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Record of a dense succession of drowning phases in the Alpstein mountains, north-eastern Switzerland: part I—the Lower Cretaceous Tierwis Formation (latest Hauterivian to latest Barremian)

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Abstract

In the Alpstein massif of north-eastern Switzerland, a complete succession of uppermost Hauterivian to uppermost Barremian condensed hemipelagic sediments crops out. This succession is known as Tierwis Formation, comprising in ascending order, the Altmann and Drusberg members. The sedimentary succession bears a number of fossiliferous glauconite- or phosphate-rich beds. A large number of newly discovered ammonites from these key beds and from several poorly explored levels of the Tierwis Formation allows for a new age calibration. The new dating as well as revised sequence stratigraphic interpretations and geochemistry contribute to a better understanding of the lithostratigraphic complexity of the Tierwis Formation and its spatio-temporal relationship with the Schrattenkalk Formation. The new lithostratigraphic observations, backed by ammonites, shows that the Altmann type-section and the Tierwis paratype-section do not cover the same stratigraphic interval because of dynamic sedimentation processes as erosion and sedimentation in submarine channels. We suggest that a phosphatic conglomerate in the Dursberg Member of middle late Barremian age corresponds to the Chopf Bed, which we recognised for the first time in the Alsptein massif. The Drusberg Member strongly thickens toward the southeast and progressively covers an upward extended stratigraphic range. Furthermore, the new dating of the key-surfaces and beds highlight a dense succession of drowning phases which occurred through the latest Hauterivian to late Barremian time interval. The latest Hauterivian onset of the glauconite-rich sedimentation of the Altmann Member is associated with a first major drowning phase, followed by the Faraoni oceanic anoxic event. The change of sedimentation to a rhythmic marl-limestone alternation of the Drusberg Member takes place over a polyzonal phosphatic conglomerate. This conglomerate coincides with a second major drowning phase and the onset of the Mid-Barremian Event, which is calibrated on the Tethyan ammonite biozonation.

Keywords: Helvetic Domain, Säntis nappe, Biostratigraphy, Sedimentology, Hauterivian, Barremian

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1 Introduction

The Tierwis Formation in the Alpstein massif is a reference area for the upper Hauterivian and Barremian sedimentary succession in the Helvetic Domain because of the quality of its extended sections and its richness in ammonite fossils. However, the previous dating and sequence stratigraphic interpretations of the Tierwis

Formation often did not come to an agreement due to an inhomogeneous distribution of biomarkers (e.g., Bodin et al., 2006b; Bonvallet et al., 2019; Clavel et al., 2014; Godet et al., 2013). This situation led to contradictory hypotheses regarding the onset of the Schrattenkalk shallow-water carbonate platform as well as doubtful small- and large-scale correlations of drowning surfaces and controversial interpretations of palaeoceanographic and paleoenvironmental changes.

Drowning phases are regarded as a powerful tool for large-scale correlation if they are sufficiently well dated with biomarkers. Föllmi et al. (1994) and Weissert et al. (1998) postulated possible links between drowning phases, palaeoceanographic and/or paleoenvironmental change affecting carbonate factories. Furthermore, drowning phases are relatively contemporaneous to organic-rich mud deposits (black shales) in deeper marine environments, a typical feature of Oceanic Anoxic Events (OAE; Godet, 2013), which can also be used for stratigraphic correlations.

Shallow-water shelves such as the Helvetic platform are particularly sensitive to environmental and oceanographic change (Föllmi et al., 2006, 2007). The Tierwis Formation is interspersed with several key surfaces associated with authigenic mineral such as glauconites and phosphates and with ammonite fossils (Bodin et al., 2006b) that could be interpreted as the result of a succession of platform drowning phases. In the Helvetic Domain, drowning phases were particularly intense during the latest Hauterivian and early Barremian with sustained condensation, phosphogenesis and glauconite formation (Bodin et al., 2006b; Godet, 2013). Bodin et al. (2006b) and Föllmi et al. (2007) revised two main horizons of the Tierwis Formation. The first condensed horizon of latest Hauterivian age in the lower part of the Altmann Member is associated with the sedimentation of a lower phosphatic conglomerate and important glauconite deposits and reduced carbonate production. The second condensed horizon of late early Barremian age (Bodin et al., 2006b) is marked by an upper phosphatic conglomerate at the boundary between the Altmann and the Drusberg members. Briegel (1972) documented a third condensed horizon in the Drusberg Member, the Chopf Bed, a phosphatic conglomerate of middle late Barremian age. This bed has also been identified in Vorarlberg (Bollinger, 1988; Heim & Baumberger, 1933), eastern Switzerland (Bodin et al., 2006a; Briegel, 1972; Heim, 1910–1916; Lienert, 1965; Oberholzer, 1933; Wissler et al., 2003) and central Switzerland (Fichter, 1934; Staeger, 1944). The Chopf Bed was restudied in its type locality by Bodin et al. (2006a) and dated by ammonites to the latest part of the *T. vandenheckii* Zone and the younger part of the following *G. sartousiana* Zone. Based on sequence stratigraphic interpretations, Bodin et al. (2006a) presumed that the Chopf Bed stratigraphically corresponds to the transition between the Tierwis and the Schrattenkalk formations in the more proximal domain (Tierwis section, Säntis region). They attributed a maximum age to the installation of the Schrattenkalk carbonate platform in the proximal domain.

The present study presents a new high-resolution biostratigraphical and sedimentological model of the Tierwis Formation in the Alpstein massif. This model is discussed in terms of environmental change affecting the north-western Tethyan margin and the associated oceanic anoxic events and other organic rich muds occurring from the latest Hauterivian onward.

2 Geographical and geological setting

The Alpstein massif, situated in north-eastern Switzerland, is shared by the cantons of Appenzell Ausserrhoden, Appenzell Innerrhoden, and St. Gallen. These mountains are famous in Switzerland due to their excellently exposed Cretaceous deposits (Eugster et al., 1982; Heim, 1905; Kempf, 1966; Schlatter, 1941; Wohlwend et al., 2015). This massif is part of the Säntis nappe, which belongs to the Helvetic nappe system (Fig. 1A), thrusted and folded in a north-western direction during the Alpine orogenesis in the course of the collision between the European and the Adriatic plates. The Säntis nappe is detached from its Jurassic substratum along the Säntis Thrust (Pfiffner, 1981). It is composed of a sequence of Cretaceous to Paleogene calcareous formations (Sala et al., 2014; Trümpy, 1980). The upper Lower Cretaceous record presents a well exposed and developed uppermost Hauterivian to uppermost Barremian sedimentary succession composed of a shallow-water carbonate platform sedimentary series referred to the Schrattenkalk Formation (Heim, 1905), prograding on hemipelagic slope deposits of the Tierwis Formation (Fig. 1; Föllmi et al., 2007).

The hemipelagic deposits have captured the attention of geologists for a long time (e.g., Bollinger, 1988; Burckhardt, 1896; Escher von der Linth, 1878; Fichter, 1934; Föllmi et al., 2007; Funk, 1969, 1971; Heim & Baumberger, 1933; Jost-Stauffer, 1993; Kaufmann, 1867; Schenk, 1992; Staeger, 1944; Studer, 1834). The Tierwis Formation includes the Altmann Member at its base, which was originally described by Escher von der Linth in Kaufmann (1867) at the type locality of Altmannsattel (Altmann, Fig. 1) in the Alpstein massif. These layers occurr between the underlying Helvetischer Kieselkalk Formation and the overlying Drusberg Member. They are characterized by thin and highly condensed series of glauconite- and/or phosphate-rich sandstones and marlstones, famous for the diverse ammonite fauna.

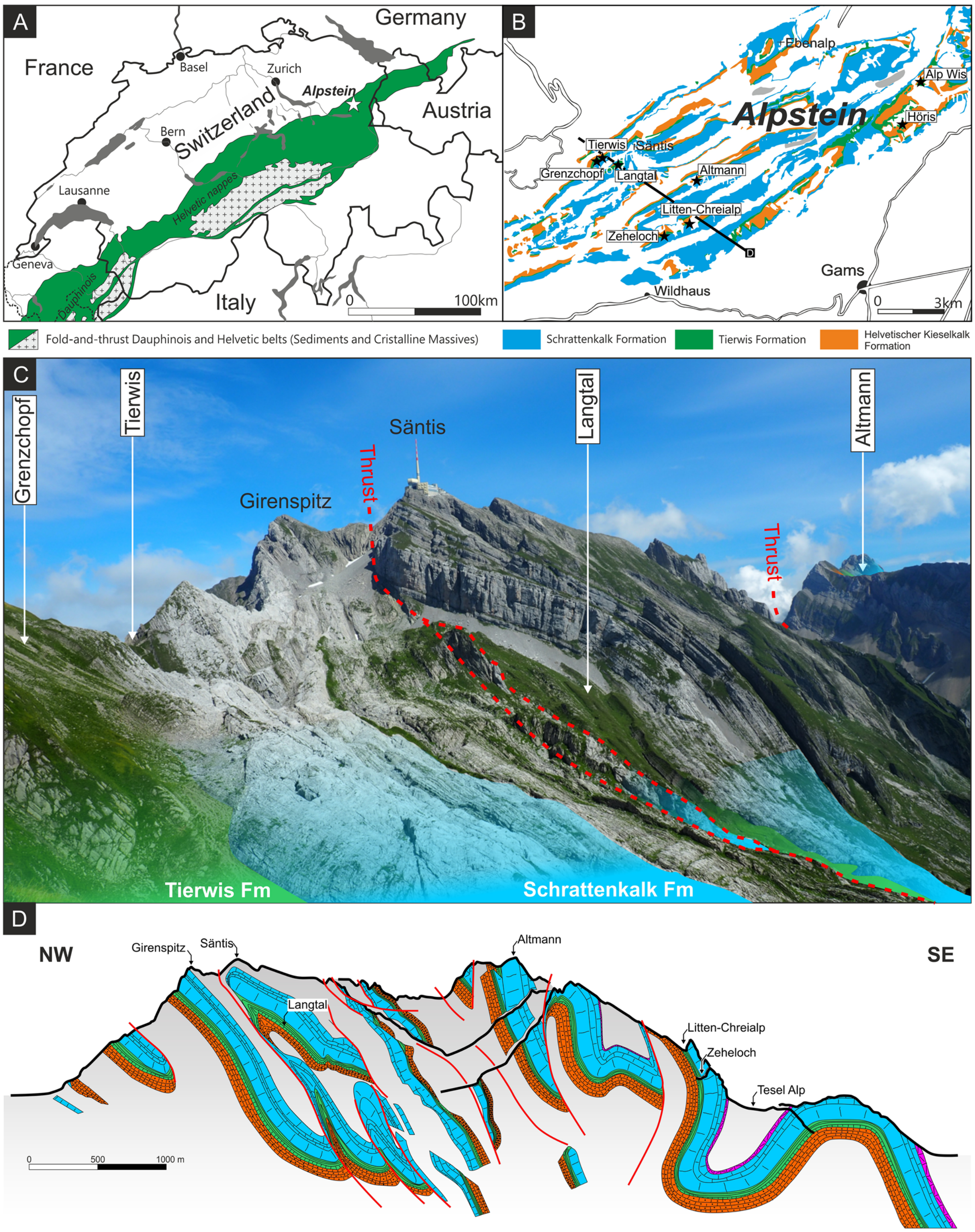

Fig. 1 **A** Location of the Alpstein massif on the Helvetic realm, simplified from Bodin et al. (2006a). **B** Simplified geological map with the location of the studied outcrops (modified after Eugster et al., 1982) with position of the cross-section illustrated at point D. **C** View of the Säntis part of the Alpstein massif with the position of some outcrops and the main thrusting faults. **D** Geological cross-section of the Alpstein massif modified after Kempf (1966)

The Drusberg Member, composing the upper part of the Tierwis Formation, was not defined in the Alpstein massif but in the Kar southeast of the Drusberg (Canton of Schwyz; Hantke, 1966) by Mayer-Eymar (1867). The boundary between the Altmann Member and the Drusberg Member is classically defined by the disappearance of glauconite grains, a key-mineral of the Altmann Member below (Fichter, 1934; Funk, 1969, 1971; Heim, 1905). The Drusberg Member consists of an up to 350 m-thick rhythmic marlstone-limestone alternation. These deposits represent the hemipelagic facies counterpart to the neritic Schrattenkalk carbonate platform (Studer, 1834), which prograded over time over the hemipelagic Drusberg Member. Both sedimentary units are thus closely related in term of space and time. The lateral and upward transition from the Drusberg Member to the Schrattenkalk Formation occurs in general gradually, which makes it difficult to delimit, especially because platform bioclastic flows are common inside the hemipelagic series (Bollinger, 1988; Schenk, 1992). Rare glauconite-bearing beds are reported inside the Drusberg Member by Merhardt (1926), Heim and Baumberger (1933), Fichter (1934), Staeger (1944), Bentz (1948) Briegel (1972) and Bodin et al. (2006a). One of them, the Chopf Bed, was introduced by Briegel (1972) in the Alvier area, 15 km southeast of the Alpstein massif. This glauconite- and phosphate-rich bed is situated in the middle part of the Drusberg series, representing more distal slope environments (e.g., Bodin et al., 2006a; Bollinger, 1988). So far, ammonite discoveries in the Drusberg Member have been exceptional and mostly related to the glauconite-bearing beds (Bodin et al., 2006a, 2006b; Briegel, 1972; Burckhardt, 1896; Heim & Baumberger, 1933; Staeger, 1944; Tobler, 1899).

Both Altmann Member and Drusberg Member were reunited by Funk (1969) in the marly Drusberg Formation. In order to avoid any confusion between the Drusberg Formation and the Drusberg Member, Föllmi et al. (2007) proposed to rename it to Tierwis Formation referring to the new type locality of Tierwis, situated in the western part of the Alpstein massif. The Alpstein massif therefore appears as a reference zone for the study of the Tierwis Formation.

3 Materials and methods

We carried out a sedimentological and palaeontological field study based on a large number of ammonite (> 200 specimens) collected from the Tierwis, Langtal, Altmann (Fig. 1C), and Litten-Chreialp outcrops. Some of these specimens were described and/or figured in Bodin et al. (2006b), Tajika et al. (2017) and in Kürsteiner and Klug (2018). The ammonite sampling from the Tierwis Formation was extended to outcrops at Alp Wis and Frümsner Alp in the south-eastern range of the Alpstein massif. The systematic study of the sampled ammonite taxa is going to be published separately (Pictet et al., in prep.). The ammonite biozonation used in this work (Fig. 2) is based on the zonal scheme of the Tethyan Realm proposed at the 6th International Meeting of the IUGS Lower Cretaceous "Kilian Group" (Reboulet et al., 2018).

Geochemical measurements used here were performed by Bonvallet (2015) and Bonvallet et al. (2019). 83 samples from the sections of Tierwis, ranging from the top of the Helvetischer Kieselkalk Formation to the base of the Schrattenkalk Formation are presented herein. Carbon and oxygen stable isotope data are also documented by Wissler (2001). We used the carbon-isotope segments B1 to A1 (negative, stable or positive trend), that correspond to the nomenclature of Wissler (2001) and Wissler et al., (2002, 2003) for the Barremian stage. We split the segment B1 into two subsegments B1a and B1b, and used Hy and Hz for the two uppermost Hauterivian segments while waiting for a formal nomenclature of the corresponding intervals of the carbon-isotope curve.

