Demise of the northern Tethyan Urgonian carbonate platform and subsequent transition towards pelagic conditions: The sedimentary record of the Col de la Plaine Morte area, central Switzerland

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ABSTRACT

The sedimentary succession of the Col de la Plaine Morte area (Helvetic Alps, central Switzerland) documents the disappearance of the northern Tethyan Urgonian platform in unprecedented detail and suggests stepwise platform demise, with each drowning phase documented by erosion and phosphogenesis. The first identified drowning phase terminated Urgonian carbonate production in a predominantly photozoan mode. Using a correlation of the whole-rock δ13C record with the well-dated record from SE France, its age is inferred to as Middle Early Aptian (near the boundary between the weissi and deshayesi zones). A subsequent drowning phase is dated by ammonites and by a correlation of the whole-rock δ13C record as Late Early Aptian (late deshayesi to early furcata zone). A third drowning phase provides an ammonite-based age of Early Late Aptian (subnodosocutum and melchioris zones) and is part of a widely recognized phase of sediment condensation and phosphogenesis, which is dated as latest Early to Middle Late Aptian (late furcata zone to near the boundary of the melchioris and noimi zones). The fourth and final drowning phase started in the latest Aptian (jacobl zone) as is also indicated by ammonite findings at the Col de la Plaine Morte. The phases of renewed platform-carbonate production intervening between the drowning phases were all in a heterozoan mode. During the ultimate drowning phase, phosphogenesis continued until the Early Middle Albion, whereas condensation processes lasted until the Middle Turonian. Coverage of the external margin of the drowned Urgonian platform by a drape of pelagic carbonates started only in the Late Turonian. During the Santonian, the external part of the drowned platform underwent normal faulting and saw the re-exposure of already lithified Urgonian carbonates at the seafloor. Based on the here-inferred ages, the first drowning phase just precedes oceanic anoxic episode 1a (OAE 1a or "selli event") in time, and the second drowning phase partly overlaps with OAE 1a. The onset of the third drowning event slightly predates two further periods of increased organic-matter accumulation in the Vocontian Basin (Noir and Falloït levels), and the onset of the fourth and final drowning phase may coincide with two further periods of increased organic-matter accumulation in the Vocontian Basin (Jacob and Kilian levels, part of OAE 1b). These correlations indicate a relationship between the so-called anoxic episodes and the stepwise demise of the Urgonian platform, even if the onset of environmental change is registered earlier on the platform than in basinal sediments.

Keywords: Cretaceous, Col de la Plaine Morte, Helvetic Zone, Switzerland, Urgonian platform drowning, Selli event

1. Introduction

The Late Early to Early Late Cretaceous witnessed a suite of recurrent oceanic anoxic episodes, which was unique for the entire Mesozoic and Cenozoic if one considers its frequency and multiple impact on the environment (e.g., Schlanger and Jenkyns, 1976; Arthur and Schlanger, 1979; Jenkyns, 1980; Leckie et al., 2002). The “mid”-Cretaceous anoxic episodes are an expression of major environmental change during this period, for which its manifestation was not limited to ocean basins, but extended also onto the adjacent shelves and continents (e.g., Schlager and Philip, 1990; Gröcke et al., 1999).

Multiple links have been proposed between chemical and environmental change on the continents, the shelf regions and deeper basins during these episodes, such as increased methane release from slope sediments (Wissler et al., 2003), ocean acidification (Weisert and Erba, 2004) and increased nutrient input from continents (Erba, 1994; Föllmi et al., 1994). These interpretations are all dependent on positive correlations between the numerous proxies of environmental change in the different compartments. Their precision is, however, often hampered by the lack of convincing bio- or chemostratigraphic time control.

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The sedimentary remains of a vast shallow-water carbonate platform attached to the northern Tethyan shelf and presently locked up in the Helvetic Alps have been revealed to have sensitively recorded paleoenvironmental change during the latest Jurassic and Early Cretaceous (Funk et al., 1993; Föllmi et al., 1994, 2006, 2007). They have furthermore the advantage that time control by ammonite stratigraphy is good, and as such they provide valuable insight into the effects of environmental change associated with the anoxic episodes.

During the evolution of this platform, a phase of important platform progradation and aggradation has been recognized, which resulted in the buildup of a prominent and predominantly photozoan carbonate succession — the so-called “Urgonian” (e.g., Lienert, 1965; Arnaud-Vanneau et al., 1976; Funk et al., 1993; Michalik, 1994; Arnaud et al., 1998; Bernaus et al., 2003; Bodin et al., 2006a; Godet et al., submitted for publication). Coeval sediments of equivalent or at least comparable facies are also documented from the Arabian peninsula (e.g., Immenhauser et al., 2004) and from the Cupido carbonate platforms of northeastern Mexico (Bralower et al., 1999; Lehmann et al., 1999; cf. also Ager, 1981). Along the northern Tethyan margin, the onset of Urgonian platform growth is dated as Late Barremian (e.g., Arnaud-Vanneau et al., 1976; Arnaud et al., 1998; Bodin et al., 2006a; Föllmi et al., 2006, 2007; Godet et al., submitted for publication). The demise of the Urgonian platform appears to be diachronous: whereas in western and central Europe its disappearance is dated as Early Aptian (e.g., Arnaud et al., 1998), in eastern Europe this facies appears to continue well into the Albanian (e.g., Michalik, 1994). Repeated interferences between environmental change, the “mid”-Cretaceous oceanic anoxic episodes and the evolution of the Urgonian platform in general are highly likely and may explain the ultimate disappearance of this platform system (e.g., Föllmi et al., 2006, 2007).

Once drowned, the platform sediments of the northern Tethyan margin became covered by a mixture of detrital, glauconite and phosphate-rich sediments, which often show the influence of sedimentary condensation processes (Heim and Seitz, 1934; Heim, 1934; Schaub, 1936; Föllmi, 1986, 1989, 1990; Föllmi and Ouwhand, 1987; Ouwhand, 1987; Delamette, 1988; Delamette et al., 1997). Subsequently, the external part of the northern Tethyan margin experienced a transition to more pelagic conditions.

The stratigraphic succession exposed in the Col de la Plaine Morte area (Helvetic Alps of central Switzerland; Fig. 1) is in so far unique in that it embodies one of the most complete successions for the Early Aptian hitherto documented from the northern alpine Helvetic Zone. This succession reveals the history of the drowning of the Urgonian platform in unprecedented detail, and the combination of new ammonite findings and a whole-rock δ13C record allows to infer precise ages for each drowning step and to improve their correlation with the Early Aptian anoxic episode OAE 1a (“Selli event”).

