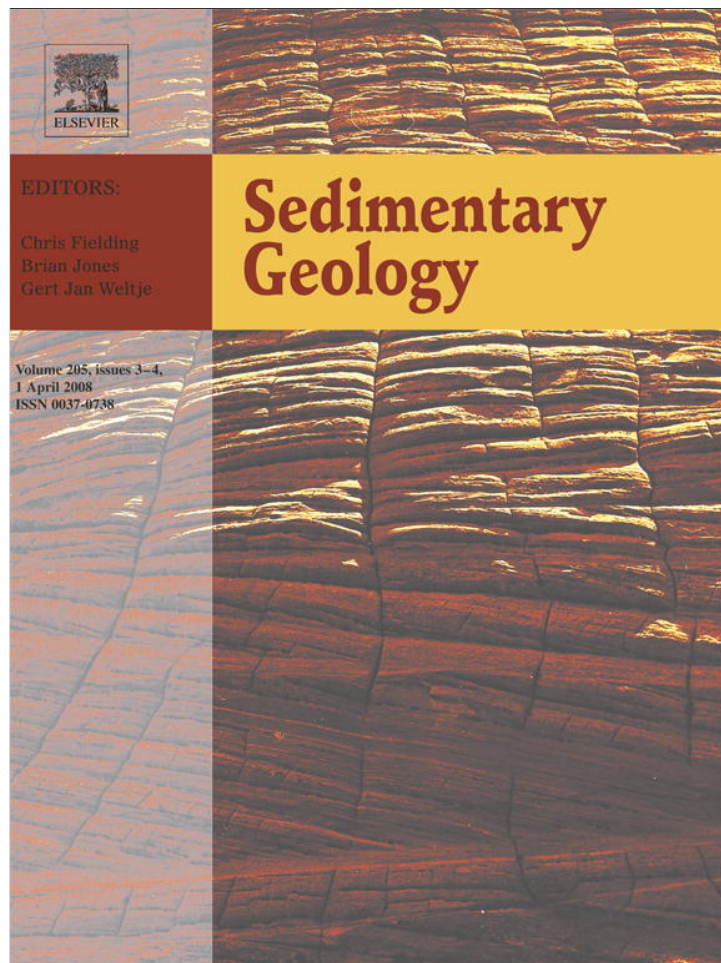


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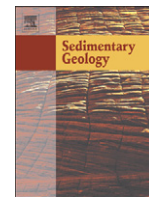
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## Sedimentary Geology

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# 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

Karl B. Föllmi\*, François Gainon

Geological Institute, University of Neuchâtel, Rue Emile Argand 11, 2009 Neuchâtel, 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  $\delta^{13}\text{C}$  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  $\delta^{13}\text{C}$  record as Late Early Aptian (late *deshayesi* to early *furcata* zone). A third drowning phase provides an ammonite-based age of Early Late Aptian (*subnodosocostatum* 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 *nolani* zones). The fourth and final drowning phase started in the latest Aptian (*jacobi* 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 Albian, 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 Falot 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.

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## 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 (Weissert 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.

\* Corresponding author. Tel.: +41 32 718 26 55; fax: +41 32 718 26 01.  
E-mail address: [karl.foellmi@unine.ch](mailto:karl.foellmi@unine.ch) (K.B. Föllmi).

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 Albian (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 Ouwehand, 1987; Ouwehand, 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  $\delta^{13}\text{C}$  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 Schrattekalk 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 Schrattekalk 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 Schrattekalk 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 ( $\text{H}_3\text{PO}_4$ ). The results were calibrated to the PDB scale with standard errors of 0.1‰ for  $\delta^{18}\text{O}$  and 0.05‰ for  $\delta^{13}\text{C}$ .

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

## 4. Stratigraphy

### 4.1. Kieselkalk Formation (Hauterivian)

The approximately 200 m thick Kieselkalk 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 Late Early Barremian)

The Altmann Member follows directly on top of the Kieselkalk Formation and starts with a thin (approximately 0.1 m) limestone bed

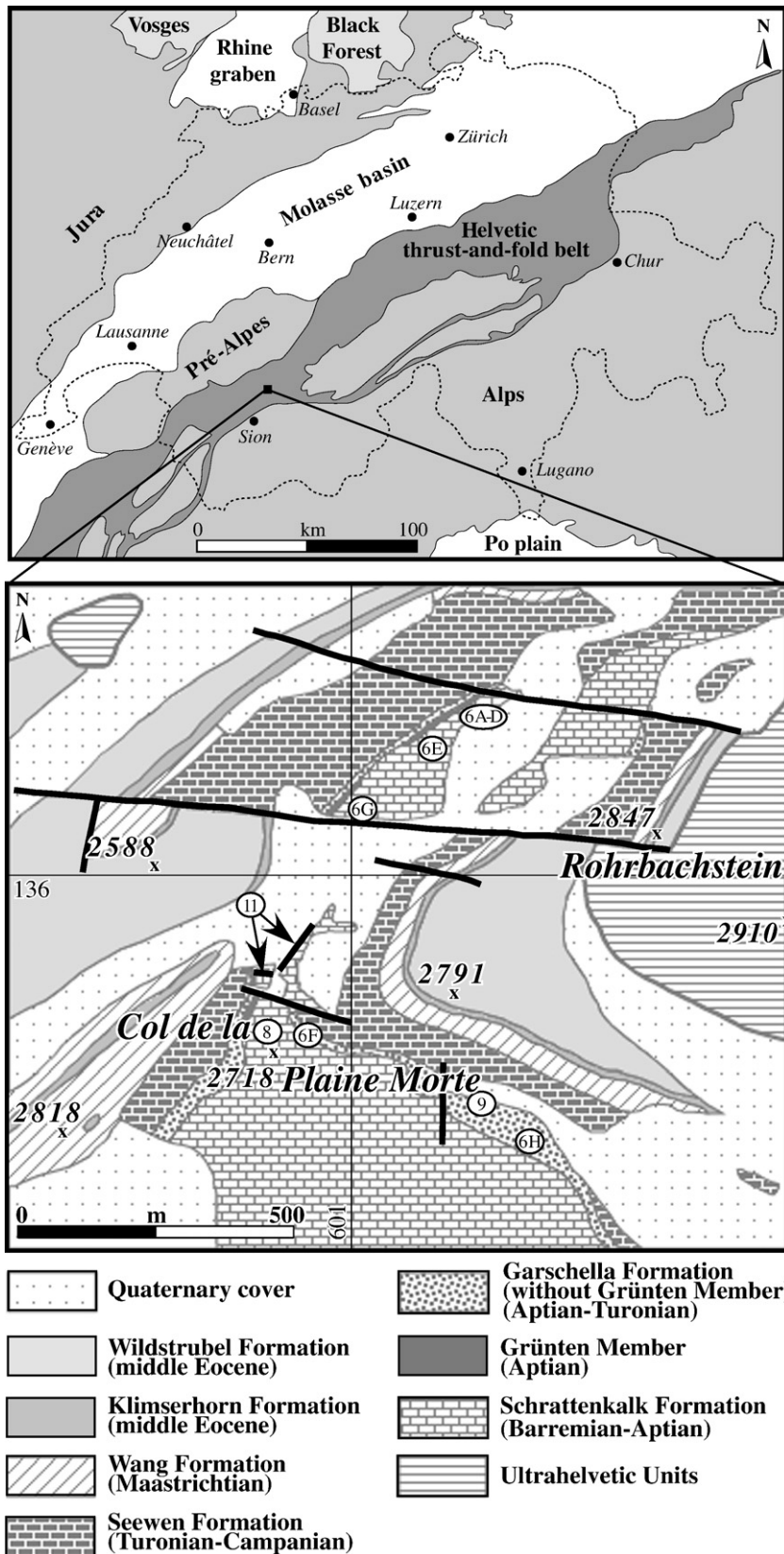


Fig. 1. Tectonic overview of Switzerland with indication of the location of the Col de la Plaine Morte area. The geological map is an excerpt from a geological map by Gainon (2001). The general tectonic overview is after Bodin et al. (2006b). Labeled oval insets indicate exact locations of photographed outcrops and samples in Figs. 6, 8, 9, and 11. Arrows point to the two syndimentary normal faults described in this contribution (Gainon, 2001; Fig. 11).