Discontinuity surfaces are indicated on the lithological logs and figures and are numbered from D1 to D14. These surfaces were correlated with the sequence stratigraphic scheme of Arnaud (2005), derived from the Barremian stratotype of Angles (SE France). However, an additional key surface is recognized at the boundary between the *T. vandenheckii* and the *G. sartousiana* zones (Fig. 2; see Pictet, 2021). We interpret this surface as a sequence boundary, labelled SB B3'. The sequence stratigraphic interpretation is given on the right side of the lithological logs.

The definition of the boundary between the Altmann Member and the Drusberg Member is currently based on the presence of glauconite and/or the relative importance of marly interbeds. This definition is questionable from a cartographic point of view because it ignores the main facies boundary. In our study, we use the "upper phosphatic conglomerate" as a marker bed for the top of the Altmann Member in the Alpstein massif. This is better adapted to field work and mapping (see "Discussion" chapter).

4 The key sections

The sections at Tierwis, Langtal, Altmann, and Litten-Chreialp are described following a northwest–southeast platform-to-basin transect.

4.1 The Tierwis section

The Tierwis outcrops on the north-western side of Grauchopf (Fig. 3) were first described by Kempf (1966). Funk (1969) logged and described a section situated 150 m southwest of Tierwis-Hütte, which he chose as

	STAGE		ZONE	SUBZONE
TETHYAN PROVINCE	BARREMIAN	UPPER	*Martelites sarasini*	*Pseudocrioceras waagenoides*
				Martelites sarasini
			Imerites giraudi	*Heteroceras emerici*
				Imerites giraudi
			Gerhardtia sartousiana	*Hemihoplites feraudianus*
				Gerhardtia provincialis
				Gerhardtia sartousiana
			Toxancyloceras vandenheckii	*Gassendiceras alpinum*
				Toxancyloceras vandenheckii
		LOWER	*Moutoniceras moutonianum*	
			Kotetishvilia compressissima	*Holcodiscus caillaudianus*
				Holcodiscus fallax
			Nicklesia pulchella	
			Kotetishvilia nicklesi	
			Taveraidiscus hugii	*Psilotissotia colombiana*
				Taveraidiscus hugii
	HAUTERIVIAN *p. p.*	UPPER	*Pseudothurmannia ohmi*	*Pseudothurmannia picteti*
				Pseudothurmannia catulloi
				Pseudothurmannia ohmi
			Balearites balearis	*Spathicrioceras seitzi*
				Crioceratites krenkeli
				Binelliceras binelli
				Balearites balearis

Fig. 2 The standard Mediterranean ammonite zonation of the upper Hauterivian *pro parte* and of the Barremian stages (Reboulet et al., 2018)

paratype section of the Altmann Member (Coordinates 2742′970/1234′730/2035 system CH1903+/LV95; Figs. 4 and 5). Lienert (1965) briefly documented the Schrattenkalk Formation. Wissler (2001) took a lithological log of the Tierwis and Schrattenkalk formations and carried out the first carbon and oxygen stable isotopes analyses of this section. Föllmi et al. (2007) proposed this section as type section of the Tierwis Formation in replacement of the Drusberg Formation. The section was relogged and newly described in detail by Bodin et al. (2006b), who measured a total thickness of 56 m for the Tierwis Formation. The Tierwis Formation was later resampled by Bonvallet (2015) for a high-resolution carbon and oxygen stable isotope analyses. A recent log of Tajika et al. (2017) focused more on the paleontological aspects of the section.

The section begins at the top of the Helvetischer Kieselkalk Formation, which consists of a succession of dark grey to reddish, siliceous sandy echinodermic limestone (Funk, 1969, 1971; Kaufmann, 1867). The occurrence of channel structures and tempestites (Föllmi et al., 2007) attests to a highly dynamic shallow-water depositional environment facing the open sea. The top of the Helvetischer Kieselkalk Formation is marked by an erosive discontinuity surface termed D1 (regarding the numbering of discontinuity surfaces, see Figs. 5 and 9).

The overlying Tierwis Formation begins with the Altmann Member, an approximately 31 m-thick hemipelagic heterozoan succession composed of sandy, clayey carbonates and limestones (="Cephalopods green sands" or "*Crioceras* beds"; Heim, 1905; Fig. 4C). Bodin et al. (2006b) introduced several subunits, which we list from bottom to top:

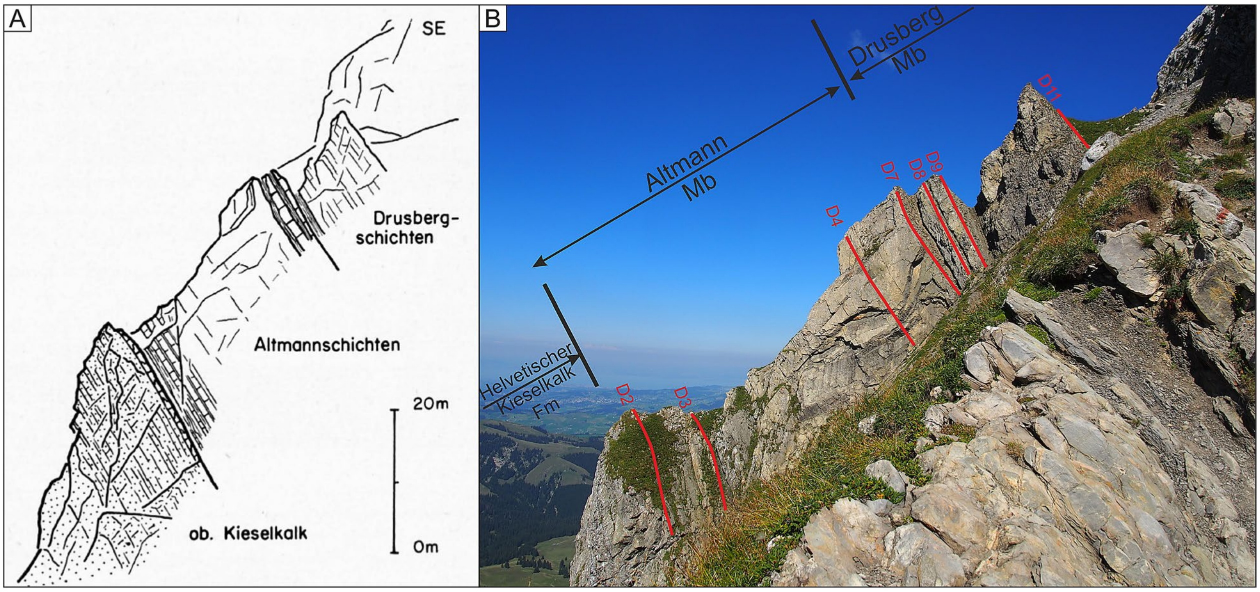

Fig. 3 **A** Illustration of the Tierwis profile (Kempf, 1966) situated on the north-western side of Grauchopf (Coordinates 2743′218/1234′893/2040). **B** Photograph of the same section, on which the main lithostratigraphic units and the discontinuity surfaces are marked

(1) On the eroded surface of the Helvetischer Kieselkalk Formation, a 4 m-thick, coarse-grained echinodermic limestone was deposited, which was first attributed to the Kieselkalk Formation by Funk (1969). This unit is composed of a monomictic conglomerate made of pluridecimetric pebbles. The clasts are composed of a fine-grained glauconitic crinoidal-bryozoan limestone coated in a brown matrix. At its top, the unit shows a strongly bioturbated horizon with ferric concretions and glauconitic crusts (D2, Funk, 1969). A first and discrete phosphatic conglomerate is observed at this surface;

(2) A green, glauconitic, crinoidal limestone-dominated succession (approx. 24 m-thick) is composed of three sedimentological units. The lower unit is characterized by an ammonite-bearing clayey carbonate (Bodin et al., 2006b; Funk, 1969; Wissler, 2001). We found two glauconite- and ammonite-rich intervals, at 2 and 5 m respectively above the base of this lower unit (Fig. 4C). The first glauconitic bed corresponds to the lower fossiliferous horizon of Funk (1971). Kempf (1966) and Funk (1971) found some ammonites identified as *Pseudothurmannia "angulicostata"* (d'Orbigny, 1841) and *Pseudothurmannia* sp. Additional ammonite discoveries were made by Bodin et al (2006b). They documented an association composed of *Parathurmannia* sp., *Pseudothurmannia* sp. gr. *mortilleti* (Pictet & de Loriol, 1858), *Paraspiticeras* gr. *percevali* (Uhlig, 1883), and *Plesiospitidiscus* sp. Our own investigations added *Pseudothurmannia mortilleti* (Pictet & de Loriol, 1858), *P.* cf. *mortilleti* (Pictet & de Loriol, 1858), *Plesiospitidiscus communis* Busnardo, 2003 and *Hamulina* aff. *meyrati* (Ooster, 1860). The newly collected material as well as our reinvestigation of previously reported fossils allow the stratigraphic assignment to the *B. catulloi* Subzone. The second glauconitic interval overlies a strongly bioturbated surface (discontinuity surface D3) encrusted by ferric crusts. We found *Emericiceras koechlini* (Astier, 1851) and *E. emerici* (Léveillé, 1837) in this level, from which no ammonites were reported previously. This suggests the earlier Barremian *Taveraidiscus hugii* Zone. The middle unit is a glauconitic, crinoidal, thickening-upward limestone succession (approx. 15 m-thick), capped by a

(See figure on next page.)
Fig. 4 **A.** Locality map of the Tierwis section and photographs of Tierwis Hütte (**B**) and Tierwis-Grenzchopf (**C**–**F**) outcrops. **B** View of the Tierwis Hütte outcrops with the incriminated formations. **C** View of the Tierwis-Grenzchopf outcrop with the incriminated formations and main beds. **D** Polyphased hardground at the boundary between the Altmann Member and the Drusberg Member (D7). **E** Firmground with bored pebbles in the lower part of the Drusberg Member (D8). **F** Oyster-rich firmground at the boundary between the carbonate-dominated succession and the marly interval composing the Drusberg Member

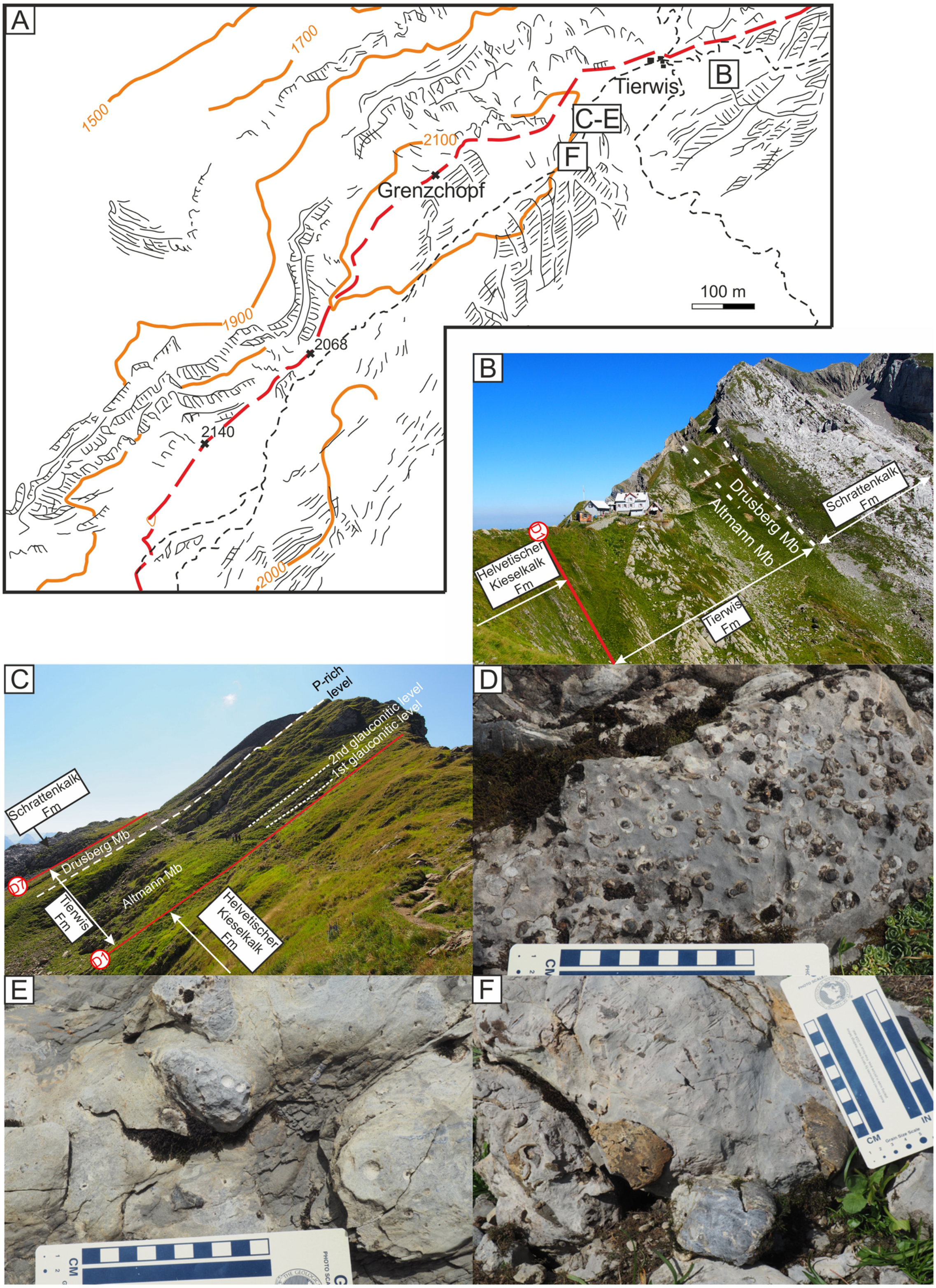

Fig. 4 (See legend on previous page.)

