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Stratigraphic revision and reconstruction of the deep-sea fan of the Voirons Flysch (Voirons Nappe, Chablais Prealps)

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Abstract

The Voirons Flysch (Caron in *Eclogae Geologicae Helvetiae* 69:297–308, 1976), is a flysch sequence aggregated into the sedimentary accretionary prism of the Chablais and Swiss Prealps. Its palaeogeographic location is still debated (South Piedmont or Valais realm). We herein present a stratigraphic revision of the westernmost unit of the former Gurnigel Nappe sensu Caron (*Eclogae Geologicae Helvetiae* 69:297–308, 1976): the Voirons Flysch. This flysch is subdivided into three lithostratigraphic units at the formation level (the Voirons Sandstone, the Vouan Conglomerate, the Boège Marl), with an additional unit (Bruant Sandstone) of uncertain attribution, ranging from the early Eocene to probably the late Eocene. We further propose a new model of the depositional setting of the deep-sea of the Voirons Flysch based on palaeocurrent directions, the overall geometry and sedimentary features. This model depicts an eastward deflected deep-sea fan. The stratigraphic record of the proximal part of this fan is fairly complete in the Voirons area, whereas its most distal part is only represented by one small exposure of thinly bedded sandstones in the Fenalet quarry. The stratigraphic evolution of the Voirons Flysch shows two major disruptions of the detrital sedimentation at the transition between Voirons Sandstone—Vouan Conglomerate and Vouan Conglomerate—Boège Marl. The cause of these disturbances has to be constrained in the framework of the palaeogeographic location of the Voirons Flysch.

Keywords: Voirons Nappe, Voirons Flysch, Chablais Prealps, Eocene, Density-flow deposits, Stratigraphy

1 Introduction

During the Alpine convergence, Penninic sedimentary covers were mostly detached from their respective basement, following a thin-skinned, in-sequence thrusting (Stampfli et al. 2002). These nappes aggregated into a fold-and-thrust belt (Cretaceous to Paleogene), and correspond nowadays to the Chablais and Swiss Prealps (Fig. 1) in the Western to Central Alps (Stampfli et al. 1998; Handy et al. 2010). The Prealps nappes originate from a range of palaeogeographic domains straddling the European passive margin (Ultrahelvetic realm) to the Piemont Ocean (Piemont

domain) in ascending structural order (Fig. 1). Nowadays, they are thrust over the Helvetic nappes to the SE and the North Alpine Foreland Basin (NAFB) to the NW (Fig. 1a). These sedimentary cover nappes are capped by or entirely made of flysch-type deposits (e.g. Studer 1848; Wildi 1987; Homewood 1983; Homewood and Lateltin 1988) which correspond to pulses of detrital sedimentation by deep-sea density flows along the active southern margin of the Alpine Tethys spanning the Late Cretaceous and the Paleogene. Hence, flyschs represent the last depositional phase in the successive palaeogeographic domains before their subduction and subsequent accretion into the sedimentary accretionary prism (Stampfli et al. 2002; Handy et al. 2010).

Following discussions on the relevance of correlating the different flyschs of the Gurnigel Nappe sensu Caron (1976) between them, the former Gurnigel Nappe is now subdivided into four tectonic units from west