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),

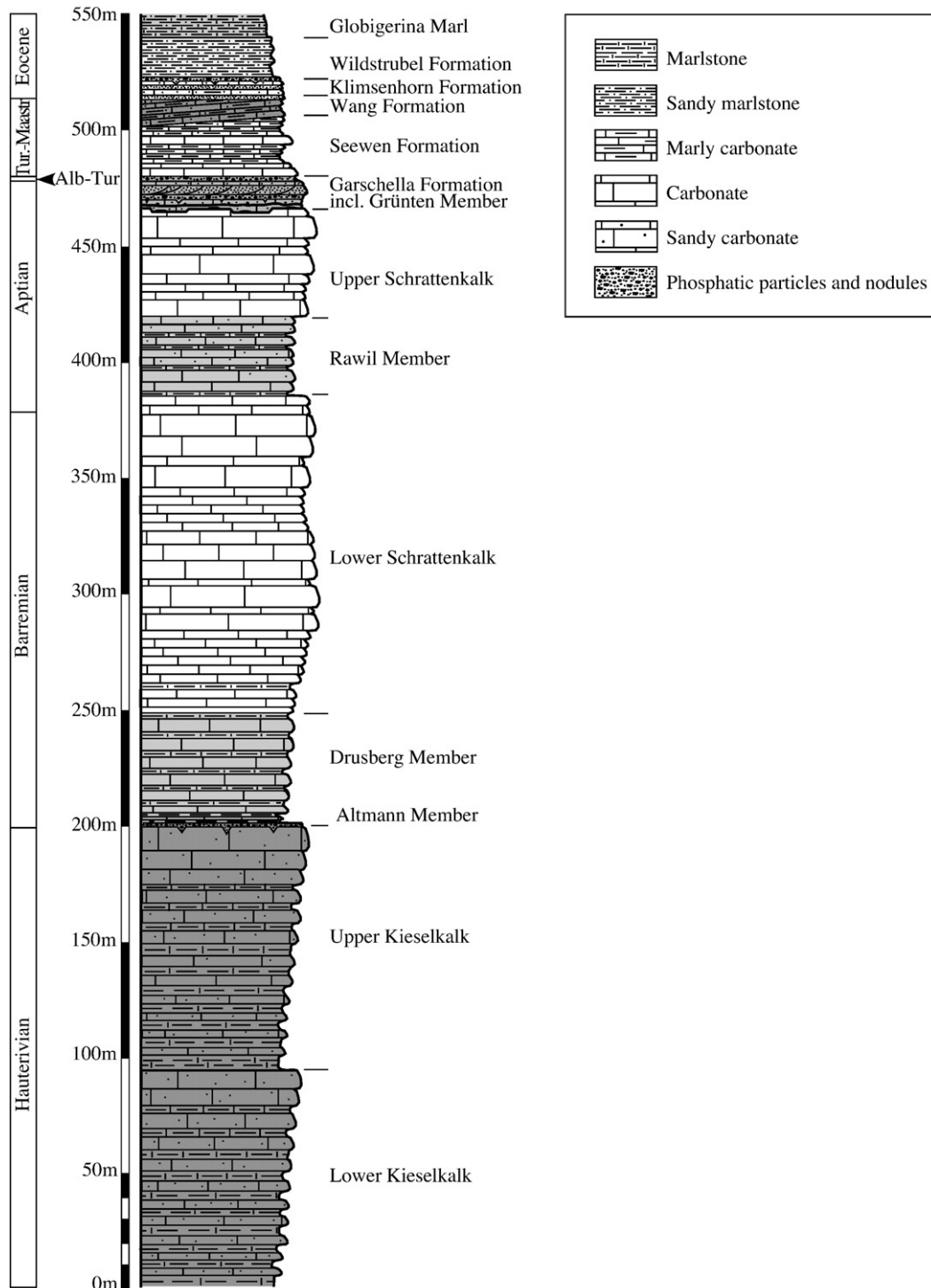


Fig. 2. Lithostratigraphic log of the sedimentary succession outcropping in the region of the Col de la Plaine Morte and north of it (modified from Gainon (2001) and Schenk (1992)).