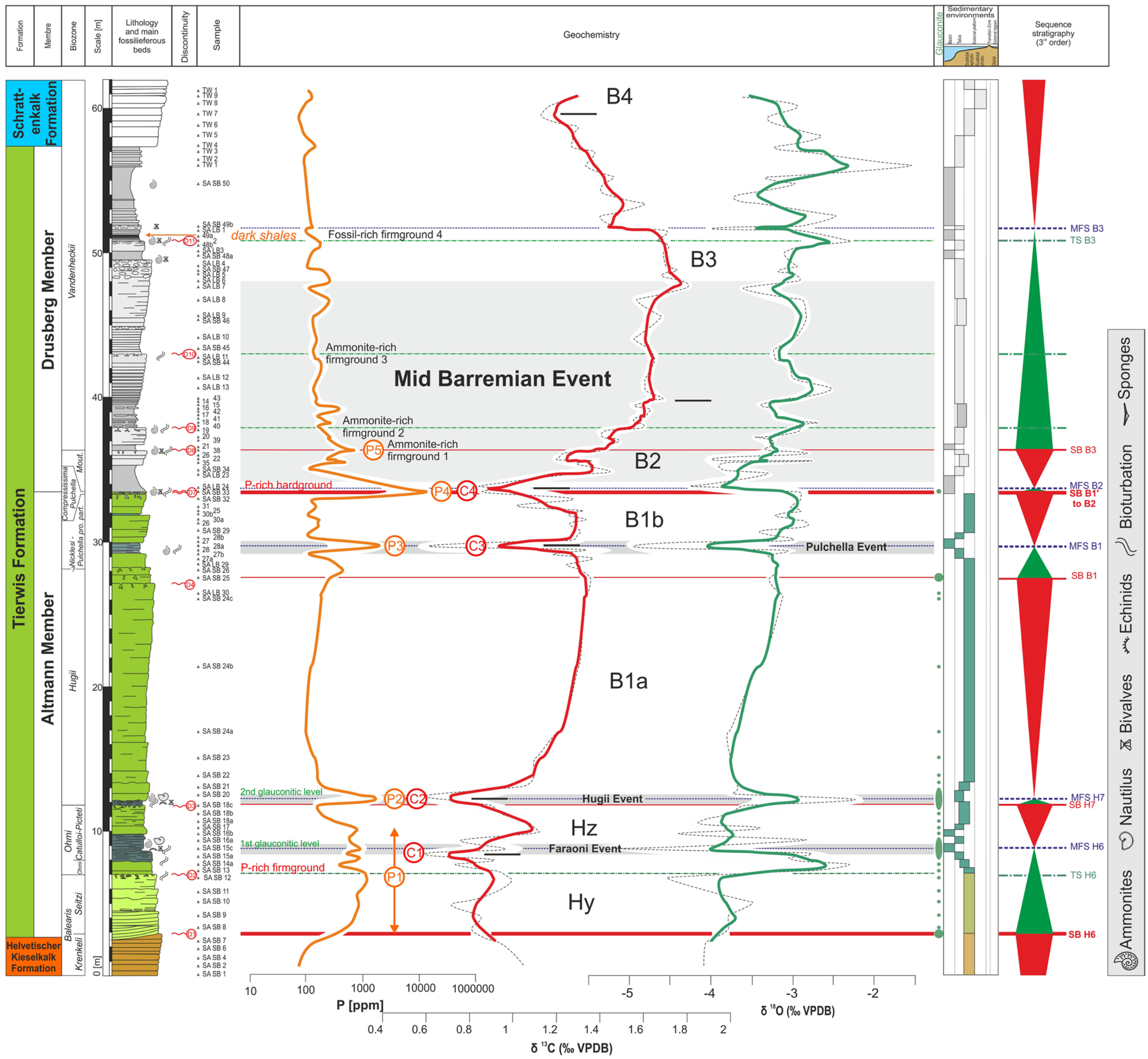

Fig. 5 Tierwis section. Lithological log modified after Bodin et al. (2006b) with main fossil-bearing levels, discontinuities, microfacies, and sequence stratigraphic interpretation. Sequence boundaries (SB) are indicated by bold red lines, transgressive surfaces (TS) by dash–dot green lines, and maximum flooding surfaces (MFS) by dashed blue lines. The phosphorus curve is taken from Bonvallet (2015) and Bonvallet et al. (2019). Sample positions and carbon and oxygen isotopes curves are form Bodin et al. (2006b), Bonvallet (2015), Bonvallet et al. (2019) and Godet et al. (2013). Carbon-isotopic segments B1 to A1 reported on the δ13C curve are labelled after the nomenclature of Wissler (2001), and Wissler et al. (2002, 2003). We split the segment B1 in two subsegments B1a and B1b, and temporary named the two uppermost Hauterivian segments as Hy and Hz

layer full of *Thalassinoides*, *Ophiomorpha* and *Skolithos* burrows (discontinuity surface D4). The upper unit is a 6 metres-thick, glauconitic, clayey crinoidal limestone. The first metre presents a *Cruziana—Glossifungites* ichnofacies (Bodin et al., 2006b). The top of the upper unit is capped by a hardground. This unit yielded a single specimen of *Montanesiceras karakaschi* (Simionescu, 1898) at Grenzchopf and some very large specimens of *Honnoratia thiollierei* (Astier, 1851), *Torcapella fabrei* (Torcapel, 1884), and *Montanesiceras* cf. *tshuprenense* (Dimitrova, 1967) in the nearby Langtal section (Coordinates 2743′666/1234′442 to 2743′177/1234′204). Even if this faunal association is less characteristic, it points to the *Kotetishvilia nicklesi* and/or *Nicklesia pulchella* zones.

Atop of the unit, the hardground contains two generations of borings (Fig. 4D). The first generation is filled by glauconitic limestone (D5) and the second generation by black phosphate (D7). The younger one is sealed with a second phosphatic conglomerate. This layer corresponds with the "Altmann–Fossilschicht" of Kempf (1966), the "upper fossiliferous horizon" of Funk (1971), the bed 24 from Funk (1969) and the bed Sa 33 from Bodin et al. (2006b). This "upper phosphatic conglomerate" is used in our study as marker bed of the upper boundary of the Altmann Member in the Alpstein region (see "Methods" and "Discussion" chapters). It contains numerous macrofossils such as ammonites, oysters, sponges, belemnites and encrusting organisms, as well as phosphate-coated clasts. Bodin et al (2006b) documented few ammonites from this level [*Emericiceras* sp. and *Torcapella* gr. *davydovi* (Trautschold, 1886)]. This faunal assemblage is characteristic for the *Nicklesia pulchella* and *Kotetishvilia compressissima* zones.

The Drusberg Member consists of an approximately 24 m-thick marlstone-limestone alternation, whose microfacies consists of peloids, benthic foraminifera, sponge spicules, fragments of crinoids and bivalves (Bodin et al., 2006b). The Drusberg Member can be subdivided into the following subunits:

(1) A 3 m-thick interval composed of marlstones which grades upward to a limestone bed. This bed is capped by a strongly bioturbated surface, associated with reworked limestones pebbles, which are bored and coated with phosphate crusts (firmground 1 on Figs. 4E and 5; discontinuity surface D8). Numerous ammonites are exposed on this surface, occasionally partially coated with phosphate. Additional ammonites were collected in the paratype-section and in adjacent outcrops located between Tierwis and Grenzchopf. We collected in the first decimetre of the unit *Moutoniceras nodosum* (d'Orbigny, 1850). From the top of the firmground 1, Bodin et al. (2006b) collected *Subtorcapella* sp. Additionally, we discovered *Barremites* cf. *difficilis* (d'Orbigny, 1841), *Barremitites strettostoma* (Uhlig, 1883), *Torcapella "falcata"* Busnardo, 1970, *T.* aff. *suessiformis* Busnardo, 1970, *T. capillosa* Busnardo, 1970, *T.* sp., *Melchiorites rumanus* (Kilian, 1910), *Melchiorites fallaciosus* (Kilian, 1910), *M.* sp., and *Moutoniceras moutonianum* (d'Orbigny, 1850). This faunal assemblage indicates the *Kotetishvilia compressissima* and the *Moutoniceras moutonianum* zones;

(2) A 2 m-thick interval beginning with a 0.2 m-thick, clayey limestone bed rich in shark teeth, followed by a few decimetres of marlstone grading upward into an alternating marlstone-limestone bundle. The top surface is a bioturbated firmground (firmground 2 on Fig. 5; discontinuity surface D9), which yielded *Barremitites strettostoma* (Uhlig, 1883), *Puezalpella haugi* Breskovski, 1966 and *Torcapella* sp. nov.;

(3) A 1.5 m-thick marly interval [base of the Drusberg Member sensu Funk (1969) and Bodin et al. (2006b)] grading upward to a 3.5 m thickening-upward limestone-marlstone alternation. This alternation is capped by the bioturbated firmground 3 (see Fig. 5; discontinuity surface D10), which delivered *Torcapella* sp. aff. *falcata* Busnardo, 1970, *Torcapella* sp. nov., *Barremitites strettostoma* (Uhlig, 1883), and *Toxancyloceras* sp. aff. *ebboi* Delanoy, 2003. This last genus indicates the upper Barremian *Toxancyloceras vandenheckii* Zone;

(4) A 6.5 m-thick sedimentary package composed of: (i) a 2 m-thick limestone-marlstone alternation with layers of densely-packed oysters (*Exogyra*) in its upper third, grading upward into; (ii) a 4.5 m-thick grey, nodular limestone; (iii) a 0.8 m-thick marly intercalation; and (iv) a second oyster-rich bed. This bed ends with a fossiliferous firmground 4 (see Fig. 5; discontinuity surface D11) covered with belemnites, nautilids, and scarce ammonites such as *Torcapella* sp. nov. (Langtal section) and *Barremitites strettostoma* (Uhlig, 1883);

(5) A 6.5 m-thick marly interval composed of: (i) few decimetres of dark grey shales; (ii) a thinning-upward marlstone-limestone alternation including a layer of densely packed oysters at its base (*Exogyra*; Fig. 4F); (iii) a 2.5 m-thick marl; and (iv) 1.2 m-thick, thickening-upward, marlstone-limestone alternation.

The marlstone-limestone alternation of the Drusberg Member progressively grades upward into the light grey carbonates of the Schrattenkalk Formation (Fig. 4B).

The phosphorus content (P, orange line in Fig. 5) of the Tierwis Formation was measured by Bonvallet (2015). She revealed that the highest values are recorded in the Altmann Member and in the first metres of the Drusberg Member. The phosphorus record shows a stable background signal around 100 ppm. Five levels or intervals of enrichment occur (P1 to P5, Fig. 5). These phosphorus enrichments are situated in the condensed beds or intervals, with phosphorus values reaching up to 11700 ppm. Peak P1 (1000 ppm) is situated in the lowermost part of the section and differs from the other phosphorus peaks by its thickness, corresponding to a larger sedimentary interval (subunit 1 plus first glauconite-rich level). Peak P2 (1700 ppm) coincides with the second glauconite-rich level. Peak P3 (1815 ppm) is measured in the more marly bioturbated level in the upper fourth of the Altmann Member. Peak P4 with a maximum enrichment of 11700 ppm corresponds to the upper phosphatic conglomerate. Peak P5 (657 ppm) is situated within the firmground 1 in the lowermost part of the Drusberg Member.

Stable carbon isotope values measured by Bonvallet (2015) show strong fluctuations in the Altmann Member with values ranging from + 0.5 to + 1.5‰, while the Drusberg Member records a positive excursion followed by a decrease in $\delta^{13}C$ values (Fig. 5). We divide the isotope curve into seven segments termed Hy to B4 (see chapter "Material and methods" for more information). The lack of statistically significant correlation between $\delta^{13}C$ and $\delta^{18}O$ values (covariance $R^2 = 0.11$; Bonvallet, 2015, pp. 87 and 89) for the sections of Tierwis excludes diagenetic modification of the primary carbonate C isotope signature.

4.2 The Langtal section

The Tierwis Formation of this section is not described in detail because it corresponds very closely to the Tierwis section. However, ammonites are more abundant in the uppermost layers of the Altmann Member (Fig. 6B), and especially in the upper phosphatic conglomerate at the top of the Altmann Member, which overlies the discontinuity surface D7 (Fig. 6A). The discontinuity surface present in this section looks more like a firmground than a hardground. Furthermore, the Drusberg Member seems to stratigraphically extend further upward than in the Tierwis section, passing progressively into the Schrattenkalk Formation (Fig. 6C).

4.3 The Altmann section

The Altmannsattel locality is known for over a century owing to its fossiliferous "Altmann horizon". The section was described for the first time by Escher von der Linth (1878). Funk (1969) chose the NE side of the Altmannsattel as a type-section of the Altmann Member (Coordinates 2746′510/1234′060/2180). We logged our stratigraphic section along the SW side (Fig. 7B), which is more complete and similar to the section described by Kempf (1966) on the Altmannsattel ridge. Although the Altmannsattel ridge is affected by a fault (Funk, 1969), this is not the case at our section. The section begins at the top of the Helvetischer Kieselkalk Formation with a sharp discontinuity surface (D1, Coordinates 2746′057/1233′809/2230, Figs. 8 and 9).

Above the Helvetischer Kieselkalk Formation, the Altmann Member of the Tierwis Formation begins with an approximately 14 m-thick hemipelagic heterozoan limestone and clayey limestone succession, composed from the bottom to the top of:

(1) A 0.4 m-thick sandy conglomeratic limestone bed of clast-supported, grey, echinodermic limestone pebbles in a brown sandy matrix covered by a first and discrete lower phosphatic conglomerate (D2), which yielded a small phosphatic mould of the ammonite *Pseudothurmannia* cf. *pseudomalbosi* (Sarasin & Schöndelmayer, 1901). This ammonite indicates the *Pseudothurmannia catulloi* Subzone;
(2) A 5 m-thick, green, glauconite-rich echinodermic limestone unit with chert intercalations. At the base of this succession, the ammonite *Pseudothurmannia mortilleti* (Pictet & De Loriol, 1858) was documented, which indicates the *Pseudothurmannia catulloi* Subzone. The top surface presents a slightly bioturbated firmground (D5);
(3) A 4.5 m-thick, grey unit composed of a 1 m-thick fine marlstone grading upward to a 3.5 m-thick bioclastic clayey limestone with abundant debris of oysters and crinoids mixed with large sponges (Fig. 7D). The top surface represents a slightly bioturbated firmground (D6). This unit pinches out near the ridge of Altmannsattel (Fig. 8);
(4) A 3 m-thick, grey marlstone-limestone alternation similar to that of the Drusberg Member (Fig. 7E; "Drusberg-like" unit in Figs. 8, 10, 11, 12). Its top presents a strongly bioturbated, burrowed, and bored firm- to hardground surface D7 (Fig. 7F). The bioturbations are filled by a green, glauconite-rich, echinodermic limestone, while the bedding plane is coated by dark iron and phosphate crusts. Above this unit, two dark grey, decimetre-thick, glauconitic beds are deposited, which compose the upper phosphatic conglomerates, very rich in sponges, ammonites, and belemnites (Fig. 7G). Like previous researchers (e.g., Escher von der Linth, 1878; Funk, 1969; Kempf, 1966), we discovered a huge number of phosphatized ammonites in this conglomerate, which includes *Nicklesia pulchella* (d'Orbigny, 1841), *Kotetishvilia compressissima* (d'Orbigny, 1841), *Metahoplites fallax* (Coquand in Matheron, 1879), *H. caillaudianus* (d'Orbigny, 1850), *P. perezianum* (d'Orbigny, 1850), *H. decorus* Avram, 1995, *H.* cf. *uhligi* Karakasch, 1907, *H.* sp., *Avramidiscus seunesi* (Kilian, 1889), *A.* sp. aff. *fallacior* (Matheron, 1880), *Parasaynoceras tzankovi* (Avram, 1995), *P.* sp., *Beviadiscus astieriformis* (Sayn, 1890), *Barremites* sp., *Barremitites* sp. nov., *Torcapella* cf. *fabrei* (Torcapel, 1884), *T. davydovi* (Trautschold, 1886), *Subtorcapella* sp., *Montanesiceras karakaschi*

Fig. 6 **A** Overview of the Langtal outcrops and of the Gir cliff on which the main lithostratigraphic units and discontinuity surfaces are reported. **B** Focus on the giant heteromophic ammonite *Honnoratia thiollierei* (Astier, 1851) in the uppermost metre of the Altmann Member. **C** Focus on the progressive facies transition between the Drusberg Member and the Schrattenkalk Formation

(Simionescu, 1898), *M. sizarolsae* Vermeulen et al., 2014, *M.* sp., *Melchiorites* sp., *Leptoceratoides* cf. *heeri* (Ooster, 1860), *Hamulinites* sp., *Hamulina* sp., *Lazarina* aff. *lepinayi* Vermeulen et al., 2009, *Rugacrioceras dreloni* Vermeulen, 2007a, 2007b. This diverse faunal association indicates the *Nicklesia pulchella* Zone to the *Gassendiceras alpinum* Subzone.