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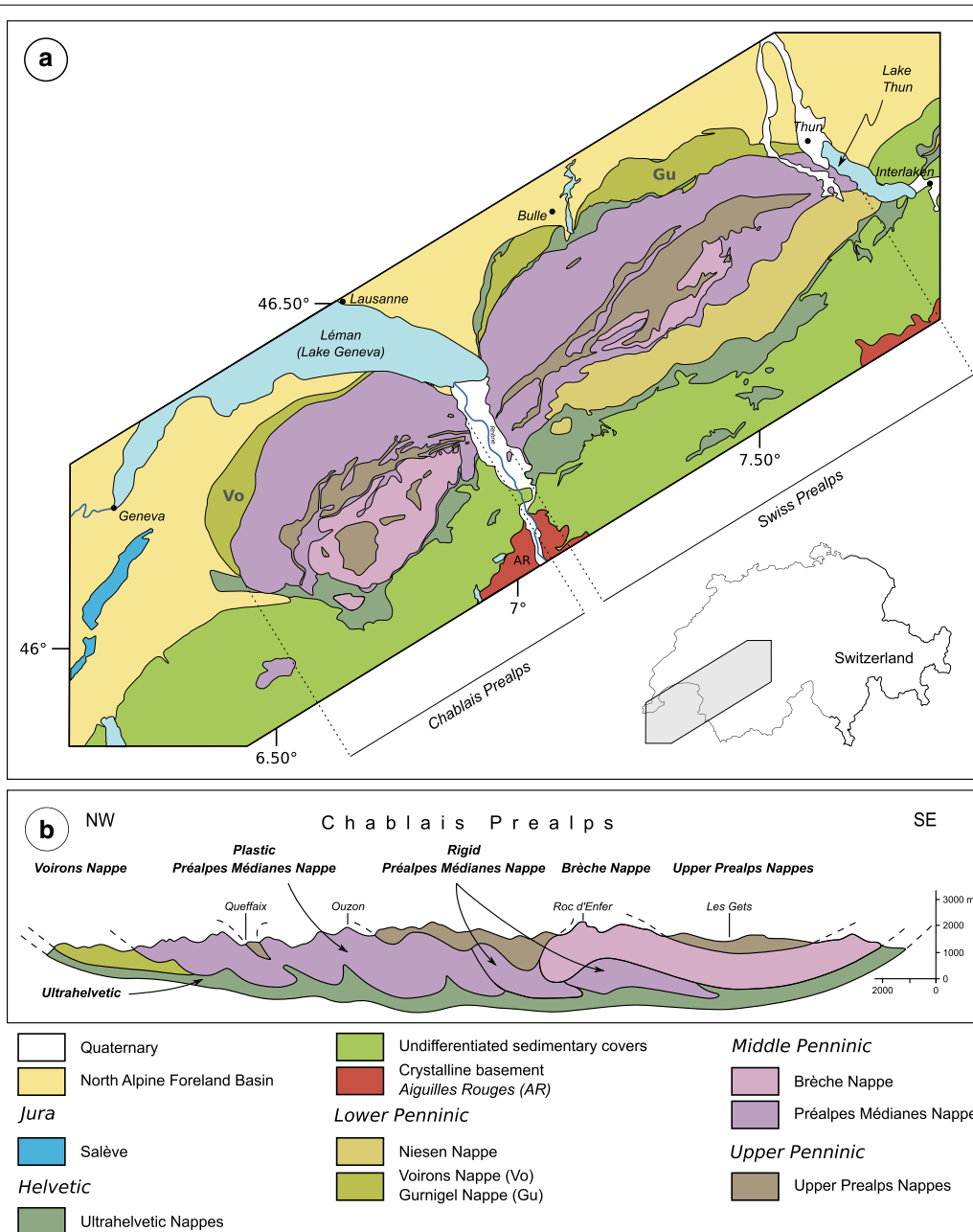


Fig. 1 Geological setting of the Voiron Nappe. **a** Simplified tectonic map of the Chablais and Swiss Prealps (SwissTopo 2008, modified). The internal subdivision of the Préalpes Médiannes Nappe are not shown. Note the external location of the Voiron Nappe within the Chablais Prealps. **b** Synthetic cross-section of the Chablais Prealps from Caron (1973, modified)

to east (Fig. 1a): the Voiron Nappe (Lombard 1940; Ujetz 1996; Ospina-Ostios et al. 2013; Ragusa 2015; Ospina-Ostios 2017; Ragusa and Kindler 2018; Ragusa et al. 2017, 2018), the Gurnigel Nappe (Tercier 1928; van Stuijvenberg et al. 1976; Weidmann et al. 1976; van Stuijvenberg 1979; Morel 1976; Weidmann 1985;

Ambrosetti 2005), the Schlieren Nappe (Winkler 1983, 1984a, 1993; Winkler et al. 1985b, 1990; Büttler et al. 2011) and the Wägital Nappe (Winkler et al. 1985). Each unit is defined as a nappe (e.g. the Voiron Nappe) from a tectonic point of view, and as a flysch (e.g. the Voiron Flysch) when considered as a stratigraphic unit.

Although these units share similar lithostratigraphic and petrographic characteristics, and range in age from the Campanian to the late Eocene (van Stuijvenberg 1979; Winkler 1984a; Caron et al. 1989; Ragusa et al. 2018), these correlations are taken for granted,

although there is currently no consensus on the relationship of the different flyschs. Likewise, the palaeogeographic origin of the Gurnigel Nappe sensu Caron (1976) remains controversial as it is either ascribed to the South Piemont domain (Caron 1976; Winkler 1983;

