et al., 2004; Martinez et al., 2015). The Weissert episode is preceded by a phase of significant palaeoenvironmental and palaeoclimate change, which occurred during the late Berriasian and early Valanginian. In the western European domain (England, Germany, France and Switzerland), a phase of enhanced humidity began during the late Berriasian, and probably reached a maximum in the earliest Valanginian (Hallam et al., 1991; Schnyder et al., 2005; Föllmi, 2012; Morales et al., 2013). A general increase in marine nutrient levels in ocean basins is recorded from the latest Berriasian to the late Valanginian (Föllmi, 1995; Duchamp-Alphonse et al., 2007) and on northern Tethyan platforms (Föllmi et al., 2007; Morales et al., 2013), which interfered with the evolution of carbonate platforms at that time. In addition, carbonate production was impacted by sea-level variations, the occurrence and timing of which are not well-constrained and still under debate (Schlager, 1981; Haq et al., 1987; Hardenbol et al., 1998; Gréselle & Pittet, 2010; Haq, 2014). Finally, and on a more regional scale, the change in platform morphology from a distally steepened ramp to a swell-dominated ramp and the disappearance of a barrier close to the Berriasian–Valanginian boundary documented in the Jura region probably influenced the distribution of continental fluxes on the northern Tethyan shelf and in the adjacent basin (Morales et al., 2013).

The Helvetic platform succession, which is presently preserved in the northern part of the central European Alps, documents the aforementioned palaeoenvironmental changes in great detail. A change from photozoan to heterozoan carbonate production has been observed near the Berriasian–Valanginian boundary (Ischi, 1978; Burger, 1985; Wyssling, 1986; Mohr, 1992; Föllmi et al., 1994, 2007), and two condensed phosphatic and glauconitic-rich layers of early Valanginian (Büls Beds), and late early Valanginian to Hauterivian age (Gemmsmättli Bed), highlighted the occurrence of two successive incipient drowning phases (Haldimann, 1977; Wyssling, 1986; Kuhn, 1996). While the presence of ammonites within these two beds permits the two drowning episodes to be accurately dated, the stratigraphy of the platform carbonates deposited prior to the formation of these two condensed beds is less well-constrained, impeding its correlation with the general record of environmental change during the late Berriasian and earliest Valanginian.

In this contribution, a detailed study of three representative sections along a proximal-distal transect through the upper Berriasian and Valanginian Helvetic succession is presented. An improved stratigraphic framework based on ammonite, benthic foraminiferal and calpionellid biosтратigraphy is established and combined with δ13C bulk-rock chemostratigraphy and sequence stratigraphy. The evolution in facies and microfacies associated with variations in mineralogical and phosphorus contents are used to examine changes in accommodation, ecology, nutrients and climate. The goal thereby is to trace the onset and evolution of the impact of palaeoenvironmental change prior to and during the Weissert episode on the northwestern Tethyan carbonate platform. In a second step, the Helvetic sedimentary succession is compared with sediments preserved in the Provence, Pyrenean and Jura Platforms, which allows a regional view of the palaeoenvironmental changes that occurred along the northern Tethyan margin to be developed. Finally, the potential influence of intense volcanic activity on palaeoecological and environmental changes is evaluated.

**GEOLOGICAL SETTING AND DESCRIPTION OF STUDIED SECTIONS**

The succession of Early Cretaceous platform deposits (Funk et al., 1993; Föllmi et al., 2006, 2007) starts with the Zementstein Formation, which is characterized by dark and monotonous marly carbonate deposits and dated from the Berriasella jacobi and Subthurmannia occitanica zones by ammonites and calpionellids (early Berriasian; Mohr, 1992). It is overlain by the Öhrli Formation, which documents the development of a photozoan carbonate platform with the predominant deposition of oolitic and bioclastic sediments, containing a rich and diverse fauna of benthic foraminifera, corals, green algae and echinoderms (Burger, 1985, 1986; Mohr, 1992). The Öhrli Formation includes two marly and calcareous intervals – the Lower Öhrli Marl Member, Lower Öhrli Limestone Member, Upper Öhrli Marl Member and Upper Öhrli Limestone Member, respectively. The age of the Öhrli Formation is poorly constrained. A maximum age is provided by calpionellids and ammonites found at its base, which indicate an early Berriasian age (S. occitanica zone) (Mohr, 1992). The Öhrli Formation passes laterally into the monotonous hemipelagic marly succession of the Palfris Formation (Burger, 1985, 1986; Wyssling, 1986).

Both formations are overlain by the marly and sand-rich Vitznau Formation, which was attributed to the early Valanginian based on palynomorphs (Pantic & Burger, 1981). The overlaying Betlis Formation is rich in echinoderms and bryozoans and marks the development of a heterozoan platform. The occurrence of the ammonite
Thurmanniceras thurmani s.l. (Wyssling, 1986) indicates a T. pertransiens age. Distal occurrences of the Betlis Formation include the condensed and phosphatic Büls Bed, which was dated as late T. pertransiens – early B. campylotoxus zone (Kuhn, 1996). The overlying condensed and phosphatic Gemsmättli Bed and its lateral equivalent, the sandy Pygurus Bed, provides a minimum age corresponding to the S. verrucosum zone (Wyssling, 1986; Kuhn, 1996; Föllmi et al., 2007).

Three sections were selected, which represent inner shelf, barrier and outer shelf settings along a proximal-distal transect (Säntis, Dräckloch, Vitznau; Fig. 1). The Säntis section (47°15′3″N; 9°19′16″E) is located at the foot of the Säntis Mountain close to Schwägalp (canton Appenzell Ausserrhoden). It belongs to the Säntis-Drusberg nappe. The measured succession is approximately 105 m thick and includes the Upper Öhrli Limestone Member, Vitznau Formation, Betlis Formation, and the Gemsmättli Bed (Fig. 2). The Dräckloch section (46°58′27″N, 8°56′7″E) is part of the Gassenstock Mountain (Bös Fulen summit), situated 5 km south of the village of Richisau on the border between the cantons of Glarus and Schwyz. The measured section is 400 m thick and starts with the Öhrli Formation (Fig. 3A), Upper Öhrli Limestone Member and Upper Öhrli Marl Member (Upper Öhrli Limestone Member), and goes on with the Vitznau and Betlis formations (Fig. 3B). The Betlis Formation is overlain by the sandy, coarse-grained sediments of the Pygurus Bed. The Vitznau section (47°0′25″N; 8°30′23″E) is situated close to the village of Vitznau (canton Lucerne). Tectonically it belongs to the ‘Randkette’ attached to the Wildhorn nappe. The measured section is approximately 60 m thick and includes the Palfris Formation, the Upper Öhrli Limestone Member, and the Vitznau and Betlis formations (Fig. 4).
MATERIAL AND METHODS

Biostratigraphy

In total, 334 thin sections were examined for their benthic foraminiferal and calpionellid assemblages (152 for the Säntis section, 134 for the Dräckloch section and 48 for the Vitznau section). The stratigraphic range of marker benthic foraminifera species was attributed following Darzac (1983), Boisseau (1987), and Blanc (1996), and of calpionellids following Remane (1963, 1985), Remane et al. (1986, 1998), Blanc (1996), and Blau & Grün (1997). In addition, an ammonite was identified from the Vitznau section.

Microfacies and sequence stratigraphy

The outcrops, samples and thin sections were analysed for their facies and microfacies, which were described and interpreted following the classification of Arnaud-Vannneau & Arnaud (2005). Twelve facies zones were thereby differentiated, from F1 corresponding to hemipelagic environments, to F10 attributed to shallow subtidal to tidal environments. The sequence stratigraphic framework was established using field observations and trends in facies and microfacies (Vail et al., 1987; Catuneanu et al., 2009).