Furthermore, this succession shows very nicely how the drowned platform was consequently subjected to a persistent phase of condensation and phosphogenesis, which lasted for approximately 30 million years and terminated during the Middle Turonian. The excellent outcrop conditions allow for the observation of sedimentological and biostratigraphic details which elucidate how this condensation phase proceeded. Finally, a sheet of pelagic carbonate covered the drowned platform and its topography became accentuated by the emplacement of normal fault structures.

The goal of this contribution is therefore to document the outcrops at the Col de la Plaine Morte in detail and to trace each drowning step and the period following the final drowning phase, and precisely document its sedimentological and chronostratigraphic context, wherever available.

2. The Col de la Plaine Morte area

The region of the Col de la Plaine Morte is part of the Helvetic thrust-and-fold belt of the northern Alps of central Switzerland (Wildhorn nappe; Fig. 1). It exposes a succession of Cretaceous and Eocene marine sedimentary rocks, which are representative for the external part of the northern Tethyan margin (Fig. 2). This succession includes a nicely differentiated, fairly complete, and remarkably well-exposed series of Late Early to Late Cretaceous age (Figs. 3, 4, and 5), which has been the subject of different publications and theses: Lugeon (1918) published a first detailed description of the tectonic context of this region, and was the first to recognize the presence of synsedimentary, normal faults in sediments of Late Cretaceous age. Schaub (1936, 1948) gave a first detailed compilation of the stratigraphy of this area and proposed a sedimentary model for the genesis of the condensed phosphate-rich beds of Aptian to Turonian age (Plattenwald Bed, see below), in which reworking and lateral transport were important mechanisms. Schenk (1992) investigated the Barremian Tierwis Formation (formerly Drusberg Formation; Föllmi et al., 2007) and Urgonian Schrattenkalk Formation with regard to their lithology, facies and age. Based on orbitolinid biostratigraphy (by R. Schroeder, Frankfurt), she postulated an Early Barremian age for the onset of the Schrattenkalk Formation, thereby placing the subjacent Drusberg Member in the Late Hauterivian or earliest Barremian; she also attributed an latest Aptian–Early Albian age for the top of the Schrattenkalk Formation. These postulated ages are not compatible with current age models for these formations (Bollinger, 1988; Föllmi et al., 2007; Fig. 4), and this discrepancy provided us with an incentive to explore the stratigraphic succession of the Col de la Plaine Morte area in more detail.

3. Methods

Stratigraphic sections were examined, measured and sampled during the late summers of the last 15 years, during periods when the snow cover was minimal. Late summer 2003 was characterized by exceptional warm and dry weather conditions and allowed the examination of outcrops, which are normally covered by snow. Samples were cut and polished, and thin sections were systematically prepared.

Stable carbon and oxygen isotope analyses were performed on powdered samples at the University of Berne using a VG Prism II ratio mass spectrometer equipped with a common acid bath (H2PO4). The results were calibrated to the PDB scale with standard errors of 0.1‰ for δ13C and 0.05‰ for δ18O.

Scanning electron micrographs were taken at the Center of Electronic Nano- and Microscopy, University of Neuchâtel, using an environmental SEM (Philips XL30) and a conventional SEM (Philips XL20).

4. Stratigraphy

4.1. Kiesekalk Formation (Hauterivian)

The approximately 200 m thick Kiesekalk Formation in the area north of the Col de la Plaine Morte consists of two coarsening-upward successions which are each characterized by a marly base which progressively passes into a well-bedded, crinoidal and spiculitic limestone (Fig. 2). The top of the upper succession is composed of a 1.5–2 m thick interval of coarse-grained, glauconite-containing, crinoidal limestone (Schaub, 1936; Gainon, 2001). The two successions are dated by correlation to fossiliferous outcrops in central and eastern Switzerland: the lower succession covers the middle part of the Early Hauterivian (loryi to nodosoplicatum zones), whereas the upper succession is attributed to the Middle Late Hauterivian (ligatum to angulicostatum zones; Kuhn, 1996; Van de Schootbrugge, 2001; Van de Schootbrugge et al., 2003; Bodin et al., 2006b).

4.2. Tierwis Formation (latest Hauterivian to Early Late Barremian)

4.2.1. Altmann Member (latest Hauterivian to Early Late Barremian)

The Altmann Member follows directly on top of the Kiesekalk Formation and starts with a thin (approximately 0.1 m) limestone bed
rich in phosphate nodules, partly silicified belemnites, quartz, and glauconite (Fig. 2). This bed is overlain by a 3–4 m thick succession of glauconite-bearing marl and limestone, which is rich in small fish teeth at the top. A good outcrop is present NE of Graui Felse (CH-Coord.: 600.825/137.125) Schaub, 1936; Gainon, 2001; Bodin et al., 2006b). Recently, Bodin et al. (2006b) gave a precise age for central
and eastern Swiss and western Austrian occurrences of the Altmann Member, which is used for this occurrence by extrapolation: the Altmann Member spans the time interval between the angulicostatum zone (latest Hauterivian) and darsi zone (latest Early Barremian).

4.2.2. Drusberg Member (Early Late Barremian)

The Drusberg Member consists of a coarsening-upward succession of well-bedded spiculitic carbonates rich in crinoids and bivalves, alternating with marls (minimally 30 m in thickness). Its latest Early to Early Late Barremian (darsi to sartousiana zone) age is determined by benthic foraminifera, rare ammonites, and the age of the underlying Altmann Member and the Chopf Bed which is overlying this member in eastern Switzerland (Bollinger, 1988; Bodin et al., 2006a). The age proposed by Schenk (1992) for the onset of this member (latest Hauterivian or earliest Barremian; based on orbitolinid biostratigraphy; determination: R. Schroeder, Frankfurt; Fig. 4) cannot be accepted.

4.3. Urgonian Schrattenkalk Formation (Late Barremian to Early Aptian)

The Urgonian stage in the development of the carbonate platform of this area has been investigated by Schaub (1936) and Schenk (1992).

Fig. 2. Lithostratigraphic log of the sedimentary succession outcropping in the region of the Col de la Plaine Morte and north of it (modified from Gainon (2001) and Schenk (1992)).
who both distinguished two phases of platform development (lower and upper Schrattenkalk), which was interrupted by a phase of increased detrital input ("lower Orbitolina Beds" = "Orbitolina Member"; Fig. 2). Schenk proposed the name "Rawil Beds" for this member and this name has recently been retained as the official name for this member in the Helvetic Zone (cf. Föllmi et al., 2007). The lower Schrattenkalk is composed of approximately 150 m of bioclastic and oolitic limestone, which includes increasing amounts of rudist and coral remains towards the top. The Rawil Member consists of approximately 20 m of well-bedded limestone and marly limestone, and the upper Schrattenkalk is represented by 30–50 m of coarsely bedded bioclastic limestone, which is rich in rudists and corals towards the top.

