The Cretaceous of the Swiss Jura Mountains: an improved lithostratigraphic scheme

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Abstract In the course of the HARMOS project of the Swiss Geological Survey, the lithostratigraphic subdivisions of the Cretaceous sedimentary rocks outcropping in the Swiss Jura Mountains were revisited. New formation names are proposed where only inadequate facies terms existed so far. As in some cases outcrop conditions in the Swiss Jura do not allow for logging complete sections to characterise the formations, type localities in neighbouring France have been chosen. The following formations (Fm.) are defined to describe the Cretaceous lithological units (from bottom to top): Goldberg Fm., Pierre-Châtel Fm., Vions Fm., Chambotte Fm., Vuache Fm., Grand Essert Fm., Gorges de l'Orbe Fm., Vallorbe Fm., Perte du Rhône Fm., Narlay Fm. Dating of the formations is based on biostratigraphy (ammonites, echinids, dasycladalean algae, foraminifera, calpionellids, dinocysts, nannofossils). The fossils indicate Berriasian through to Coniacian ages. The lithostratigraphic units describe the general evolution from a shallow, peritidal platform to deeper-water shelf environments, then the installation of a carbonate platform, and finally the drowning of this platform followed by the predominance of pelagic conditions. The common lateral and vertical changes in facies and sedimentation rates as well as numerous hiatuses within the formations testify to a complex interplay of tectonics, climate, and sea level that controlled the Swiss Jura realm during the Cretaceous.

Keywords Swiss Jura · Cretaceous · Lithostratigraphy · Geological maps

Résumé Dans le cadre du projet HARMOS du Service géologique suisse, les subdivisions lithostratigraphiques des roches sédimentaires crétacées du Jura suisse ont été nouvellement définies. De nouveaux noms de formation sont proposés pour remplacer quelques termes de faciès inadéquats. Dans certains cas, les conditions d'affleurement dans le Jura suisse ne permettent pas de lever des coupes complètes qui caractérisent les formations : des coupes en France voisine ont donc été choisies. Les formations (Fm.) suivantes sont définies pour décrire les unités lithologiques du Crétacé, de la base au sommet : Fm. du Goldberg, Fm. de Pierre-Châtel, Fm. de Vions, Fm. de la Chambotte, Fm. du Vuache, Fm. du Grand Essert, Fm. des Gorges de l'Orbe, Fm. de Vallorbe, Fm. de la Perte du Rhône, Fm. de Narlay. La datation des formations est basée sur la biostratigraphie (ammonites, échinides, algues dasycladales, foraminifères, calpionelles, dinocystes, nannofossiles). Ces fossiles indiquent des âges Berriasien à Coniacien. L'enchaînement des unités lithostratigraphiques résulte de l'évolution générale d'une plate-forme peu profonde, voire péritidale, vers des milieux d'eau plus profonde, suivie par l'installation d'une plate-forme carbonatée, et finalement l'ennoiement de cette plate-forme et la prédominance de conditions pélagiques. Des changements de faciès et de taux de sédimentation latéraux et verticaux ainsi que de

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nombreuses lacunes sont courants au sein des formations, ce qui indique une interaction complexe de changements tectoniques, climatiques et eustatiques qui contrôlaient l'évolution de la région du Jura suisse durant le Crétacé.

1 Introduction

The Swiss Geological Survey has initiated the HARMOS project in order to update and homogenise the lithostratigraphic nomenclature and the legends of the Swiss Geological Atlas 1:25,000 (see Strasky et al. 2016, this volume). At the same time, this was an occasion to revise the lithostratigraphic subdivisions forming the geological record in Switzerland.

Here, we present a revision and improvement of the lithostratigraphic scheme for the Cretaceous sedimentary deposits in the Swiss Jura Mountains. So far, several units have not been defined as formations complying with the recommendations of the International Commission on Stratigraphy (Salvador 1994) or of the Swiss Committee on Stratigraphy (Remane et al. 2005). For example, facies terms such as "Purbeckian" or "Urgonian" are still found in the legends and descriptions of many previously published geological maps. It is our goal to propose a coherent scheme that subdivides the Cretaceous sedimentary record into formations that can easily be identified in the field and that can be mapped at the 1:25,000 scale. Where appropriate, we also propose members that further subdivide the sediment stack and may be used as guide horizons in field mapping and in lateral correlation of logs (however, it is beyond the scope of this contribution to describe and formally define these members). Although the scheme basically focuses on lithostratigraphy, short chapters dealing with the dating of the units and the palaeogeographic evolution of the Jura realm are included.

2 Cretaceous formations

Cretaceous outcrops in the Swiss Jura Mountains are found only in the area southwest of Biel but extend into France towards the west and south (Fig. 1). While the Berriasian to Barremian sedimentary rocks are well represented over the entire area, the Aptian, Albian, and Late Cretaceous in the Swiss part of the Jura are visible only as isolated patches. For several formations, outcrop conditions in the Swiss Jura do not allow a full description; therefore, their type localities have been chosen in France. This is feasible because the overall lithologies of the formations involved are similar in nearby France, although the formation thicknesses and ages may change significantly. Some of the historical type localities are not accessible any more (abandoned quarries, vegetation cover) and it will be necessary to choose reference sections suitable for future detailed studies.

Figure 2 summarises the proposed scheme for the lithostratigraphic subdivisions of the Cretaceous in the Swiss Jura. The most common historical terms corresponding to these formations are listed in Table 1. It is important to note that the limits between the formations are not necessarily isochronous, that hiatuses are common, and that the age attribution of some units presented here is disapproved by some authors (see below). Figure 3 is a compilation of the formation thicknesses given in the descriptions to the maps of the Swiss Geological Atlas 1:25,000. In Fig. 4, the formations are plotted along the time axis and the ammonite zones (according to Hardenbol et al. 1998 and Reboulet et al. 2014). In the following, each formation is briefly characterised. Detailed information is also available in the on-line stratigraphic lexicon developed by the Swiss Committee on Stratigraphy and the Swiss Geological Survey (www.strati.ch). The coordinates of the type sections are given in Table 2.

2.1 Goldberg Formation

This formation was first defined in the area of Biel by Häfeli (1964, 1966), the type locality being in an abandoned quarry (Fig. 1; Table 2). It corresponds to the "Purbeck facies" of the western and southern Jura Mountains (Lory 1857). The formation overlies the Twannbach Formation (Häfeli 1966; Bläsi 1980), mostly of Tithonian age. The lower boundary of the Goldberg Formation has been originally placed above the "calcaire âpre" (Jaccard 1869; Häfeli 1966), a horizon with cornieule texture interpreted as the result of subaerial exposure (Rameil 2005). However, this boundary is often difficult to locate due to the poor outcrop conditions of the Goldberg formation. The Goldberg Formation is overlain by the Pierre-Châtel Formation, the base of which is commonly expressed as a sharp transgressive surface (Fig. 5a, b).

The deposits are characterised by alternations of limestone beds and marly layers, with locally a predominance of marls (usually leading to a morphological depression: "combe purbeckienne"). The thickness of the formation varies between 5 and 30 m, depending on the geographical location (Fig. 3). At Mount Salève (map 48, Genève), Lombard (1965) indicated 42–46 m, whereas Strasser and Hillgärtner (1998) measured only 23 m. This discrepancy is due to the difficulty of placing the boundary with the underlying Twannbach Formation that displays, at Salève, very similar lithologies.

Facies of the Goldberg Formation are extremely variable, representing lacustrine, tidal-flat, beach, hypersaline,