Carbon and oxygen isotope analyses

The carbon and oxygen isotope composition (δ13C and δ18O values) of 266 bulk-rock carbonate samples (69 from Säntis, 145 from Dräckloch and 52 from Vitznau) was determined using a Thermo Fisher Scientific carbonate-preparation device and GasBench II connected to a Thermo Fisher Scientific Delta Plus XL isotope ratio mass spectrometer, which was operated in a continuous helium flow mode. The CO2 was extracted by reaction with crystalline orthophosphoric acid of pro-analysis quality shifted to liquid state through heating at 70°C. Ratios of
carbon and oxygen isotopes are reported in the delta (δ) notation as the per mil (‰) deviation relative to the Vienna– Pee Dee belemnite standard. Replicate analyses demonstrated an analytical reproducibility for the international calcite standard NBS-19 and the laboratory standards Carrara Marble of better than ±0.05‰ for δ13C and ±0.1‰ for δ18O.

**Phosphorus content**

Total phosphorus (P) contents were measured on 320 bulk-rock samples (129 from the Säntis section, 143 from the Dräckloch section and 48 from the Vitznau section) following the procedure described in Bodin et al. (2006). The concentration of P was obtained in ppm by calibration with known standard solutions using a UV/Vis photometer (Perking Elmer UV/Vis Photometer Lambda 10, λ = 865 nm) with a mean precision of 5%.

**Bulk-rock mineralogy**

The bulk-rock mineralogy was determined with a Thermo scientific ARL X’TRA IP2500 X-ray diffractometer using a semi-quantification method using external standards and following the procedures of Kübler (1983, 1987) and Adatte et al. (1996). The precision was 5 to 10% for phyllosilicates and 5% for grain minerals. A total of 113 samples were run for the section at Säntis, 147 for the section at Dräckloch, and 47 for the section at Vitznau. Relative contents of phyllosilicates, quartz, K-feldspar, Na-plagioclase, calcite, dolomite, pyrite, goethite and ankerite were determined. Variations in K-feldspar, Na-plagioclase, dolomite, pyrite, goethite and ankerite proportions were not significant enough to be shown in this publication. They were nevertheless taken into account in the calculation of the percentages of the other minerals.

**DATA DOCUMENTATION AND INTERPRETATION**

**Lithostratigraphy and microfacies**

**Säntis section**

The lower part of the section (the first 53 m) corresponds to the upper part of the Öhrli Formation (Figs 2 and 5). This unit includes abundant large benthic foraminifera accompanied by green algae, rudists, gastropods, calcareous sponges, corals, bivalves and echinoderms. Its microfacies ranges from F2 to F10 (Table 1), and is largely dominated by shallow-water limestone deposited at either side of a shoal. Three dissolution levels were observed within the Upper Öhrli Limestone Member. The first is located 20 m above the base of the section, where dissolution features infilled by mud (Fig. 6) affect 2 m of the underlying sediment. A second level occurs at 26 m above the base of the section, where muddy cavity infillings are present (Figs 5 and 7A). The Öhrli Formation terminates with facies characterized by enhanced microbial activity (intense micritization of clasts) and an abundance of gastropods and thin miliolids (F10). Its top surface is a complex surface marked by dissolution vugs, microscopic borings and infillings by mudstone of the overlying Vitznau Formation (Fig. 6). These borings are also present in the overlying bed, indicating the superposition of two hardgrounds. The three dissolution levels are interpreted as epikarstic layers.

The base of the Vitznau Formation (between 53 to 57 m above section base) is characterized by a microfacies rich in crinoids and bryozoans with an important degree of sedimentary reworking (F4/FT). This microfacies type is replaced at 57 m above the base of the section by peloidal, crinoid-rich microfacies showing a relatively scarce and poorly diversified fauna of bivalves, bryozoans and circalittoral foraminifera (F3). Based on these observations, the Vitznau Formation indicates a change towards heterozoan carbonate production.

At the base of the Betlis Formation (69 to 72 m above the base of the section), oncoids and reworked bioclasts were observed (F4/FT). Numerous chert nodules occur between 67 and 86-5 m above the base of the section. An erosive surface was identified at 86-5 m. The upper part of the Betlis Formation (from 96 to 107 m above the base of the section) shows an important increase in detrital quartz, with the occurrence of well-rounded and broken quartz grains (0.2 to 1 mm). The top of the Betlis Formation is characterized by a hardground with borings infilled by phosphatic and glauconitic sediment of the overlying condensed Gemsmättli Bed (Fig. 8B).

**Dräckloch section**

The Dräckloch section (Figs 3 and 9) starts with the Lower Öhrli Limestone Member, which shows a microfacies rich in quartz, circalittoral foraminifera, sponge spicules, echinoderms and containing sparse larger agglutinated foraminifera (F2/3) typical of platform slope deposits. This member evolves (22 to 55 m above the base of the section) towards coarser grainstone containing large benthic foraminifera, echinoderms and small ooids, together with numerous large rounded mud intraclasts and bioclasts (shallow-water photozoan facies F5/6). The few samples collected from the marly upper part of the Lower Öhrli Limestone Member and the Upper Öhrli Marl Member (55 to 130 m above section base) show a return to facies F2/3.
The microfacies of the overlaying Upper Öhrli Limestone Member shows an increasing proportion of large benthic foraminifera, echinoderms and green algae (F6/7) between 130 and 174 m above the base of the section. At 174 m, a rapid change towards facies F3 is noted, and an evolution towards coarser grainstone (up to F8) follows to a point 246 m above the base of the section. Fringing cements and dissolution vugs with mud and microsparite infillings (Fig. 8C and D) were observed between 236 and 246 m above the base of the section. From 246 to 260 m above section base, a change in biota occurs: corals and calcareous sponge debris become dominant and benthic foraminifera nearly disappear with the exception of *Andersenolina* (Fig. 8E). The presence of dolomitic extraclasts indicative of a confined and very shallow environment mixed with mud of outer shelf origin (containing *Lenticulina*), hermatypic and ahermatypic coral debris, rudists and bryozoans (Fig. 7H) suggest strong sedimentary reworking (F5/FT). The thickness of this interval (246 to 260 m above section base) could not be evaluated because of the presence of a fault zone (indicated in Figs 3 and 10). Nevertheless, the floro-faunal microfacies associations are similar below and above this faulted zone, indicating a certain continuity in facies. The top of the Upper Öhrli Limestone Member shows borings infilled by a complex succession of partly phosphatized sediments including mud with small peloids, and pyrite (Fig. 10A and B), suggesting a hardground (Fig. 11A) and condensation. The uppermost bed of the Upper Öhrli Limestone Member shows evidence of sediment reworking with the occurrence of detrital mud pebbles with dolomite extraclasts (FT). Bladed circumgranular cements are observed in this bed (Fig. 8F), pointing to early diagenetic cementation in the vadose zone.