According to orbitolinid biostratigraphy in the upper Schrattenkalk by Schroeder in Schenk (1992), this member extends well into the Late Aptian (for the area immediately north of the Col de la Plaine Morte) and maybe even into the Early Albian (for the Interlaken area). New ammonite findings in the underlying Grünten Member (= "upper Orbitolina Beds"; Linder et al., 2006) occurs only locally in the form of lenticular bodies (max. 5 m thick, min. several 100 m long), as was already noted by Schaub (1936). A first occurrence is present approximately 800 m NNE of the Col de la Plaine Morte (CH-coordinates: 601.100/136.200; Fig. 3) and a second occurrence is located on the western flank of the Col de la Plaine Morte (CH-coordinates: 600.700/135.700; Gainon, 2001). In places where sediments of the Grünten Member are present, the contact to the underlying upper Schrattenkalk Member is a clear-cut unconformity, characterized by the local presence of high-angle incisions, angular discontinuities, and fissure infills (Fig. 6A). The top surface of the upper Schrattenkalk is marked by patchy phosphatic mineralisations (Fig. 5B). This phase of macroscopic phosphate precipitation correlates to a phase of phosphogenesis and glauconitization, which is materialized in a thin layer rich in glauconite at the base of the Grünten Member in the Helvetic Alps of central Switzerland and Allgäu, and which is named Rohrbachstein Bed (Föllmi et al., 2007). The type locality is the here-described outcrop NNE of the Col de la Plaine Morte, west of the Rohrbachstein (Fig. 1).

4.4. Garschella Formation (Late Early Aptian to Middle Turonian)

4.4.1. Grünten Member ("upper Orbitolina Beds"; Late Early Aptian)

The Grünten Member (= "upper Orbitolina Beds"; Linder et al., 2006) occurs only locally in the form of lenticular bodies (max. 5 m thick, min. several 100 m long), as was already noted by Schaub (1936). A first occurrence is present approximately 800 m NNE of the Col de la Plaine Morte (CH-coordinates: 601.100/136.200; Fig. 3) and a second occurrence is located on the western flank of the Col de la Plaine Morte (CH-coordinates: 600.700/135.700; Gainon, 2001). In places where sediments of the Grünten Member are present, the contact to the underlying upper Schrattenkalk Member is a clear-cut unconformity, characterized by the local presence of high-angle incisions, angular discontinuities, and fissure infills (Fig. 6A). The top surface of the upper Schrattenkalk is marked by patchy phosphatic mineralisations (Fig. 5B). This phase of macroscopic phosphate precipitation correlates to a phase of phosphogenesis and glauconitization, which is materialized in a thin layer rich in glauconite at the base of the Grünten Member in the Helvetic Alps of central Switzerland and Allgäu, and which is named Rohrbachstein Bed (Föllmi et al., 2007). The type locality is the here-described outcrop NNE of the Col de la Plaine Morte, west of the Rohrbachstein (Fig. 1).
The sediments of the Grünten Member consist of a sandy and glauconite-bearing carbonate rich in crinoidal remains, bryozoans, and benthic foraminifera, which is marly at its base. The detrital and glauconite content diminishes towards the top and carbonate contents rise from around 50% to 90% (Gainon, 2001). Within the Grünten Member, a phosphatic bed occurs, which is rich in up to 15 cm large and often irregular carbonate pebbles and cobbles, which are systematically peripherally phosphatized (Fig. 6C). In addition, this bed contains sparse phosphatized particles, oyster remains, belemnites and rare ammonites, amongst which fragments of Deshayesites sp. and Aconoceras nisus (d’Orbigny) (Fig. 7). The Deshayesites fragment is indicative of the deshayesi zone, according to Jean-Pierre Thieuloy (University of Grenoble; personal communication), whereas the A. nisus (d’Orbigny) indicates the furcata and the subnodosocostatum zones, according to Michel Delamette (Chartreuse National Park; personal communication) (Fig. 7). Furthermore, an isolated pebble of crystalline rock (mica schist; Fig. 6D) was found within this phosphatic horizon. Using the $^{40}$Ar/$^{39}$Ar dating method, Michael Cosca (University of Lausanne; personal communication) obtained an age of approximately 330 Ma (Late Early Carboniferous) on a selection of extracted mica grains. This bed is named Plaine Morte Bed, and its type locality is the outcrop NNE Col de la Plaine Morte, identical with the type locality of the Rohrbachstein Phase or Bed (Föllmi et al., 2007).

In the outcrop NNE of the Col de la Plaine Morte, the lenticular body of the Grünten Member disappears to the west, and the Plaine Morte Bed unifies laterally with the overlying phosphate-rich Luitere Bed (Fig. 5E).

### Lithostratigraphy

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<th>Lithostratigraphy</th>
<th>Orbitolinid biostratigraphy</th>
<th>Ammonite biostratigraphy</th>
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<tr>
<td>Plattenwald Bed</td>
<td><strong>Hypacanthopilites</strong></td>
<td><strong>Leymeriella</strong></td>
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<td><strong>Dowvilleiceras</strong></td>
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<td>Brisi Beds</td>
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<td>Luitere Bed</td>
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<td><strong>Colombiceras</strong></td>
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<td><strong>Cheloniceratidae</strong></td>
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<td>(early Late Aptian)</td>
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<td>Grünten Member</td>
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<td></td>
<td><strong>Aconoceras</strong></td>
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<td><strong>Deshayesites</strong></td>
<td>(middle Early Aptian)</td>
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<td>Upper Schrattenkalk Member</td>
<td><strong>Orbitolina (sexana)-subconcaava</strong></td>
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<td><strong>Pseudochoofratella cuvillieri</strong></td>
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<td><strong>Coskinolita santanderensis</strong></td>
<td>(Late Aptian, ev. earliest Albian)</td>
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<td>Rawil Member</td>
<td><strong>Paracostinolina mayeni</strong></td>
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<td><strong>Cribellopsis neolongata</strong></td>
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<td>(Earliest Aptian, ev. latest Barremian)</td>
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<td>Lower Schrattenkalk Member</td>
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<td><strong>Paracostinolina mayeni</strong></td>
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<td>(Earliest Barremian)</td>
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<td>Drusberg Member</td>
<td><strong>Cribellopsis cuvillieri</strong></td>
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<td><strong>Paracostinolina reicheli</strong></td>
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<td><strong>Urgonicella aceriphilis</strong></td>
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<td>(Earliest Barremian, ev. latest Hauterivian)</td>
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<td><strong>Urgonicella aceriphilis</strong></td>
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<td><strong>Seisitz–dorsis Zone</strong></td>
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<td>(late Hauterivian - latest Early Barremian)</td>
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**Fig. 4.** Biostratigraphies of the upper lower Cretaceous succession of the Col de la Plaine Morte region based on orbitolinids (by Schroeder in Schenk, 1992) and based on ammonites, which were found during this study in the region of the Col de la Plaine Morte or ammonite-based stratigraphies, which were recently published from the same members in central and eastern Switzerland (Bodin et al., 2006a,b).