The Drusberg Member, approximately 32 m-thick, begins above this phosphatic conglomerate with:

(1) An 8 m-thick, grey, monotonous marlstone-limestone alternation composed of decimetre-thick beds and inter-beds, topped by a 0.3 m-thick darker grey clayey interval (dark grey shales level) followed by a 1 m-thick nodular limestone unit. Rare ammonites as *Barremitites strettostoma* (Uhlig, 1883) and *Montanesiceras* sp. were found;
(2) A 7 m-thick, grey, marlstone-limestone alternation followed by a 2.5 m-thick limestone unit (S1);
(3) A 15 m-thick, grey, marl-dominated alternation;

The member progressively grades upward into the Schrattenkalk Formation.

4.4 The Litten-Chreialp section

The less well known but excellently exposed section of Litten-Chreialp was logged by Kempf (1966, Fig. 9). We worked on the eastern side of the Tristen Sattel (Figs. 10, 11, 12, Coordinates 2745′973/1232′325/1810), at which a sedimentary succession from the uppermost Helvetischer Kieselkalk Formation to the base of the Schrattenkalk Formation crops out. The top of the Helvetischer Kieselkalk Formation is deeply eroded, showing two superimposed erosional surfaces of several tens of metres in width (Fig. 10). The depressions are filled by sediments of the Altmann Member.

The Altmann Member with a thickness of about 20 m, consists of the following units in ascending order:

(1) An up to 10 m-thick, green, glauconite-rich echinodermic limestone (Fig. 11B and C). This channelised unit rapidly disappears laterally on the outcrop, within a dozen of metres (Fig. 10). It is notched by a second channel generation, which is cutting down locally into the Helvetischer Kieselkalk Formation. This erosive surface is marked by an inconspicuous bioturbated firmground (discontinuity surface D5);
(2) An up to 10 m-thick grey, marlstone-limestone alternation (Fig. 11C), which is similar to that found in the overlying Drusberg Member but differing by the presence of sparse glauconite grains and thicker beds. The basal first metre is extremely glauconitic, more calcareous and bioclastic (Fig. 11D). It yielded a rich fauna of brachiopods, belemnites, and large clubbed echinoid spines. The middle part of the unit is more marl-prone and delivers poorly preserved ammonites. It grades upward into clayey carbonates, then to sandy, glauconitic carbonates (Fig. 11E). We found ammonite fragments attributed to large *Honnoratia* sp. and *Acrioceras* sp. in the scree, which do not allow for their exact levelling. The top surface is a strongly bioturbated firmground (D7), coated by dark iron and phosphate crusts. The burrows are filled by a green, glauconitic, echinodermic limestone and/or by a phosphatic gravel originating from the overlying conglomerate (Fig. 11F). The conglomerate is extremely rich in sponges, belemnites and ammonites that include *Maurelidiscus* aff. *vandeckii* (d'Orbigny, 1850), *Avramidiscus fallacior* (Matheron, 1880), *Holcodiscus caillaudianus* (d'Orbigny, 1850), *Holcodiscus decorus* Avram, 1995, *Parasaynoceras tzankovi?* (Avram, 1995), *Arnaudiella schlumbergeri* (Nicklès, 1894), *Nicklesia pulchella* (d'Orbigny, 1841), *Montanesiceras* cf. *tschuprenense* (Dimitrova, 1967), *M. karakaschi* (Simionescu, 1898), *Barremites* sp., *Barremitites* sp. nov., *Rugacrioceras martinsi* (Reynès, 1876). This faunal association indicates a time interval ranging from the earliest Barremian to the *Gassendiceras alpinum* Subzone.

The Drusberg Member is represented by a 15–20 m-thick succession of three grey, thickening upward marlstone-limestone alternations. The last sequence grades upward to the Schrattenkalk Formation (Fig. 11G). The boundary is not clearly defined as the facies change is very gradual. A few ammonites were collected ex-situ in the Drusberg Member like *Dissimilites dissimilis* (d'Orbigny, 1842) and *Montanesiceras* sp, which indicate a time interval ranging from the *Kotetishvilia compressissima* Zone to the *Toxancyloceras vandenheckii* Zone without further details.

(See figure on next page.)
Fig. 7 **A** Locality map of the Altmann section and photographs of the Altmann area. **B** Altmannsattel with the Tierwis Formation on the left side (depression). **C** The Tierwis Formation on the opposite side of the coomb. **D** Focus on a sponge from the sponge-rich unit of the middle part of the Altmann Member. **E** Focus on the upper part of the Altmann section. **F** Focus on the firmground at the base of the upper phosphatic conglomerate. **G** Focus on the ammonite-bearing upper phosphatic conglomerate

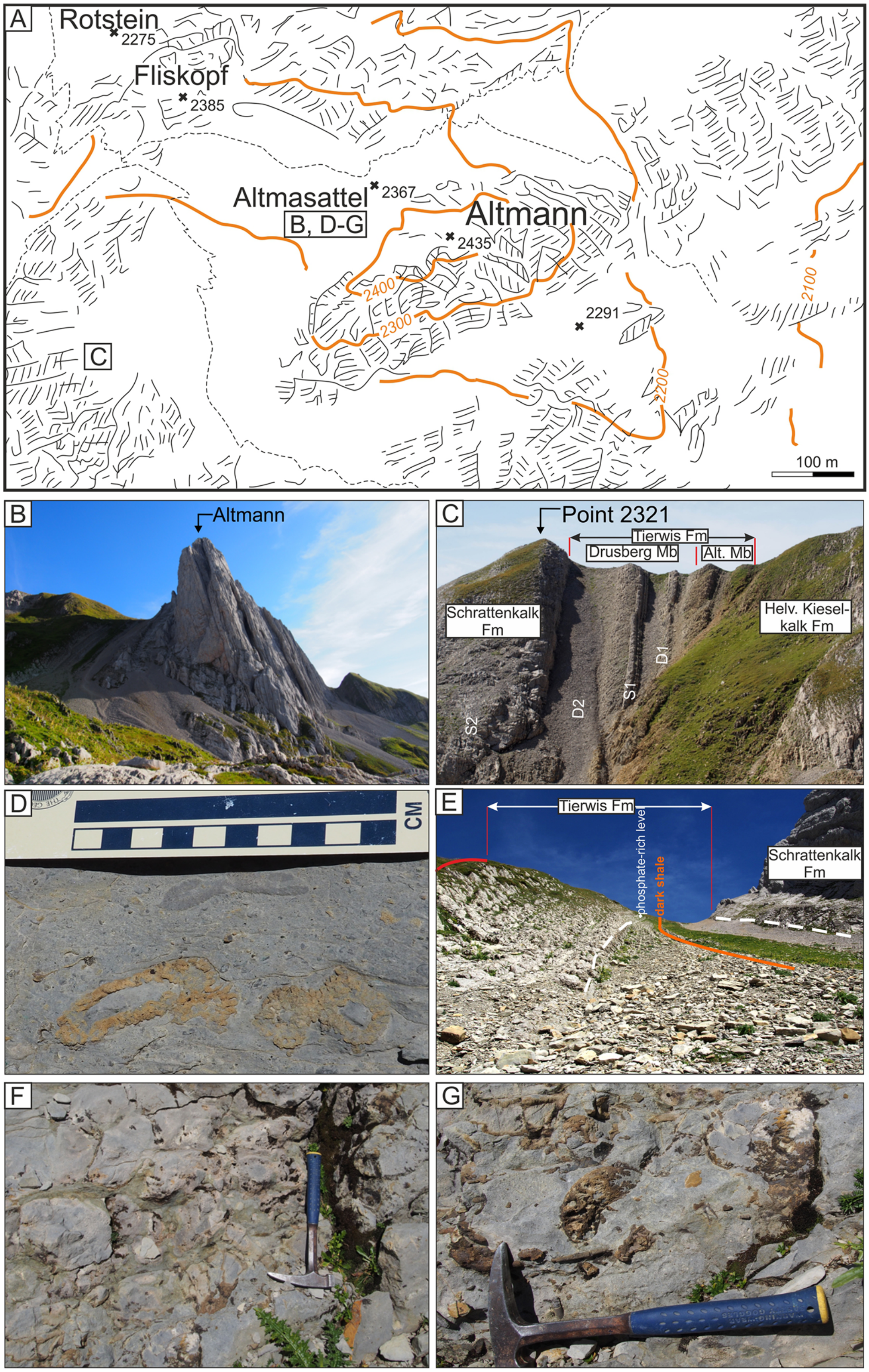

Fig. 7 (See legend on previous page.)

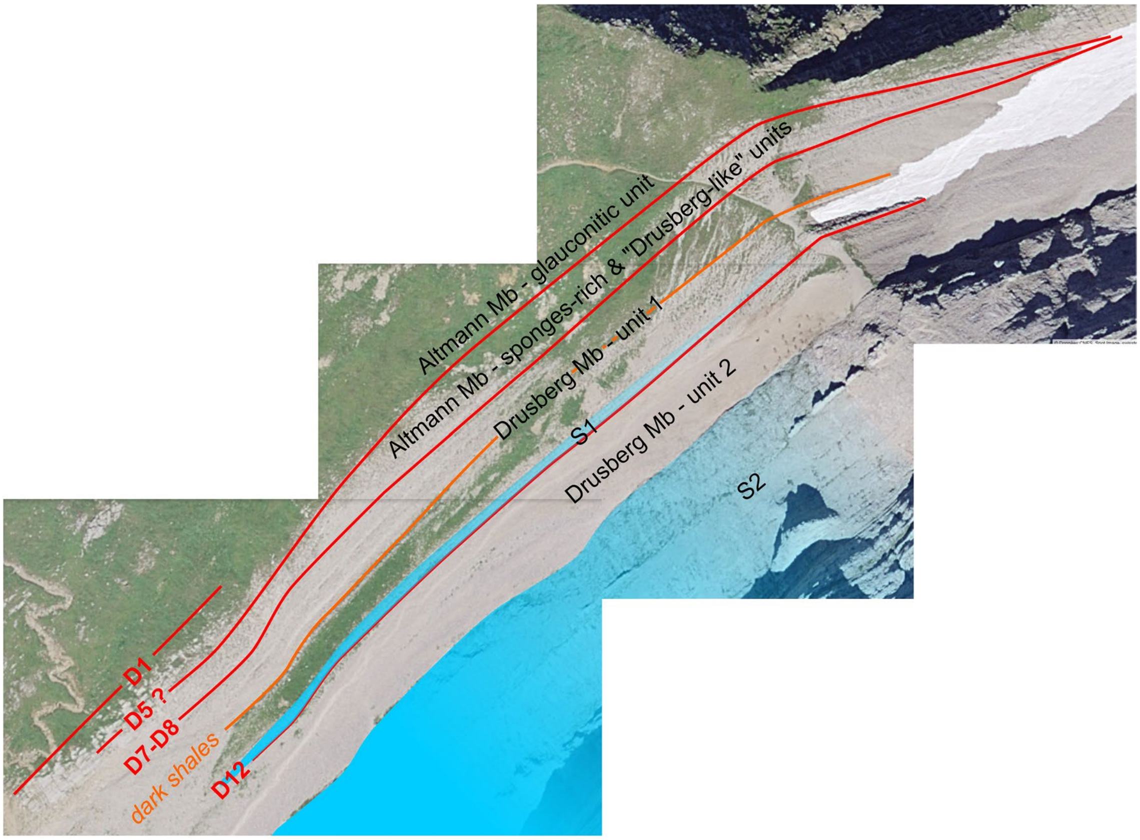

Fig. 8 Orthophoto (© swisstopo) of Altmannsattel on which are reported the main lithostratigraphic units, key beds, and discontinuity surfaces. Note the lateral pinching toward the northeast of the sponge-rich and "Drusberg-like" units in the upper part of the Altmann Member

4.5 The Zeheloch section

Because some stratigraphic intervals of the Drusberg Member are covered by screes in the Litten-Chreialp section, we studied the Zeheloch section where the entire member is exposed. This locality is situated 950 m southwest of the Litten-Chreialp section (Coordinates 2745′013/1231′817/1816; Figs. 13 and 14).

The Altmann Member begins above a firmground on top of the Helvetischer Kieselkalk Formation. It is reduced to 3 m-thick massive, echinodermic limestone of grey-brown colour. The uppermost decimetres of the unit represent a bioturbated surface, corresponding to a firmground, topped by a 10 cm-thick, condensed bed extremely rich in sponges and small phosphatic clasts.

The Drusberg Member dominates with a thickness of about 30 m and is built up by three thickening upward marlstone-limestone packages which are, in ascending order:

(1) A 10.5 m-thick, *Toxaster*-bearing interval, beginning with 6.5 m of grey to bluish marlstones with some intercalated limestone beds, grading upward to a 4 m-thick, fine-grained limestone unit (labelled "S1" on Figs. 13 and 14). Some coquina-bearing beds are present, containing numerous neritic fossils showing affinities with the Schrattenkalk Formation. The top of the package is a bioturbated firmground surface (D12; Fig. 13B);

(2) A 5 m-thick interval, beginning with 3 m of marlstones. The lowermost 30 cm are composed of a glauconitic, thin-bedded, marlstone-limestone alternation (Fig. 13C). Belemnite rostra are common in the basal marlstone filling the bioturbations of the firmground below. Above the glauconitic interval follow grey marlstones including sporadic calcareous nodular levels. The marlstones grade upward into a 2 m-thick, carbonate bundle, composed of marlstone-limestone alternations. Limestone beds measure 15–30 cm-thick and alternate with marly inter-beds of 5 to 15 cm-thick. The basal limestone beds delivered a large specimen of *Torcapella capillosa* Busnardo, 1970;

(3) A 6.5 m-thick thin layered marlstone-limestone alternation. Its lower third is dominated by marl-

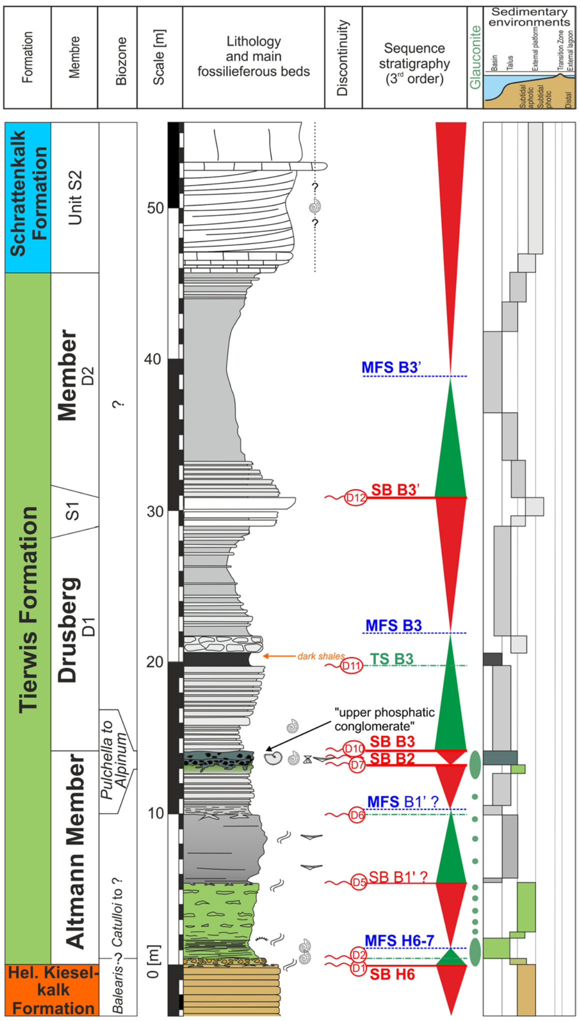

Fig. 9 Altmann section. Lithological log with main fossil-bearing levels, discontinuities, sequence stratigraphic interpretations and microfacies

stones (Fig. 13D). Upwards, the alternation changes progressively into echinids-bearing, light grey bioclastic limestones, very similar to the facies of the Schrattenkalk Formation.