The overlying Vitznau Formation starts with a layer containing abundant reworked bryozoans, corals, *Gryphaea* and serpulids floating in a clayey matrix (FT, Figs 10C and 12C), which documents a change towards heterozoan carbonate production. A second hardground with borings infilled with pyrite is observed at the top of this interval. The lower part of the Vitznau Formation at 246 to 300 m above the base of the section shows limestone-marl alternations containing abundant *Gryphaea* in life position or weakly transported, some brachiopods,
Table 1. Facies description and their palaeoenvironmental significance (adapted from Arnaud-Vanneau & Arnaud, 2005)

| Facies type | Description | Location |
|-------------|-------------|----------|
| F1 Wackestone with sponge spicules | Marl and bluish-grey argillaceous limestone containing significant amount of clay and silted quartz. Sponge spicules and ostracods are found in abundance. The fauna also includes irregular sea urchins, Gryphaea, and small agglutinated foraminifera. | Hemipelagic facies |
| F2 Wackestone with irregular sea urchins and small benthic foraminifers | Marly limestone including irregular sea urchins, small agglutinated foraminifera and peloids in abundance, and sponge spicules, ostracods and serpulids in a lesser extent. | Lower offshore, quiet subtidal |
| F3 Packstone-grainstone with echinoderm fragments and small benthic foraminifers | Well sorted and slightly more calcareous (less detrital grains) than F2 with sparse macrofauna. Preponderance of echinoderm fragments, peloids and small benthic foraminifera. | Lower and upper offshore, deep subtidal |
| F4 Packstone-grainstone with bryozoans and crinoids | Hydrodynamic facies often cross-bedded with coarser grains predominantly constituted of bryozoans and crinoid debris. Sarcic presence of reworked large benthic foraminifera such as Lenticulina or Andersenolina | Lower and upper offshore, deep subtidal, below the photic zone |
| F5 Grainstone with large rounded bioclasts | Limestone deposited under high energy, often showing oblique and cross stratifications. Contain abundant round-sized benthic foraminifera, mixed with diverse clasts (echinoderms, bivalves, gastropods, green algae, calcareous sponges, etc.) | Upper offshore and shoreface, shallow subtidal to tidal, photic zone |
| F6 Grainstone with oolites | High energy limestone with oblique and cross stratifications, characterized by the abundance of oolites | Shoreface, shallow subtidal to tidal, photic zone |
| F7 Grainstone and boundstone with hermatypic corals | High energy limestone with rounded skeletal debris, often containing oolites | Edge of the platform: photic zone, subtidal to tidal |
| F8 Packstone-wackestone with large benthic foraminifera and rudists | Coarse limestone with abundant and diversified fauna of large benthic foraminifera, but also rudists, gastropods, calcareous sponges, green algae and a high percentage of micritized bioclasts, as evidence of microbial activity, echinoderms are still present | External part of the inner platform |
| F9 Packstone-wackestone with milolidae | Massive calcareous meter-thick beds with micritized debris and milolids. Absence of echinoderms | Inner platform, shallow subtidal |
| F10 Packstone-grainstone with oncolites and Bacinella | Massive calcareous meter-thick beds with micritized debris, oncolites and Bacinella. Absence of echinoderms | Inner platform, shallow subtidal to tidal |
| FT Facies of transgression | High degree of reworking, leading to the mixing of biota living in different environments | Initiation of a relative sea-level rise |

circalittoral foraminifera and sponge spicules (deep subtidal facies F2/F3). Limestone layers are absent in the upper part of the Vitznau Formation (300 to 315 m above section base) and Gryphaea is less abundant.

The Betlis Formation begins 315 m above the base of the section with a layer containing ooids, abundant crinoids, sparse bryozoans, small benthic foraminifera, sponges and gastropods, together with reworked mud pebbles from the Vitznau Formation (FT). From 315 to 370 m, a peloidal microfacies containing crinoids and bryozoans is present (F3 to F4). Similarly to the Säntis section, numerous chert layers and nodules are present in the interval between 315 and 357 m (Fig. 11B). At 370 m, a level containing crinoids, bivalves, small benthic foraminifera, Lenticulina and ostracods shows important reworking (FT). The Pygurus Member on top of the Betlis Formation includes millimetre-sized, rounded and fractured quartz grains, and bioturbation is important.

Vitznau section

The Vitznau section (Fig. 13) starts with the upper part of the Palfris Formation, in which muddy facies containing sparse bioclasts of echinoderms and reworked circalittoral foraminifera (F1/F2) evolve towards a grainstone facies with peloids, sparse bryozoans and small benthic foraminifera (F3). In the overlying Upper Öhrli Limestone Member, 12.5 to 23.4 m above the base of the section, a change towards coarser grainstone with mud pebbles, echinoderms, sparse ooids, large benthic foraminifera, corals and sponges (F5) is observed. The last 1.6 m of the Öhrli Formation shows a complex succession of erosive surfaces and hardgrounds. A first irregular erosive surface associated with limestone lag pebbles (Fig. 11C) occurs at 23.4 m above section base. The overlying calcareous layer is perforated and the borings are infilled by marls of the covering layer (Fig. 11D). This
thin marly layer is rich in reworked and pyritized extraclasts (Fig. 10D). The next two layers have an erosive base (Fig. 11E). Their microfacies consists of peloids, echinoderms and small benthic foraminifera with sparse reworked platform debris (benthic foraminifera, ooids and extraclasts) (F3). In the uppermost part of the Upper Öhrli Limestone Member, the microfacies additionally contains calcareous sponges, corals and ooids (F6). A

Fig. 6. Sedimentology, geochemistry and mineralogy of the Säntis section. Microfacies classification after Arnaud-Vanneau & Arnaud (2005). Five sequence boundaries are identified. An abrupt change of carbonate production and an important hiatus are highlighted at the Berriasian-Valanginian boundary. Generally higher $\delta^{13}C$ values, and low P are observed within Berriasian photozoan limestone, whereas lower $\delta^{13}C$ values, and higher P characterise Valanginian heterozoan limestone. In the top part of the section, late Valanginian platform drowning is materialized by a condensed phosphatic layer infilling perforations. The Weissert episode is associated with peaks in P and quartz contents. Numerical data are included in Appendix.

Fig. 7. Marker benthic foraminifera identified in the studied sections. Scale 1 is used for *Pseudotextularia courtionensis* sp. and *Pseudotextularia courtionensis* (upper lower – lower upper Berriasian, images A and B, and C to J respectively), scale 2 for *Montsalevia elevata* (upper Berriasian, K to R), *Montsalevia salevensis* (lower Valanginian, S), and *Pfenderina neocomiensis* (upper Berriasian – Valanginian, T). (A) Dräckloch, Upper Öhrli Marls Member (GAS70); (B) Dräckloch, Upper Öhrli Limestone Member (GAS111); (C) Säntis, Upper Öhrli Limestone Member (SA99); (D) Dräckloch, Upper Öhrli Limestone Member (GAS109); (E) Dräckloch, Upper Öhrli Limestone Member (GAS111); (F) Dräckloch, Upper Öhrli Limestone Member (GAS135); (G) Dräckloch, Upper Öhrli Limestone Member (GAS139); (H) Dräckloch, Upper Öhrli Limestone Member (GAS143); (I) Dräckloch, Upper Öhrli Limestone Member (GAS155); (J) Vitznau, Upper Öhrli Limestone Member (Vz40); (K) Säntis, Upper Öhrli Limestone Member (I15); (L) Säntis, Upper Öhrli Limestone Member (SA87); (M) Dräckloch, Upper Öhrli Limestone Member (GAS109); (N) Dräckloch, Upper Öhrli Limestone Member (GAS125); (O) Dräckloch, Upper Öhrli Limestone Member (GAS127); (P) Dräckloch, Upper Öhrli Limestone Member (GAS153); (Q) Vitznau, Upper Öhrli Limestone Member (Vz40); (R) Vitznau, Upper Öhrli Limestone Member (Vz43); (S) Säntis, Betlis Formation (SA9); and (T) Säntis, Upper Öhrli Limestone Member (SA66) (GASV8), Dräckloch.
hardground is observed on top of the Upper Öhrli Limestone Member, whose borings are often filled with pyrite (Fig. 10E). A further marine hardground occurs on top of the first marl-limestone alternation of the Vitznau Formation. The corresponding microfacies shows intense reworking with ostracods, microbial mats, bryozoans, broken serpulids, micritized crinoids and corals, together with mud pebbles rich in quartz (FT), up to 26·3 m above the base of the section (Fig. 10F). From 26·3 to 56·8 m, the microfacies consists of monotonous wackestone containing ostracods, sponge spicules and serpulids (F1/F2). Numerous Gryphaea were observed in life position or reworked.