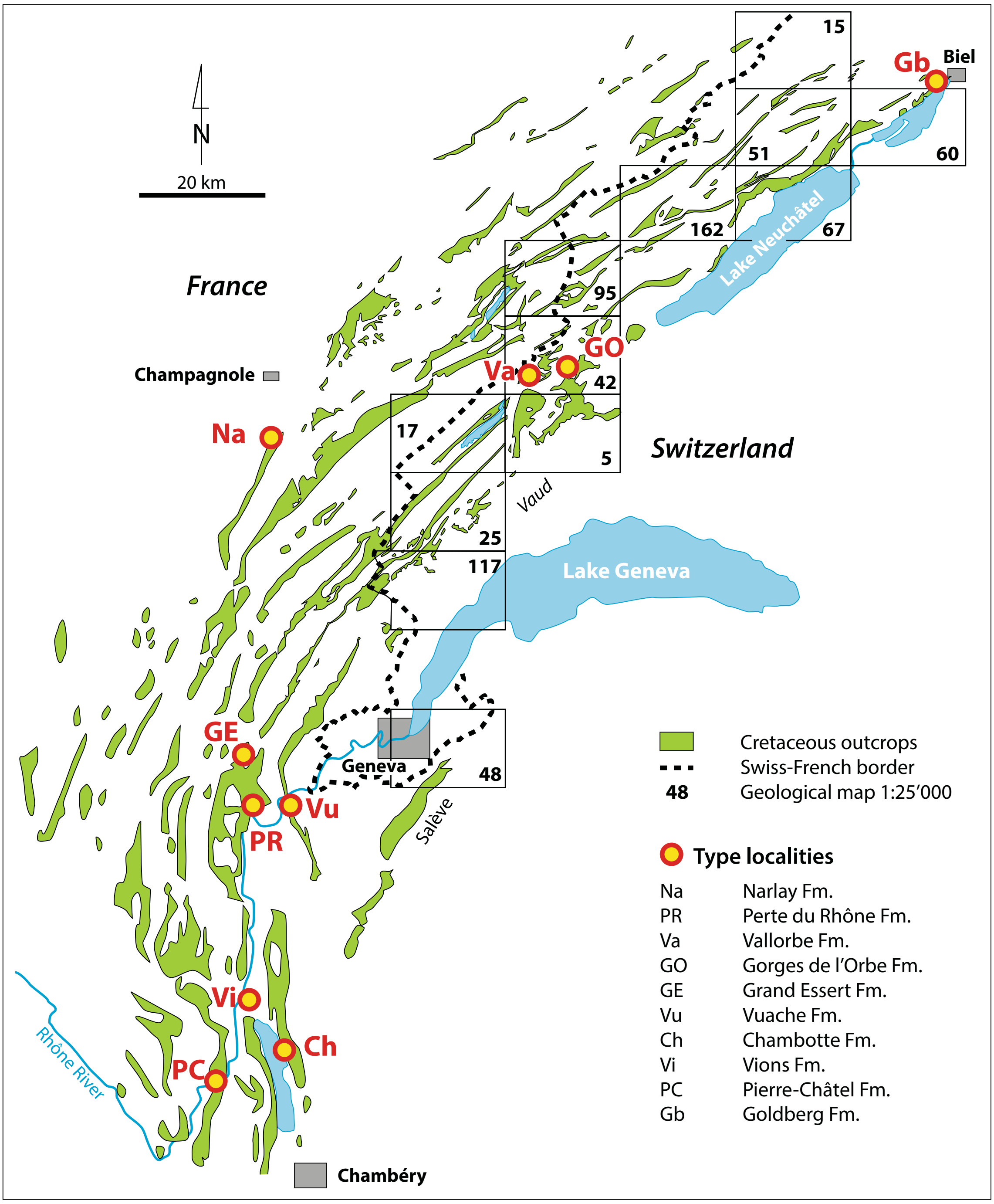
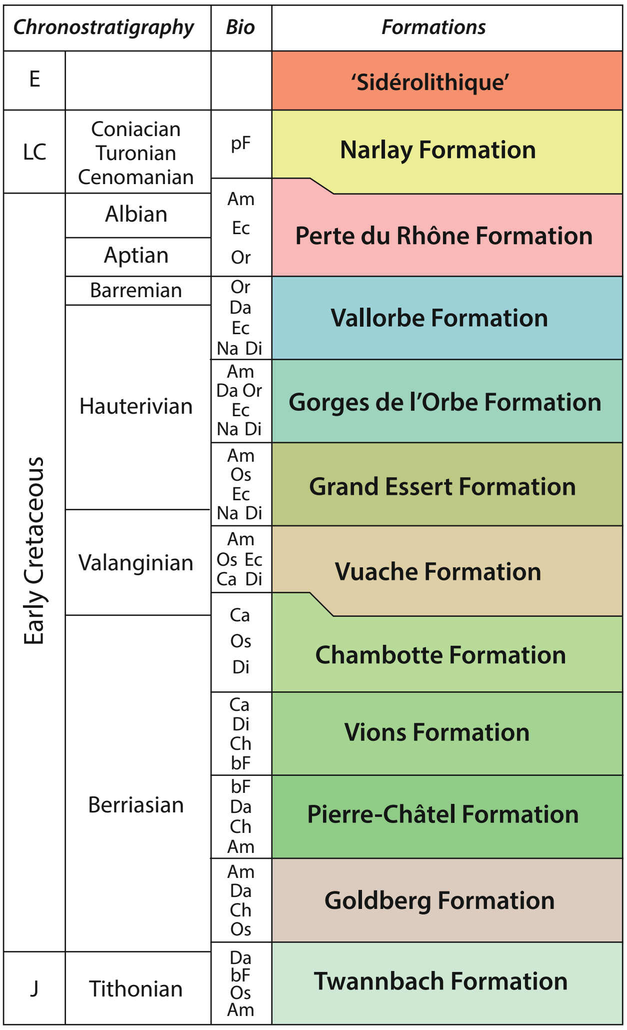


Fig. 1 Cretaceous outcrops in the Swiss and French Jura Mountains, compiled from the on-line geological maps supplied by the Swiss and French geological surveys (swisstopo and BRGM, respectively). The type localities of the formations and the positions of the maps listed in Fig. 3 are indicated

brackish, normal-marine lagoonal, ooid shoal, and bioclastic shoal environments. Periods of subaerial exposure are indicated by black pebbles and calcretes (Häfeli 1966; Strasser and Davaud 1983). Locally, the sediment is dolomitised and may contain evaporite pseudomorphs. Collapse breccias and conglomerates form marker horizons. The facies are arranged in small-scale shallowing-up sequences (Strasser 1988), and the hierarchical stacking of these sequences implies a control by orbital cyclicity in the Milankovitch frequency band (Strasser and Hillgärtner 1998).

The formation is dated by ammonites and ascribed to the Jacobi Zone of the early Berriasian and to the base of the



Am: ammonites; bF: benthic foraminifera; Ca: calpionellids; Ch: charophytes; Da: dasycladalean algae; Di: dinocysts; Ec: echinids; Na: nannofossils; Or: orbitolinids; Os: ostracodes; pF: planktonic foraminifera

Fig. 2 Lithostratigraphic nomenclature of Cretaceous formations in the Swiss Jura (colours correspond to the codes of the Swiss Geological Survey). Fossils important for biostratigraphy are indicated in the column "Bio". *J* Jurassic, *LC* Late Cretaceous, *E* Eocene. Vertical time axis not to scale (for the distribution of geological ages see Fig. 4). For the geographical distribution and completeness of the formations see Fig. 3 and text (this concerns mainly the Vions, Chambotte, and Vallorbe formations). Note that some stage boundaries are not always well defined in the sediment stack, and that formation boundaries may be diachronous (see text). The Chambotte Formation in the Swiss Jura ends in the latest Berriasian whereas in France it reaches into the earliest Valanginian. The top of the Perte du Rhône Formation, at its type locality in France, has a Cenomanian age, while in Switzerland this formation ends in the latest Albian

Subalpina Subzone (Clavel et al. 1986; Charollais et al. 2007, 2008). The base of the overlying Pierre-Châtel Formation belongs to the Subalpina Subzone of the Occitanica Zone (Charollais et al. 2007, 2008). In addition, Mojon and Strasser (1987) and Mojon (2002) have dated the formation with charophyte-ostracode assemblages (zones M1b, M2, and M3). Martin-Closas and Salas (1998) stated that the M3 zone corresponds to part of the Subalpina Subzone.

2.2 Pierre-Châtel Formation

The type locality of the Pierre-Châtel Formation is an abandoned quarry about 1 km to the west of Yenne (Savoie, France; Fig. 1; Table 2), where Steinhauser and Lombard (1969) gave a first description and formal definition.

The base of the formation is commonly marked by a sharp transgressive surface (Fig. 5a, b), which separates it from the underlying Goldberg Formation (Pasquier 1995; Tresch 2007; Tresch and Strasser 2010). The lower part of the formation commonly is dominated by metre-thick beds of bioclastic and/or oolitic grainstones and packstones, representing subtidal dunes ("Unité inférieure oolithique" of Steinhauser and Charollais 1971). Locally, this interval displays marly layers ("Mergel- und Kalk-Zone"; Häfeli 1964, 1966), which may contain charophytes, thus pointing to lacustrine episodes (Pasquier 1995; Tresch 2007). The upper part of the formation is characterised by packstones and wackestones reflecting a lagoonal depositional environment, but intervals of oolitic and bioclastic grainstones still occur ("Unité moyenne calcaire massive" of Steinhauser and Charollais 1971).

The term "Marbre bâtard" was introduced by Desor (1854) to describe the ensemble of today's Pierre-Châtel, Vions, and Chambotte formations (Table 1). Baumberger and Moulin (1899) and Baumberger (1901) then distinguished a lower, more marly part ("Zone des calcaires et marnes oolithiques gris") from the limestone-dominated "Marbre bâtard" above. The lower, marly interval thus corresponds to the "Mergel- und Kalk-Zone" of Häfeli (1964), whereas the limestone facies of the "Marbre bâtard" includes the "Unité inférieure oolithique" and the "Unité moyenne calcaire massive" as well as the Vions and Chambotte formations.

Locally, the top of the Pierre-Châtel Formation is defined by a karstic surface and/or by a hardground, implying subaerial exposure and condensation (Pasquier 1995; Hillgärtner 1999). In the region of Biel, Blanc and Mojon (1996) described a breccia resulting from the collapse of a karstic cave. Some surfaces within the Pierre-Châtel Formation contain dinosaur footprints (Pasquier 1995; Charollais et al. 2007).

In outcrop, the formation commonly forms a massive, yellow-reddish limestone cliff (Fig. 6b). At the type locality it measures 33 m, but the thickness varies from 42 m at Val de Fier in the south-southwest to 14 m at Biel in the northeast (Steinhauser and Charollais 1971; Pasquier 1995).