**Fig. 5.** Geology of the Col de la Plaine Morte. Circle indicates the locality of the steep erosional interface between sediments of the Grünten Member and overlying Brisi Beds shown in more detail in Fig. 8. The red line indicates the location of a synsedimentary fault associated with breccia shown more in more detail in Fig. 11. BB = Brisi Beds, GM = Grünten Member, SF = Schrattenkalk Formation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
A δ¹³C record was obtained on a selection of whole-rock samples of the Grünten Member in the section NNE of the Col de la Plaine Morte, which shows a rather stable plateau with values of around 2.2‰ for the basal 2 m, followed by an increase towards a maximum value of 3‰ approximately 1 m below the top of the Grünten Member (Gainon, 2001; Fig. 3). As these values are approximately in the range of Early
Aptian values obtained on sections outside the Alps (e.g., Menegatti et al., 1998; Kuhnt et al., 1998) and as the general trend makes sense, these data are later on used for the interpretation of the age of this member.

4.4.2. Luitere Bed (Early Late Aptian)

The sediments of the Grünten Member or directly the sediments of the upper Schrattenkalk Member (in case the Grünten Member is absent) are overlain by a 5–20 cm thick, nodular phosphatic horizon — the Luitere Bed, which is rich in coarse-grained quartz sand (Fig. 6E). Sediments of this bed may penetrate the underlying sediments of the Grünten Member in burrow-like fissure infills. This bed is particularly well-exposed in the outcrops NNE of the Col de la Plaine Morte, whereas further north (“Graui Felse”) and on the Col de la Plaine Morte itself (CH-Coord.: 600.820/135.620), its occurrence is restricted to fissure infills within the uppermost Schrattenkalk, right at the contact to the overlying Brisi Beds. The Luitere Bed contains Colombiceras sp. and Cheloniceras sp., which are both indicative of the sub-nodosocostatum and melchioris zones (Early Late Aptian; Fig. 7).

4.4.3. Brisi Beds (Middle Late Aptian)

The sediments of the Luitere Bed or directly the upper Schrattenkalk (in case the Grünten Member is absent and the Luitere Bed is limited to fissure infills at the top of the Schrattenkalk Formation) are overlain by an up to 6 m thick, coarse-grained glauconite and phosphate-bearing sandstone, which grades into an alternation of coarse-grained quartz sands and calcarenite towards the top (i.e., Brisi Sandstone and Brisi Limestone; max. thickness 6 m; Fig. 3). The Brisi

Beds show distinct cross-stratifications with predominant southwards current directions (Fig. 6F). They are rich in small fish teeth.

An interesting juxtaposition of the Brisi beds and the Grünten Member is observed directly on the Col de la Plaine Morte itself, on its western flank, where a succession of upper Schattenkalk–Grünten Member–Plattenwald Bed–Seewen Formation is replaced to the south by a succession of upper Schattenkalk–Brisi Beds–Plattenwald Bed–Seewen Formation (Figs. 5 and 8). The lateral contact between the sediments of the Grünten Member and the Brisi Beds is interpreted as synsedimentary, related to local erosion and removal of the sediments of the Grünten Member during deposition of the sediments belonging to the younger Brisi Beds. A: Overview; B: Local horizontal infillings of coarse-grained sands of the Brisi Beds into the fine-grained marly carbonates of the Grünten Member by bioturbation; C: Phacoid consisting of sediments of the Grünten Member at the base of the Brisi Beds; D: Infiltration of sediments of the Brisi Beds into the Grünten Member. The exact locations of B, C, and D is indicated in A, and the exact location of A is indicated in Figs. 1 and 5.

4.4.4. Plattenwald Bed (latest Aptian–Middle Turonian)

The Plattenwald Bed covers the sediments of the Brisi Beds and locally directly the sediments of the Grünten Member. It consists of a maximally 40 cm thick nodular phosphatic bed, which shows a variety of matrices consisting of glauconitic sandstone, glauconitic sandy micritic limestone, and micritic limestone (from the base to the top). In the outcrop NNE of the Col de la Plaine Morte, an isolated glauconitic sandstone lens with a length of approximately 70 cm and a maximal thickness of 4 cm showing internal cross-laminations appears in the middle part of the Plattenwald Bed (Fig. 6G). A quartzite pebble with a maximum diameter of 3.4 cm was found within the Plattenwald Bed at the Col de la Plaine Morte (Fig. 6H).

The Plattenwald Bed contains abundant phosphatized fossil remains, including ammonites, brachiopods, inoceramid bivalves, bellemnites, and gastropods. A single fragment of Chuetetopsis sp. was observed (Reitner and Föllmi, 1991). The outcrops at the Col de la Plaine Morte show stromatolitic structures within the micritic limestone at the top of the Plattenwald Bed (Fig. 9). An inspection of a selection of stromatolite samples by electronic scanning microscope reveals the presence of filamentous microbial-like structures, which are excellently preserved (Fig. 9).

The Plattenwald Bed at and south of the Col de la Plaine Morte yielded an interesting ammonite fauna, which in terms of biostratigraphic markers is restricted to *Hypacantholites, Leymeriella* and *Douvilleiceras* (Fig. 7). Schaub (1936) also identified *Hoplites* of the *dentatus* group and *Lyellliceras*; in the collection of M. Lugeon, a single specimen of *Mariella bergeri* was identified from this region (Schaub, 1936). This association indicates a latest Aptian to Early Middle Albian age (*jacobi, tardefurcata, mammillatum* and *dentatus* zones) for the main phase of phosphogenesis, if we discard the single *Mariella* specimen. According to Schaub (1936), occurrences of the Plattenwald Bed further to the north contain predominantly ammonites of Late Albian age (Schaub, 1936).