At 56·8 m above the base of the section, an erosive bank rich in bivalves is present (Fig. 11F), which is followed by a recessive marly interval of 1 m. Finally, field observations indicate that the Betlis Formation is composed of a peloidal echinodermal carbonate (F3). The lack of samples in this interval is due to difficult access in steep terrain and the presence of vegetation hiding the transition between the Vitznau and Betlis formations.

Carbon and oxygen isotope data
Oxygen isotope values (see supplementary data) oscillate between $-5^\circ$ and $-2^\circ$ in the Säntis section (with a mean...
of −3·5‰ and a standard deviation of 0·4‰), and −6 and −2‰ in the Dräckloch and Vitznau sections (with means of −3·7 and −3·5‰ and standard deviations of 0·8 and 0·7‰, respectively). The δ¹⁸O values reflect significant diagenetic overprint (Choquette & James, 1987) and are not further discussed here.

The δ¹³C long-term trends are similar between the three sections (Figs 5, 9, 10 and 12): relatively heavy but variable values (with mean values of 1·3, 1·1 and 0·9‰ and standard deviations of 0·7, 0·6 and 0·4‰, in the Säntis, Dräckloch and Vitznau sections, respectively) are observed in the Öhrli Formation and its distal equivalent, the Palfris Formation. In contrast, lower δ¹³C values (with mean values of 1·3, 0·5 and 0·3‰ and standard deviations of 0·2, 0·4 and 0·2‰ in the Säntis, Dräckloch and Vitznau sections, respectively) are recorded in the Vitznau and the Betlis formations. The Säntis section is the only section that records a positive δ¹³C shift (of 1·2‰) at the top of the Betlis Formation. The decrease in δ¹³C values (0·7‰) is abrupt and

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Fig. 9. Marker calpionellids and ammonite. (A) Remaniella filipesculi, calp. zones B to D3, Upper Öhrli Limestone Member (Vz45), Vitznau; (B) Calpionellopsis oblonga, calp. zones D2 to D3, Upper Öhrli Limestone Member (Vz45), Vitznau; (C) Calpionellopsis oblonga, calp. zones D2 to D3, Upper Öhrli Limestone Member (Vz45), Vitznau; (D) Calpionellopsis simplex, calp. zones D2 to D3, Upper Öhrli Limestone Member (Vz45), Vitznau; (E) Calpionellopsis simplex, calp. zones D2 to D3, Upper Öhrli Limestone Member (SA66), Säntis; (F) possible Tintinnopsis longa, calp. zones D1 to E2, Vitznau Formation; (G and H) Thurmanniceras thurmanni s.str. (upper Berriasian, T. ototeta ammonite zone), ventral and umbilical views, respectively.
occurs at the limit between the Upper Öhrli Limestone Member and the Vitznau Formation in the Säntis and Vitznau sections, and within the upper part of the Upper Öhrli Limestone Member in the Dräckloch section.

The circulation of meteoric or altered marine pore waters tends to decrease the oxygen and carbon-isotopic values in carbonates during diagenesis (Choquette & James, 1987). As such, a minor overprint of δ¹³C values is to be expected. However, the δ¹³C vs. δ¹⁸O plot (Fig. 14) exhibits a relatively poor correlation coefficient ($R^2 < 0.4$). In general, carbon-isotope records in neritic carbonates have been shown to be only marginally affected by burial diagenesis, and have been used as a reliable stratigraphic tool (Ferreri et al., 1997; Hennig, 2003; Föllmi et al., 2006; Weisert et al., 2008). Exceptions are, however, possible in the presence of erosion surfaces and depending on mineralogy (for instance aragonite versus calcite; Ferreri et al., 1997; Swart & Eberli, 2005; Weisert et al., 2008). The consistent trends between the sections, as well as the comparable δ¹³C trends and value ranges with correlated sections in the Jura Mountains and the Vocontian Basin (La Chambotte, Juracime, Montclus; Morales et al., 2013), suggest that the δ¹³C records are rather well preserved.

**Phosphorus content as a nutrient tracer**

Low P contents were measured in the Lower Öhrli Limestone Member, followed by higher values in the Upper Öhrli Marl Member (100 and 250 ppm on average in the Dräckloch section). In the Palfris Formation of the Vitznau section, P values oscillate around 200 ppm (Fig. 13). A decrease in P concentrations was measured in the overlying Upper Öhrli Limestone Member with mean values of 60, 80 and 70 ppm in the Säntis (Fig. 6, with the exception of two samples with values close to 1000 ppm), Dräckloch and Vitznau sections (Fig. 12), respectively. In the Öhrli Formation, variations in P concentrations are therefore associated with lithological changes. Therefore, the level of nutrients in the sea water was significantly controlled by depth.

Phosphorus contents abruptly increase at the base of the Vitznau Formation in the three sections. In this formation, mean values of 110, 250 and 300 ppm were measured in the Säntis, Dräckloch and Vitznau sections, respectively, which are similar to those in the Betlis Formation. In the Säntis and Dräckloch sections, the uppermost part of the Betlis Formation shows a progressive increase in P values up to 3700 and 2750 ppm, respectively. The increase in P levels in the Vitznau and Betlis
formations is associated with the proliferation of suspension-feeding organisms (essentially crinoids and bryozoa), leading to the production of heterozoan carbonates. The relatively high P contents observed in the Betlis Formation indicate that depth was not the only factor controlling the nutrient level, and that additional sources were involved.

**Bulk-rock mineralogy as a proxy for detrital input**

The phyllosilicate and quartz contents increase in the Lower Öhrli Limestone Member and Upper Öhrli Marl Member in the Dräckloch section (from 5 to 35% and from 10 to 25%, respectively), as well as in the Palfris Formation in the Vitznau section (up to 20% and 25%, respectively). They decrease below the detection limit of the XRD (<5%) in the overlying Upper Öhrli Limestone Member in all three sections. Therefore, these trends show a good correlation with lithological changes and are comparable to trends in P values.

In the Vitznau Formation, the phyllosilicate and quartz contents increase to 17% and 18%, respectively in the Dräckloch section, and up to 32 and 47%, respectively in the Vitznau section, indicating a strong increase in detrital material. In the Säntis section, they remain below the detection limit (<5%), perhaps linked to the more proximal location of this section. In the Betlis Formation, the
Phyllosilicate content falls below 10% in all three sections, but a different behaviour for the quartz content is observed. In the Dräckloch section, relatively high values occur at the base of the formation (36% at section meter 326). In the Säntis and Dräckloch sections, the quartz content falls below 5% and rises in the uppermost part of the formation to 44% and 36%, respectively. This goes along with the presence of large (>1 mm) rounded quartz grains and a concomitant increase in P values shortly before the drowning of the Weissert episode.