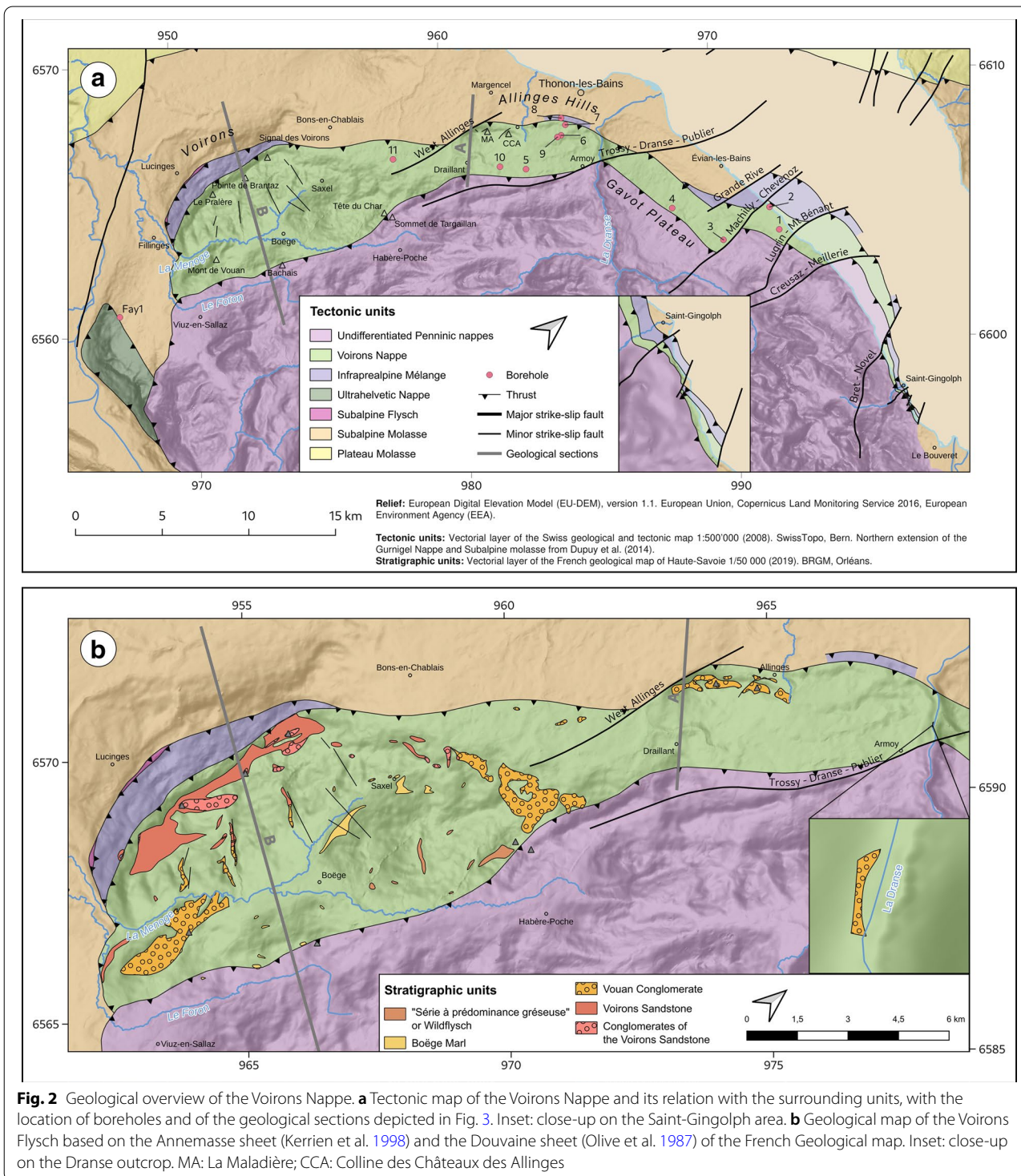


Fig. 2 Geological overview of the Voironns Nappe. **a** Tectonic map of the Voironns Nappe and its relation with the surrounding units, with the location of boreholes and of the geological sections depicted in Fig. 3. Inset: close-up on the Saint-Gingolph area. **b** Geological map of the Voironns Flysch based on the Annemasse sheet (Kerrien et al. 1998) and the Douvaine sheet (Olive et al. 1987) of the French Geological map. Inset: close-up on the Dranse outcrop. MA: La Maladière; CCA: Colline des Châteaux des Allinges

Table 1 Comparative table showing the name of the stratigraphic units defined in this work, the translation in French, and the names used in previous papers