The base of the Pierre-Châtel Formation is dated by ammonites from the Subalpina Subzone of the middle

Table 1 Historical terminology of lithostratigraphic units in the Cretaceous of the Swiss and French Jura Mountains. Only the most common terms are listed, and only the authors of the first introduction of the name of the unit are indicated

Formations presented in this paper	*Older terminology corresponding to these formations*	*Smaller units within the formations*	
Narlay	Calcaires crayeux blancs (Guillaume 1966)	Rotomagien (Renevier 1868)	
Perte du Rhône		Vraconnien s.str. (Renevier 1868) Albien gréseux à petites huîtres (Renz and Luterbacher 1965) Albien pyriteux (Renz and Luterbacher 1965) Albien sableux (Renz and Luterbacher 1965) Aptien gréseux (Renz and Luterbacher 1965)	Vraconnien (Renevier 1868)
		Rhodanien (Renevier 1855)	
Vallorbe	Calcaire de Noirvaux-Dessus (Marcou 1959), Urgonien supérieur (Desor and Gressly 1859), Urgonien blanc (Custer 1928)	Calcaires marneux de la Rivière (Conrad 1969) Marne de la Russille (Conrad 1969)	Roches de Mauremont (Marcou 1859)
Gorges de l'Orbe	Calcaire jaune urgonien (Campiche and De Tribolet 1858), Urgonien inférieur (Desor and Gressly 1859), Russilien (Schardt and Dubois 1903), Urgonien jaune (Bertschy 1958)	Marnes et calcaires jaunâtres à échinodermes (Jaccard 1869)	
Grand Essert		Pierre jaune de Neuchâtel (Marcou 1859), Marnes des Uttins (Jordi 1955)	
		Marnes d'Hauterive (Montmollin 1835)	
Vuache	Calcaire roux (Jaccard 1861), Formation du Bourget (Steinhauser and Lombard 1969)	Couches à bryozoaires (De Tribolet 1859), Couche à *Astieria* (De Tribolet 1859), Calcaire à *Alectryonia rectangularis* (Schardt 1891)	
		Marnes d'Arzier (De Loriol 1868)	
Chambotte	Chambotte (Steinhauser and Lombard 1969)	Calcaire du Val de Fier (Mouty 1966), Chambotte inférieure - Membre du Guiers - Chambotte supérieure (Steinhauser and Lombard 1969)	Marbre bâtard (Desor 1854)
Vions	Couches de la Corraterie (Mouty 1966)	Unité supérieure gréseuse (Steinhauser and Charollais 1971)	
Pierre-Châtel		Calcaire de Thoiry (Mouty 1966), Unité moyenne calcaire massive (Steinhauser and Charollais 1971)	
		Marnes valanginiennes (Desor and Gressly 1859), Zone des calcaires et marnes oolithiques gris (Baumberger and Moulin 1899), Mergel- und Kalk-Zone (Häfeli 1964), Unité inférieure oolithique (Steinhauser and Charollais 1971)	
Goldberg	Dubisien (Desor and Gressly 1859), Marnes de Villers-le-Lac (Marcou 1859), Purbeckien (Lory 1857)		

Berriasian Occitanica Zone (Charollais et al. 2007, 2008). According to the same authors, the base of the overlying Vions Formation provided ammonites and calpionellids, which place it in the Paramimounum Subzone (Boissieri Zone, late Berriasian).

2.3 Vions Formation

This formation was formally defined by Steinhauser and Lombard (1969) at the Mollard de Vions (Savoie, France), 3 km SE of Culoz (Fig. 1; Table 2). In the area of Neuchâtel, the "Unité supérieure gréseuse" of Steinhauser and Charollais (1971) corresponds to the lower part of the formation, the top having been eroded. The comparatively marly lithologies commonly form a depression between the limestone cliffs of the Pierre-Châtel and Chambotte formations (Fig. 6b, c). The thickness of the formation varies between 50 and 19 m. It pinches out towards the northeast of the Jura chain and is no longer present in the area of Biel (Fig. 3).

The individual beds (10 cm to 1.2 m thick) are dark-coloured due to the presence of quartz sand, iron oxides and hydroxides, and organic matter. The facies are variable and include claystones, sandy marls, sandy marly limestones, and oolitic and bioclastic limestones. Bioturbations (*Thalassinoides*) are common, creating nodular bedding surfaces. Coal seams and root traces appear locally. Charophytes and freshwater or brackish-water ostracodes point to the occasional presence of coastal lakes.

The base of the formation contains ammonites (*Mazenoticeras broussei*, *Picteticeras* gr. *moesica-jauberti*) and calpionellids (*Tintinnopsella carpathica*), ascribing it to the late Berriasian Paramimounum Subzone (Clavel et al. 1986; Bulot 1995; Charollais et al. 2007). Calpionellids from the middle part of the formation indicate the Picteti and Alpillensis subzones (Zaninetti et al. 1988; Bulot 1995; Charollais et al. 2007, 2008). The base of the formation is commonly characterised by an echinoderm-

Formations / Maps (SSW → NE)	48 Genève Lombard (1965)	117 Nyon Arn et al. (2005)	25 Les Plats Marchairuz... Falconnier (1951)	17 Vallée de Joux Aubert (1941)	5 Mont-la-Ville La Sarraz... Custer (1935)	42 Orbe Aubert (1963)	95 Ste-Croix Rigassi (2011)	162 Travers Pasquier et al. (2013)	67 Neuchâtel Meia & Becker (1976)	51 Val de Ruz Suter & Lüthi (1969)	15 Biaufond Les Bois ... Bourquin (1946)	60 Bieler See Schär (1971)
Narlay			Cénomanien (small outcrop)	Cénomanien (small outcrops)			Cénomanien - Albien tardif (small outcrops)	Cénomanien (small outcrops)				Cenoman-Kalke (small outcrop, 20)
Perte du Rhône			Gault (small outcrop)	Aptien - Albien (small outcrops)	Aptien - Albien (small outcrops)	Aptien (small outcrops)	Albien moyen - Aptien (small outcrops)	Aptien - Albien (small outcrops)				
Vallorbe	Faciès urgonien (110-115)	Urgonien blanc (50)	Urgonien (100)	Urgonien (50-60)	Urgonien supérieur (10-15)	Urgonien (40)	Barrémien (80-100)	Urgonien blanc - M. de la Russille - Urgonien jaune (?)	Urgonien blanc - Urgonien jaune (25-30)	Urgonien blanc (10)		Urgonien (?)
Gorges de l'Orbe		Urgonien jaune (10-20)		Barrémien inférieur (30)	Urgonien inférieur (15-20)	Barrémien inférieur (30)				Urgonien jaune (10-20)		
Grand Essert	P. j. N. (35) Marnes (58-60)	P. j. N. (40-45) M. d'H. (20)	P. j. N. (40-70) M. d'H. (20-30)	P. j. N. (40-50) M. d'H. (40)	P. j. N. (20) M. d'H. (65)	P. j. N. (30-40) M. d'H. (40)	P. j. N. (40-50) M. d'H. (30-35)	P. j. N. (50) M. d'H. (25)	P. j. N. (50-70) M. d'H. (15-20)	P. j. N. - Unteres Hauter. (20-50)	P. j. N. - M. d'H. (20-50)	P. j. N. - M. d'H. (20-60)
Vuache	Calcaire roux (44)	Calcaire roux s.l. Marnes d'Arzier (40)	Calcaire roux Marnes d'Arzier (30-60)	Calcaire roux (20-30)	Calcaire roux Marnes d'Arzier (15-35)	Calcaire roux (20-30)		Calcaire roux Marnes d'Arzier (15)	Calcaire roux Marnes d'Arzier (12-15)			
Chambotte	Marbre bâtard (25)	Chambotte (10-17)					Calcaire roux - Marbre bâtard (50-60)			Calcaire roux - Marbre bâtard (25-55)	Calcaire roux - Marbre bâtard (25-50)	Calcaire roux - Marnes d'Arzier - Marbre bâtard - Mergel- und Kalkzone (40-50)
Vions	Couches de la Corraterie (50)	Vions (39)	Berriasien (80-100)	Berriasien (50-80)	Berriasien (60)	Berriasien (40)		Vions - Pierre-Châtel (40)	Marbre bâtard (40)			
Pierre-Châtel	Calcaire de Thoiry (22)	Pierre-Châtel (23)										
Goldberg	Purbeckien (42-46)	Goldberg (25-30)	Purbeckien (30)	Purbeckien (25)	Purbeckien (12-30)	Purbeckien (5-30)	Purbeckien (20-30)	Goldberg (25)	Purbeckien (10-20)	Purbeckien (10-12)	Purbeckien (10-12)	Purbeckien (10-15)

Fig. 3 Compilation of nomenclature and thicknesses (metres in parenthesis) of the Cretaceous formations according to the published descriptions to selected maps of the Swiss Geological Atlas 1:25'000. On some maps, two or more formations have been grouped together if their limits cannot be defined in the field. For the geographical position of the maps see Fig. 1. M. d'H. Marnes d'Hauterive; P. j. N. Pierre jaune de Neuchâtel