**Age control and correlation of sections**

A combination of lithological, biological and sequence stratigraphic tools were used to correlate the sections. Stratigraphic sequences were determined on the base of key surfaces (sequence boundaries, transgressive and maximum flooding surfaces). Sequence boundaries in shallow-water deposits can be recognized by the presence of unconformities associated with erosion and subaerial exposure (Vail *et al.*, 1987). Transgressive surfaces are often erosive and overlaid by reworked deposits, and maximum flooding surfaces are indicated by a maximum of accommodation space. In certain cases, accommodation maxima (between the transgressive and highstand systems tracts) correspond to a transitional interval termed maximum flooding zone (mfz). Parasequences were interpolated based on (micro-)facies and lithological observations, and are indicated in the corresponding figures. However, given the locally unequal sampling resolution due to limited access and fault zones, the determination of parasequences should only be considered as an

Fig. 12. Stratigraphy, sedimentology, geochemistry and mineralogy of the Dräckloch section. Microfacies classification after Arnaud-Vanneau & Arnaud (2005). Five sequence boundaries are identified. An abrupt change in carbonate production and important hiatuses are highlighted through the Berriasian-Valanginian boundary. Highly reworked deposits on top of an epikarst, hardgrounds and an abrupt negative shift in δ¹³C values witness the time gap. Note that the Weissert carbon-isotope excursion (CIE) is not preserved at the top of the section (the contact between the Pygurus Member and the Kieselkalk Formation is faulted), but peaks in P and quartz contents witness the ongoing drowning. Numerical data are included in Appendix.
approximation. The studied sections include a total of seven sequences, labelled from I to VII.

The age of the sequences was determined from their content in stratigraphic marker species (benthic foraminifera, calpionellids, ammonites), which allowed the sections to be correlated (Table 2). The stratigraphic distributions of marker benthic foraminifera appear to be consistent with those in various western Tethyan regions (Fig. 15): the Jura Mountains (Darsac, 1983; Blanc, 1996; Morales et al., 2013), Pyrenees (Peybernès & Combes, 1994) and Provence (Virgone & Masse, 1996; Virgone, 1997). The distribution of *Pseudotextulariella courtionensis* is particularly notable, since this foraminifer was identified in all three Helvetic sections. This species has a relatively wide geographic distribution since it has been recorded in the French Alps (Arnaud-Vanneau & Darsac, 1984), the French and Swiss Jura Mountains (Darsac, 1983; Boisseau, 1987; Pasquier, 1995; Blanc, 1996), the Pyrenees (Peybernès & Combes, 1994), Provence (Virgone & Masse, 1996; Virgone, 1997), and in the Helvetic Alps (Pasquier, 1995). Its biostratigraphic range probably extends back to the late early Berriasian (calpionellid zone C) and covers the early late Berriasian (*S. boissieri* ammonite zone, *Malbosiceras paramimounum* ammonite subzone, which corresponds to calpionellid zone D1). This was established in the Jura Mountains (Darsac, 1983; Boisseau, 1987; Blanc, 1996), and a compatible age range is noted in the Pyrenees and Provence (Peybernès & Combes, 1994; Virgone & Masse, 1996; Virgone, 1997).

*Pseudotextulariella courtionensis* may be associated with another large foraminifer, *Pavlovecina allobrogensis*, which has a shorter biostratigraphic range. *Pavlovecina allobrogensis* is found in a 1 to 2 m thick marker horizon in the Jura Mountains (Darsac, 1983; Boisseau, 1987; Adatte,
1988; Blanc, 1996), and indicates an early late Berriasian age (early S. boissieri ammonite zone, M. paramimounum ammonite subzone; early calpionellid zone D1; Blanc, 1996).

The first appearance of Montsalevia elevata and Pfendererina neocomiensis and the last appearance of Pseudotextulariella courtionensis mark the later part of the late Berriasian (Darsac, 1983; Boisseau, 1987; Adatte, 1988; Blanc, 1996). The presence of Montsalevia salevensis (Darsac, 1983; Boisseau, 1987; Adatte, 1988; Blanc, 1996).

The first sequence (sequence I), is marked by the joint presence of Pseudotextulariella courtionensis and Montsalevia elevata, and as such is of late early – early late Berriasian age. Sequence I is well-documented in the Dräckloch section (Fig. 15). Since this section is composed of outer shelf to outer platform deposits, sequence boundaries are not necessarily defined by emersion surfaces, and lowstand systems tracts (LST) can be preserved. There, sequence I starts 25 m above the base of the section, where the first sequence boundary (SB I) is placed.

The question mark is related to the uncertainty of the sedimentary interval to which the ammonite belong.
at a change from facies F5/6 to F2/3. The overlying shallow-upward interval thickens towards the west (e.g. towards the basin, Fig. 3) and is interpreted as a LST. The deepening upward trend towards facies F2 constitutes the transgressive systems tract (TST), and the mfz is placed in the more recessive layers covered by vegetation. The HST is well developed and documents the progressive installation of the photozoan platform. In the more distal Vitznau section, *Pseudotextulariella courtionensis* is the only stratigraphic marker found in the first sequence (from 0 to 12 m above section base). Since this foraminifer is also present in the overlying sequence and since *Pavlovecina allobrogensis* is generally found in shallow-water deposits, this first sequence is attributed to sequence I.

The following sequence (sequence II) contains also *Pseudotextulariella courtionensis* and *Montsalevia elevata*, but *Pavlovecina allobrogensis* is absent. This association is documented in the three sections. In the Säntis succession, sequence II is present at the base of the section and continues 20 m up section. In the Dräckloch section, SB II is placed at an abrupt change in facies from F5/F8 to F3 at 175 m above section base. Sequence II shows a shallowing-upward trend towards facies F8 up to 246 m above the base of the section, corresponding to a HST. In the Vitznau section, SB II is placed at the base of a more prominent calcareous bed showing reworked platform clasts (F5). The following interval with a deepening trend from facies F5 to F3 is interpreted as a TST. The mfz is placed where the most distal facies (F2/3) is observed 20-6 m above the base of the section.

Sequence III is marked by the disappearance of *Pseudotextulariella courtionensis*. Sequence IV shows the first appearance of *Pfenderina neocomiensis* and is the last sequence observed in the photozoan platform succession of the Upper Öhrli Limestone Member. In the Säntis section, SB III corresponds to the first epikarstic level. Above, the facies shows a rather abrupt deepening to facies F3 corresponding to a TST, which is followed by a shallowing-upward trend to facies F9/10, typifying the HST. SBIV is placed 26 m above the base of the section, where a second epikarst level is observed. The upper part of the Upper Öhrli Limestone Member is dominated by facies F8, but shows abrupt changes to facies F2 and F3.

Fig. 15. Correlation of the sections across a NE/SW proximal-distal transect according to biostratigraphy and sequence stratigraphy; and comparison with the Vocontian Basin based on biostratigraphy and chemostratigraphy (Montclus, Morales et al., 2013).
The presence of parasequence boundaries, local tectonic activity, and/or the transfer by storms (washover) may explain the occurrence of such outer platform deposits in the external lagoon.

In the Dräckloch section, fringing cements and dissolution vugs indicative of conditions close to emersion are observed between 236 and 246 m above the base of the section. SB III is placed at 246 m, where the δ13C record shows an abrupt shift to lighter values, indicating the presence of an important hiatus. Above this level (from 246 to 260 m above the base of the section), shallow-water organisms still largely dominate carbonates, but an abrupt change in the carbonate fabric is observed with a clear dominance of corals and calcareous sponges, and the near disappearance of benthic foraminifera (except for Trocholinae which are found in abundance, and Moehleriina basiliensis). Sequences III and IV are therefore not observed in the Dräckloch section. This implies that sequence boundaries III, IV and V are combined, and a significant part of the late Berriasian is missing.

In the Vitznau section, an important erosional surface associated with lag pebbles marks a sequence boundary at 23-5 m above section base. Between 23-5 and 26-3 m above the base of the section, a succession of erosional surfaces is present. The top of this interval shows the reworking of partly lithified sediments rich in ooids and bioclasts. Given the relatively distal position of the Vitznau section, this interval is interpreted as a falling-stage systems tract (FSST). The marker calpionellid Calpionellopsis oblonga and Remaniella filipescui (Fig. 9), and with the benthic foraminifera Montsalevia elevata (Fig. 7). Pseudo-textulariella courtionensis, which is abundant in the underlying sequence, is absent from these reworked deposits. Consequently, this FSST may belong either to the combination of sequences III, IV and V, or to sequence V alone.