This paper	French correspondence	Previous attribution	Comments
Voirons Flysch	Flysch des Voirons	Voirons Flysch	
Voirons Sandstone	Grès des Voirons	Voirons Sandstone	New internal subdivision
Bons Mb.	Mb. de Bons	Voirons Sandstone	New unit
Allinges Mb.	Mb. des Allinges	Vouan Conglomerate (Olive et al. 1987) or Voirons Sandstone (Vial et al. 1989)	Attribution fixed
Signal Mb.	Mb. du Signal	Voirons Sandstone	New unit
Vouan Conglomerate	Conglomérat du Vouan	Vouan Conglomerate	New boundary defined
Boège Marl	Marne de Boège	Boège Marl or Saxel Marl	Initially described as a member (van Stuijvenberg and Jan du Chêne 1980)
Bruant Sandstone	Grès du Bruant	mélange (Kerrien et al. 1998) or Priabonian sandstone (Charollais et al. 1998)	Uncertain attribution: stratigraphic unit or Voirons Sandstone tectonic slice
Fenalet Sandstone	Grès du Fenalet	Ultrahelvetic flysch (Badoux 1996)	Attribution fixed but remains not laterally constrain in the stratigraphy of the Voirons Flysch

Caron et al. 1989; Büttler et al. 2011; Beltrán-Triviño et al. 2013) or to the Valais domain (Schmid et al. 2005; Trümpy 2006; Ospina-Ostios et al. 2013; Ospina-Ostios 2017; Ragusa et al. 2017, 2018).

In this paper, we redefine the stratigraphic scheme of the Voirons Flysch (Fig. 2; Table 1) based on a thorough revision of previous studies, and on new geological data acquired during the past fifteen years (Ragusa 2009, 2015; Ospina-Ostios 2017). Indeed, except for the Boège Marl (van Stuijvenberg and Jan du Chêne 1980), the constituent units of this flysch were never formally defined, and the affiliation of some rock bodies (e.g. the Allinges Hills) remains up to now unsolved. Furthermore, extensive fieldwork gave us the unique opportunity to reconstruct the overall geometry of this ancient deep-sea fan. In contrast, the question of the palaeogeographic origin of this unit is beyond the scope of this paper.

2 Geographical setting

The Voirons Nappe is exposed to the south of Lake Geneva (Léman), mostly in France (Fig. 1). Most outcrops are concentrated in the Voirons area (Fig. 2b). The flysch appears as subdued landforms surrounding the upper part of the drainage basin of the Menoge River (Fig. 2), which are represented in decreasing elevation by the Voirons (1480 m), the Grande Combe (1293 m), the Tête du Char (1249 m), the Bachais (Ludran Hills, 1074 m) and the Mont de Vouan (978 m) (Figs. 1b, 2). The SE boundary of the Voirons Nappe is defined by the thrusting front of the Préalpes Médiannes Nappe (Middle Penninic), broadly represented by the upstream part of the Menoge River and by the Foron River (Figs. 2 and 3). These rivers also define the SW limit of the nappe. The Voirons