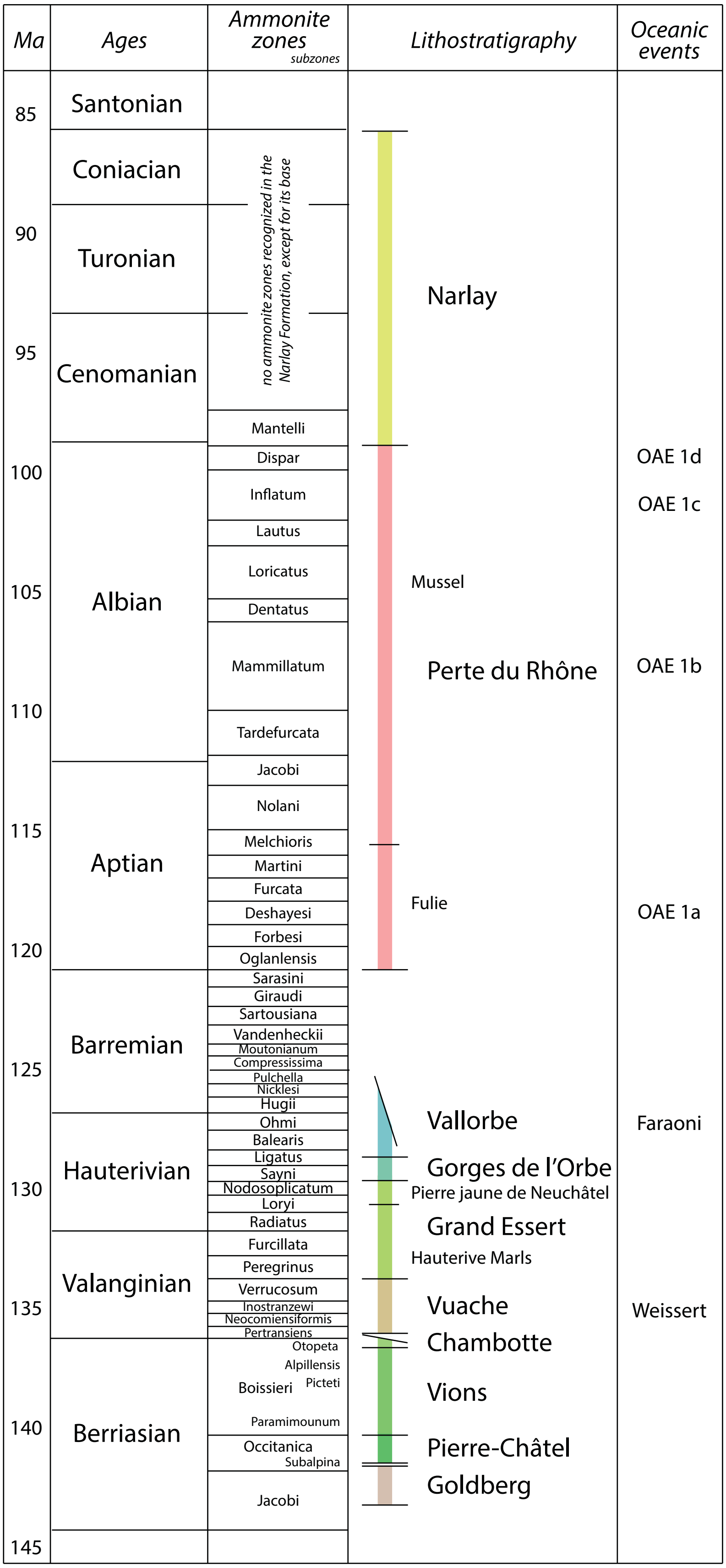


Fig. 4 Distribution of the formations along the time axis, their calibration on ammonite zones, and major oceanographic events. Note the very unequal durations. The Poncin Member of the Perte du Rhône Formation is not indicated, as it does not occur in Switzerland. Ages and ammonite zones from the Berriasian to the middle Albian according to Reboulet et al. (2014), from the late Albian to Santonian according to Hardenbol et al. (1998). Only the subzones mentioned in the text are indicated. The approximate timing (in Ma) is taken from Hardenbol et al. (1998) for the whole column (Reboulet et al. 2014 did not furnish a time scale). Although a newer chronostratigraphic scale is available (www.stratigraphy.org), the one of Hardenbol et al. (1998) is retained because it contains the ammonite zones

Table 2 Coordinates of the bases of the type sections and their locations (CH: Swiss coordinates MN95; F: French coordinates Lambert 2 extended)

Formation	*Coordinates*	*GPS WGS84 °*	*Topographic map 1:25'000*	*Location*
Narlay	F 873 386 / 2188 122	5.9086 E 46.6372 N	IGN 3326 ET	Along road D75 south of Lake Narlay
Perte du Rhône	F 868 880 / 2128 620	5.8154 E 46.1042 N	IGN 3330 OT	Below pillar of motorway A40, west of Bellegarde-sur-Valserine
Vallorbe	CH 2517'840 / 1173'900	6.3641 E 46.7112 N	1202 Orbe	Cliff behind the Vallorbe train station
Gorges de l'Orbe	CH 2527'840 / 1175'680	6.4946 E 46.7284 N	1202 Orbe	Along footpath in the Orbe valley, southwest of Montcherand
Grand Essert	F 870 122 / 2138 208	5,8370 E 46,1899 N	IGN 3328 OT	Along road D991 on the left side of the Valserine valley
Vuache	F 875 263 / 2130 328	5.8989 E 46.1170 N	IGN 3330 OT	Along road D908a between Chevrier and Arcine
Chambotte	F 874 342 / 2093 469	5.8656 E 45.7861 N	IGN 3331 OT	Along road 991B from Chindrieux to Chambotte,
Vions	F 869 479 / 2098 727	5.8061 E 45,8353 N	IGN 3331 OT	Abandoned quarry 1 km north of Vions, along small road east of Le Mollard
Pierre-Châtel	F 865 464 / 2084 065	5,7463 E 45,7051 N	IGN 3332 ET	Abandoned quarry along road 521B, 1 km W of Yenne
Goldberg	CH 2583'830 / 1220'320	7.2254 E 47.1336 N	1125 Chasseral	Abandoned quarry close to road Biel - Vingelz

rich limestone containing the large benthic foraminifer *Pavlovecina (Keramosphaera) allobrogensis.*

2.4 Chambotte Formation

Steinhauser and Lombard (1969) formally defined this formation along road 991B close to Saint-Germain-la-Chambotte (Savoie, France; Fig. 1; Table 2). The formation generally consists of a massive, whitish limestone complex, with bed thicknesses ranging from a few tens of centimetres to a few metres (Fig. 5c, f). Locally in France, however, it is subdivided by the marly Guiers Member into a lower and an upper part (Steinhauser and Lombard 1969; Figs. 5e, 6a). The complete formation is visible only south of Seyssel (France); its upper part is absent farther to the north of the type locality, and in the Swiss Jura it is entirely missing. The best explanation for this fact is that the Jura platform was tectonically tilted during or after the deposition of the upper part of the Chambotte Formation, leading to its non-deposition and/or erosion in the northern part of the platform (Fig. 3; Steinhauser and Charollais 1971).

The facies contain ooids and bioclasts and represent a shallow-marine environment with high-energy shoals and lagoons. The lower part of the formation may be dolomitised. Locally, a palaeokarst infill below the top of the lower Chambotte Formation yielded a brackish to freshwater malacofauna as well as teeth of dwarfed crocodiles, implying an important drop in relative sea level (Mojon 2006).

The age attribution is provided by calpionellids (*Tintinnopsella carpathica*, *Calpionellites darderi*; Deville 1991) and dinocysts (*Muderongia macwahaei* forma A, B; Monteil 1992). The base of the formation is placed in the latest Berriasian (Otopeta Subzone). At the type locality in France, the top of the formation is in the Valanginian Pertransiens Zone. In the Swiss Jura, however, where the upper part of the formation is missing, only the Otopeta Subzone is represented (Charollais et al. 2008).

2.5 Vuache Formation

The reddish Valanginian sedimentary rocks in the Jura Mountains are commonly described as "Calcaires roux" (Jaccard 1861). In order to replace this facies term, the new Vuache Formation is proposed. The type locality extends along road D908a, on the northern termination of Mount Vuache (Haute-Savoie, France; Figs. 1, 7a; Table 2). Separately, a complete section has been logged in the tunnel of motorway A40 passing through this mountain (Charollais, unpublished data; a detailed description of the formation is in preparation).

The Vuache Formation measures 36 m at the type locality, but its thickness varies from about 10 to 60 m along the Jura chain (Fig. 3). It is characterised by typically reddish limestone beds (cm to tens of cm thick) that in many cases display hummocky and swaley cross-stratification implying storm activity (Fig. 7b). The facies are bioclastic and oolitic packstones to grainstones rich in echinoderm and bryozoan fragments (a predominantly heterozoan assemblage). Locally, some glauconite is present, while quartz grains are rare. Chert layers occur in the region of the type locality. The depositional environment was that of an open shelf.