(4) An 8 m-thick carbonate succession, beginning with 2.5 m of thin-bedded bioclastic limestones. This bundle rapidly passes upward into a marlstone-limestone alternation dominated by thick limestone beds, characterising the transition to the light grey massive limestone of the Schrattenkalk Formation (S2 and above units; Fig. 13D and E) in this part of the massif.

4.6 South-eastern mountain range

This mountain range was prospected for ammonites in the Drusberg Member, but only few have been reported. At Höris (Coordinates 2753′160/1235′847/1143), below Frümsner Alp, a limestone mold of *Gerhardtia sartousiana* (d'Orbigny, 1841) was collected in the Drusberg Member. Like in Zeheloch, a bioturbated firmground filled with glauconite-rich infills (Fig. 15B) was found at Frümsner Alp (Fig. 15A). However, in this section, the discontinuity surface is topped by an ammonite-bearing phosphatic conglomerate. The nearby Alp Wis section, situated 1.7 km to the northeast (Coordinates 2753′772/1237′392/1116) exposes the same phosphatic conglomerate with belemnite rostra and the ammonites (Fig. 15C) *Parasaynoceras* cf. *tzankovi* Avram, 1995, *P. perezianum toulai* (Tzankov, 1935), *P.* sp. aff. *perezianum* (d'Orbigny, 1850), *Dissimilites* sp. and *Gerhardtia sartousiana* (d'Orbigny, 1841). This faunal association is characteristic for the *Holcodiscus fallax* Subzone to the *Gerhardtia sartousiana* Subzone.

5 Discussion

5.1 Lithostratigraphic implications

New lithostratigraphic data of the Altmann Member enabled us to divide the member into three subunits (Fig. 16). Subunit A1 is composed of coarse-grained echinodermic and glauconitic limestones, which are lithologically very similar to the Helvetischer Kieselkalk Formation. This is the reason why Kaufmann (1867) named these layers "Kieselkalk–Echinodermenbreccie". Subunit A2 is a glauconitic, limestone-dominated unit (mostly representing the Altmann Member from the Tierwis paratype section). Subunit A3 is a marlstone-limestone alternation similar to that present in the overlying Drusberg Member (upper two-third of the Altmann Member at the Altmann type section). Observations on the Litten-Chreialp outcrop (Figs. 10 and 11) reveal that the subunits A1 and A2 are restricted to a first generation of topographical depressions. These depressions can be up to 30 m deep, as recorded by the Altmann Member from the Tierwis paratype section. These lower subunits are cut by genuine channels filled by sediments of subunit A3 (Fig. 10). This subunit can be distinguished from the overlying Drusberg Member by its content of large glauconite grains, its more massive bedding and its stratigraphical position below the upper phosphatic conglomerate. The maximum thickness for the subunit A3 is 11 m and corresponds to the depth of the second generation of channels. Moreover, ammonite discoveries in the Altmann Member indicate that the subunits A1 and A2

Fig. 10 Litten-Chreialp outcrop presenting a temporal succession of depressions (tectonically induced depressions and/or channels?) filled by the Altmann Member

belong to the uppermost Hauterivian *Pseudothurmannia ohmi* Zone to lowermost *Nicklesia pulchella* Zone. Field observations show that the subunit A3 is topped and laterally replaced toward the channel margins by the phosphatic conglomerate. The subunit A3 yielded ammonites associated with the *Nicklesia pulchella–Kotetishvilia compressissima* zones. Our study regarding the new dating and the depositional geometries reveals that the Altmann Member of the Tierwis paratype section and the Altmann type section do not cover the same stratigraphic interval. This difference in stratigraphic range could be explained by a significant differential sedimentary dynamic caused by syntectonic and erosional processes, as well as sedimentation in channels as visible in the Litten-Chreialp outcrop. Accordingly, the two type sections become even more complementary.

The Altmann Member shows significant lateral variations in thickness and facies. Thickness changes occur within just a few metres in distance as outlined above and up to hundreds of metres. For instance, the member measures about 20 m in Litten-Chreialp and is significantly reduces south-westward (e.g., about 5 m at the locality Chridegass and 3 m at the Zeheloch section; for location see Fig. 13A). Furthermore, other lithostratigraphic units seem to be affected likewise. Two processes seem to be involved in such channelization, a syntectonic activity and the bottom-sea winnowing, acting independently or simultaneously. The older sediments of the Altmann Member were likely deposited within tectonically

(See figure on next page.)

Fig. 11 **A** Locality map of the Litten-Chreialp section and photographs of Altmann Member (**B**–**F**) and of the Drusberg Member (**G**). **B** View of the pinching glauconitic unit. **C** Other view of the Altmann Member and its two subunits. **D** Focus on the glauconitic facies from the base of the "Drusberg-like" unit. **E** View of the "Drusberg-like" unit. **F** Focus on the upper phosphatic conglomerate. **G** View of the uppermost marly interval of the Drusberg Member passing upward to the Schrattenkalk cliff

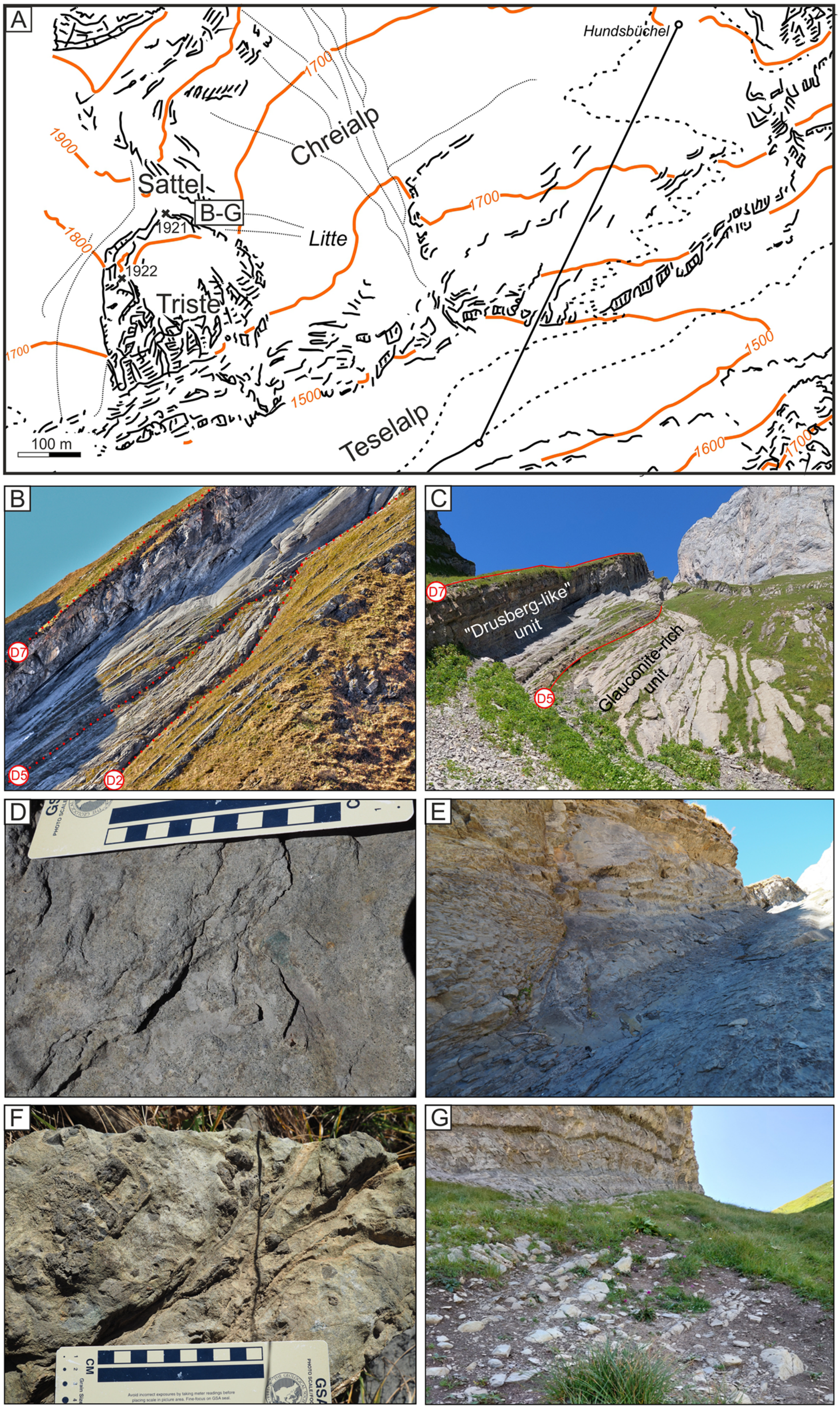

Fig. 11 (See legend on previous page.)

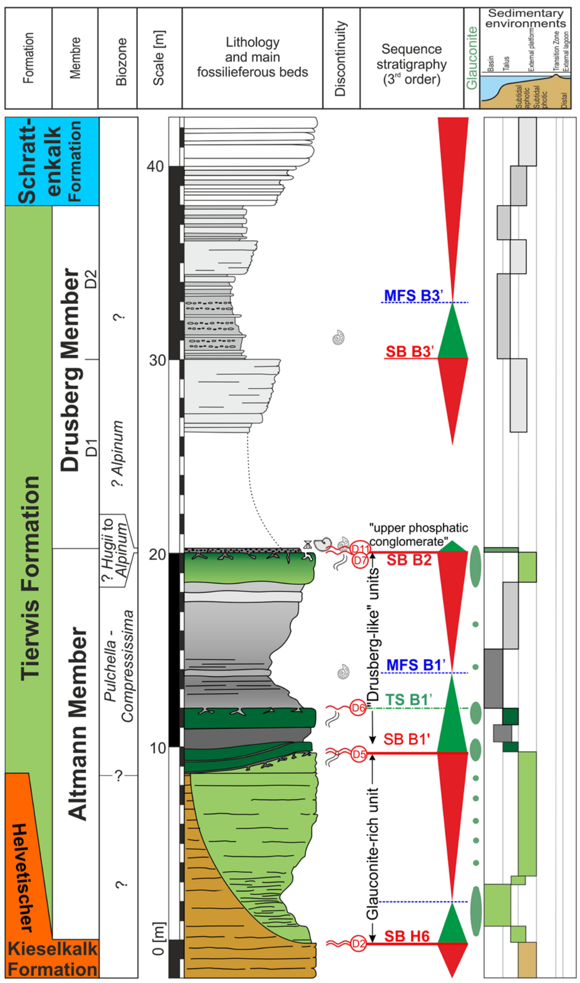

Fig. 12 Litten-Chreialp section. Lithological log with mains fossil-bearing levels, discontinuities, sequence stratigraphic interpretations and microfacies

induced depressions that could have protected them from winnowing currents (Bodin et al., 2006b). Facies variations within a defined facies zone also plead in favour of synsedimentary tectonics (e.g., Föllmi, 1981). Zerlauth et al. (2014) suggest that synsedimentary normal faults caused changes in thickness and facies of the various strata present in the Alpstein massif and played a crucial role in deformation behaviour. The tectonic inversion occurring during the Cenozoic Alpine nappe formation would have reactivated synsedimentary normal faults as ramps and tear faults (Zerlauth et al., 2014). Thus, the successive thrust sheets composing the Alpstein massif are most likely inherited from tilted blocks. By progressively filling these tectonically induced depressions, the younger sediments of the Altmann Member have been probably less protected and locally underwent winnowing and channelling. Longitudinal border currents have been suggested to explain the formation of phosphorites on the Helvetic platform (Delamette, 1985, 1988a; Föllmi, 1986, 1989a, 1989b; Heim, 1924, 1934, 1958; Ouwehand, 1987). The presence of truncated beds in the substratum associated with downcutting hardgrounds is considered indicative of a channel system formed by persistent bottom currents (Gale et al., 2013). The axial part of the channel system is characterized by regionally strongly condensed sedimentation, erosion and hardground formation. Nevertheless, channel orientations were possibly controlled by the orientation of bottom-sea currents as well as by tectonic factors.