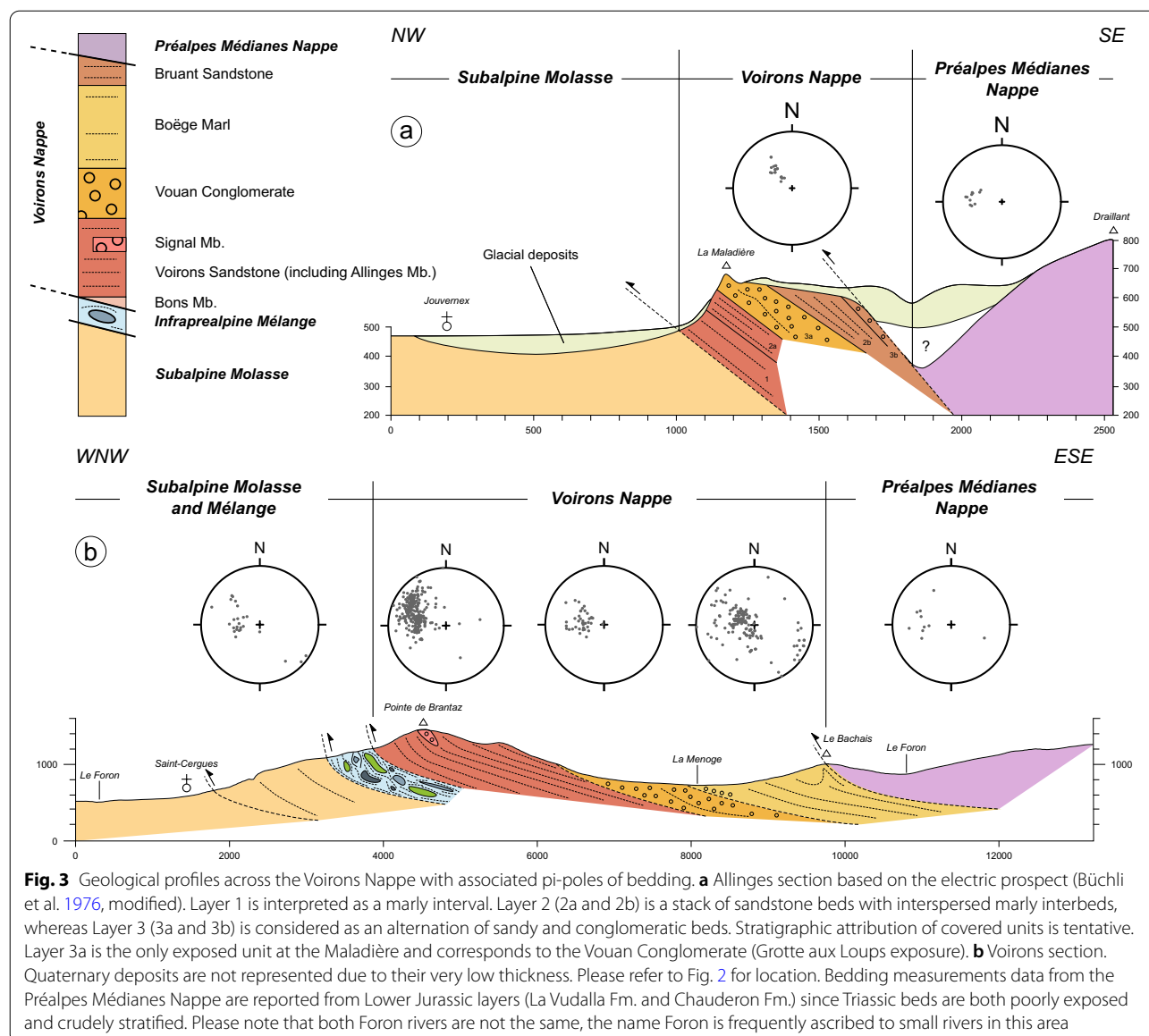
Flysch does not extend further southward as suggested on the Swiss Tectonic Map (SwissTopo 2008). Although no petrographic data are available, Ospina-Ostios (2017) considered that the Voirons Flysch is indeed not correlated to the uppermost layer of flysch retrieved from the borehole Faucigny 1 (Fay1; Fig. 2, Table 2). The NW limit of the Voirons Nappe is located on the western flank of the Voirons where it overthrusts a series of tectonic slices of Oligocene age (Fig. 3).

Towards the NE, the Voirons Nappe is mostly covered by m-thick Quaternary deposits (Dray 1971; Vial et al. 1976; Dray 1993), but it is locally exposed in several low hills, the most important of which being the Allinges Hills (754 m; Cogulu 1961; Olive et al. 1987; Vial et al. 1989) (Figs. 2 and 3), and along the Dranse river (Fig. 2a) (Jan du Chêne et al. 1975; Dupuy et al. 2014). Neither the lower nor the upper boundaries are not exposed leading to an approximate geometry. Further to the NE, outcrops completely disappear beneath the Quaternary deposits of the Gavot Plateau and of the southern bank of Lake Geneva. Ultimately, the Fenalet quarry, near Saint-Gingolph in Switzerland (Badoux 1996; Dupuy et al. 2014; Ragusa 2015), exposes the easternmost outcrop of the Voirons Nappe.

3 Geological setting

3.1 Sedimentology and petrography of the Voirons Flysch

The Voirons Flysch comprises a stack of density-flow deposits (Kuenen and Carozzi 1953; Frébourg 2006; Ragusa 2015). The presence of peculiar agglutinated foraminifera (*Rhabdamina* fauna; Brouwer 1965; Weidmann 1967a, b; Van Stuijvenberg et al. 1976; Ujjetz 1996,



Ospina-Ostios 2017) further suggest a deep-marine depositional environment.

Detrital deposits are of lithic arkose to quartzarenite composition ranging from siltstone to conglomerates. Heavy minerals are dominated by apatite, garnet and the zircon-tourmaline-rutile group (ZTR) (Ragusa 2015; Ragusa et al. 2017). Pebbles and cobbles reveal a wide spectrum of source-rock lithologies (Hubert 1967; Frébourg 2006; Ragusa 2015; Ragusa et al. 2017) including (1) plutonic rocks of Paleozoic and Precambrian age, (2) volcanic rocks probably derived from the Carboniferous–Permian magmatic events, (3) Pre-Triassic? metamorphic rocks, (4) Mesozoic limestones of various composition, and (5) minor inputs of terrigenous rocks including

peculiar black sandstones to conglomerates of Paleozoic age and Triassic quartzarenite. These detrital sediments are thought to derive from a complex continental source located somewhere between the Sesia-Dent Blanche nappes and the Briançonnais microcontinent. They have been subdivided into two petrofacies (Ragusa et al. 2017). The *Quartzose petrofacies*, the main detrital composition, is a quartz-rich sediment with variable amounts of magmatic and sedimentary lithoclasts. The subordinate *Feldspathic petrofacies* comprises a feldspar-dominated assemblage characterised by metamorphic rocks. Furthermore, the modal distribution of intrabasinal grains (e.g. bioclasts, glauconite), calcite cement, and lithoclasts, as well as the grain-size distribution describe a basinward