Fig. 5 **a** Sharp contact between the soft, marl-dominated Goldberg Formation below and the massive limestone cliff of the Pierre-Châtel Formation above (along road 521B west of Yenne). **b** Contact between the Goldberg Formation below and the Pierre-Châtel Formation above (abandoned quarry at Rusel southwest of Bienne, 1.5 km southwest of the type locality of the Goldberg Formation). **c** Top of the Vions Formation and base of the Chambotte Formation at Mount Salève. The soft, retreating contact is where the Corraterie trail passes. **d** Contact between the softer Vions Formation below and the massive limestone beds of the Chambotte Formation above (along road 991B from Chindrieux to Chambotte). **e** Top of the lower part of the massive Chambotte Formation below and the softer Guiers Member above (along the road from Chindrieux to Chambotte). **f** Top of the Chambotte Formation (at the level of the hammer). The overlying marly interval is the equivalent of the Arzier Marls, followed by the reddish limestones of the Vuache Formation (along the road from Chindrieux to Chambotte). Hammer is 33 cm long

In the area of the type locality, the base of the formation contains a 2–3 m thick marly, oolitic, and fossiliferous interval (Charollais et al. 2013), which, in a quarry close to St.-Cergue (Swiss Jura), measures 5.7 m and has been described as the "Marnes d'Arzier" (De Loriol 1868; Jaccard 1869; Arn et al. 2005). In the southern Jura, the top of the

Fig. 6 **a** Type locality of the Chambotte Formation, along road 991B from Chindrieux to Chambotte (looking north). The massive limestone beds in the cliff are the lower and upper parts of the formation, separated by the softer Guiers Member. **b** Type locality of the Pierre-Châtel Formation in the Défilé de Pierre Châtel west of Yenne (looking north). The lower limestone cliff represents the Pierre-Châtel Formation, the upper one the Chambotte Formation. The softer Goldberg and Vions formations below and above the lower cliff are covered by trees. **c** Type locality of the Vions Formation, on the northern side of the hill next to the hamlet of Vions (looking south)

formation displays the thin, condensed *Alectryonia rectangularis* limestone ("Calcaire à *Alectryonia rectangularis*"; Schardt 1891), which is rich in oysters, brachiopods, crinoids, bryozoans, serpulids, and sponges. Towards the north, this horizon grades laterally into bryozoan-rich marls ("Couches à bryozoaires"; De Tribolet 1859; Jordi 1955) and nodular, fossil-rich marls ("Couche à *Astieria*"; De Tribolet 1859; Baumberger 1901; Frei 1925).

The main part of the Vuache Formation is dated as early Valanginian by ammonites (Baumberger 1901, 1903–1910), ostracodes, echinids, and calpionellids (Busnardo and Thieuloy 1989; Deville 1990; Blondel 1990; Charollais et al. 1983, 1989, 2008, 2013a). Specifically, the "Marnes d'Arzier" at the base of the formation have furnished dinocysts (*Muderongia macwahaei* forma B), which correspond to the Pertransiens ammonite zone (Monteil 1992, 1993; Leereveld 1997). This is confirmed by the ammonite *Thurmanniceras thurmanni* cited by Bulot (1995). The typical reddish facies of the Vuache Formation, as dated by ammonites and dinocysts, belong to the Pertransiens and Neocomiensiformis zones (Charollais et al. 2008; Jan du Chêne et al. 2016), while the top of the formation (i.e., the *Alectryonia rectangularis* limestone and its lateral equivalents) is situated at the transition between the Verrucosum and Peregrinus ammonite zones (Charollais et al. 2008).

2.6 Grand Essert Formation

This new formation is proposed to group together the facies terms "Marnes d'Hauterive" (Montmollin 1835) and "Pierre jaune de Neuchâtel" (Marcou 1859). The type locality is an outcrop along road D991 on the left side of

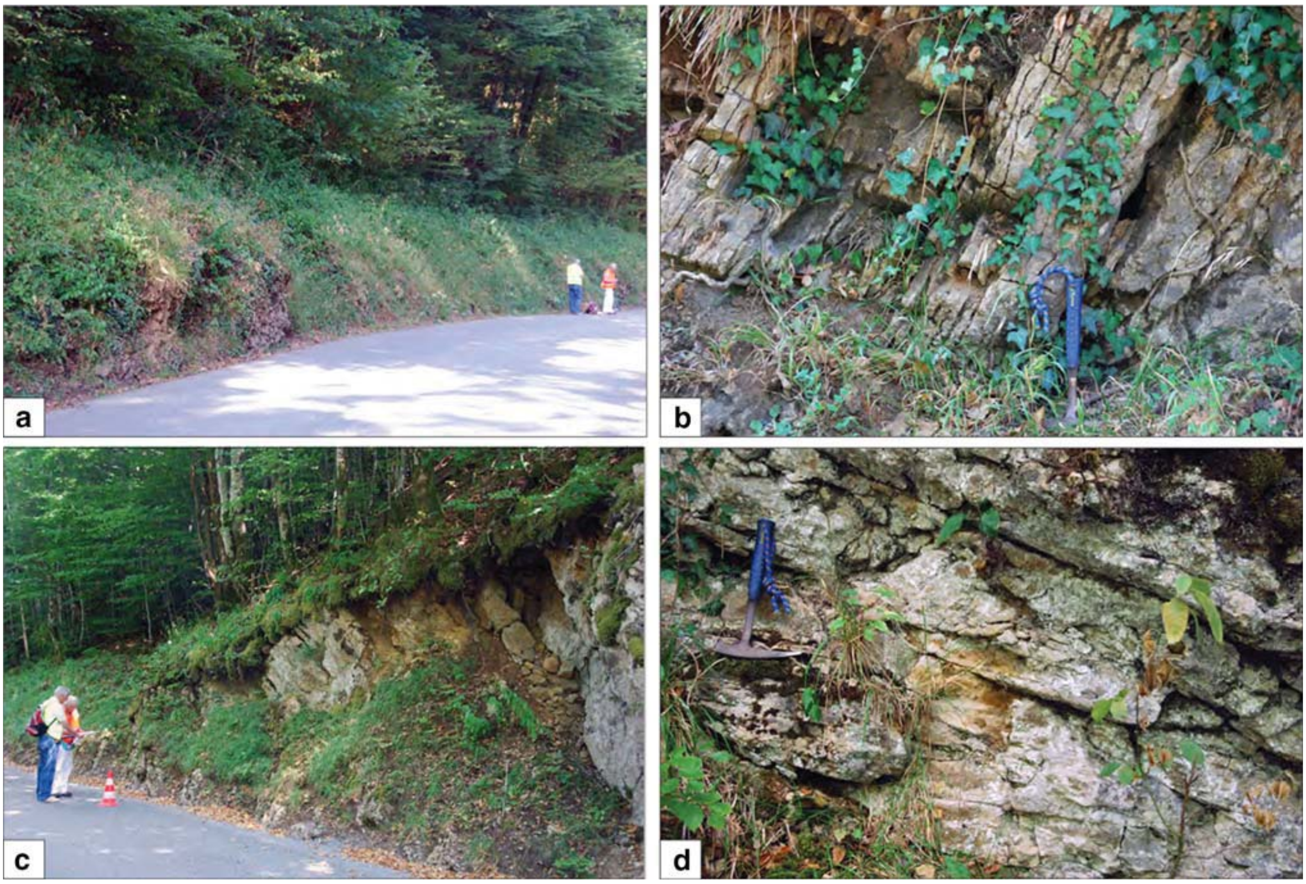


Fig. 7 **a** Type locality of the Vuache Formation along road D908a, looking west. The limestone beds crop out well while the marly intervals are covered by vegetation. **b** Thinly bedded, reddish limestones at the type locality of the Vuache Formation displaying swaley cross-stratification (to the *left of hammer*). Top of section is towards the *left*. **c** Type locality of the Grand Essert Formation along road D991, looking north. Limestone beds are well visible but marly intervals are covered. The picture shows the upper part of the formation: the Marnes des Uttins to the *left* (behind the geologists), the upper part of the Pierre jaune de Neuchâtel to the *right*. **d** Sandwave (*below* and to the *right* of hammer) composed of yellowish grainstones. Lower part of the Pierre jaune de Neuchâtel Member at the type locality of the Grand Essert Formation. Hammer is 33 cm long

the Valserine Valley (Ain, France; Fig. 1; Table 2). Its thickness at the type locality is 90 m but diminishes to some 20 m towards the north of the Jura (Fig. 3). The section was first logged by Mouty (1966). A detailed description of the formation is in preparation.

The Grand Essert Formation is subdivided into two distinct lithological units. The lower unit, the Hauterive Marls with member rank, is composed of about 40 m (at the type locality) of fossil-rich limestone-marl alternations usually forming a topographical depression. The marls are brownish-blue-grey and rich in detrital quartz, while the limestone beds are yellowish-grey, nodular, and rich in quartz grains and glauconite. These sediments were deposited in an open-marine setting below the influence of waves and tidal currents.

The upper unit, which we propose to call the Pierre jaune de Neuchâtel with member rank, commonly forms a cliff (Fig. 7c). At the new type locality of the Grand Essert Formation, this member measures about 50 m. It is characterised by decimetre- to metre-thick, yellowish-greenish, cross-bedded (Fig. 7d), bioclastic and oolitic limestone beds with detrital quartz and some glauconite. The sedimentary structures (sand waves) indicate the influence of strong tidal currents. The Pierre jaune de Neuchâtel is informally subdivided into a lower and an upper part by a marly bed, the “Marnes des Uttins” (“Marnes à *Eudesia semistriata* auct.”; Jordi 1955). This bed measures some 4 m in the Neuchâtel area but reaches 15 m in the type section of the Grand Essert Formation.