The boundary between the Altmann Member and the Drusberg Member was defined on the disappearance of the glauconite grains in the sediments (Briegel, 1972; Fichter, 1934; Funk, 1969, 1971; Heim, 1905). This definition is subject to personal observations and interpretations of each author (e.g., Kempf, 1966 versus Bodin et al., 2006b for the Tierwis section) and stratigraphically differs between the sections (Funk, 1971; Heim, 1905; Lienert, 1965). Furthermore, other important glauconitic levels such as the Chopf Bed lie stratigraphically higher in the Drusberg Member (Bollinger, 1988, p. 21). Such a boundary is not mappable since it does not correspond to the main lithological change between the calcareous glauconitic and echinodermic dominated facies of the Altmann Member and the very finely grained marlstone-limestone alternations and marlstone facies of the Drusberg Member. We find that the upper phosphatic conglomerate is an easily recognizable marker bed, widely present in the entire Alpstein massif and clearly separating the two facies. We tentatively suggest this boundary between the Altmann and Drusberg members, although a larger-scale study is needed to corroborate our hypothesis regarding the lithostratigraphic subdivision of the Tierwis Formation. From a chronostratigraphic point of view, this bed indicates the *Nicklesia pulchella* and *Kotetishvilia compressissima* zones *pro parte* in inner slope environments (Tierwis section). In the middle slope (Altmann section), the upper phosphatic conglomerate yielded stratigraphically younger ammonites like *Rugacrioceras dreloni* Vermeulen 2007, which appears in the early late Barremian *Gassendiceras alpinum* Subzone (Vermeulen, 2007b). In the more distal slope (Litten-Cheialp section), the same bed yields ammonites from the earliest Barremian *Taveraidiscus hugii* Zone up to the early late Barremian *Gassendiceras alpinum* Subzone. Thus, the upper phosphatic conglomerate is diachronic, containing an increasing period of time in south-eastward direction, i.e. toward the open sea. Finally, we cannot rule out that the upper phosphatic conglomerate locally merges with the Chopf

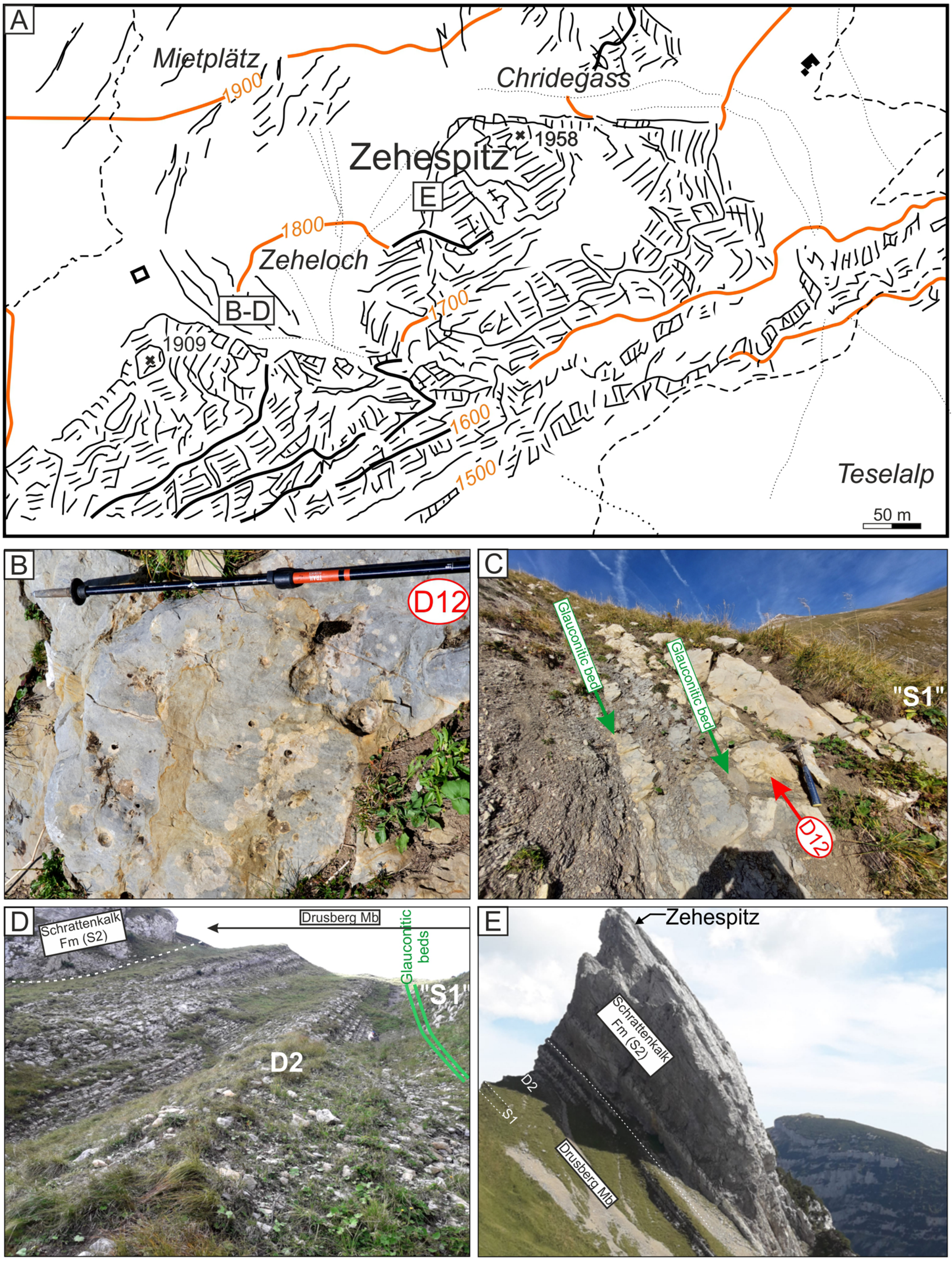

Fig. 13 **A** Locality map of the Zeheloch section and photographs of the Drusberg Member. **B** Bioturbated firmground (D12) in the middle of the Drusberg Member. **C** Glauconite-rich Chopf Bed topping the firmground (D12). **D** Focus on the upper Drusberg unit D2. **E** View on the Drusberg-Schrattenkalk transition at Zehespitz

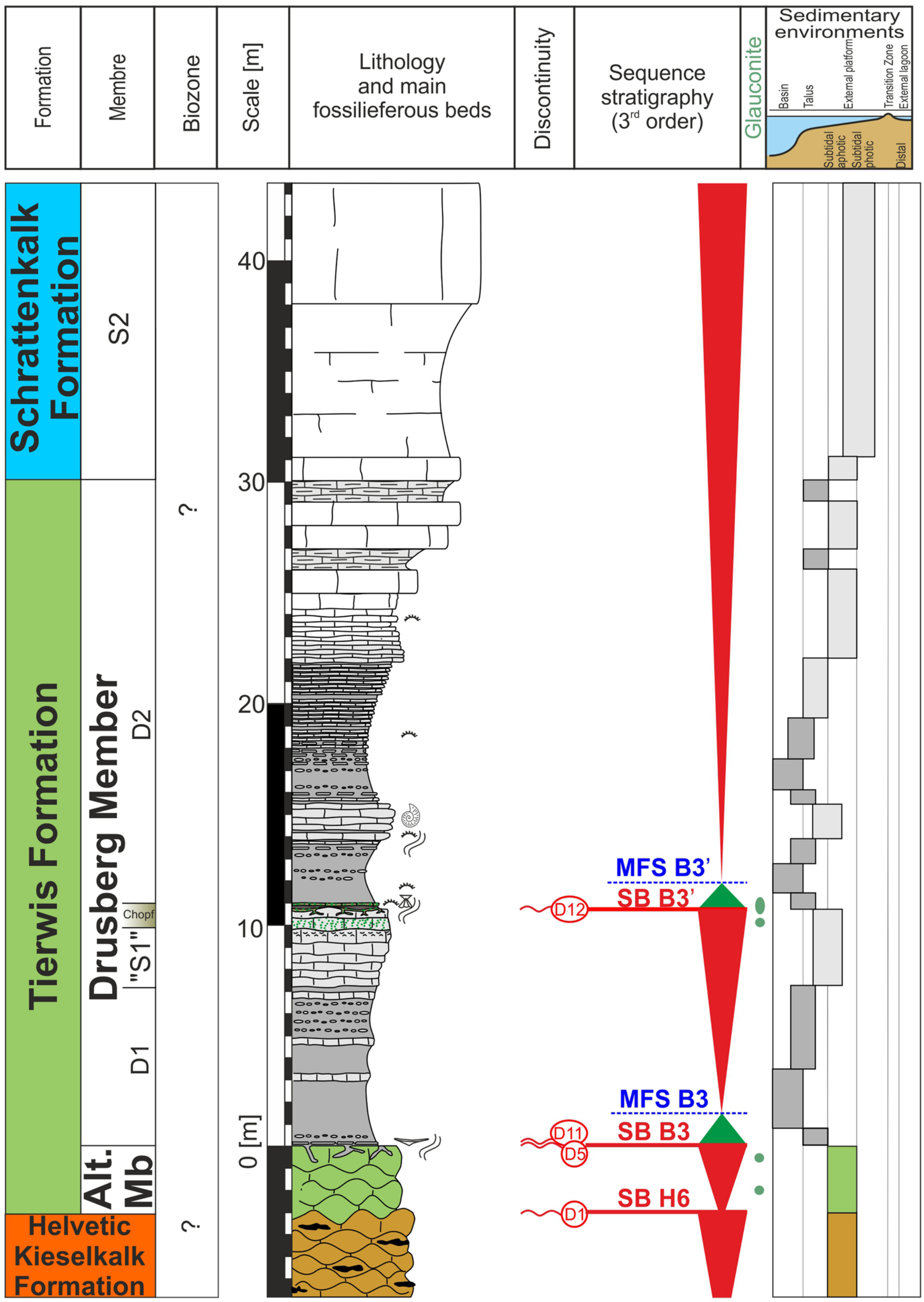

Fig. 14 Zeheloch section. Lithological log with main fossil-bearing levels, discontinuities, sequence stratigraphic interpretation and microfacies

Bed, another phosphatic conglomerate present in the last and more south-eastward mountain range of the Alpstein massif.

We separate at least two subunits inside the Drusberg Member based on lithostratigraphic observations and high-resolution dating by ammonites (Fig. 16). The

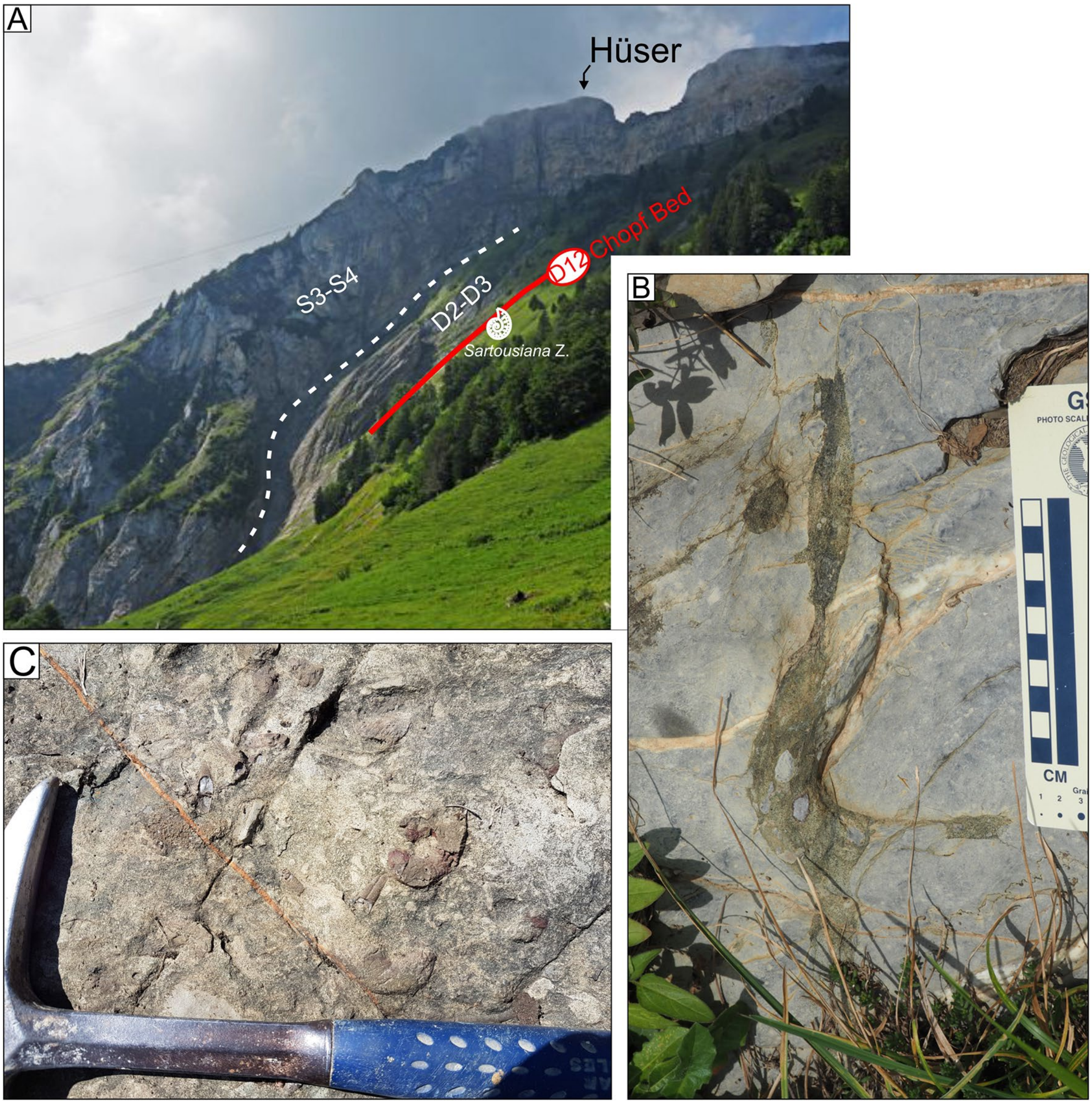

Fig. 15 Photographs of the south-eastern mountain range. **A** View on the Hüser cliff from Frümsner Alp with the stratigraphical position of the Chopf Bed, the Drusberg Member and the Schrattenkalk Formation. **B** Focus on the bioturbated firmground (D12) at the base of the Chopf Bed with its glauconitic infill, Frümsner Alp. **C** Focus on the overlaying Chopf Bed at Alp Wis

two subunits are separated by a condensed bed, attributed to the Chopf Bed. The subunit D1 forms the entire Drusberg Member on the inner slope like in the Tierwis and Langtal sections, which is dated to the *M. moutonianum* and *T. vandenheckii* zones and is characterized by the presence of a dark grey shale near its top. The subunit D2 forms the upper half of the Drusberg Member on the middle slope like in the Altmann, Litten-Chreialp and Zeheloch sections. The subunits D1 and D2 are separated by a light grey limestone related to the distal part of clinoforms of the Schrattenkalk Formation (subunit S1) or by the Chopf Bed in more distal sections. The subunit D2 is dated by ammonites to the *G. sartousiana* Subzone.

5.2 Key beds and ammonite bio-events

The link between Early Cretaceous episodes of carbonate platform drowning and, more widespread, profound environmental changes has long been postulated in the Helvetic Realm (Föllmi et al., 1994; Godet et al., 2013; Weissert et al., 1998). Following Föllmi et al. (2006), the Helvetic platform succession documented the influence of regional environmental changes, such as relative sea