Table 2 General informations on the boreholes carried out in the Voirons Flysch and in the adjacent units from Dupuy et al. (2014)

Name	Coordinates X/Y (Lambert II étendu)	References	Description
1 Les Crêts	931.850/2164.750		Dark grey marls and sandstones. Dating at Priabonian (NP20)
2 Torrent	930.494/2165.143		Dark sandstones
3 GAV SP 3 Les Ingels	930.257/2161.218		Black marls and grey calcareous sandstone. Dating at Priabonian (NP 18, 120,7 to 139,7 m) and Bartonian (NP 17, 143,1 to 148,2 m)
4 GAV L4 Ijeux	926.970/2160.765		Dark schistous marls and grey calcareous sandstones. Dating at early Priabonian (NP 18, 175.5 m) and late Bartonian (NP 17, 178,05 m)
5 Sorcy	919.871/2155.691	Chazal and Grange (2002)	Undescribed flysch
6 Lonnaz	919.649/2158.503	Chazal and Grange (2002)	Undescribed flysch
7 Chessy	919.332/2159.073	Dray (1971)	Rich Maastrichtian planktonic foraminifera. Described as equivalent to the Hellstätt Fm.
8 Mapad 1	918.875/2159.136		Undetermined limestone between -129 and -210 m
9 Bouvier-Dubouloz	918.593/2158.270	Chazal and Grange (2002)	Undescribed flysch
10 Maugny	918.804/2154.622	Chazal and Grange (2002)	Undescribed flysch
11 Fessy	914.550/2150.130	Chazal and Grange (2002)	Undescribed flysch
Fay1 Faucigny 1	911.6/2132.2	Charollais et al. (1993)	

trend in deposition (Ragusa and Kindler 2018) embracing: (1) coarse-grained, moderately cemented and porous, terrigenous deposits (lithofacies L1 to L3) in channels; (2) fairly cemented, well-sorted, fine sandstone to coarse siltstone with increasing amount of intrabasinal grains (lithofacies L4 and L5) in lobes; and (3) a porous glauconitic quartzarenite with no calcite cement (lithofacies L6) interpreted as a reworked distal turbiditic deposit or possibly a contourite. Additionally, the downslope increase in calcite cement and bioclasts results in the deposition calcareous sandstone in distal settings.

3.2 Tectonic structure of the Voirons Nappe

The Voirons Nappe overthrusts tectonic slices and a mélange (van Stuijvenberg and Jan du Chêne 1980; Carletti 1987; Badoux 1996; Ujetz 1996; Charollais et al. 1998) which formed in front of the Prealps nappes during their thrusting (Figs. 2, 3). These tectonic slices comprise Oligocene deposits affiliated to the Val d'Illicz Sandstone (Subalpine Flysch; Lombard 1937, 1940; Vuagnat 1943; Lombard and Vernet 1964; Ujetz et al. 1994) and to the lower marine Molasse (UMM) of the NAFB (Subalpine Molasse; Carletti 1987; Ujetz 1996). These tectonic slices are separated from the Voirons Nappe by the Infrapre-alpine Mélange (Plancherel 1990), also called wildflysch (Lombard 1940). The description of several km-scale embedded lenses (Pilloud 1936; Lombard 1940) was complemented by Charollais et al. (1998). They comprise Mesozoic limestones and Paleogene flysch-type deposits

of Ultrahelvetic affinity which are wrapped into an presumably Priabonian shaly matrix (Kapellos 1973; Charollais et al. 1998).

The Voirons Nappe is itself overthrust by the Triassic sole of the Préalpes Médiannes Nappe (Figs. 2, 3) (Chaix 1913, 1928; Coppo 1999). This boundary is best observed at the Fenalet quarry. No mélange is reported along this thrusting front, in contrast to the Gros Plané Mélange which overlies the Gurnigel Nappe in the Swiss Prealps (Morel 1976).