Associations of planktonic foraminifera of different age are associated with different types of micritic matrix: 1) a micrite rich in quartz and glauconite contains *Rotalipora tichensis* (Gandolfi), *R. cushmani* (Morrow), and *Praeglobotruncana stephani* (Gandolfi) (Late Albian to Late Cenomanian; this type of matrix is restricted to occurrences north of the Col de la Plaine Morte); 2) a micrite with few glauconite and quartz grains includes *Dicarinella hagni* (Scheibenerova), *D. algeriana* (Caron), *Praeglobotruncana gibba* Klaus, *Whiteinella archeocretacea* Pessagno, *W. inornata* (Bolli), *Helvetoglobotruncana praehelvetica* (Trujillo), *H. helvetica* (Bolli) (Late Cenomanian to Middle Turonian) (Fig. 10).
4.5. Seewen Formation (Late Turonian–Campanian)

The Plattenwald Bed is directly overlain by pelagic, micritic carbonates of the Seewen Formation, which are very rich in calcispheres, inoceramid prisms and planktonic foraminifera, and which reach a thickness of approximately 40 m at the Col de la Plaine Morte. The micritic matrix of the upper part of the underlying Plattenwald Bed is comparable to the sediments of the Seewen Formation with regards to its facies (Föllmi, 1986). The Seewen Formation itself consists from base to top of 5 m pelagic, micritic limestone, 15 m sand-containing marlstone, 3 m pelagic micritic limestone, and 10 m sandy marlstone.

The limestone at the base of the Seewen Formation is composed of a pure micrite rich in calcispheres, inoceramid prisms, and Saccocoma, in which D. hagni, Marginotruncana pseudolinneiana Pessagno, M. coronata (Bolli), M. schneegansi (Sigal), M. sigali (Reichel), and Falsotruncana maslakovae Caron were identified (Late Turonian). The lower marly interval includes Dicarinella concavata (Brotzen), D. asymmetrical (Sigal), and M. pseudolinneiana Pessagno (Santonian). The upper calcareous part contains Globotruncanita sp., Rosita fornicata Plummer, and M. pseudolinneiana Pessagno (Late Santonian), whereas the upper marly interval hosts Globotruncana arca Cushman, Globotruncana stuartiformis (Dalbzie), and Archeoglobigerina cretacea (d’Orbigny) (Late Santonian to Late Campanian) (Fig. 10).

4.6. Normal faults in association with the Seewen Formation

Breccia deposits are located north of the Col de la Plaine Morte (CH-Cord.: 600.780/135.830; Figs. 1 and 11). The breccia components consist of sediments from the Schrattenkalk Formation, the Garschella Formation, and the Seewen Formation, which are embedded in a matrix of pelagic micrite of the Seewen Formation. The breccia deposits are associated with two subvertical normal faults, which separate the Urgonian Formation from the Seewen Formation (Fig. 11). The first fault is approximately N-S oriented and the second approximately E-W (Figs. 1 and 5).

A sample of the Seewen Formation directly in contact with the breccia deposits include Dicarinella asymmetrical (Sigal), D. concavata (Brotzen), M. pseudolinneiana Pessagno, and M. marginata (Reuss), indicating an age not younger than the Santonian for the generation of the normal faults and formation of the associated breccia deposits.

4.7. Wang Formation (Maastrichtian), Klimeshorn and Wildstrubel Formations (Middle Eocene) and “Globigerina Marl” (Late Eocene)

On the Col de la Plaine Morte, the sediments of the Seewen Formation are directly overlain by approximately 20 m well-bedded, sandy and marly limestone, which belong to the Wang Formation. This formation shows an angular discontinuity at its base, and to the west and south of the Col de la Plaine Morte, it may directly follow on top of sediments of the Garschella and Schrattenkalk Formations, thereby gaining in thickness (up to 200 m; Stacher, 1980). This formation is dated as Late Campanian to Late Maastrichtian (Stacher, 1980).

The sediments of the Wang Formation are overlain by approximately 7 m of glauconitic and quartz sandstone, and sandy limestone rich in Dictyocyclina and Nummulites, which are followed by approximately 20 m of sandy shales (Klimeshorn and Wildstrubel Formations; Middle
Fig. 11. Synsedimentary normal faults juxtaposing sediments of the Schrattenkalk Formation and Seewen Formation north of the Col de la Plaine Morte; A. and C. Sediments of Schrattenkalk Formation in lateral contact with sediments of the Seewen Formation. A breccia plasters the contact zone; B. and D. Sediments of the Schrattenkalk Formation are cut off by a synsedimentary fault associated with breccia. E. Polished slab of breccia showing components of the Schrattenkalk Formation (A), Grünten Member (B) and Seewen Formation (D), and phosphatic nodules and particles of the Garschella Formation. The exact locations are indicated in Figs. 1 and 5.
Eocene; Menckfeld-Grüller, 1995, 1997), and maximally 200 m of marl (“Globigerina Marl”; Late Eocene).

5. Discussion

5.1. Timing of the drowning phases of the Urgonian carbonate platform in the Col de la Plaine Morte area

The Aptian sediments of the Col de la Plaine Morte area represent one of the most differentiated successions of the entire Hettangian realm (Linder et al., 2006). Usually, in more proximal areas, the Grünsand Member is missing and the Urgonian Schrattentalkalk Formation is directly overlain by sediments of the Lutere Bed or younger sedimentary units of the Gerschel Formation (Föllmi, 1986, 1989; Föllmi and Ouwehand, 1987; Ouwehand, 1987; Delamette, 1988; Delamette et al., 1997). In distal sections, where sediments of the Grünsand Member are present, they normally do not include phosphatic horizons, which are as well-developed and individualized as in the Col de la Plaine Morte area (Linder et al., 2006).

The age of the Grünsand Member at this particular site is constrained both by the findings of Deshayesites and Ammonites (d’Orbigny) within the Grünsand Bed, which is therefore attributed to the deshayesi and furcata zones, as well as by the evolution of the \(\delta^{13}C\) record, which – if our correlation with the general \(\delta^{13}C\) record of SE France is correct – indicates that the time equivalent of almost the entire deshayesi zone and most of the furcata zone is represented by this member (Fig. 12).

The first episode of erosion and phosphogenesis, recorded in the Rohrachstein interval directly on top of the Urgonian Schrattentalkalk Formation, can therefore not be younger than the base of the deshayesi zone. We correlate this phase with the onset of the “upper Orbitolina Beds” in the Vercors area, where it has been dated as latest weissi zone, near the boundary between the weissi and deshayesi zones (SaA2; Arnaud et al., 1998) (Fig. 13).

The second phase of phosphogenesis, preserved within the Grünsand Member, was associated with a halt in sedimentation and the formation of a nodular phosphatized surface (Plaine Morte Bed). According to the \(\delta^{13}C\) record and the presence of ammonites, the Plaine Morte Bed is dated as equivalent to the late part of the deshayesi zone and the early part of the furcata zone, and may – for its onset – correspond in age to oceanic anoxic episode 1a (OAE 1a; Goguel or Selli level), which is also correlated with a positive shift in the \(\delta^{13}C\) record (Menegatti et al., 1998) (Fig. 13). Unlike Weissett and Erba (2004) and Gradstein et al. (2004), who dated the positive shift in the \(\delta^{13}C\) record and OAE 1a as equivalent to the weissi zone, we place OAE 1a within the deshayesi zone, thereby using the ammonite-calibrated evolution of the \(\delta^{13}C\) record in the area of Cassis–La Bédoule (Kuhnt et al., 1998; cf. also Föllmi et al., 2006) and the age of the “niveau Goguel”, which is dated as deshayesi zone (e.g., Bréhéret, 1997).