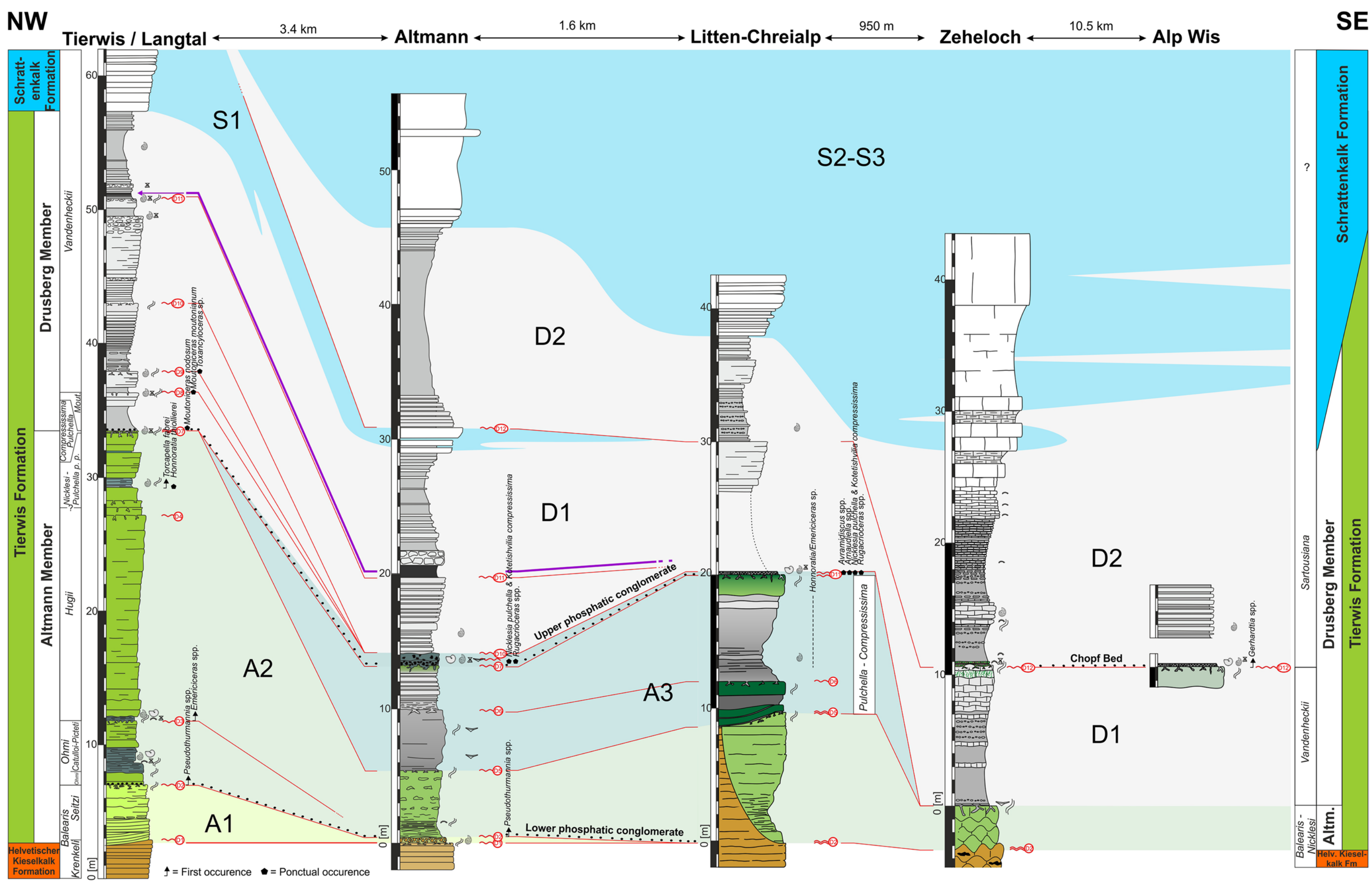

Fig. 16 Transect across the Alpstein Massif from the landward direction to the left side to the seaward direction to the right side following a NW to SE axis. Key-events, beds, and surfaces used for correlations between sections are marked by the coloured lines. The first occurrence datums of the main ammonite biomarkers are reported on the right side of the lithological logs

level fluctuations, variations in ambient sea-surface water temperature, and the type and intensity of detrital influx. Föllmi et al. (2006) observed that the onset of each palaeoceanographic and paleoenvironmental change was often associated with a relative sea-level rise, with a sedimentological change toward an heterozoan carbonate production in combination with periods of increased coarse-grained detrital input and to glauconite and phosphate authigenesis. Furthermore, the authors stated that each drowning phase was quickly followed by a major positive carbon-isotope excursion. Such modifications in the carbon and phosphorus cycles are associated with global oceanic anoxic events (Föllmi et al., 1994; Weissert et al., 1998; Wissler et al, 2003), which took place in neighbouring basins. The latest Hauterivian and Barremian time interval records a succession of short and repeated periods of dysaerobic to anaerobic conditions that took place in the Vocontian basin (Masse & Machhour, 1998), the central Tethys (eg., central Italy; Baudin, 2005; Baudin et al., 2002; Cecca et al., 1994; Coccioni et al., 1998, 2006), the Boreal basins (Greenland and Norway; Mutterlose et al., 2003), and the Lower Saxony basin (northern Germany; Mutterlose & Böckel, 1998; Mutterlose & Bornemann, 2000; Mutterlose et al., 2009, 2010), associated with the deposition of a succession of pelagic organic-rich deposits.

A succession of marker-beds observed within the Tierwis Formation is associated with: (i) positive excursions in oceanic phosphorus burial; (ii) notable carbon isotope fluctuations with negative and following positive excursion; (iii) condensed intervals sometimes combined with important phosphate authigenesis; and (iv) ammonite accumulations and bio-events. These beds are interpreted as the result of drowning phases. Our revised calibration substantially modifies the dating of the drowning phases and other key surfaces as well as sequence stratigraphic interpretations and consequently the dating of the Tierwis Formation, which was developed in the last decades. We recognized six lithologically, chemically and biologically exceptional event beds of regional significance, which are distributed across the latest Hauterivian to the early late Barremian.

5.2.1 Sequence boundary (SB) H6

The top of the Kieselkalk Formation (D1) is marked by channels and other depressions, which probably originated from a sea-level drop associated to erosional processes and/or to syntectonic activity. In more internal parts of the carbonate ramp, like in the Pilatus outcrops (canton of Lucerne), Godet et al. (2013) highlighted some vadose silts infiltrated in the top surface of the Helvetischer Kieselkalk Formation. Such sedimentological feature reflects the influence of gravitational sedimentation within the meteoritic vadose domain. Following Bodin et al. (2006b), at the Tierwis location, this erosive surface lacks any indication of emersion. The authors point to a coeval late Hauterivian sea-level drop, which is defined in global sequence stratigraphic schemes by Haq et al. (1987) and Hardenbol et al. (1998). We also interpret this surface D1 as a sequence boundary and follow its attribution to the late Hauterivian SB H6.

A following drowning phase is marked by the onset of the sedimentation of highly condensed hemipelagic marlstones and limestones of the Tierwis Formation. As expressed by Bodin et al. (2006b), the following onset of the Altmann Member is coeval with a second order sea-level rise (e.g., Hardenbol et al., 1998; Ruffell, 1991), well documented on several Mediterranean platforms (Arnaud-Vanneau & Arnaud, 1990; Company et al., 1992; Föllmi et al., 1994). With the transgression, ammonite-bearing beds formed. The first horizon with ferric concretions, glauconitic crusts and phosphatic nodules marks the onset of an upwelling system (Burnett et al., 1983). It may thus be attributed to a transgressive surface (TS), as proposed by Bodin et al. (2006a). The scarce ammonites from the surface D2 indicate the *Pseudothurmannia ohmi* Zone. This dating is reinforced by additional ammonites originating from this bed from other sections [e.g., Oberlänggli, St. Gallen, Bodin et al. (2006b); Schwendi, Bern]. These sections yielded well-preserved late Hauterivian phosphatized ammonites. These datings support the attribution of the underlying discontinuity surface D1 to the SB H6 as postulated by Bodin et al. (2006b). According to this sequence stratigraphic attribution, it is thus possible to assign the discontinuity surface D1 to the *Crioceratites krenkeli* Subzone (Company et al., 2005). The sharp lithological change between the Helvetischer Kielselkalk and the Tierwis formations is associated with a prominent geochemical shift with a phosphorus enrichment up to 1000 ppm (P1) and a depletion of the $\delta^{13}C$ values of 0.4‰ just on top of the SB H6, which might reflect the establishment of upwelling currents (Godet et al., 2013) and to an intensified biogeochemical weathering. It may have led to an acceleration of the hydrologic cycle and thus an increase in continental run-off, which led to enhanced supply of phosphorus and dissolved inorganic carbon to the ocean (Bodin et al., 2006b; Godet et al., 2006). Clay minerals such as the appearance of kaolinite indicate a change from a seasonally contrasted climate towards a more humid and warmer intertropical climate (Föllmi et al., 2012; Godet et al., 2008) as proposed by Bodin et al. (2006c). These interpretations point to a major palaeoceanographic and paleoenvironmental change associated with the onset of drowning phases, to high-nutrient levels and eutrophication of the platform and to sediment starvation and/or current-induced winnowing on the Helvetic domain (Bodin et al., 2006b).

5.2.2 Faraoni event

At the Tierwis section, the overlying first glauconitic layer is marked by more marly sediments that are strongly bioturbated and characterized by abundant Crioceratitidae such as *Pseudothurmannia mortilleti* (Pictet & De Loriol, 1858) (Bodin et al., 2006b; Tajika et al., 2017). The deepest facies met in this level is interpreted as a maximum flooding surface (MFS). *Pseudothurmannia mortilleti* (Pictet & De Loriol, 1858) indicates the *P. catulloi* Subzone, allowing to link this dark, glauconitic marly interval to the uppermost Hauterivian MFS H6. This flooding is thus contemporaneous with the Faraoni anoxic event (Bodin et al., 2006b) recorded in the Tethys. The attribution of our glauconitic level to the Faraoni episode is herein corroborated by $\delta^{13}C$ values, which show a negative $\delta^{13}C$ isotopic peak C1 (Fig. 5). A contemporaneous carbonate crisis is recorded in other carbonate platforms like in the Jura mountains (eastern France and western Switzerland) with the Cul du Nozon Bed. It is characterised by a marly interval comprising strongly glauconitic and phosphatic sediments associated with a faunal turnover (Pictet, 2021). Deeper basinal sedimentary successions are also affected by the presence of a series of thin, organic-rich mudstone layers, which have been interpreted as the result of short-lived and cyclically reappearing anoxic episodes (Föllmi et al., 2012 and references therein). It indicates the progressive installation of dysaerobic conditions in the basins, which culminated in the Faraoni event (Cecca et al., 1994). Thus, the Faraoni event likely was the climax of an important carbonate crisis (Bodin et al., 2006b; Föllmi, 2012; Föllmi et al., 2012; Pictet, 2021) associated with an evolutionary change and turnover affecting shallow-water organisms like rudists (Masse & Fenerci-Masse, 2008) and deeper marine biota like ammonite faunas (Company et al., 2005; Hoedemaeker & Leereveld, 1995).

5.2.3 SB H7 and following "Hugii" event

The third key interval begins with a strongly bioturbated discontinuity surface (D3) with ferric crusts having all characteristics of a mineralized firmground. The overlying second glauconitic layer, in all respects similar to the one below, is marked by abundant emericiceratids such as *Emericiceras emerici* (Léveillé, 1837) and *E. koechlini* (Astier, 1851). This association was typically dated to the lowermost Barremian *Taveraidiscus hugii* Zone (e.g., Company et al., 2008). Consequently, the bioturbated discontinuity surface D3 can be attributed without doubt to the SB H7 and the second glauconite-rich layer to the MFS H7. The age of the firmground coincides with a drastic sea-level fall, which lead to the exposure and erosion of the of large areas of the perimediterranean shelves (Arnaud & Arnaud-Vanneau, 1991; Company et al., 1992) and to a strong ammonite turn over (Company et al., 2005; Vermeulen, 2005).

According to its ammonites, the second glauconitic level appears to be contemporaneous to a condensed interval at the Clos de Baral section of to the lowermost Barremian *Taveraidiscus hugii* Zone (Arnaud, 2005) (Fig. 17). Additionally, phosphorus values recorded an enrichment (P2) associated with the negative $\delta^{13}C$ isotopic peak C2 (Fig. 5). Contemporaneous lowermost Barremian black shales were identified in the Tethys (Bersezio et al., 2002; Cecca et al., 1995) and the Lower Saxony Basin (Malkoč & Mutterlose, 2010; Mutterlose & Böckel, 1998; Mutterlose & Bornemann, 2000; Mutterlose et al., 2009), which suggest to consider this level as a regional event, tentatively called "Hugii" event.

The "Hugii" event is followed by a time interval characterised by the progressive disappearance of numerous ammonite taxa which had originated in the late Hauterivian (Vermeulen, 2005). Vermeulen identified five successive evolutionary intervals in the ammonite record of the Barremian stratotype of Angles (SE France) and its surroundings. The first faunal association stretches from the base of the *Taveraidiscus hugii* Zone to the top of the *Kotetishvilia nicklesi* Zone, a time interval covalent to the onset of the first main Urgonian shallow-water carbonate platform development on the northern Subalpine chains (Clavel et al., 2014), the western Helvetic chains (Renevier, 1890), the Vercors platform (Arnaud et al., 1998), the Languedoc platform (Clavel et al., 2012, 2014), and the western Jura platform (Pictet, 2021).

5.2.4 "Pulchella" event

A remarkable more marly and strongly bioturbated level is present in the upper third of the Altmann Member, which yielded a few ammonites. Rare gigantic specimens of *Honnoratia thiollierei* (Astier, 1851) as well as *Torcapella fabrei* (Torcapel, 1884) collected in this level point to a the *Kotetishvilia nicklesi-Nicklesia pulchella* zones (Vermeulen in Arnaud et al., 1998). This ammonite occurrences are consistent with the sequence stratigraphic interpretation, which points to the MFS B1, dated to the Barremian series of Angles to the transition between the *K. nicklesi* and *N. pulchella* zones (Arnaud, 2005). This level is also associated to a strong phosphorus enrichment, and to a sharp negative $\delta^{13}C$ peak C3 (Fig. 5) pointing to a probable additional regional event,

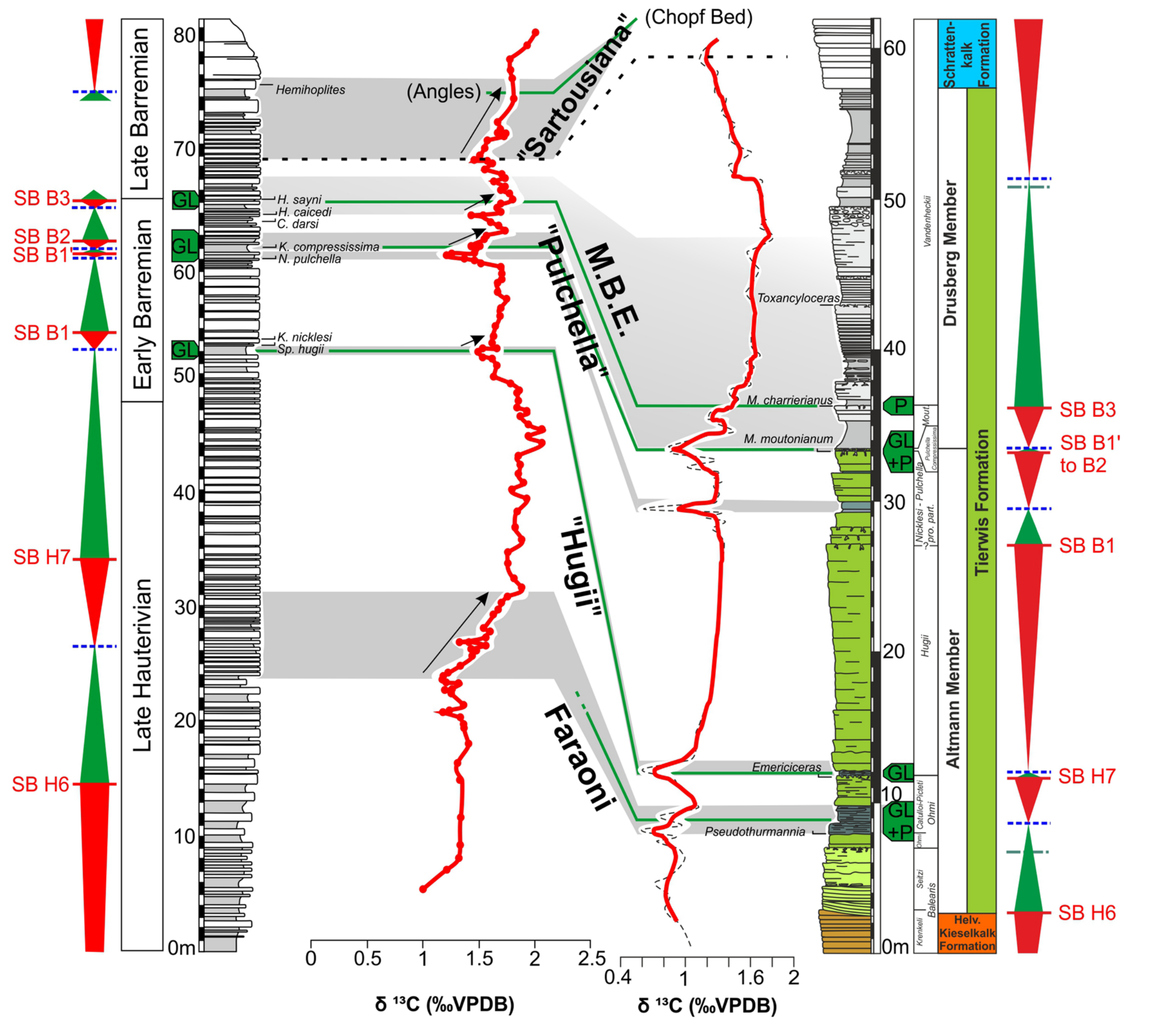

Fig. 17 Correlation figure between the Tierwis section and the Clos de Barral section (SE France) based on chemo-, bio- and sequence-stratigraphy and on condensed beds. Grey intervals correspond to environmental perturbations and associated laminated, organic-rich muds into the basins. Green lines indicate the glauconite and phosphate-rich beds. Lithological log of the Clos de Barral section and associated sequence stratigraphic interpretation (modified), ammonites and $\delta^{13}C$ curve are from Godet et al. (2013)

tentatively called "Pulchella event". This event is hypothetically correlated with organic-rich layers in the basins as discussed above.