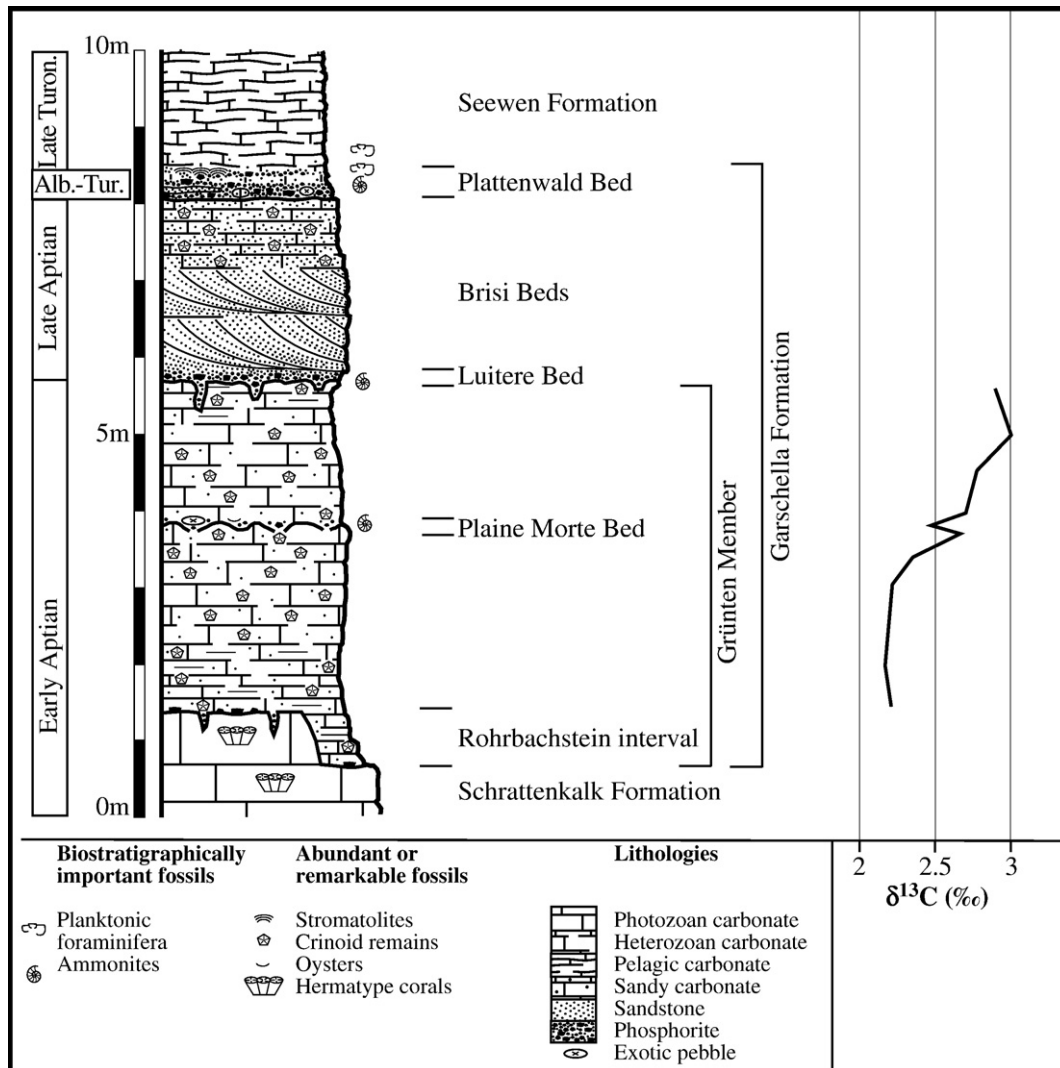


Fig. 3. Lithostratigraphic section of the Garschella Formation in the area NE of the Col de la Plaine Morte and evolution of whole-rock  $\delta^{13}\text{C}$  values measured in the Grünten Member (Gainon, 2001).

who both distinguished two phases of platform development (lower and upper Schratenkalk), 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 Schratenkalk 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 Schratenkalk 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 Schratenkalk 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 overlying Grünten Member (= “upper Orbitolina Beds”) and the Luitere Bed in the Col de la Plaine Morte area, however, do not confirm the orbitolinid-derived ages (see below) and place a Middle Early Aptian age (top *weissi* zone) as upper age limit for the upper Schratenkalk.

#### 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 Schratenkalk 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 Schratenkalk 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).

Lithostratigraphy	Orbitolinid biostratigraphy	Ammonite biostratigraphy
Plattenwald Bed		<i>Hypacanthoplites</i> <i>Leymeriella</i> <i>Douvilleiceras</i> (latest Aptian - early Albian)
Brisi Beds		
Luitere Bed		<i>Colombiceras</i> <i>Chelonoceras</i> (early Late Aptian)
Grünten Member		<i>Aconoceras</i> <i>Deshayesites</i> (middle Early Aptian)
Upper Schrattekalk Member	<i>Orbitolina (texana)-subconcava</i> <i>Pseudochoffatella cuvillieri</i> <i>Coskinolinella santanderensis</i> (Late Aptian, ev. earliest Albian)	
Rawil Member	<i>Palorbitolina lenticularis</i> <i>Paracoskinolina maynci</i> <i>Cribellopsis neoelongata</i> (Earliest Aptian, ev. latest Barremian)	
Lower Schrattekalk Member	<i>Paleodictyonus cuvillieri</i> <i>Paracoskinolina reicheli</i> <i>Paracoskinolina maynci</i> (Earliest Barremian)	
Drusberg Member	<i>Paleodictyonus cuvillieri</i> <i>Cribellopsis elongata</i> <i>Paracoskinolina reicheli</i> <i>Urgonina alpillensis</i> (Earliest Barremian, ev. latest Hauterivian)	top Drusberg Member: <i>sartousiana</i> zone (middle Late Barremian) Bodin et al., 2006a
Altmann Member	<i>Paleodictyonus cuvillieri</i> <i>Cribellopsis elongata</i> (Earliest Barremian)	<i>seitzi</i> - to <i>darsi</i> Zone (late Hauterivian - latest Early Barremian) Bodin et al., 2006b

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).

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 nissus* (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. nissus* (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  $^{40}\text{Ar}/^{39}\text{Ar}$  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).

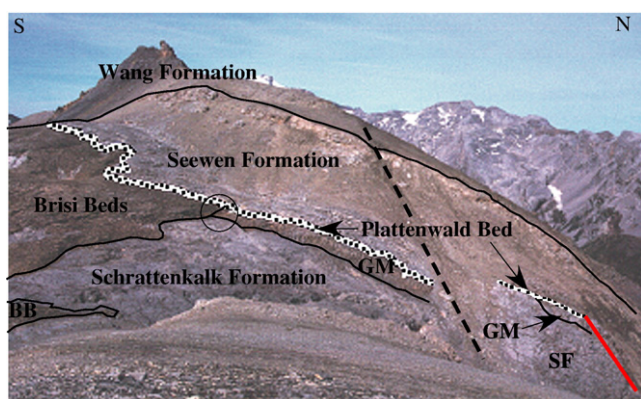
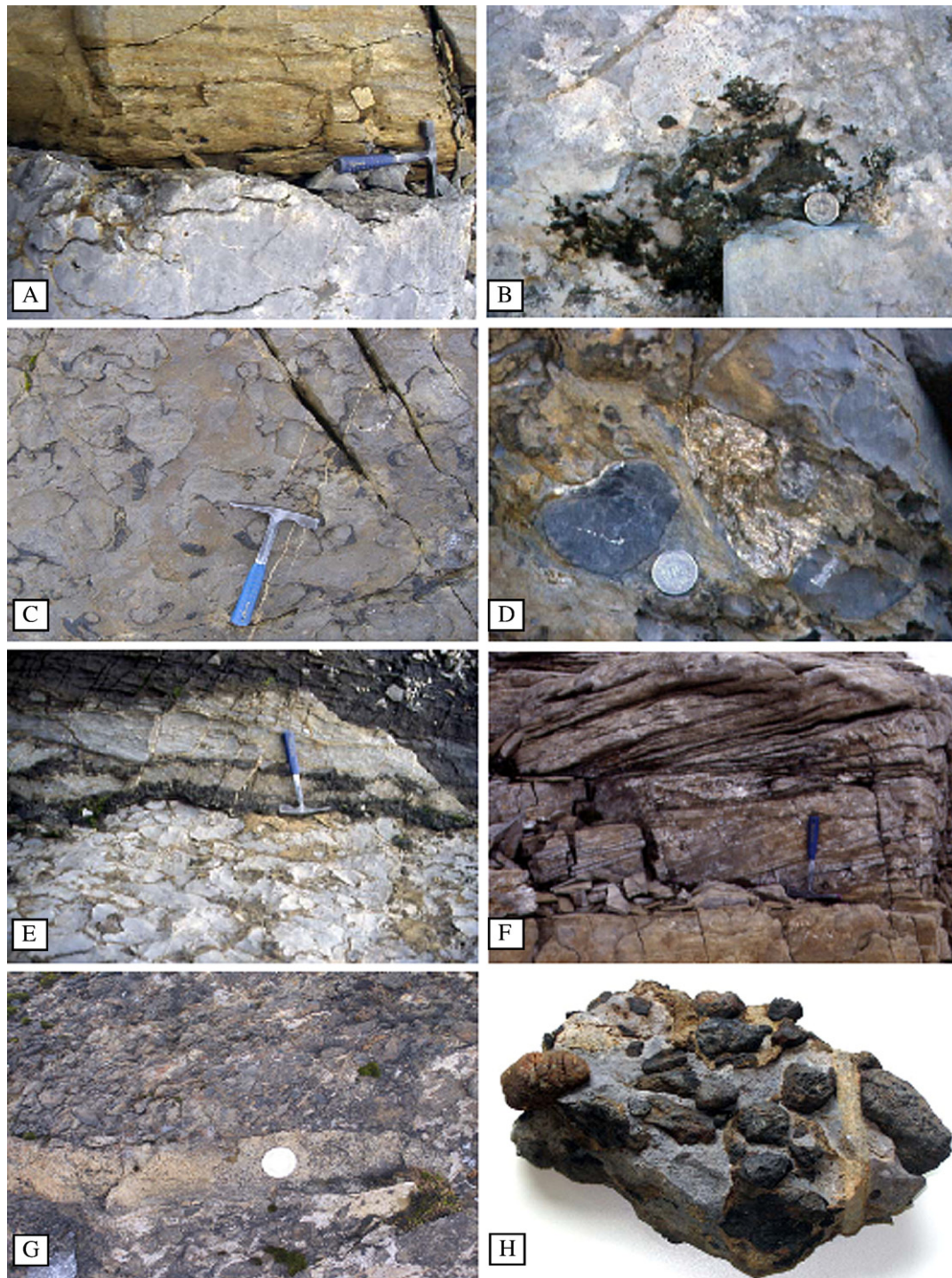