Sequence V is marked by an increase in detrital minerals, a change towards heterozoan carbonate production, and a lower diversity and abundance in benthic foraminifera (large specimens are no longer observed). In the Säntis section, SB V is documented by an epikarst overlapped by a hardground at 53 m above the base of the section, indicating that this sequence boundary is combined with the transgressive surface. The occurrence of a second and similar hardground in the immediately overlying bed, and of an interval containing reworked extralasts of corals and calcareous sponges together with extralasts of heterozoan organisms (58 m above section base) witness an important transgression (TST). A mfs is then placed where the deepest microfacies was observed (F2, outer shelf).

In the Dräckloch section, SB V is placed where dissolution vugs indicate conditions close to the emersion. Sequence V starts with the uppermost beds of the Upper Öhrli Limestone Member, where important sediment reworking is observed. This facies is interpreted as a lag on top of the transgressive surface, and the overlying interval as a TST. The phosphatic and pyritic infillings of the hardground on top of the Upper Öhrli Limestone Member, as well as the presence of a second hardground on top of a reworked layer in the Vitznau Formation confirms the occurrence of major relative sea-level rise during sequence V. The mfs of this sequence is placed within the more recessive part of the Vitznau Formation, which is covered by vegetation (between 309 and 315 m above section base).

In the Vitznau section, this transgression of major amplitude is equally documented by two hardgrounds and sediment reworking, located on top of the FFST (26-3 m above section base). The mfs of this sequence is also placed in the more recessive layers of the Vitznau Formation (facies F1). The ammonite Thurmamiceras thurmanni s.str. (Fig. 9) indicating the early part of the T. otopeta zone (latest Berriasian) was found in the scree. Ahermatypic corals were found in the host rock of the ammonite, which were also observed in the Dräckloch section in the early TST of sequence V (lower part of the Vitznau Formation). Stable isotope and P analyses performed on the host rock of the ammonite indicate that its origin is from the Vitznau Formation (values of 0-20‰ δ13C, -2-70‰ δ18O, 137 ppm P are only found at 33 m). If the determination and the position of the ammonite are correct (Thurmamiceras thurmanni s.l. has an extended range into the T. pertransiens ammonite zone; Wippich, 2003; Bujtor, 2013), the lower part of the Vitznau Formation at Vitznau (e.g. early TST of sequence V) has a latest Berriasian age.

Sequence VI shows the development of heterozoan carbonates deposits and corresponds to the uppermost part of the Vitznau Formation in the Vitznau section, and to the lower part of the Betlis Formation in the Vitznau, Dräckloch and Säntis sections. In the three sections, its sequence boundary is mingled with the transgressive surface, and overlain by lag deposits. SB VI is placed at 69 m above the base of the Säntis section, at 315 m above the base of the Dräckloch section, and at 56-8 m above the base of the Vitznau section where erosive banks showing intense sediment reworking are observed. Because no significant change in facies occurs within sequence VI in the Säntis and Dräckloch sections, the mfs probably coincides with the sequence boundary. In the Vitznau section, the mfs is placed within the overlying marly interval, which probably corresponds to a deeper depositional environment as it shows the most
recessive layers of the sequence. There, only the lower part of the Betlis Formation is accessible, and interpreted as the base of a HST. Marker benthic foraminifera indicate an age close to the Berriasian-Valanginian boundary for sequence VI (Table 2).

Sequence VII corresponds to the top of the heterozoan Betlis Formation. In the Santis section, SB VII is placed at 86.6 m above the base of the section, where an erosive surface associated with reworked oncoids was observed. The mfs is then placed within the hardground associated with the Gemsmättli Bed at the top of the Betlis Formation. In the Dräckloch section, SB VII is noted at 370 m above the base of the section with a level of important reworking. The uppermost part of this interval corresponds to the Pygurus Member, which is part of the Pygurus-Gemsmättli complex documenting the major drowning phase of the Valanginian Helvetic platform (Haldimann, 1977; Wyssling, 1986; Kuhn, 1996; Föllmi et al., 2006, 2007). This sequence is thereby characterized by significant detrital input and ends with a major condensation phase. The duration of the condensation of this level (more than 3 Myr, from the late Valanginian to the early Hauterivian) implies the presence of several sequence boundaries within this level (Godet, 2013), therefore highlighting a complex sequence stratigraphic surface (SB VIII).

**DISCUSSION**

**Global sea-level change during the late Berriasian – early Valanginian**

The stratigraphic distribution of marker foraminifer and calpionellid species allows for a correlation of the Helvetic platform with other shallow-water deposits in the northwestern Tethyan area (Fig. 16), and therefore permits differentiation between local and global factors controlling sedimentation. Faunal associations characteristic of sequences I and II were identified in the Pierre Châtel and Vions formations (Jura Mountains; Darsac, 1983; Morales et al., 2013), in the Calcaire Blanc Inférieur Formation and in the Membre Marneux Inférieur of the Marnes Vertes Infracrétacées Formation (Provence; Virgone, 1997), and the Calcaires à Trocholines et Dasycladacées (Pyrenees; Peybernès & Combes, 1994). Similarly, marker species of sequences III and IV were found in the top of the Vions Formation and the Lower Member of the Chambotte Formation (Jura Mountains), the Membre Carbonaté of the Marnes Vertes Infracrétacées (Provence) and the Calcaires Roux (Pyrenees). These sequences were correlated following the scheme proposed in Fig. 15. The sedimentary successions show comparable changes in accommodation space, which are interpreted to express north-western and northern Tethyan sea-level variations during the late early and the late Berriasian.

An important transgression is recorded through the Berriasian-Valanginian boundary. This sea-level event is marked by the general deposition of more open marine marly facies in the Helvetic region (Vitznau Formation, sequence V), the Jura Mountains (Guiers Member of the Chambotte Formation), Provence (Membre Marneux Supérieur of the Marnes Vertes Infracrétacées), and the Pyrenees (uppermost part of the Calcaires Roux Formation). This transgression is also associated with a succession of two hardgrounds in the Helvetic Alps separating the Upper Öhli Limestone Member and the base of the Vitznau Formation and the deposition of condensed layers rich in ammonites in the Jura Mountains (Fontanil fauna, Blanc et al., 1992) and the Pyrenees (Marnes de Franczal; Peybernès & Combes, 1994).

Differences in the pattern of sedimentary deposits are, however, observed between the Helvetic and the northwestern Tethyan platforms during the early Valanginian. In the Jura Mountains, Provence, and the Pyrenees, photozoan carbonate facies are observed with the Upper Member of the Chambotte Formation, the Calcaire Blanc Supérieur Formation, and the Calcaires Gravelieux à Pfenderines, respectively. Conversely, these oligotrophic deposits are not seen in the Helvetic sections. This is related to an enhanced subsidence phase recorded in the Helvetic domain compared to the north-western Tethyan areas (Stampfli et al., 2002), which may be associated with the local influence of nutrient-rich waters onto the northern Tethyan shelf.