At the type locality, a late Valanginian to Hauterivian age is indicated by ammonites, echinids, ostracodes, dinocysts, and nannofossils (Mouty 1966; Clavel et al. 2007). This is confirmed by biostratigraphic data in the neighbouring regions (Charollais et al. 2013a; Mojon et al. 2013). The Hauterive Marls start in the late Valanginian Peregrinus Zone and reach up into the early Hauterivian Loryi Zone (the upper part of the Peregrinus Zone and the Furcillata Zone are condensed). The Pierre jaune de

Neuchâtel covers the upper part of the Loryi Zone and the Nodosoplicatum Zone.

2.7 Gorges de l'Orbe Formation

This new formation is proposed to replace facies terms such as "Urgonien jaune", "Urgonien inférieur" or "Russillien" (Desor and Gressly 1859; Schardt and Dubois 1903; Bertschy 1958). The type locality is well exposed on a 1.4 km-long natural outcrop extending on both sides of the Orbe river valley, southwest of Montcherand (Figs. 1, 8a; Table 2). The first, detailed description of this locality was given by Conrad and Masse (1989a). Later on, the same interval was also partly sampled by Blanc-Alétru (1995).

Towards the northeast in Canton Neuchâtel, the Gorges de l'Orbe Formation and the underlying Pierre jaune de Neuchâtel (the upper member of the new Grand Essert Formation) may be difficult to distinguish in the field: they are separated by a hardground but display a similar facies with various amounts of ooids (e.g., Blanc-Alétru 1995). In the opposite direction, the distinction between the two units is unambiguous (Fig. 8a). The thickness of the Gorges de l'Orbe Formation is 56 m at the type locality but, according to the published maps, varies laterally between 10 and 30 m (Fig. 3).

The lithology consists of decimetre- to metre-thick beds of a slightly argillaceous limestone, separated by millimetre- to centimetre-thick marly interbeds. The limestone is gray-blue when freshly broken, yellowish upon alteration, typically nodular (Fig. 8b), planar or cross-bedded, commonly bioturbated, channelised, and presenting truncated surfaces. The texture is bioclastic, showing partly oolitic grainstones or packstones (the amount of ooids increases laterally towards the northeast). Detrital quartz and glauconite remain minor components. The biota, in situ or transported, is typical of shallow-water to deeper open-marine habitats: brachiopods, bivalves, echinids, crinoids, displaced colonies of scleractinians, bryozoans, sponges, foraminifera including orbitolinids, dasycladalean algae, and other algae of uncertain affinities.

The Gorges de l'Orbe Formation contains several conspicuous marly levels. One of these has been named "Marne de la Russille" by Jaccard (1869; the type-locality west of La Russille is now covered by thick artificial deposits). This term has been taken up by Conrad and Masse (1989a) and Blanc-Alétru (1995) to describe a 2.5-m argillaceous interval now placed at the base of the Vallorbe Formation.

Assemblages of orbitolinids and dasycladalean algae were collected in the type locality (e.g., algal associations A1, A2 and A3; Conrad and Masse 1989b) and in several other surface and subsurface locations in Cantons Vaud and Neuchâtel. They indicate a late Hauterivian age for the Gorges de l'Orbe Formation. This is confirmed by Clavel et al. (1997, 2007, 2013, 2014) who assign it to the Sayni Zone and the lower part of the Ligatus Zone. An ammonite (gr. *Lyticoceras*/*Cruasiceras*) found at the base of the formation by Mouty (1966) equally indicates the Sayni Zone (Clavel et al. 2007). In the borehole of Morand (Canton Vaud), dinocysts have been recovered in marly levels at the base of the formation: they also indicate the late Hauterivian (Jan du Chêne et al. 2016).

2.8 Vallorbe Formation

This new formation is named to replace terms such as "Urgonien supérieur" or "Urgonien blanc" (Desor and Gressly 1859; Custer 1928). The type locality is a steep cliff located close to the Vallorbe railway station (Figs. 1, 8c; Table 2). A first description of this outcrop was published by Nolthenius (1921); then it was studied in detail by Conrad and Masse (1989a) and Blanc-Alétru (1995). At the type locality, the Vallorbe Formation corresponds to the 68 m-thick interval measured from a hardground surface at the top of the Gorges de l'Orbe Formation to the terminal hardground below 20 cm of yellowish clay at the base of Aptian deposits. Laterally, the thickness varies between 60 and 10 m (Fig. 3).

The lithology consists of decimetre- to metre-thick massive beds of white or light yellowish limestone commonly containing rudist debris, separated by planar, in places stylolitic joints. Locally, cross-bedded layers occur, implying tidal or storm activity, as well as breccias of inter- or supratidal origin. The texture is usually bioclastic, including grainstones, packstones, and wackestones. The biota consists of rudists and other bivalves, rare echinoderms, foraminifera including orbitolinids, and dasycladalean algae, all typical of a shallow, platform-interior marine environment.

The Vallorbe Formation is dated by orbitolinids, echinids, and dasycladalean algae calibrated on ammonite zones (Charollais et al. 2008). In the Jura west of Geneva, it ranges from the late Hauterivian Ligatus Zone to the Nicklesi Zone of the early Barremian (Clavel et al. 2014); at Vallorbe it is late Hauterivian (Ligatus to Angulicostata = Ohmi zones; Clavel et al. 1997); in the northern Jura, the age of the formation is late Hauterivian *pro parte*, including the Ligatus to Balearis zones (Clavel et al. 2014). The "Marne de la Russille", newly defined to form the base of the Vallorbe Formation, is dated by orbitolinids, dasycladalean algae, nannofossils, and dinocysts and attributed to the Ligatus Zone (Clavel et al. 2014). While the base of the formation is approximately isochronous in the Jura realm considered here (i.e., Ligatus Zone), its top is strongly diachronous due to non-deposition and/or

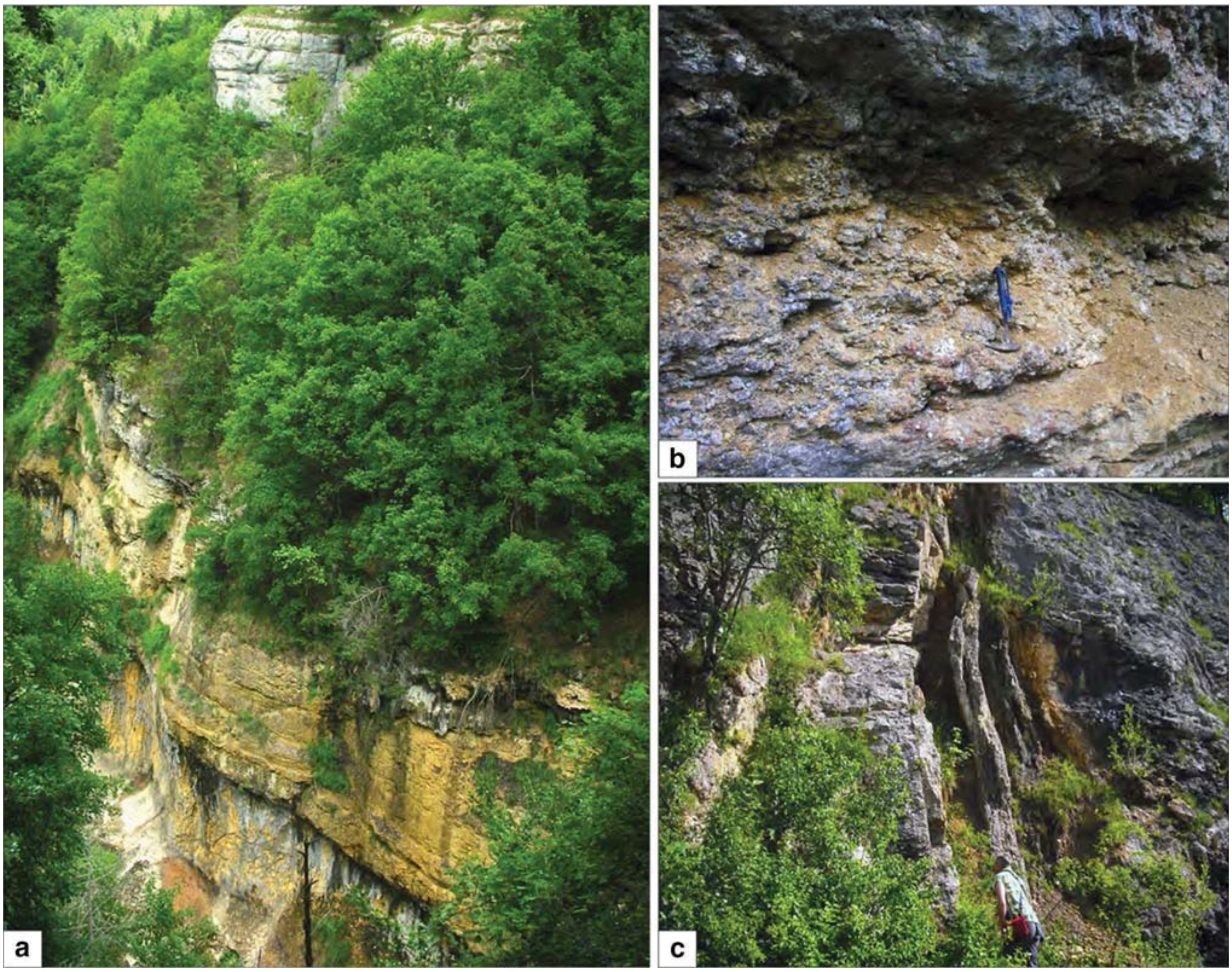


Fig. 8 **a** Gorges de l'Orbe Formation (*dark yellow*, upper part of the cliff below the trees) at the type locality, the northern flank of the east–west running Orbe river valley. The boundary with the underlying, *light yellow* and softer Pierre jaune de Neuchâtel unit of the Grand Essert Formation is sharp. **b** Nodular, *yellow-grey*, marly limestones of the Gorge de l'Orbe Formation (location is along the footpath following the southern flank of the valley). Hammer is 33 cm long. **c** Top of the Gorges de l'Orbe Formation to the *left*, followed by the limestone-marl alternations of the Marne de la Russille (sensu Conrad and Masse 1989a), and then by the lower part of the Vallorbe Formation to the *right*. Type locality of the Vallorbe Formation