The tectonic structure of the Voirons Nappe has also been a matter of debate. Initially interpreted as a complex folded structure (Favre 1867; Sarasin 1894), it was then presented as a monoclinical ramp by Lombard (1940). Following a previous study in the Gurnigel Nappe (van Stuijvenberg 1976), van Stuijvenberg (1980) proposed a subdivision of the Voirons Nappe into three tectonic slices, which was contradicted with previous biostratigraphic data (Jan du Chêne et al. 1975) and the lack of field evidences (Ospina-Ostios 2017). Based on the unequal distribution of pi-poles of pole stratification data (Fig. 3), Ospina-Ostios (2017) suggested that the Voirons Nappe forms an open conical fold with dip variations of about 20°. The large-scale dip measurements confirm the absence of tectonic slices as well as the lack of field evidence of tectonic deformation, except in the Bruant Sandstone. Coppo (1999) described several NW–SE dextral strike-slip faults in the Voirons (Fig. 2) such as

the Chandouze fault, initially described by Lombard (1940), and further investigated by Ospina-Ostios (2017). Coppo (1999) proposed that a dextral displacement affects the basal thrust of the Voirons Nappe. Ospina-Ostios (2017) identified prominent WNW–ESE oriented linear features in the Voirons (Fig. 2). This direction is similar to that of the Saint-Cergues fault (Dupuy 2006). However, only a small apparent sinistral displacement has been locally observed at the Ruisseau de Curseille (Ospina-Ostios 2017).

Toward the NE, the tectonic structure is poorly constrained due to the thick Quaternary cover and the lack of accurate subsurface data. A subordinate family of lineaments is possibly related with SW-NE oriented structures (Ospina-Ostios 2017) such as the Bonnevaux fault (Raymond et al. 1996), and is consistent with regional-scale, sinistral strike-slip faults identified in the eastern portion of the Voirons Nappe (Dupuy et al. 2014), and also shifting the Préalpes Médiannes Nappe (Fig. 2) (Dupuy et al. 2014). In the easternmost part of the Voirons Nappe, the tectonic situation of the Fenalet Sandstone is blurred by the Préalpes Médiannes Nappe which, in this area, successively overthrusts the tectonic slices of the Subalpine Molasse, the Mesozoic layers of the Ultrahelvetic Nappe and the Voirons Flysch. Several models have been proposed (Lugeon 1901; Peterhans 1923; Badoux and Guigon 1958; Badoux 1996) to explain the tectonic framework. Recently, Dupuy et al. (2014) suggested a strike-slip model possibly inherited from the motion of thrust sheets.

4 Methods

A total of 52 outcrops of variable extension (road cuts, quarries and streams) were investigated (Ragusa 2015; Ospina-Ostios 2017). Applied methods included biostratigraphy, structural analysis, sedimentology (measurements of flute-cast and groove-cast directions for palaeocurrent interpretation) and petrography (semi-quantitative analysis of the detrital composition). Outcrop datasets of the Voirons Flysch are available on the GitHub repository of the first author (<https://github.com/jragusa>). The important vegetation cover makes lateral and vertical correlations difficult, but some streams provide extended and quasi-continuous outcrops. Likewise, the scarcity of peculiar lithostratigraphic variations and tectonic complications make bed by bed correlations difficult. Overall, the lack of good exposures and the absence of marker beds in some areas preclude an accurate mapping, especially in the marly intervals. Lithostratigraphic units are primarily defined by petrographic criteria (Ragusa 2015; Ragusa et al. 2017). The main criteria and the list of type and reference sections are summarised in Additional files 1 and 2, respectively.

A sand:marl ratio was computed to best describe the sand-marl alternations of each unit (Additional file 1). This ratio is defined as follows: the sand factor includes the total thickness of conglomerate to siltstone layers and corresponds to the extrabasinal inputs, whereas the marl factor mostly comprises the total thickness of intra-basinal, hemipelagic sediments since very fine-grained hemipelagic layers of green colour (Hubert 1967; Winkler 1984b) are rare. For calculation purposes, a thickness of 0.1 cm was assumed for marly interbeds equal to zero (Martín-Fernández et al. 2003). Hence, the relative distribution of sandy beds and of marly interbeds illustrates the relative location on the deep-sea fan (Walker 1986).

The thickness of each unit was corrected to assess an accumulation rate (Additional file 1). Following the compaction values used by Winkler (1993) and based on the burial/porosity relationship of Sclater and Christie (1980), the applied ratios are the following: 20% (Vouan Conglomerate), 40% (Voirons Sandstone and Bruant Sandstone) and 50% (Boège Marl). These are minimal values as they do not include the erosion which could be notably high, especially in the Vouan Conglomerate.