Stratigraphically above the lower Valanginian photozoan carbonates of the Jura Mountains, Provence and the Pyrenees, a second major transgression is recorded by the deposition of deeper marly facies, locally associated with hardgrounds and condensed layers containing ammonites (from the *Busnardoides campylo toxus* zone) in Provence (Marnes Grises; Virgone, 1997) and the Pyrenees (Peybernès & Combes, 1994). The onset of condensation may be correlated with the condensed phosphatic layer of the Büls Bed in the Helvetic Alps, which is dated from the late *Tirnovella pertransiens – early Busnardoides campylo toxus* ammonite zones (Kuhn, 1996). In the Pyrenees, heterozoan carbonate deposits are described on top of this condensed layer (Calcaires Jaunes à Bryozoaires). The latter formation is attributed to the Hauterivian based on brachiopod stratigraphy (Peybernès & Combes, 1994) but the ‘low stratigraphic interest of micropalaeontological descriptors’ mentioned by the authors suggests that this age attribution may need to be reviewed. In the Helvetic and the Jura regions, shallow-water heterozoan carbonates (sequence VI and VII, and Bourget Formation,
respectively) appear below the highly condensed sediments of the Marnes à Astieria (Jura Mountains) and the Gemsmättli-Pyrgurus complex.

Sequence boundaries identified in this contribution have been correlated with global sequence boundaries of Haq (2014, Fig. 16). Following calpionellid determinations, SB III would correspond to KBe3 (early zone D), SB V to KBe4 (latest zone D); SB VI (mid zone E) to KVa1 (earliest zone E), and SB VII to KVa2 (Fig. 16). SB I (zone C) may correspond to KBe2 (at the boundary between zones B and C). Interestingly, SB III, SB V and SB VI are associated with biostratigraphic boundaries of foraminiferal faunas (discontinuities d1, d2 and d3 of Darsac, 1983), which might confirm their importance (medium cycle boundaries of Haq, 2014).

**Effects of tectonics on palaeogeography**

The biostratigraphy of the outer shelf section at Dräckloch indicates the occurrence of an important hiatus related to the absence of the late Berriasian sequences III and IV (Fig. 15). This hiatus is linked with an emersion; its duration corresponds to an important part of the S. boissieri ammonite zone, that is, of the late Berriasian. A relatively similar succession is observed in the Helvetic platform section of Lämmerenplatten (Pasquier, 1995), consisting of nearly identical environments (close to or at the barrier) but with a less well-constrained temporal framework. During the Early Cretaceous, major fault zones affected the Helvetic region (Funk, 1985; Detraz et al., 1987) and an important subsidence phase is recorded from the Oxfordian to the Hauterivian (Funk, 1985; Stampfli et al., 2002). Thus, the different stratigraphic records of the three studied successions are probably linked to a phase of tectonic activity during the late Berriasian – early Valanginian, which is likely related to extensive movements affecting the northern Tethyan margin. The generally high subsidence rates documented in the Helvetic plateau was commonly linked to the opening of the Alpine Tethys and of the North Atlantic (Stampfli et al., 2002).

The Dräckloch section, which is close to the platform margin, was probably located near the top of a tilted block, whereas the Säntis section, which is composed of more lagoonal deposits, is thought to have been located within an intrashelf depression formed by the tilting process (Fig. 17). The topographic effect of tilting blocks may also be evident in the Säntis section, where parasequences involving high amplitude relative sea-level variations were observed in the sedimentary succession and microfacies of the Upper Öhrli Limestone Member. The slope section of Vitznau records a FSST, which may also be linked to the topographic effects of block tilting.
Palaeoenvironmental and palaeoclimate changes

In the late early and early late Berriasian, the increase in P and detrital input observed in sequence I (upper part of Lower Öhrli Limestone Member and Upper Öhrli Marl Member) are linked on the Helvetic platform to a period of transgression (Fig. 18). Outer shelf deposits typically show an increase in detrital minerals basinwards (Fig. 18). The following sequences do not show major changes in these parameters, which is different from the Jura areas, where an increase in quartz and P is observed in the Vions Formation. The sections examined in the Helvetic area were more distant from the continental coast, which may explain these different records.

An increase in P and detrital minerals is also recorded in the Vitznau Formation, which again corresponds to a sea-level rise of probably wider importance (Fig. 16). Platform carbonate production changed from photozoan to heterozoan assemblages in the Helvetic region. Less diagenetically altered, age equivalent sections in the Jura Mountains and Vocontian Basin (La Chambotte and Montclus; Morales et al., 2013) indicate that this interval also corresponds to a maximum in humidity, indicated by high kaolinite contents in both platform and basinal environments. Thus, with an important transgression and a highly hydrolysing climate, biotas were subjected to increasing stress leading to the disappearance of oligotrophic organisms. The presence of phosphates and reworked pelagic sediments on top of the Upper Öhrli Limestone Member at Dräckloch, associated with a series of superimposed hardgrounds in all three sections indicates a platform drowning phase associated with this important transgressive phase. Following the drowning phase, a mesotrophic fauna including bryozoans, crinoids and proliferating Gryphaea, brachiopods, ostracods and serpulids, was installed in the distal part of the platform.

With the Betlis Formation (sequences VI and VII), platform carbonate production recovered in heterozoan mode. Excess nutrients are also indicated by the presence of chert nodules, which are related to a higher proportion of filter-feeding siliceous sponges, and the presence of a phosphatic bed separating the Betlis Formation into two members in more distal sections (Kuhn, 1996). This phosphatic bed indicates a second drowning phase of the carbonate platform. The Jura Platform (where a similar heterozoan facies is observed) and the Vocontian Basin sections provide evidence, however, of a decrease in humidity during this period (Morales et al., 2013).

At the top of sequence VII, strong detrital input is recorded. The top of sequence VII is poorly documented in the Jura Mountains (Hennig, 2003) and clay mineral analyses were not performed. Nevertheless, the abundance of millimetre-sized quartz grains (Fig. 8C), sometimes containing a ferruginous coating, indicates an important phase of erosion on the continent. This is correlated with an increase in P contents, which suggest increased nutrient input to the ocean. This phase of enhanced weathering, combined with a sea-level rise was responsible for the third, long-lasting and most important drowning phase of the carbonate platform in the Helvetic area during the Weissert episode.

The early Valanginian negative CIE: a prelude to the Weissert Event?

The comparison of the $\delta^{13}$C records of the Säntis, Dräckloch and Vitznau sections highlight similar trends, which can be correlated with the Vocontian Basin (section of Montclus, Morales et al., 2013), and which are in adequacy with the sequence stratigraphic interpretation (Fig. 15). A general increase in $\delta^{13}$C values is observed during the Berriasian, whereas a decrease in $\delta^{13}$C values is highlighted during the early Valanginian, finally followed by the global positive $\delta^{13}$C shift characterizing the Weissert episode. On the Helvetic platform, which is marked by emersion and condensation phases, this results in a significant negative shift (of $-0.7%_{\text{o}}$) at the boundary between the Upper Öhrli Limestone Member and the

![Fig. 17. Schematic representation of the depositional sequences during the latest Berriasian and the earliest Valanginian.](image-url)
Vitznau Formation. By comparison with the δ¹³C record of the Vocontian Trough, where the amplitude of variations in δ¹³C values should be reduced compared to the platform record (Morales et al., 2013), the duration of the hiatus occurring through the Berriasian-Valanginian boundary may be close to 800 kyr (counting Milankovitch cycles). Thus, our results show that in addition to biostratigraphy and sequence stratigraphy, the general trends of the δ¹³C records may be used to correlate the sections within this Helvetic transect. The negative excursion is mainly attributed to a change in carbonate production from photozoan to heterozoan carbonate production on the platform (Föllmi et al., 2006; Morales et al., 2013).

In the Helvetic area, this change in carbonate production coincides with a major relative sea-level rise linked to a transgression and local tectonics, a maximum in humidity, and associated higher nutrient levels. Similarly, a negative δ¹³C shift and a change towards heterozoan carbonate deposits are observed in the Jura Mountains (Bourget Formation, Morales et al., 2013), but may not be entirely synchronous with the Helvetic record. This may be explained by different tectonic contexts. A likely similar succession is observed in the Pyrenees, where the heterozoan Calcaires Jaunes à Bryozoaires might be correlated with the upper part of the Betlis and the Bourget formations (of the Helvetic and Jura platforms, respectively). In the Provence area, shallow-water water heterozoan deposits are scarcely observed (with the exception of the Olioulles succession; Virgone, 1997; Schroeder et al., 2000; Masse et al., 2009; Bonin et al., 2012).