erosion (which explains the diminishing thickness from SSW to NE; Fig. 3). The predominantly late Hauterivian age, however, is questioned by Godet et al. (2011, 2013) who advocate a late Barremian age.

2.9 Perte du Rhône Formation

Outcrops representing Aptian and Albian sedimentary rocks in the Swiss Jura are rare and continuous sections even more so. In the Swiss part of the Jura Mountains, isolated outcrops were described for example at La Presta in the Val de Travers (Frey 1922; Pasquier et al. 2013) and at La Vraconne in the region of Sainte-Croix, where Renz and Luterbacher (1965) compiled a schematic section, including the historically important, fossil-rich "Vraconnien s.str." (Renevier 1868). A new type locality with a complete, composite section (25 m thick) has been proposed by Michel Delamette and Antoine Pictet at the Perte du Rhône close to Bellegarde-sur-Valserine (Ain, France; Fig. 1; Table 2). This locality has previously been described in detail by Renevier (1855), then by Jayet (1927). More recently, a complete section has been logged by M. Delamette in a hole dug for a pillar of the motorway A40 but is not accessible anymore; however, isolated outcrops (Fig. 9a, b) now allow for assembling a complete section. A detailed characterisation of the formation is presented by Pictet et al. (2016, this volume).

The Perte du Rhône Formation comprises three dominant facies complexes, which qualify as members. The lower complex is more marl-dominated (corresponding to the ancient term "Rhodanien"; Renevier 1855). It starts with shallow-water platform sediments rich in gastropods (*Harpagodes pelagi*) and echinids (*Heteraster oblongus*, typical of the early Aptian), but which also delivered an ammonite (*Deshayesites* gr. *saxbii*; Martin-Closas et al. 2009). The overlying marls are dominated by an open-marine fauna including ammonites (*Deshayesites* gr. *grandis*, *Dufrenoyia furcata*, *Epicheloniceras martini*, and *Parahoplites melchioris*; Renz and Jung 1978) and nautilids (*Eucymatoceras* sp. aff. *plicateum*). The middle part of the Perte du Rhône Formation is dominated at its type locality by glauconite-rich sandstones ("Aptien gréseux", "Aptien sableux", "Albien gréseux à petites huîtres", "Vraconnien s.str."). Its Aptian part formed in a shallow-water environment, while the Albian part represents an open-marine environment containing rich ammonite assemblages. The uppermost early and early middle Albian is represented by marls, which are more developed in the Swiss part of the Jura Mountains (up to 30 m thick), and which contain pyritized ammonites ("Albien pyriteux"). The third, upper part of the formation is a mica-rich sandstone with variable amounts of glauconite. This unit is present only in the southern French Jura. It passes laterally (northwards) and upwards into the Narlay Formation.

The lower part of the formation is newly classified as the Fulie Member, the middle part as the Mussel Member, and the upper part as the Poncin Member (Pictet et al. 2016). The "Vraconnien s.str." is considered as part of the Mussel Member, despite of its historical and biostratigraphical importance. The section contains numerous discontinuities expressed by erosion surfaces and hardgrounds (Fig. 9b).

The richness in ammonites allows for a detailed biostratigraphic calibration (Renz and Luterbacher 1965; Pictet et al. 2016). Consequently, the Fulie Member covers the earliest Aptian Oglanlensis to the late Aptian Melchioris ammonite zones, while the Mussel Member is dated from the Melchioris to the latest Albian Dispar Zone. The Poncin Member is dated at least from the Mantelli Zone to the middle and ?late Cenomanian (cf. genus *Calycoceras*).

2.10 Narlay Formation

As for the Aptian-Albian deposits, the Late Cretaceous in the Swiss Jura occurs only in small, discontinuous outcrops (a well-studied example is found at Cressier, northeast of Lake Neuchâtel; Schardt 1899; Renz et al. 1963). A new type locality characterising the lithology therefore has been chosen along the road south of Lake Narlay in France (Jura; Fig. 1; Table 2). There, the Narlay Formation is 25 m thick. The section was described in detail by Guillaume (1966), although now it is covered by vegetation (that, however, can easily be removed if necessary). It consists of moderately to well-stratified, white to yellowish chalky limestones locally containing chert layers. Fossils include abundant planktonic foraminifera, pithonellids, inoceramus prisms, and sponge spicules. These pelagic biomicrites were called "Calcaires crayeux blancs" by Guillaume (1966), or "Calcaires crayeux à silex" by Donzeau et al. (1997).

A Cenomanian to Coniacian age of the formation is assigned by planktonic foraminifera (Globotruncanids; Guillaume 1966; Donzeau et al. 1997). The base of the formation is diachronous, becoming older in the direction of the Swiss Jura (Pictet et al. 2016). The type section itself spans the Turonian to Coniacian interval (Guillaume 1966). In the La Vraconne area in the Swiss Jura, however, Renz and Luterbacher (1965) found ammonites that indicate an early Cenomanian age for the base of the formation (Mantelli Zone; the "Rotomagien" of Renevier 1868).

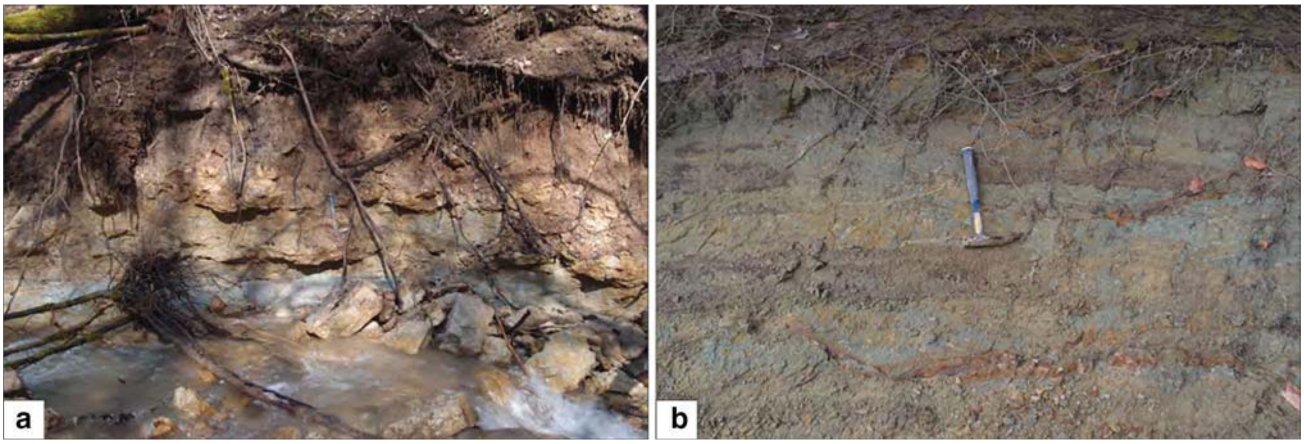


Fig. 9 Perte du Rhône Formation. **a** Irregular limestone beds in the otherwise marly Fulie Member, outcropping in the Ruisseau du Poet Bellegarde. Hammer in centre of photograph is 33 cm long. **b** Multicoloured glauconite-rich sandstone from the Mussel Member, outcropping along the Rhône River at the Perte du Rhône type locality

At the type locality, the eroded top of the Narlay Formation is overlain by Oligocene conglomerates ("gompholite"). At Alfermée, on the shores of Lake Biel (Switzerland), a Palaeogene breccia contains reworked microfossils (*Orbitoides, Siderolites vidali*; Renz 1936) of Maastrichtian age in a neritic facies. This implies that the deep-water facies of the Narlay Formation did not extend up into the Maastrichtian in this area.