These ages allow us to develop a scheme of stepwise drowning of the Urgonian platform, which started with a first halt in platform buildup, accompanied by erosion and phosphogenesis just before the limit between the weissi and deshayesi zones (Fig. 13). This drowning phase terminated platform buildup in a predominantly photozoan mode accompanied by patch-reef growth so typical for the upper part of the upper Schrattentalkalk. This first drowning phase was followed by carbonate production in a heterozoan mode, which started during the early deshayesi zone (lower Grünsand Member). During the late deshayesi zone and early furcata zone, a second phase of phosphogenesis occurred, which was accompanied by erosion and hardground formation. Both the phase of carbonate production in a heterozoan mode and part of the following drowning phase are identical in time with OAE 1a (Figs. 12 and 13). During the later part of the furcata zone, carbonate production continued in a heterozoan mode (upper Grünsand Member). The ammonites of the Lutere Bed indicate a further, protracted phase of halt in carbonate production, which is dated on the Col de la Plaine Morte as subnodosocostatum and melchioris zones, and which is generally inferred to have lasted from the late furcata zone to near the boundary between the melchioris and nolani zones (Föllmi et al., 2007). The Bristi Beds document a return to shallow-water carbonate production in a heterozoan mode, which occurred during the nolani zone. The base of the Plattenwald Bed, which is dated in the Col de la Plaine Morte area as Early to Early Middle Albian, is generally inferred to have already started during the jecobi zone. The Plattenwald Bed indicates the renewed return to phosphogenesis and condensation marks the final drowning phase of the northern Tethyan carbonate platform (Fig. 13).

The onset of platform drowning occurred prior to the widespread deposition of organic-rich sediments associated with OAE 1a and the accompanying positive excursion in pelagic \(\delta^{13}C\) records. The oceanic anoxic episode is materialized in the subsequent phase of heterozoan carbonate production and the second step of the drowning process, which is documented by condensation and phosphogenesis recorded in the Plaine Morte Bed. This offset in timing was already observed (Föllmi et al., 1994, 2007) and maybe related to the possibility that the Urgonian shallow-water carbonate platform reacted very sensibly to environmental change, whereas it took some additional time for the entire oceanic carbon cycle to adjust and correspondingly change its isotopic signature.

![Fig. 12. Proposed correlation between the whole-rock \(\delta^{13}C\) record measured in the Grünsand Member (Gainon, 2001) and the Early Aptian \(\delta^{13}C\) record from SE France (date shown by rectangles from Godet et al., 2006; by crosses from Moullade et al., 1998; by circles from Herre et al., 2004; after Föllmi et al., 2006).](image-url)
5.2. Erosion, condensation and phosphogenesis

5.2.1. The Rohrbachstein phase

The stepwise-drowning phases of the Urgonian platform and the subsequent phase towards pelagic sedimentation are all marked by erosion, sediment reworking, and phosphogenesis. The Rohrbachstein phase is associated with differential erosion of the surface of the Urgonian Schrattenkalk Formation, leading to local incisions of up to several meters depth, which accommodated the main sedimentary volume of the subsequent Grünten Member (Fig. 14). The eroded surface of the Urgonian Schrattenkalk Formation underwent a subsequent phase of phosphogenesis, which affected selected parts of the surface, such as exposed coral remains (Linder, in prep.).

5.2.2. The Plaine Morte phase

The second phase of phosphogenesis documented in the Plaine Morte Bed is equally accompanied by erosion, which in this case led to the formation of a nodular surface, and peripheral phosphatization of the limestone nodules (Figs. 6C, 13, and 14). This horizon is associated with detrital quartz grains, glauconite, and sparse phosphate...
**Rohrbachstein Phase** (Early Aptian: near the boundary between the weissi and deshayesi Zones)
Erosion and phosphogenesis at the top of the Schrattenkalk Formation

Deposition of the lower succession of the **Grünten Member** (Early Aptian: early deshayesi Zone)

**Plaine Morte Bed** (Early Aptian: late deshayesi Zone to early furcata Zone)
Erosion, phosphogenesis

Deposition of the upper succession of the **Grünten Member** (Early Aptian: furcata Zone)

**Luitere Bed** (latest Early to Late Aptian: late furcata Zone to near the boundary melchioris-nolani Zones)
Erosion, phosphogenesis, condensation

Deposition of the **Brisi Beds** (Late Aptian: nolani Zone)

**Plattenwald Bed** (latest Aptian (jacobi Zone) to middle Turonian)
Erosion, phosphogenesis, condensation

Deposition of the basal succession of the **Seeven Formation** (Late Turonian)

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![Diagram](image)

- E-W directed main current
- N-S directed transfer of detrital sediments

**Fig. 14.** Sequence of time frames in which the deposition of different sediments of the Garschella Formation in the area of the Col de la Plaine Morte is reconstructed (after Gainon, 2001).
nodules and particles — amongst them the above-mentioned phosphatized fragments of Deshayesites sp. and A. nisus (d’Orbigny). The presence of a mica-schist pebble of hercynian age indicates the rare inclusion of exotic material in this horizon (Fig. 6D). A further crystalline cobble was found in the Garschella Formation of Unter Klien, Vorarlberg, Austria, which was dated as Late Proterozoic (Föllmi, 1989). The origin of the pebble of the Plaine Morte Bed is probably similar to the one proposed for the Austrian cobble; i.e., a dropstone which was associated with floating wood (for example captured in the root network). Given its hercynian origin and the reconstructed east–west oriented current system that followed the northern Tethyan margin, it may have originated from the western part of the Bohemian massif, which was exposed at that time (e.g., Föllmi and Delamette, 1991; Stampfli and Borel, 2002; Golonka, 2004).

The Plaine Morte phase of phosphogenesis is also known from distal occurrences of the Garschella Formation in Vorarlberg and Allgäu, where phosphates of this phase became integrated in phosphatic sediments of the younger Luitere Bed (Föllmi, 1986; Linder et al., 2006). In the Col de la Plaine Morte area, a local bundling of the Plaine Morte Bed with the overlying Luitere Bed is also observed (Figs. 6E, and 14).