Higher nutrient levels control the settlement of heterozoan carbonates, characterized by suspension-feeding organisms (James, 1997). Enhanced humidity and runoff, however, are probably not the main factors driving nutrient fluxes, as the Bourget Formation (Jura Platform) is depleted in kaolinite (relative to smectite and chlorite; Darsac, 1983; Adatte, 1988). Instead, nutrient-rich currents associated with a major transgression may have played a role. The sea-level rise may have favoured water-mass exchanges between the Boreal and Tethyan oceans (van de Schootbrugge et al., 2003). The opening of the
Polish gateway was probably initiated during the early Valanginian, as testified by the deposition of open marine sediments belonging to the *Tirnovella pertransiens* ammone zone on top of a Tithonian karstified limestone in the Polish Basin (Kutek *et al.*, 1989; Morales *et al.*, 2015), and the migration of Boreal calcareous nanofossils and ammonites to the Tethyan realm (Bulot, 1996).

These nutrient-rich water masses may result from an upwelling system explained by the inundation of continental margins, which would have triggered enhanced evaporation and wind velocities, resulting in stronger westerlies (Poulsen *et al.*, 1998; Godet, 2013). There is, however, no strong evidence for cooler water during the *Tirnovella pertransiens*-lower *Busnardoides campylotoxus* interval. Nutrients may also come from the intense weathering of landmasses located north-eastwards, which may have been transported westwards by the circum-Tethyan current. A very humid climate is indeed known from the Polish Basin (Morales *et al.*, 2015). The existence of these currents might also explain why the Helvetic platform turned to a heterozoan carbonate production earlier than other platforms located further to the west, and why the consistent association of phosphate and platform drowning in the Helvetic region (Kuhn, 1996) is not known in the Jura, Provence and Pyrenees platforms.

In this context, the third and major drowning phase of the Valanginian (corresponding to the Gemsmättli-Pygurus Beds in the Helvetic area) is related to a phase of intense weathering, as witnessed by the high quartz contents in the Gemsmättli-Pygurus complex, linked with a peak in humidity (higher kaolinite contents in the Vocontian Basin, Duchamp-Alphonse *et al.*, 2011; Föllmi, 2012), and combined with a sea-level rise. This drowning phase affected a platform that was already weakened by high nutrient levels resulting in two incipient drowning phases and previous rapid relative sea-level changes.

A general increase in volcanic activity, eventually related to the eruption of the Paraná–Etendeka continental flood basalts is viewed as the main trigger of environmental changes, leading to an increase in $pCO_2$ levels and profound climate modifications. The increase in magmatic activity may have been linked to enhanced oceanic crust production that triggered eustatic sea-level rise. Martinez *et al.* (2015) recently re-calibrated the Valanginian astronomic time scale and suggested that the main volcanic pulse of the Paraná Etendeka may coincide with the onset of the positive $\delta^{13}C$ excursion. Their calibration also shows a rather good correlation between the initiation of the volcanism, and the early Valanginian decrease in $\delta^{13}C$ values recorded in the Vocontian Basin. Since it is not clear yet if the latter is of global significance, the decrease in stable carbon-isotope values is rather attributed to a change of carbonate production than to volcanic activity.

**CONCLUSIONS**

The installation, growth and demise of the Berriasian–Valanginian carbonate platform have been documented using a transect of sections across the Helvetic Alps. A more accurate age control is proposed for the studied sections of the Säntis, Dräckloch and Vitznau locations, based on benthic foraminifera, calpionellid and ammonite biostratigraphy, chemostratigraphy, and sequence stratigraphy. This integrated stratigraphic approach provides a base for detailed correlation of the three studied sections, and enables the comparison with equivalent records from the Vocontian Basin, the Jura Mountains, Provence and the Pyrenean platforms. Thereby, this contribution provides a more balanced view of shallow-water ecological changes to global perturbations, by highlighting the superimposed influence of regional tectonic and palaeogeographic factors. The Helvetic sedimentological record is different from those of other northern and north-western Tethyan platforms, which is interpreted as reflecting the combined effect of palaeoceanographic differences, with the Helvetic platform being more exposed to the northern nutrient-carrying Tethyan current, and of enhanced subsidence in the Helvetic domain. Block tilting is the most likely mechanism to explain a major hiatus present in the upper part of the Upper Öhli Limestone Member in the Dräckloch section, encompassing a significant part of the late Berriasian.

A major sea-level rise is documented, which started in the latest Berriasian and progressively flooded the platform. This sea-level rise, combined with a strongly subsiding setting and enhanced humidity led to the disappearance of photozoan faunas and provoked a first major drowning phase in the Helvetic domain. During the early Valanginian, suspension feeders dominated shallow-water organisms in the northern and north-western Tethyan area, as a response to higher nutrient rates in the ocean. The nearby continents, however, underwent a decrease in humidity and runoff. The turn to heterozoan carbonate production is interpreted as the consequence of palaeoceanographic changes, which may be related to the establishment of upwelling currents. During the late early and early late Valanginian, phases of enhanced detrital input linked with strong continental weathering, and sea-level rises were responsible for a second and a third, widespread demise of the already weakened carbonate platform: near the boundary of the *pertransiens – campylotoxus* zone and during the *verrucosum* zone, respectively. In the Helvetic domain, the latter shallow-water carbonate...
crisis is evidenced by a quartz-rich phosphatic and gua-
donic crust on top of a hardground (Gemsmttli Bed) or a quartz and phosphate-rich, highly bioturbated inter-
val (Pygurus Member). These condensed horizons docu-
ment the almost complete disappearance of shallow-water calcifying organisms for more than 3 Myr. The renewed
development of a carbonate platform in the Helvetic
region is only recorded from the middle early Hauterivian
 onwards.

ACKNOWLEDGEMENTS

The authors are thankful to Pilar Ramirez de Arellano,
Cyril Baudon, Aurélie Bonin, Morgan Peel, and Lucie
Bonvallet for fieldwork assistance. We also acknowledge
Antoine Pictet and Luc Bulot for the preparation and
determination of the ammonite and Tiffany Monier for
assistance in the laboratory. We thank Ian Jarvis and an
anonymous reviewer for their constructive and thoughtful
reviews. The detailed and very constructive comments of
associated editor Adrian Immenhauser were very helpful
in the revision of the manuscript. We also thank editor
Peter Swart for his assistance. Financial support from the
Swiss National Science Foundation (project
200020_126455) is appreciatively acknowledged.

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**Supporting Information**

Additional Supporting Information may be found online in the supporting information tab for this article:

- **Appendix S1.** Stratigraphic variation in carbon and oxygen stable isotopes along a proximal-distal transect (bulk-rock measurements in $\%\text{ VPDB}$).
- **Appendix S2.** Raw data of bulk-rock $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses performed on the Säntis section.
- **Appendix S3.** Raw data of bulk-rock $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses performed on the Dräckloch section.
- **Appendix S4.** Raw data of bulk-rock $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses performed on the Vitznau section.
- **Appendix S5.** Raw data of bulk-rock mineralogical analyses performed on the Säntis section.
- **Appendix S6.** Raw data of bulk-rock mineralogical analyses performed on the Dräckloch section.
- **Appendix S7.** Raw data of bulk-rock mineralogical analyses performed on the Vitznau section.