Fig. 5. Geology of the Col de la Plaine Morte. Circle indicates the locality of the steep erosional interface between sediments of the Grünten Member and overlying Brisi Beds shown in more detail in Fig. 8. The red line indicates the location of a synsedimentary fault associated with breccia shown more in more detail in Fig. 11. BB = Brisi Beds, GM = Grünten Member, SF = Schrattekalk Formation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

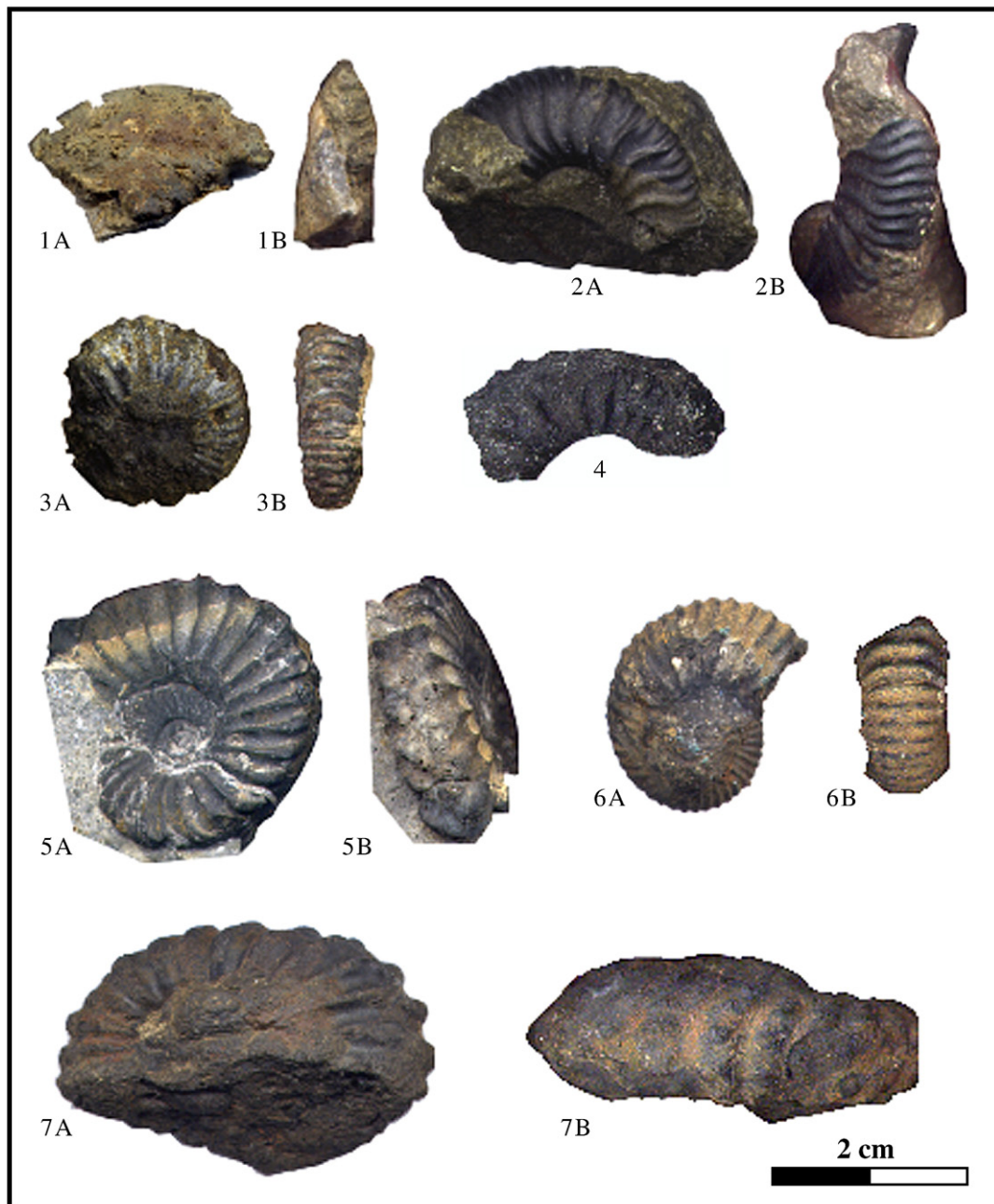


**Fig. 6.** Photos of outcrops and samples of the Garschella Formation in the area of the Col de la Plaine Morte. The exact locations are indicated in Fig. 1: A. Contact between the whitish neritic photozoan limestone of the Schrattekalk Formation and the overlying yellowish marly heterozoan limestone of the Grünen Member. Note the irregular top surface of the Schrattekalk Formation, which is interpreted as a discontinuity surface shaped by erosion during the Rohrbachstein phase; B. A patch of an autochthonous phosphate crust covering the top surface of the Schrattekalk Formation directly underneath the sediments of the Grünen Member. The here documented phase of phosphogenesis is related to the Rohrbachstein phase, which is inferred to have taken place near the boundary between the *weissi* and *deshayesi* zones; C. View on the top surface of the Plaine Morte Bed within the Grünen Member. Note the nodular character of this bed and the peripheral phosphatization of the nodules; D. A unique and exotic subangular pebble consisting of a silver-shining mica schist occurs in the nodular Plaine Morte Bed. The  $^{40}\text{Ar}/^{39}\text{Ar}$  age of isolated mica flakes is approximately 330 Ma (coin diameter=2.1 cm); E. Phosphatic nodular Luitere Bed in direct contact with the Plaine Morte Bed. The Luitere Bed is here divided into two separate nodular layers and the bed itself is overlain by coarse-grained sandstone of the Brisi Beds; F. Cross-stratified sandstone at the base of the Brisi Beds, directly on top of the Schrattekalk Formation; G. Isolated lens (approximately 70 cm long and 4 cm thick) consisting of a cross-stratified glauconitic sandstone within the nodular phosphatic Plattenwald Bed, which represents a relic sediment transported in an offshore direction (coin diameter=2.3 cm) (cf. Föllmi, 1996); H. Sample of the Plattenwald Bed showing an exotic yellow-brown quartzite pebble on its left side (pebble length=3.4 cm); the other pebbles and nodules consist of phosphatized fossil debris and sediment. The intervening non-phosphatized sediment is composed of a micritic carbonate comparable to that of the overlying Seewen Formation.