5.2.3. The Luitere phase

The third phase of erosion and phosphogenesis is preserved in the sediments of the Luitere Bed. The base of the Luitere Bed is highly irregular and marked by the infill of fissures that may penetrate the underlying Grünten Member or upper Schrattenkalk for several 10’s of cm. The bed itself includes up to cobble-sized fragments of reworked sediments of the Grünten Member and Schrattenkalk Formation. The ammonites found in this area indicate an Early Late Aptian age, whereas more complete ammonite collections elsewhere in the Helvetic Zone indicate a time enveloping the latest Early Aptian to the Late Aptian (late furcata zone to near the boundary between the melchioris and nolani zones). The fact that this bed is very thin (max. 20 cm) and in larger areas reduced to the fissure infills indicates the importance of erosion during and after its deposition. The bioclastic graphic spread of ammonites in the Luitere Bed in general indicates a maximal time span of approximately 6 to 7 million years of condensation, according to Gradstein et al. (2004) (Fig. 14).

5.2.4. The Plattenwald phase

Schaub (1936) described the presence of different types of sediments in ammonites of different biostratigraphic ages occurring within the Plattenwald Bed of the region of the Col de la Plaine Morte and north of it (Rawil, Wildstrubel, Schneidehorn). Using differences in grain-size distributions of quartz and glauconite, differences in the degree of roundness, and presence of foraminifera and bioclasts, he was able to distinguish eight different types of sediment infill in ammonites of different biostratigraphic zones in the latestmost Aptian and the entire Albian. Ammonites of the same biostratigraphic zone include the same type of sediment infill. He concluded that the formation of the Plattenwald bed witnessed at least eight phases of 1) sedimentation; 2) sediment infill of ammonites, phosphogenesis, and fossilization; 3) erosion, winnowing and transport; and 4) reworking of coarser grained particles (phosphatic nodules, fossils) into the following phase of sedimentation (see also Schaub, 1948). He also noted that whereas most ammonites in the region of the Col de la Plaine Morte indicate a latest Aptian to Early Middle Albian age, the ammonites within the same bed in regions north of the Col de la Plaine Morte indicate preferentially a Late Albian age.

The scenario of formation of the Plattenwald Bed in the region of the Col de la Plaine Morte proposed by Schaub (1936) is confirmed and complemented here. We assume that the zone of condensation was current-swept (Föllmi and Delamette, 1991) and episodically covered by relict sands, which were bypassed to the outer-shelf zone (Föllmi, 1986, 1989, 1990). A small cross-bedded sand lens within the Plattenwald Bed (Figs. 6G and 14) is interpreted as such a body of relict sand that remained preserved in the area of condensation. The presence of cross-stratification within this lens indicates that the process of deposition was fast. The bypassing of sands may therefore have been episodic, in a stop-and-go manner, thereby burying benthic and benthos-related ecosystems, which were fossilized and phosphatized as such. After the removal of the relict sand, the phosphatized fossils and larger particles were concentrated by winnowing and eventually incorporated in a following wave of relict sand bypassing the zone of condensation.

Once the sand supply stopped, phosphogenesis stopped as well (during the Middle Albian; Fig. 13), and in the following the carpet of phosphatic fossils and particles trapped different generations of micritic sediments, which date from the Late Albian to Middle Turonian. The deliverance of micritic sediments occurred probably also under the influence of a current system impinging on the outer margin of the drowned platform, since the deposition of micritic sediments of this period are only known from the highly condensed Plattenwald Bed, whereas coeval and identical sediments were deposited within the Seeven Formation further to the north.

This signifies that the duration of phosphogenesis within the Plattenwald Bed of the Col de la Plaine Morte area was restricted from the latest Aptian to the Middle Albian, whereas further to the north, this process lasted until the Late Albian. The process of condensation itself, however, did not stop before the Middle Turonian. A comparable process of phosphogenesis and condensation of comparable duration has also been documented from distal occurrences of the Plattenwald Bed in Vorarlberg (Föllmi, 1986, 1989).

During the later, “micritic” stage in the phase of condensation,stromatolitic structures formed and were excellently preserved within the micrite filling in the pore space of the Plattenwald Bed (Fig. 9). These stromatolites are so-called deep-water stromatolites, which were installeed on the outer margin of the drowned platform. In distal areas of the drowned Urgonian carbonate platform, stromatolites are well known from Cenomanian sediments and are documented from eastern France (Delamette, 1981, 1988), from eastern Switzerland (Churfirsten region; Ouwehand, 1987) and from Vorarlberg (Föllmi, 1986, 1989).

Similar to the mica-schist pebble in the Plaine Morte Bed, the exotic quartzite pebble in the Plattenwald Bed may be interpreted as a dropstone, probably transported in the root network of a rafted tree (Fig. 6H).

5.2.5. Overall duration of condensation and phosphogenetic processes in the Col de la Plaine Morte area

In the area of the Col de la Plaine Morte, the process of condensation and phosphogenesis started already in the Early Aptian, near the boundary between the weissi and deshayesi zones, and was only interrupted by three rather short periods of carbonate accumulation in a heterozoan mode (lower and upper part of the Grünten Member, Brisi Beds) during the Aptian. The process of condensation continued during the entire Albian and Cenomanian, and ended somewhere within the Middle Turonian. Processes of phosphogenesis stopped, however, already in the Middle Albian. The sporadic inclusion of younger phosphatized fossils may be related to the reworking and lateral transport of these fossils from a more proximal realm, where phosphogenetic processes lasted until the Late Albian. This signifies that — following the initial phase of platform drowning — condensation was the predominant process reigning on what remained of the Urgonian platform during more than 30 million years (Gradstein et al., 2004). The drowned platform was current-swept during this period, and saw the episodic bypassing of relict detrital sediments towards more distal areas during the Aptian to Middle Albian. Afterwards, pelagic micritic sediments of Late Albian to Middle Turonian age became trapped in the remaining pore space within the carpet of palimpsest, partly phosphatized fossils, particles, and pebbles.
5.3. Pelagic sedimentation and the installation of normal faults

This prolonged phase of condensation ceased somewhere between the Middle and Late Turonian, to give place to the regular deposition of pelagic, micritic carbonate (Seewen Formation). The deposition of carbonates comparable in facies and equally attributed to the Seewen Formation started earlier in more proximal parts on the Helvetic shelf, between the latest Albian and Middle Cenomanian. The zone of prolonged condensation is limited to the outer margin of the drowned Urgonian platform, which became more accentuated during the Early Late Cretaceous, probably through processes of differential subsidence. In the outer shelf beyond the platform margin, the change to a pelagic regime occurred also during the latest Albian (Föllmi, 1986, 1989; Ouwehand, 1987; Delamette, 1988).