5.2.5 The upper phosphatic conglomerate and the consecutive Mid-Barremian Event (MBE)

A sharp and erosive discontinuity surface D5 marks an important sedimentary change with the end of the sedimentation of glauconitic series composing the lower part of the Altmann Member. Moreover, this surface is characterised by the formation of channels (Fig. 10). The ammonites collected in the previous and next key beds date this discontinuity surface to the *Nicklesia pulchella* Zone and thus is tentatively correlated to the SB B1'. This sequence boundary is contemporaneous with the deposition of slumps and other gravity flows in the Umbria-Marche basin (e.g., Cecca et al., 1995), and to hiatuses on the perivocontian carbonate platforms (Arnaud, 2005; Delanoy, 1992), or to highly condensed series (Arnaud, 2005; Delanoy et al., 2012; Vermeulen et al., 2013). All these field data point to an important sea-level drop during the *N. pulchella* Zone (Frau et al., 2018). In the Alpstein, an important hiatus occurred in inner slope environments, marked by a polyphased hardground recording two generations of borings (Fig. 4D). In contrast, outer slope environments shifted toward a more rhythmic sedimentation (upper part of the Altmann Member) announcing the Drusberg sedimentation type, infilling channels like in the Altmann and Litten-Chreialp sections. The more marly lithology of the upper part of the Altmann Member points to a sea-level rise and/or to an environmental change associated with a strong reduction of glauconite production. This carbonate decline is largely recorded along the perivocontian carbonate platforms. The Languedoc platform is characterized by the onset of the Seynes marlstones and the Vire du Serre de Tourre (SE France; Granier et al., 2021; Vermeulen et al., 2013) and on the Jura platform by the onset of the Bôle Member (Pictet, 2021). Sequence B1' was followed by a renewed sea-level drop, leading to the formation of a particularly sharp D7 discontinuity surface, telescoping D5 landward. Contemporaneous channel sediments occur on the Jura platform with the Marne de la Russille backfilling depressions (Pictet, 2021). This level also ends with a fossil-bearing, glauconitic and phosphate-rich conglomerate sealing the lenticular deposits.

These depressions of the Altmann Member are capped by the polyzonal upper phosphatic conglomerate. In the Tierwis section, from where geochemical samples were analysed, the hardground and consecutive phosphatic conglomerate are associated with a 12000-ppm phosphorus peak and the negative $\delta^{13}C$ peak C4 (amplitude of ca − 0.6‰), in accordance with an important sedimentological gap (Fig. 5). The time span comprised in the phosphatic conglomerate is herein considered as indicative of the duration of this hiatus, which corresponds to the whole sequence B1' in Tierwis, up to the sequence B3 in Altmann and Litten-Chreialp, and to a large part of the Barremian stage in the southwestern range. The upper phosphatic conglomerate marks an easily recognisable bed in the field, which is largely present across the massif. It forms the boundary between the Altmann Member and the Drusberg Member according to our lithostratigraphic investigations. This lag deposit is mostly formed during a renewed drowning phase of the Helvetic domain. This drowning phase is associated with a stronger phase of backstepping of the platform (Bodin et al., 2006b).

The Drusberg Member and its typical marlstone-limestones alternations start around the boundary between the *Kotetishvillia compresissima* and the *Moutoniceras moutonianum* zones for the most internal sections like Tierwis. This onset corresponds to SB B2, which initiates with a second order sea-level rise (Bodin et al., 2006b). This renewed drowning phase led to a reduction of the growth potential of the carbonate production through environmental stress, such as the reduction of water transparency, water temperature or eutrophication (Hallock & Schlager, 1986) as proposed by Bodin et al. (2006b). Such environmental stress is herein lithologically recorded by marlstones associated with a large positive and progressive 1 ‰ carbon isotope excursion and comprising beds enriched in phosphate content. At Tierwis, 2.7 m above the phosphatic conglomerate, the Drusberg Member comprises a phosphatic firm- to hardground, paved with slightly phosphatized ammonites, indicating the transition between the *Moutoniceras moutonianum* and *Toxancyloceras vandenheckii* zones (early/late Barremian boundary). A contemporaneous condensed stratigraphical interval is observed in the French perivocontian Clos-de-Barral section (Fig. 17; Arnaud, 2005). Because of the ammonite assemblage, we tentatively attribute this discontinuity surface to the SB B3. This dating is consistent with the following thick limestone-dominated succession that yielded a large fragment of the genus *Toxancyloceras*. This limestone bundle, characterised by a succession of firmground surfaces and topped by an ammonite-bearing marlstone interval, can be attributed to the lowstand systems tract (LST) of sequence B3. In the Vocontian Basin record, the *T. vandenheckii* Zone includes most of the B3 depositional sequence sensu Arnaud (2005), interpreted as an overall sea-level fall evidenced by the change from a rhythmic marlstone-limestone alternation to a limestone-dominated sequence. In basinal settings like in the Umbria-Marche basin (Italy; eg., Cecca et al., 1995) or in the Vocontian basin (SE France; Clavel et al., 2012; Ferry, 1988), the *T. vandenheckii* Zone includes the deposition of several megabreccias, slumps and other gravity flows.

Like in the Alpstein massif, carbonate platforms along the northwestern Tethyan margin recorded an important carbonate crisis, which began in the *Nicklesia Pulchella* Zone. It culminated during the *Moutoniceras moutonianum* Zone before the recover of the carbonate factory from the late *Toxancyloceras vandenheckii* Zone onward. This time interval corresponding to the *Moutoniceras moutonianum* Zone and parts of the *Toxancyloceras vandenheckii* Zone is associated with major changes in the ocean-climate system, such as global warming, eutrophication, and $\delta^{13}C$ excursions (Coccioni et al., 2003; Föllmi, 2012; Mahanipour & Eftekhari, 2017). A time-equivalent succession of dark shale deposits was highlighted in the Umbria-Marche Basin by Coccioni et al. (2003) and Sprovieri et al. (2006) and corresponds to the carbon segments B2 and B3 of Wissler et al. (2002). These organic-rich mudstones appear approximately at the lower/upper Barremian boundary within the polarity Chronozone M3 and *H. similis–H. kutznetsovae* planktonic foraminiferal Zone. Still following the authors, these organic-rich layers are characterised by chemo- litho- and biostratigraphic changes that they related to a prominent short-term event named Mid-Barremian Event (MBE). The Boreal domain also recorded contemporaneous organic-rich layers ("Hauptblätterton") associated to a basin-wide expansion of the anoxic conditions, which were documented from the north-western Germanic basin and dated to the late early Barremian (Mutterlose & Böckel, 1998). The marine life experienced an important faunal turnover. Among ammonites, the Emericiceratidae disappeared (Vermeulen, 2005). It was followed by the appearance and diversification of the Ancyloceratidae (Bert et al., 2017) and Barremitidae (Vermeulen, 2005) and by the important diversification of the Holcodiscidae (Vermeulen, 2005, 2007a). Among terebratulid brachiopods, an extinction event is also recorded from the late early to early late Barremian period (Middlemiss, 1984). Likewise, calcareous nannofossil assemblages are impacted by profound turnover (De Kaenel et al., 2020; Møller et al., 2019). These lines of evidence led Coccioni et al. (2003) to define the MBE as an important event associated with large scale changes in the ocean-climate system likely related to a pulse of volcanic activity of the oceanic Ontong-Java Plateau formation, which eventually led to the upcoming worldwide early Aptian OAE1a.

The MBE is herein calibrated by ammonites from the *Moutoniceras moutonianum* Zone to the *Toxancyloceras vandenheckii* Zone *pro parte*.

5.2.6 "Sartousiana" event

The discontinuity surface D12 (Figs. 6, 8, 9, and 13, 14, 15) of the most distal sections is associated with a glauconite and phosphate-rich conglomerate, the Chopf Bed. This marker bed is either situated in the middle of the Drusberg Member like at Zeheloch and at Kapf (Heim & Baumberger, 1906, p. 206), or merged with the "upper phosphatic conglomerate" below like possibly in Alp Wiss. Following Föllmi (2016), the phosphate beds usually tend to merge into a single bed towards outer shelf environments, thereby losing the intervening glauconitic sediments and indicating stronger and more persistent condensation (Föllmi, 1986). This fusion of beds points to the importance of currents, erosion, sediment reworking and transport in the formation of the condensed beds (Delamette, 1985, 1988a, 1988b, 1994; Delamette et al., 1997; Föllmi, 1986, 1989a, 1989b, 1990; Föllmi & Delamette, 1991; Föllmi & Gainon, 2008; Ouwehand, 1987). Toward the inner platform, the Chopf Bed progressively wedges out and transitions into a discontinuity separating two prograding limestone bodies of the Schrattenkalk Formation (S1 and S2; Figs. 8 and 16). The discontinuity surface D12 marks a noticeable sedimentary event and may be considered as an isochronic timeline through the entire platform-to-basin transect. This surface is systematically overlain by deeper facies sediments (= Vire médiane "VM" of Ferry 2017), which are interpreted as being deposited during a drowning phase. The phosphogenesis of the Chopf Bed was most likely initiated by upwelling currents in connection with the ongoing drowning of the carbonate platform.

The ammonites from the phosphatic conglomerate of the south-eastern range of the Alpstein massif are of the same age as those of the Chopf Bed in its type locality (see Bodin et al., 2006a), both dated of the uppermost *T. vandenheckii* to lowermost *G. sartousiana* zones. These two beds are therefore contemporaneous, which allowed us to attribute our phosphatic conglomerate to the Chopf Bed. This dating also enabled us to attribute the discontinuity surface D12 to the sequence boundary SB B3', situated around the boundary between the *T. vandenheckii* and *G. sartousiana* biozones. Contrary to the assumptions of Bodin et al. (2006b) and Bonvallet et al. (2019), the Chopf Bed does not correspond to the transition between the Drusberg and Schrattenkalk formations in the more proximal sections of the Säntis region.

More widely, the late Barremian is considered as a time interval characterised by lower rates of organic-matter preservation in the Tethyan basin and by the maximum extension of the Urgonian carbonate platform on the northern Tethyan margin (Föllmi, 2012). However, the Chopf Bed appears like a remainder of the previous carbonate crisis, marked by a climatic burst, which we herein call the "Sartousiana" event, which is contemporaneous with laminated, organic-rich mud (LOM) in the basins.

6 Conclusions

We dated strata of the Tierwis Formation, its subunits and its key surfaces using a large number of newly discovered ammonites from several poorly explored levels of the Altmann and Drusberg members in the Alpstein massif.

We show that the Altman Member can be divided into three subunits based on lithostratigraphy and ammonite biostratigraphy: (1) a basal echinodermic limestone subunit A1; (2) a middle glauconitic limestone-dominated subunit A2; (3) an upper marlstone-limestone alternation subunit A3 very similar to the Drusberg Member. Furthermore, the Tierwis paratype and the Altmann type section do not cover the same stratigraphic interval; the Tierwis paratype section represents only the lower third of the Altmann type section. This conclusion is easily explained by the observation of the Litten-Chreialp section, which shows a significant cut-and-fill sedimentary dynamic with erosional processes and sedimentation in depressions and/or channels. The lower depressions and its consecutive filling by the glauconitic limestone-dominated unit A1 formed during the *Balearites balearis*

Zone *pro parte* to the *Nicklesi pulchella* Zone *pro parte*. The upper generation of channel formation and consecutive filling by the marlstone-limestone alternation of unit A2 is dated to the *Nicklesi pulchella pro parte* and *Kotetishvilia compressissima* zones. The original definition of the lithostratigraphic boundary between the Altmann Member and the Drusberg Member does not seem reasonable from a cartographic point of view because it does not follow the main facies boundaries. On the basis of our field observations on the type sections of the Alpstein massif, we postulate that the boundary between the Altmann Member and the Drusberg Member lies on top of the upper phosphatic conglomerate. Additionally, we hypothesize that this is also applicable to the entire Tierwis Formation outside the Alpstein region. However, further research is needed to test this.

Newly found marker beds such as firmgrounds and hardgrounds, glauconitic beds and phosphatic conglomerates point to a total of two major drowning phases and associated environmental change (Faraoni and MBE events) as well as four minor key-beds. We dated these key beds and surfaces to the uppermost Hauterivian to upper Barremian sedimentary succession. These lithological markers are also associated with notable positive phosphorus and carbon isotope excursions and ammonite bio-events. They are tentatively correlated with other sedimentary basins and hypothetically considered as the result of isochronous environmental events, which could display a wide geography range and thus a great correlation potential.

The recognition of the Chopf Bed and its landward equivalent demonstrates that this condensed bed does not correspond to the transition between the Drusberg and Schrattenkalk formations in the more proximal sections of the Säntis region but appears to be incorporated in the Schrattenkalk Formation. An upcoming detailed study of the Schrattenkalk Formation in the Alpstein massif will bring new insights allowing to test this hypothesis.

Finally, the onset of the condensed hemipelagic Tierwis Formation and its numerous drowning phases is herein regarded as the result of a succession of paleoenvironmental changes that affected the northern Tethyan margin. The latest Hauterivian to late Barremian time interval appears to be a key period of underestimated paleoenvironmental change in the Early Cretaceous. It started with the latest Hauterivian Faraoni event (Cecca et al., 1994), the first widely recognized oceanic anoxic event of the Cretaceous (Föllmi, 2012) and continued to fluctuate up to the early Aptian, witnessing one of the major phases of paleoenvironmental change of the entire Cretaceous – the Selli episode (OAE1a; Coccioni et al., 2003; Erba et al., 2015; Föllmi, 2012). These two oceanic anoxic events are likely related to increased submarine volcanic activity of the Ontong-Java Plateau during this time interval (Coccioni et al., 2003; Erba et al., 2015; Föllmi, 2012).

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Declarations

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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