A  $\delta^{13}\text{C}$  record was obtained on a selection of whole-rock samples of the Grünen 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 Grünen Member (Gainon, 2001; Fig. 3). As these values are approximately in the range of Early





**Fig. 7.** Ammonites from the Garschella Formation near and at Col de la Plaine Morte: 1. *Aconoceras nisus* (d'Orbigny), identified by M. Delamette (Chartreuse National Park), Plaine Morte Bed; 2. *Deshayesites* sp., identified by J.-P. Thieuloy (University of Grenoble), Plaine Morte Bed; 3. *Colombiceras* sp., Luitere Bed; 4. *Cheloniceras* sp., Luitere Bed; 5. *Leymeriella* (*Neoleymeriella*) cf. *intermedia* Spath, Plattenwald Bed; 6. *Hypacanthoplites* sp., Plattenwald Bed; 7: *Douvilleiceras* sp., Plattenwald Bed.

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.

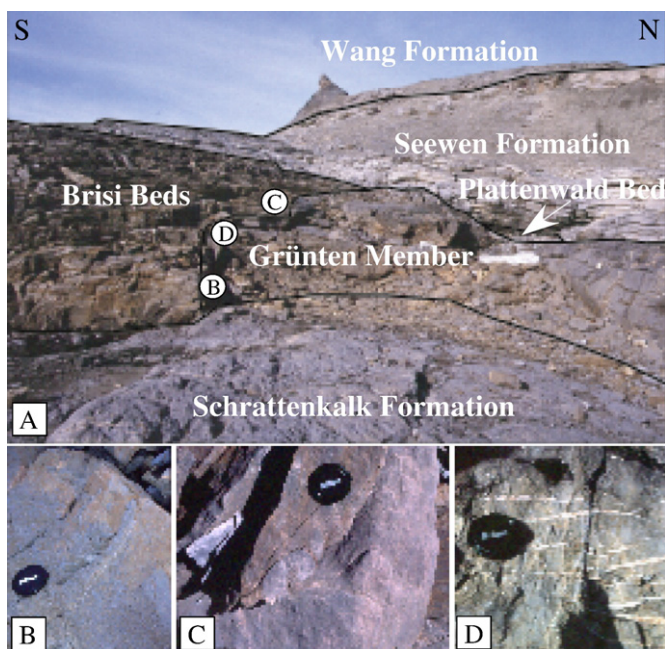
#### 4.4.2. Luitere Bed (Early Late Aptian)

The sediments of the Grünen Member or directly the sediments of the upper Schrattekalk Member (in case the Grünen 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 Grünen 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 Schrattekalk, 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 Schrattekalk (in the case the Grünen Member is absent and the Luitere Bed is limited to fissure infills at the top of the Schrattekalk 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



**Fig. 8.** An interesting juxtaposition of sediments of the Grünten Member and Brisi Beds is observed west of the Col de la Plaine Morte, where a succession of Schrattenkalk Formation–Grünten Member–Plattenwald Bed–Seewen Formation is laterally replaced to the south by a succession of Schrattenkalk Formation–Brisi Beds–Plattenwald Bed–Seewen Formation. 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 infiltrations 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 location of B, C, and D is indicated in A, and the exact location of A is indicated in Figs. 1 and 5.

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 Schrattenkalk–Grünten Member–Plattenwald Bed–Seewen Formation is replaced to the south by a succession of upper Schrattenkalk–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 very sharp, and descends in a rather steep and step-wise manner. It is locally marked by *Thalassinoides* and by the presence of up to 10 cm large cobbles and phacoids of sediments from the Grünten Member at the base of the Brisi Beds (Fig. 8).

#### 4.4.4. Plattenwald Bed (latest Aptian–Middle Turonian)

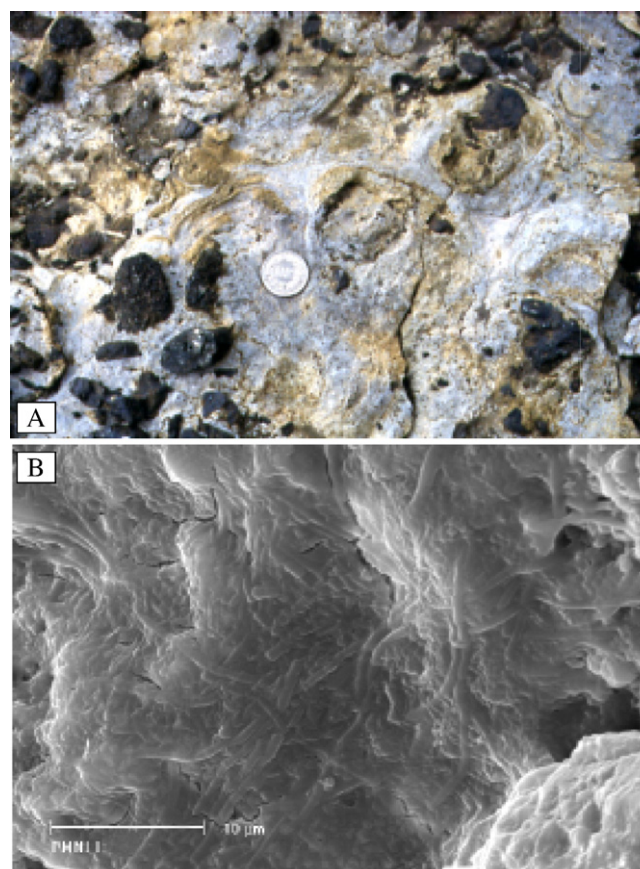
The Plattenwald Bed covers the sediments of the Brisi Beds and locally directly the sediments of the Grünten Member. It consists of a maximally 40 cm thick nodular phosphatic bed, which shows a variety of matrices consisting of glauconitic sandstone, glauconitic sandy micritic limestone, and micritic 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, bellerophonites, and gastropods. A single fragment of *Chaetetopsis* sp. was