3 Dating of the formations

Biostratigraphy is the major tool used to date the Cretaceous formations in the Swiss Jura, with ammonite biozones tied to the chronostratigraphic time scale (Fig. 4). Depending on the facies dominating the formations, different fossil groups or combinations of groups are employed (see above). In the peritidal facies of the Goldberg Formation, charophyte-ostracode assemblages do not allow for more than a very rough zonation. In the uppermost part of the Goldberg Formation and in the Pierre-Châtel Formation, these assemblages can be tied to some rare ammonites and thus to ammonite biozones. Ammonites are still rare in the overlying formations dominated by shallow-water facies (up to the Vallorbe Formation). Their zonation is therefore complemented by zonations based on echinids, dasycladalean algae, and benthic foraminifera. Some levels with deeper-water facies in the Chambotte, Vuache, and Gorges de l'Orbe formations yielded calcareous nannoplankton, calpionellids, and dinocysts. In the Hauterive Marls (Grand Essert Formation), the Perte du Rhône Formation, and at the base of the Narlay Formation, ammonites are abundant and allow for a precise zonation. The major part of the Narlay Formation is dated by planktonic foraminifera. From Fig. 4 it becomes evident that the durations of the formations vary strongly. Especially in the Hauterive Marls and in the Perte du Rhône Formation much time was consumed in condensed intervals and hardgrounds. The Narlay Formation is characterised by low sedimentation rates in the pelagic environment.

Within the bio- and chronostratigraphic framework, sequence stratigraphy is an additional tool helping with the correlation of the lithostratigraphic units. Such analyses have been performed on several Cretaceous formations in the Swiss Jura (e.g., Clavel and Charollais 1989; Strasser and Hillgärtner 1998; Charollais et al. 2008; Godet et al. 2010; Clavel et al. 2013, 2014). However, it is beyond the scope of this paper to further develop this subject.

Godet et al. (2011) dated outcrops of the Grand Essert, Gorges de l'Orbe, and Vallorbe formations with Sr-isotope ratios (measured on brachiopods) and calibrated them on ammonite zones, and they also furnished some K–Ar numerical ages (measured on glauconite). Their interpretations, however, are partly in contradiction with the biostratigraphy presented here, and the opposing views have not yet been reconciled (Charollais et al. 2013a; Godet et al. 2013; Clavel et al. 2013, 2014).

The evolution through time of the carbon stable-isotope ratio ($\delta^{13}C$) shows some distinct shifts in the Cretaceous, recording global perturbations of the carbon cycle and allowing for correlations between palaeogeographically distinct basins (Fig. 4). Thus, the Weissert event characterises the early Valanginian, the Faraoni level the late Hauterivian, the oceanic anoxic event OEA1a the early Aptian, and OAE1b, c, and d the Albian (e.g., Erbacher and Thurow 1997; Erba et al. 2004; Wissler et al. 2003; Martinez et al. 2015). However, the Weissert event is not recorded in the early Valanginian Vuache Formation (Pertransiens Zone; Morales et al. 2013). Carbon stable-isotope have been analysed for the Perte du Rhône Formation, but the values obtained reflect a signal of continental input rather than of oceanic changes (Pictet 2016). For the other formations considered here, no comprehensive C-isotope-stratigraphic study has been performed so far.

4 Evolution of the Swiss Jura realm during the Cretaceous

During the Cretaceous, the realm of today's Jura Mountains was situated at the northern passive margin of the Tethys Ocean (Ziegler 1988; Dercourt et al. 1993). Extensional tectonics created a complex pattern of faulted blocks with different subsidence histories (Wildi et al. 1989). Together with subsidence, eustatic sea-level changes controlled the accommodation potential of the sediments (Haq 2014). Furthermore, repeated climatic fluctuations between more arid and more humid conditions influenced the erosion of siliciclastics from the Hercynian massifs. Nutrients derived from the land or through upwelling from the open ocean influenced the neritic and pelagic biota. The sedimentary systems adapted to these parameters, creating the different lithologies that eventually allow for distinguishing the different lithostratigraphic units discussed here. High-frequency sea-level fluctuations, irregular platform morphology, and current-induced shifting of sediment bodies explain the complex lateral and vertical facies distributions encountered in many of the described formations.

The Goldberg Formation with its peritidal facies and evaporites characterises a very shallow, partly emergent, carbonate-dominated platform in a semi-arid climate. A major transgression then led to the deposition of the shallow-marine sediments of the Pierre-Châtel Formation. The

Vions Formation with its detrital quartz, coal layers, and predominantly heterotrophic fauna implies a more humid climate, while conditions became again more arid and oligotrophic during the time of deposition of the Chambotte Formation (Hillgärtner 1999; Morales et al. 2013). A tectonic tilt induced pinch-out (erosion and/or non-deposition) of the sediments of the Chambotte and Vions formations towards the northeast (Steinhauser and Charollais 1971).

During the Valanginian, the shallow platform developed into a ramp (Hillgärtner 1999; Morales et al. 2013). The reddish colour and heterotrophic fauna of the Vuache Formation point to a more humid climate, and the hummocky and swaley cross-stratifications to storm impact. The top of the formation shows signs of condensation (the *Alectryonia rectangularis* bed), increasing towards the northeast. The clayey and ammonite-rich Hauterive Marls of the Grand Essert Formation then clearly indicate a deepening of the depositional system, with a subsequent shallowing expressed by the tidally influenced sediments of the Pierre jaune de Neuchâtel. With the Gorges de l'Orbe Formation, a new carbonate platform installed itself in the Jura realm, continuing upwards with the Vallorbe Formation. The fossil content of these formations indicates a subtropical ecosystem. Clay input from the hinterland was more pronounced in the Gorges de l'Orbe Formation than in the overlying Vallorbe Formation.

The combined actions of tectonics and eustatic sea-level rise then led to the drowning of this platform. The ammonite-bearing, glauconite- and quartz-rich sediments of the Perte du Rhône Formation describe a complex history of accumulation, condensation, and submarine erosion in relatively deep depositional environments. Due to accentuated greenhouse conditions during much of the Aptian and Albian, the climate was generally humid (e.g., Föllmi et al. 1994). With the pelagic carbonates of the Narlay Formation, the Jura realm then recorded the deep-water conditions that characterise the Late Cretaceous. Due to tectonic uplift of the area and erosion in the course of the Tertiary, however, the Perte du Rhône and Narlay formations occur only as relics in the Swiss Jura Mountains. Pockets of the iron-rich continental facies of the "Sidérolithique", expressing the emergence of the Jura realm during the Palaeocene and Eocene, finally cap the Cretaceous system.

5 Field criteria

Because similar, recurring environmental conditions created similar facies at different times, some of the formations presented above have similar lithologies. Consequently, it can be difficult to distinguish these formations in small outcrops, in tectonised areas, and if the stratigraphic context is not clear. For the field geologist, the following lithological and/or palaeontological criteria may be helpful:

The Pierre-Châtel, Chambotte, and Vallorbe formations are all characterised by massive, whitish to yellowish limestone beds with a predominantly bioclastic composition. However, specific microfossils can be easily detected in the field with a hand-lens (Donzeau et al. 1997). In the Pierre-Châtel Formation, large benthic foraminifera (*Pseudocyclammina* sp.) and abundant calcareous algae are visible. *Pfenderina neocomiensis* is common in the Chambotte Formation, and the abundance of orbitolinids allows identifying the Vallorbe Formation. The limestones of the Gorges de l'Orbe Formation commonly are nodular, more marly, and yellower than those of the overlying Vallorbe Formation, and they typically contain ooids (some geologists called them "caviar oolite"; Wernli, pers. comm.).

Some intervals of the Goldberg and Vions formations have common features (e.g., thin beds, marls with charophytes). However, many beds of the Vions Formation are rich in detrital quartz, have a reddish colour, and display numerous bioturbations. Furthermore, the base of the Vions Formation contains the large benthic foraminifer *Pavlovecina allobrogensis.*

The Vuache Formation as well as the limestone intervals in the Grand Essert Formation contain reddish, thinly (cross-)bedded, bioclastic facies rich in echinoderms ("calcaire roux"). Generally, the beds of the Vuache Formation contain less detrital quartz and less glauconite than those of the Grand Essert Formation. However, in small and isolated outcrops, their differentiation may be difficult.

6 Conclusions

This revision of the Cretaceous lithostratigraphy of the Swiss Jura Mountains has led to the confirmation of the Goldberg, Pierre-Châtel, Vions, and Chambotte formations describing mainly the Berriasian deposits. For the overlying strata, in order to avoid the facies terms used so far, new names have been introduced: the Vuache, Grand Essert, Gorges de l'Orbe, Vallorbe, Perte du Rhône, and Narlay formations. As outcrop conditions in the Swiss Jura often do not offer complete sections, several type localities have been chosen in the neighbouring French Jura chain.

The lithostratigraphic units described herein translate the complex evolution of the Swiss Jura during Cretaceous times. Synsedimentary tectonics, eustatic sea level, and climate determined which sedimentary systems dominated. While the general, million-year trends of this evolution are expressed by the overall lithologies defining the formations, the common lateral and vertical facies heterogeneities within these formations furthermore point to rapid changes of sedimentary environments and ecological conditions through space and time. Post-sedimentary tectonic uplift led to partial erosion of some of the formations. Consequently, this lithostratigraphic study is not only an exercise aimed at defining units of sedimentary rocks to be mapped, but it also leads towards a better understanding of the dynamic history of the Jura realm.

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