Of interest here is the presence of two normal faults, which are arranged perpendicularly (Figs. 1 and 11). Normal faults associated with breccia, which exposed already lithified carbonates of the Urgonian platform are also known from the Vorarlberg area, and are associated with phases of important sediment reworking ("Götzis Beds"). These phases were probably triggered by differential compaction and subsidence, leading to a partial collapse of the outer platform margin. A tectonic influence is not excluded neither (Föllmi, 1981, 1986, 1989).

5.4. The disappearance of the Urgonian platform in the context of paleoenvironmental change

Initial drowning of the Urgonian carbonate platform during the Early Aptian has also been documented from other areas within the Helvetic Zone, such as in Allgäu (Linder et al., 2006) and Vorarlberg (Föllmi, 1986, 1989; Bollinger, 1988). A very comparable and well-correlated pattern of drowning is also known from the Vercors area (e.g., Arnaud-Vanneau et al., 1976; Arnaud et al., 1998), and from the Spanish Pyrenees (Bernaux et al., 2003). In the Monts de Vaucluse, S France, the Urgonian succession includes a rudist-bearing succession (U2 in Masse et al., 1999), which is replaced by a succession of bioclastic carbonates (U3 in Masse et al., 1999) near the limit between the weissi and deshayesi zones. The top of the bioclastic carbonate succession is dated as furcata zone (Masse et al., 1999; cf. also Masse, 1993).

In Oman, platform sediments equivalent to OAE 1a are characterized by the presence of a Lithocodium/Bacinella association, which is interpreted to have resulted from increased trophic levels (Pittet et al., 2002; Hillgartner et al., 2003; Immehausser et al., 2005). In N Mexico, the disappearance of the rudist-bearing shallow-water carbonates of the Cupido Formation is dated as Early Aptian (Bralower et al., 1999; Lehmann et al., 1999).

This compilation of platform drowning pattern during the Early Aptian across the Tethyan realm suggests that the causes are to be sought on at least a Tethyan-wide scale. The correlation between platform drowning and evolving OAE's has been evoked by many authors (e.g., Schlager and Philip, 1990), and the links between the drowning steps identified in the Col de la Plaine Morte area and OAE's probably confirm a causal relationship, even if the onset of the drowning phases slightly predates the OAE's. An often-suggested mechanism invokes increases in trophic levels, which were related to the increased availability of nutrients such as phosphate. There are several indications, which are in favor of this scenario: 1) the overall change from photozoan-dominated to heterozoan-dominated and Lithocodium/Bacinella-containing carbonates near the boundary between the weissi and deshayesi zones; 2) the importance of phosphogenesis during the drowning phases along the northern Tethyan margin; and 3) a general increase in phosphorus-burial rates during the Early Aptian, which correlates rather well with the whole-rock 813C record (Föllmi et al., 2007).

Changes in trophic levels are generally viewed as the result of climate warming and an increase in biogeochemical weathering rates on the continents, and indications for this are given in the Col de la Plaine Morte area by a corresponding stepwise increase in detrital quartz input, starting with the sediments of the Grünten Member. These changes were accompanied by general sea-level rise, which started in the weissi zone and culminated during OAE 1a in the deshayesi zone (Haq et al., 1987). The ultimate mechanism for environmental change may be linked with increased tectonic and volcanic activity, and evidence for this is given by the formation of the Ontong-Java large igneous province and eventually also by a compilation of oceanic crust production rates, in which an acceleration is suggested for the Early Aptian (Larson, 1991; Courtillot and Renne, 2003; Taylor, 2006).

Independent of all inferences and interpretations, it is more and more evident that a phase of major change occurred during the Middle Early Aptian — near the limit between the weissi and deshayesi zone, which terminated reef growth on a wider scale and lead to the widespread disappearance of Urgonian-type, photozoan carbonate platforms. This phase preceded OAE 1a, which occurred during the deshayesi zone, and which overlaps with a second phase of platform deterioration. A further phase of protracted platform drowning phase started in the late furcata zone and lasted during most of the Late Aptian. A final drowning phase occurred near the Aptian–Albian boundary, which gave a “coupe de grace” to those portions of the northern Tethyan carbonate platform system, which are presently locked up in the Helvetic Alps.

6. Conclusions

The sediments of the Helvetic thrust- and fold belt exposed in the Col de la Plaine Morte area (central Switzerland) are of special interest, since they provide one of the most complete and differentiated records of the succession of drowning phases which led to the demise of the Urgonian carbonate platform. They also document the subsequent phase of prolonged condensation, followed by pelagic sedimentation on top of the drowned Urgonian platform.

A first drowning phase associated with important erosion and local phosphogenesis, which terminated photozoan carbonate production on top of the Urgonian platform, is dated as just before the boundary between the weissi and deshayesi zones (Middle Early Aptian). This phase is followed by a phase of carbonate production in a heterozoan mode, and, consequently, by a second drowning phase associated with erosion, condensation, and phosphogenesis, which is dated as the late deshayesi to early furcata zones (Late Early Aptian). A second phase of carbonate production in a heterozoan mode is documented somewhere in the middle part of the furcata zone, and a third drowning phase associated with erosion, condensation and phosphogenesis started in the late furcata zone, and lasted until near the boundary between the nolani and melchioris zones (Middle Late Aptian). A third and final phase of carbonate production in a heterozoan mode is documented from the melchioris zone, which was followed by a fourth and final drowning phase, which is again associated with erosion, condensation and phosphogenesis, and which started somewhere in the jacobi zone (latest Aptian).

This last phase of condensation lasted until the Middle Turonian, and documents a drowned outer platform margin, which was swept by an impinging current, and which was intermittently covered by bypassing relict sands. Phosphogenesis in this particular part of the platform lasted until the Middle Albian.

From the Middle Turonian onwards, the condensed sediments of the drowned platform margin were progressively covered by pelagic, micritic sediments. During this phase of pelagic carbonate deposition, the outer platform margin became subjected to normal faulting, which partly re-exposed the already lithified carbonates of the Urgonian platform at the seafloor. This phase of platform-margin structuration is interpreted as a partial collapse related to differential subsidence — eventually in concert with a phase of increased tectonic activity.
Judging the ages obtained by ammonite biostratigraphy and δ13C-whole-rock stratigraphy, the first platform drowning phase just preceded OAE 1a, and the second drowning phase partly overlapped with OAE 1a. The onset of the third drowning event predated two further periods of increased organic-matter accumulation in the Vocontian Basin (Noird and Fallot levels), and the beginning of the fourth and final drowning phase coincided with two further periods of increased organic-matter accumulation in the Vocontian Basin (Jacob and Kilian levels, part of OAE 1b). These correlations suggest the presence of a relationship between the oceanic anoxic episodes and the stepwise demise of the Urgonian platform. Therefore, the platform appeared to have registered environmental change in a more rapid and sensitive way than the sediments in the adjacent basin.

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