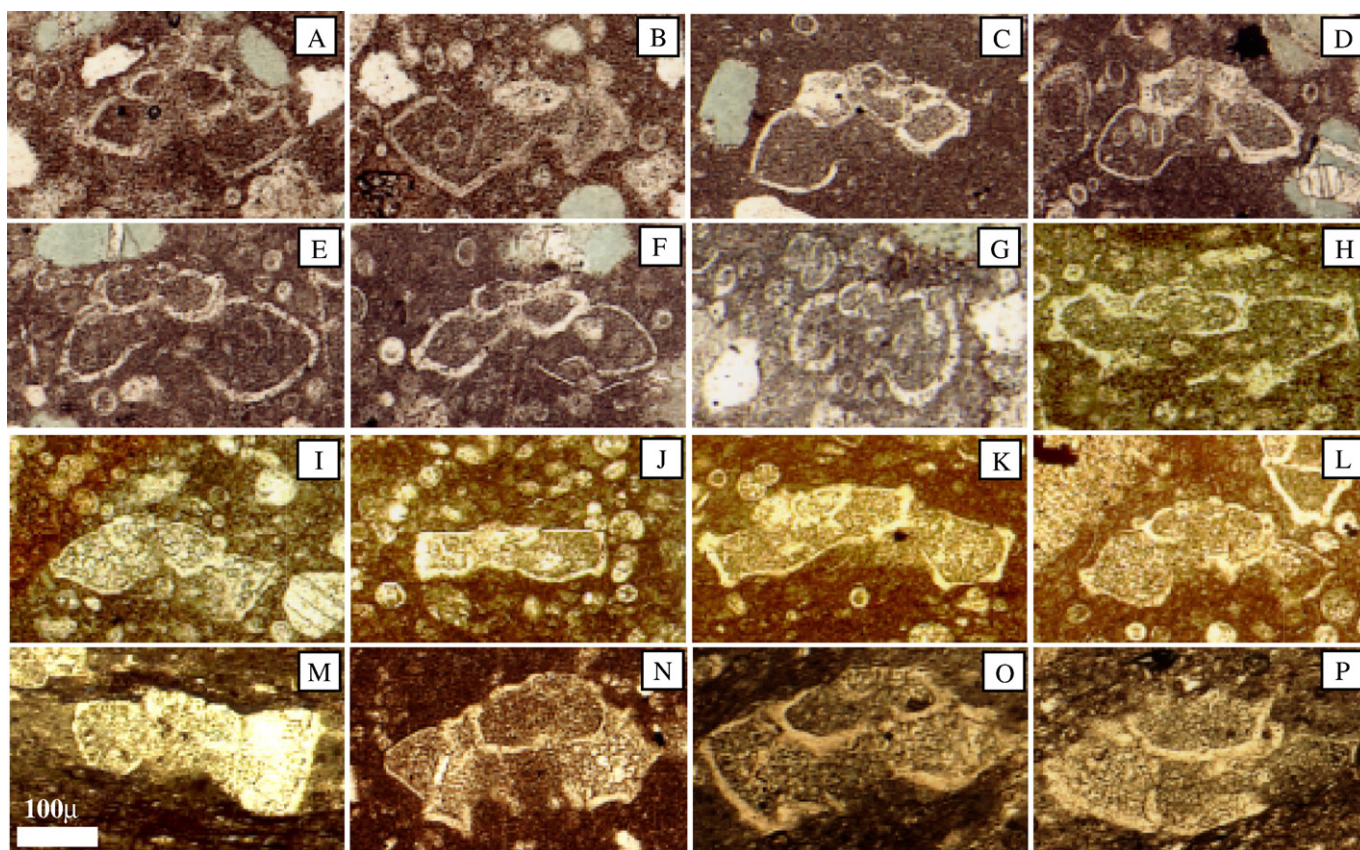
observed (Reitner and Föllmi, 1991). The outcrops at the Col de la Plaine Morte show stromatolitic structures within the micritic limestone at the top of the Plattenwald Bed (Fig. 9). An inspection of a selection of stromatolite samples by electronic scanning microscope reveals the presence of filamentous 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 *Hypacanthoplites*, *Leymeriella* and *Douvilleiceras* (Fig. 7). Schaub (1936) also identified *Hoplites* of the *dentatus* group and *Lyellicerias*; 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 ticinensis* (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* (Scheibnerova), *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).



**Fig. 9.** Stromatolitic structures preserved in micritic carbonate at the top of the Plattenwald Bed at the Col de la Plaine Morte: A. Outcrop photo (coin diameter = 2.3 cm); B. SEM micrograph showing filamentous microbial-like structures. The exact location is indicated in Fig. 1.



**Fig. 10.** Selection of Globotruncanidae identified by Michèle Caron (University of Fribourg) within the Plattenwald Bed and overlying Seewen Formation: A. *Rotalipora ticinensis* (Gandolfi) (Plattenwald Bed); B. *Rotalipora cushmani* (Morrow) (Plattenwald Bed); C. *Dicarinella hagni* (Scheibnerova) (Plattenwald Bed); D. *Dicarinella algeriana* (Caron) (Plattenwald Bed); E. *Whiteinella archeocretacea* Pessagno (Plattenwald Bed); F. *Whiteinella inornata* (Bolli) (Plattenwald Bed); G. *Helvetoglobotruncana helvetica* (Bolli) (Plattenwald Bed); H. *Marginotruncana coronata* (Bolli) (base Seewen Formation); I. *Marginotruncana schneegansi* (Sigal) (base Seewen Formation); J. *Falsotruncana maslakovae* Caron (base Seewen Formation); K. *Marginotruncana pseudolinneiana* Pessagno (base Seewen Formation); L. *Marginotruncana sigali* (Reichel) (base Seewen Formation); M. *Dicarinella concavata* (Brotzen) (lower marly interval within Seewen Formation); N. *Rosita formicata* (Plummer) (upper calcareous interval within Seewen Formation); O. *Globotruncanita stuartiformis* (Dalbiez) (upper marly interval within Seewen Formation); P. *Globotruncana arca* Cushman (upper marly interval within Seewen Formation).

#### 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. aff. asymetrica* (Sigal), and *M. pseudolinneiana* Pessagno (Santonian). The upper calcareous part contains *Globotruncanita* sp., *Rosita formicata* Plummer, and *M. pseudolinneiana* Pessagno (Late Santonian), whereas the upper marly interval hosts *Globotruncana arca* Cushman, *Globotruncanita stuartiformis* (Dalbiez), 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-Coord.: 600.780/135.830; Figs. 1 and 11). The breccia components

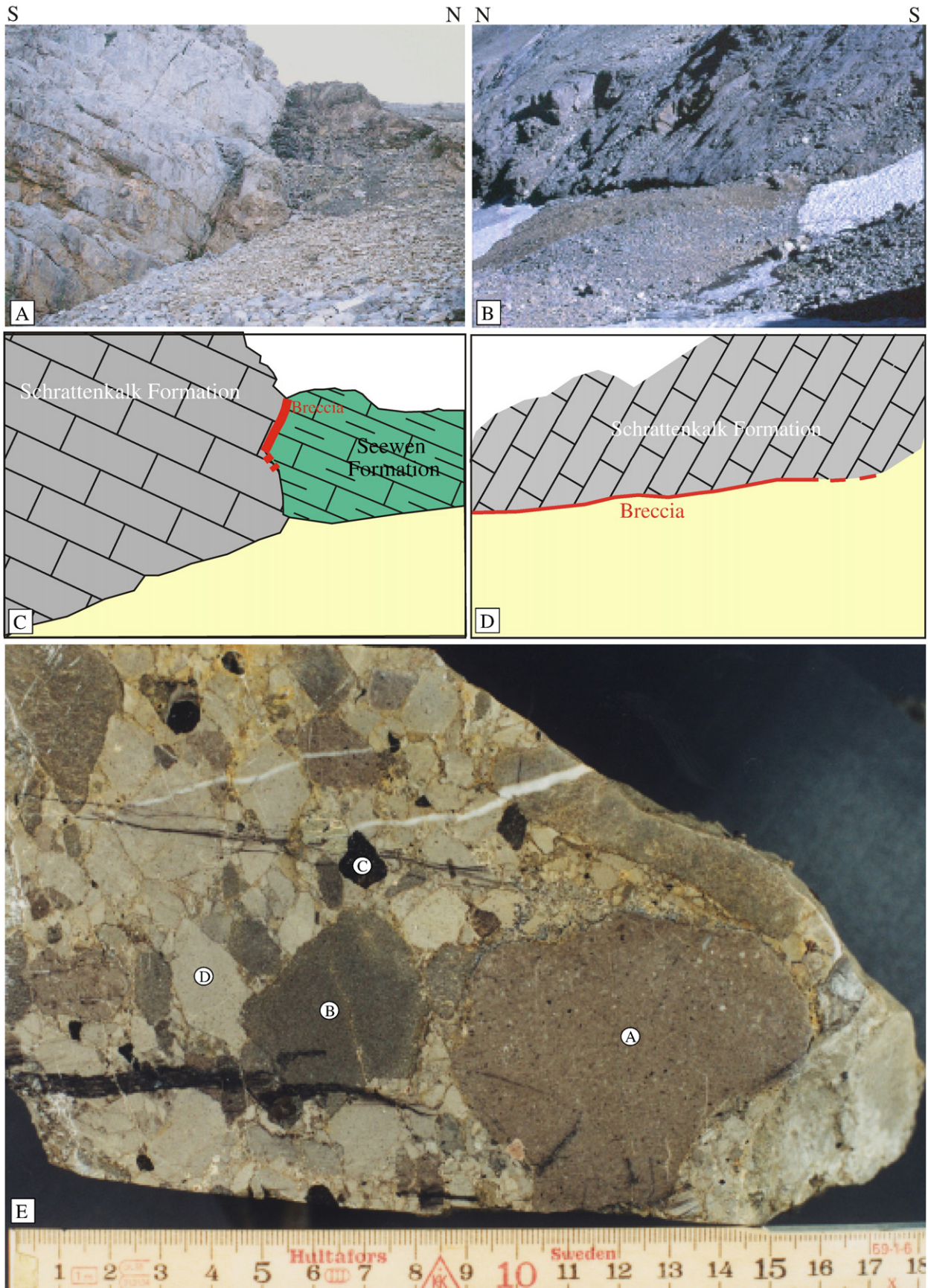
consist of sediments from the Schrattealk Formation, the Garschella Formation, and the Seewen Formation, which are embedded in a matrix of pelagic micrite of the Seewen Formation. The breccia deposits are associated with two subvertical normal faults, which separate the Urgonian Formation from the Seewen 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 asymetrica* (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), Klimsenhorn 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 Schrattealk 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 *Discocyclina* and *Nummulites*, which are followed by approximately 20 m of sandy shales (Klimsenhorn 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; Menkfeld-Gfeller, 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 Helvetic realm (Linder et al., 2006). Usually, in more proximal areas, the Grünen Member is missing and the Urgonian Schrattekalk Formation is directly overlain by sediments of the Luitere Bed or younger sediments of the Garschella Formation (Föllmi, 1986, 1989; Föllmi and Ouwehand, 1987; Ouwehand, 1987; Delamette, 1988; Delamette et al., 1997). In distal sections, where sediments of the Grünen 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 Grünen Member at this particular site is constrained both by the findings of *Deshayesites* and *A. nesus* (d’Orbigny) within the Plaine Morte Bed, which is therefore attributed to the *deshayesi* and *furcata* zones, as well as by the evolution of the  $\delta^{13}\text{C}$  record, which – if our correlation with the general  $\delta^{13}\text{C}$  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 Rohrbachstein interval directly on top of the Urgonian Schrattekalk 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 (SbA2; Arnaud et al., 1998) (Fig. 13).

The second phase of phosphogenesis, preserved within the Grünen Member, was associated with a halt in sedimentation and the formation of a nodular phosphatized surface (Plaine Morte Bed). According to the  $\delta^{13}\text{C}$  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  $\delta^{13}\text{C}$  record (Menegatti et al., 1998) (Fig. 13). Unlike Weissert and Erba (2004) and Gradstein et al. (2004), who dated the positive shift in the

$\delta^{13}\text{C}$  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  $\delta^{13}\text{C}$  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 Schrattekalk. This first drowning phase was followed by carbonate production in a heterozoan mode, which started during the early *deshayesi* zone (lower Grünen 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 Grünen Member). The ammonites of the Luitere 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 Brisi 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 *jacobi* 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  $\delta^{13}\text{C}$  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.

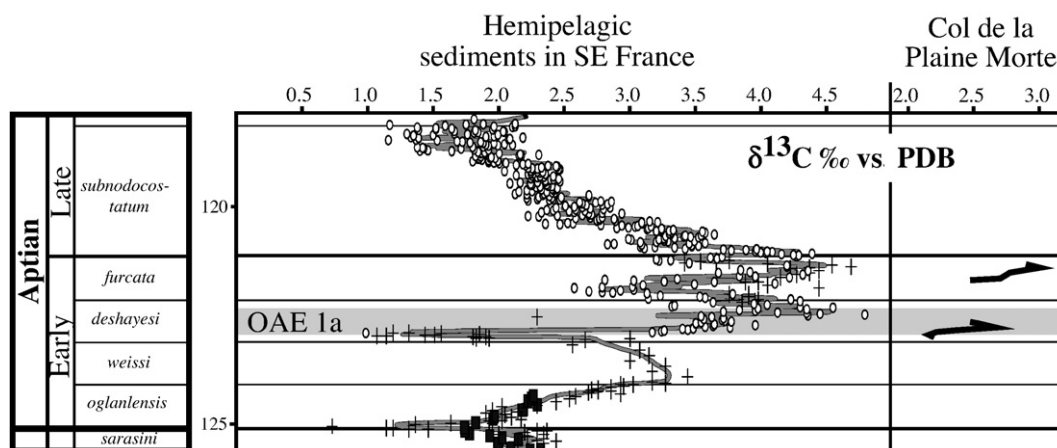


Fig. 12. Proposed correlation between the whole-rock  $\delta^{13}\text{C}$  record measured in the Grünen Member (Gainon, 2001) and the Early Aptian  $\delta^{13}\text{C}$  record from SE France (date shown by rectangles from Godet et al., 2006; by crosses from Moullade et al., 1998; by circles from Herrle et al., 2004; after Föllmi et al., 2006).

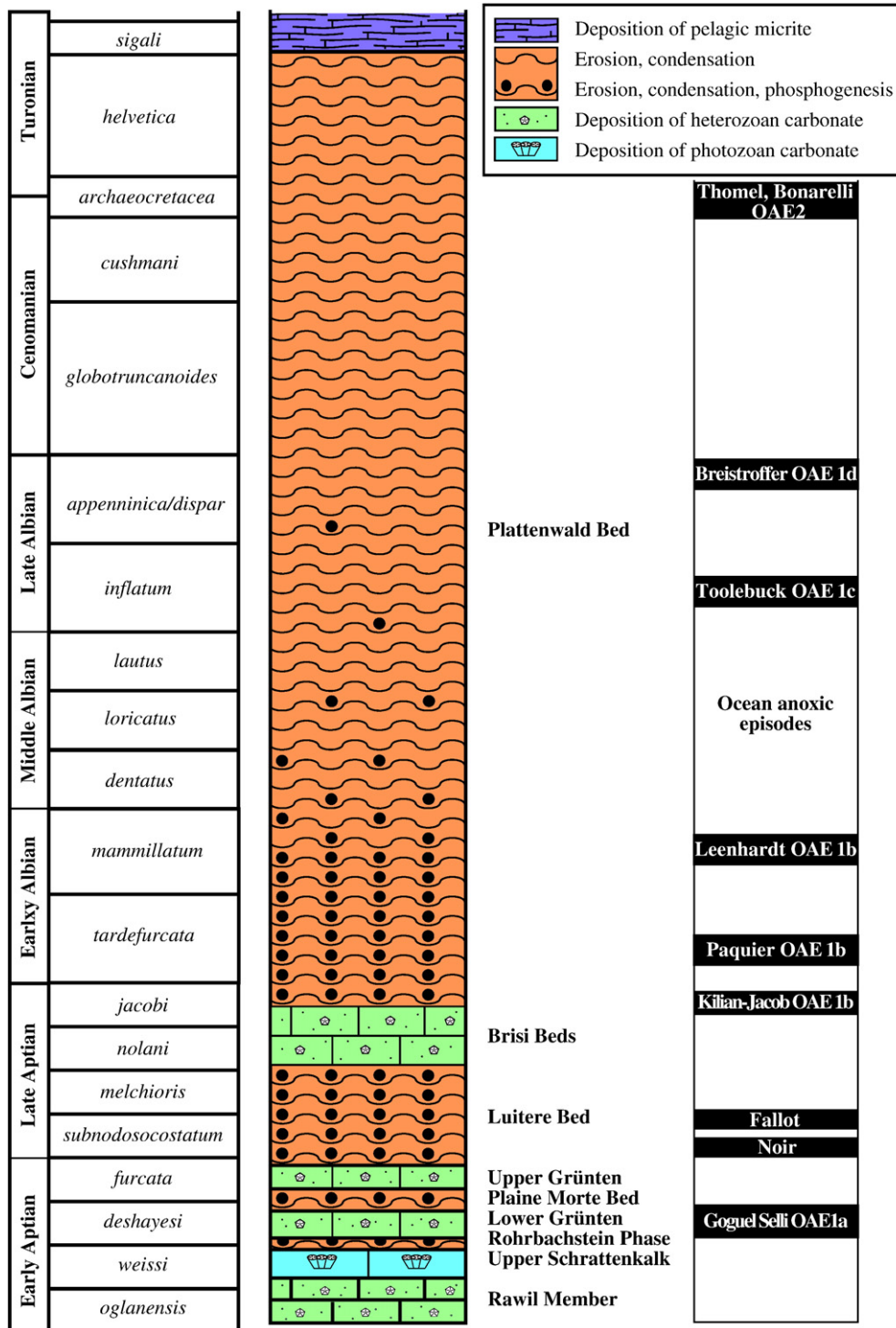


Fig. 13. Schematic time diagram showing the succession of sedimentary processes during the Aptian to the Turonian in the area of the Col de la Plaine Morte and their correlation to oceanic anoxic episodes.

## 5.2. Erosion, condensation and phosphogenesis

### 5.2.1. The Rohrbachstein phase

The stepwise-drowning phases of the Urganian 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 Urganian Schratenkalk Formation, leading to local incisions of up to several meters depth, which accommodated the main sedimentary volume of the subsequent Grüntes Member (Fig. 14). The eroded

surface of the Urganian Schratenkalk 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

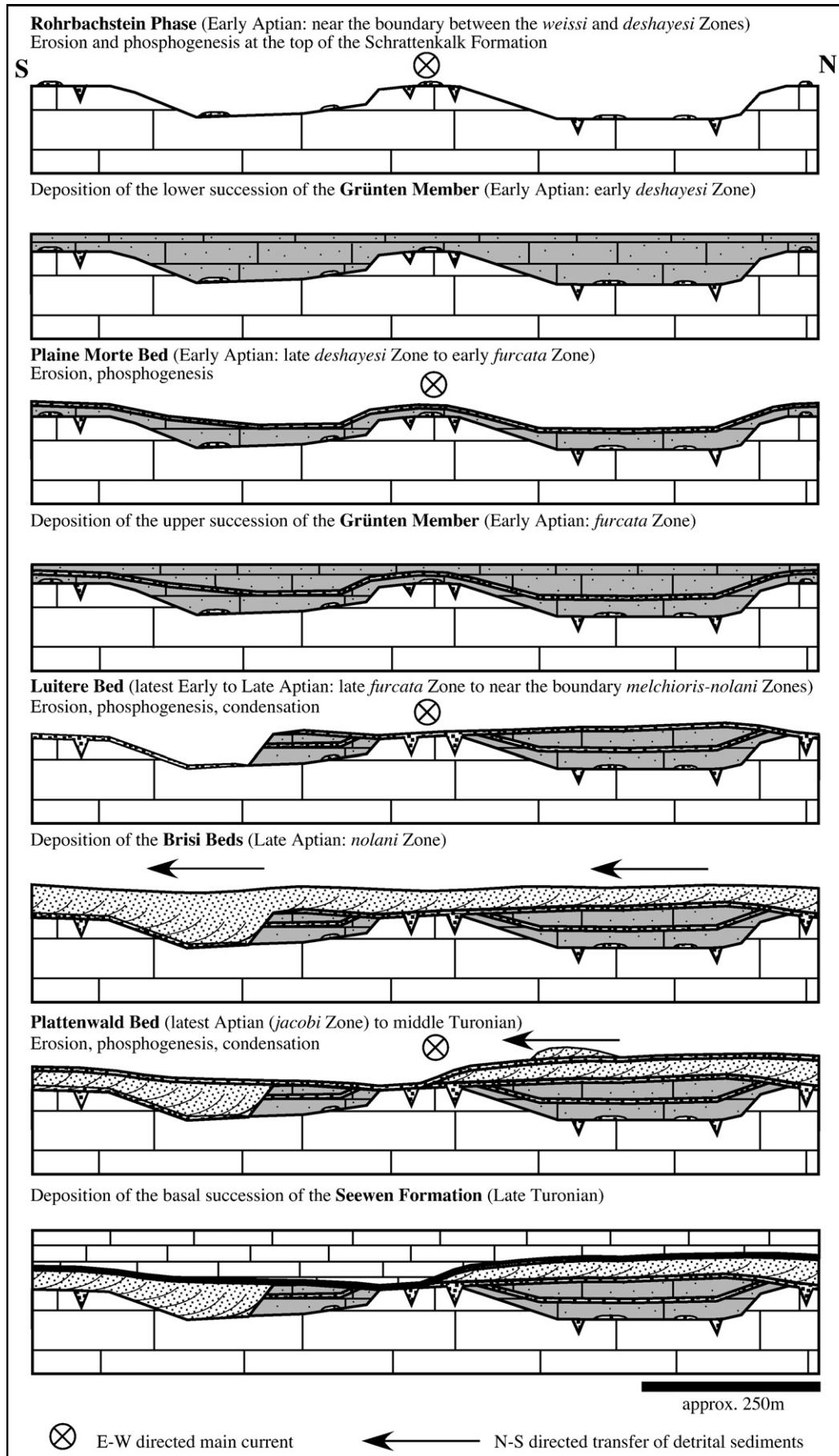


Fig. 14. Sequence of time frames in which the deposition of different sediments of the Garschella Formation in the area of the Col de la Plaine Morte is reconstructed (after Gainon, 2001).

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 Schrattekalk for several 10's of cm. The bed itself includes up to cobble-sized fragments of reworked sediments of the Grünten Member and Schrattekalk 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 envelop spanning 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 biostratigraphic 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 Seewen 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 installed on the outer margin of the drowned platform. In distal areas of the drowned Urganian carbonate platform, stromatolites are well known from Cenomanian sediments and are documented from eastern France (Delamette, 1981, 1988), from eastern Switzerland (Churfürsten region; Ouweland, 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 Urganian 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 Urganian 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 Urganian 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 Urganian platform in the context of paleoenvironmental change

Initial drowning of the Urganian 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 (Bernaus et al., 2003). In the Monts de Vaucluse, S France, the Urganian 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; Hillgärtner et al., 2003; Immenhauser 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  $\delta^{13}\text{C}$  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 led to the widespread disappearance of Urganian-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 Urganian carbonate platform. They also document the subsequent phase of prolonged condensation, followed by pelagic sedimentation on top of the drowned Urganian platform.

A first drowning phase associated with important erosion and local phosphogenesis, which terminated photozoan carbonate production on top of the Urganian 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 Urganian 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  $\delta^{13}\text{C}$ -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 (Noir 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. Thereby, the platform appeared to have registered environmental change in a more rapid and sensible way than the sediments in the adjacent basin.

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