Palaeocurrent directions obtained from flute- and groove-casts measurements (Additional file 3) were also considered to identify the main orientation path of the density flows building the Voirons Flysch. However, the translation of the Adria plate with respect to the stable European plate was associated with a counter-clockwise rotation (Handy et al. 2010). Rotation values range between 16 and 20° during the Cenozoic (Kempf et al. 1998; Collombet et al. 2002; Márton et al. 2010), whereas Winkler (1984a) used increasing values from west to east, grading from 30° in the Fayaux-Pléiades area to 50° in the Berra-Schwyberg region and finally to 70° in the Gurnigel Flysch. A clockwise restoration of 20° was thus considered as it remains consistent with previous results.

5 Lithostratigraphy of the Voirons Flysch

Figure 4 provides an overview of the stratigraphic succession of the Voirons Flysch.

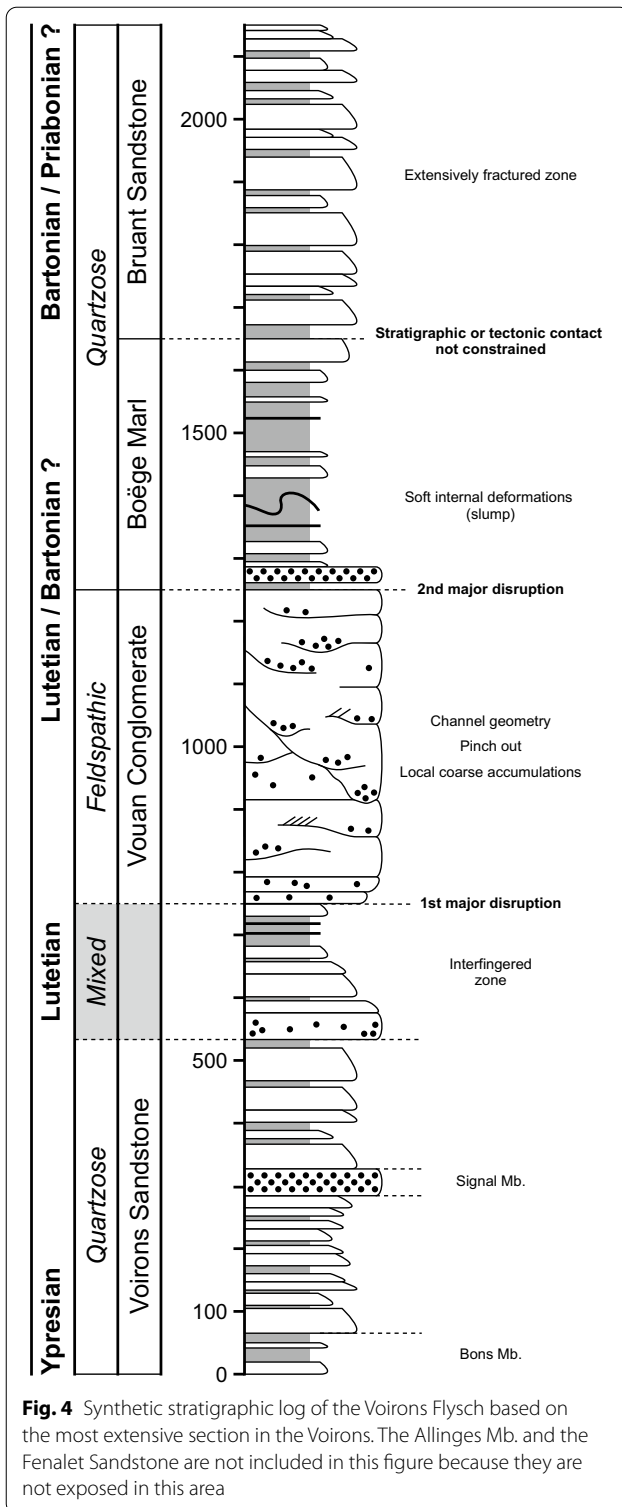
5.1 Voirons Sandstone

5.1.1 Origin of the name

The name refers to the Voirons mountain (Fig. 2a) which is the major landform exposing this unit. The name is preserved since it has been extensively used in the literature.

5.1.2 Type and reference sections

The type section is located on the eastern flank of the Voirons along the upper part of the Ruisseau de Curseille (Fig. 5; 46.2010° N, 6.3693° E). This stream provides a good exposure, and represents the largest outcrop of



the Voiron Sandstone. The reference section includes the Nant de Manant (46.2185° N, 6.3722° E), which runs parallel to the Ruisseau de Curseille. Both sections show the boundary with the overlying Vouan Conglomerate,

and are located along NW–SE oriented strike-slip faults (Ospina-Ostios 2017). The exposure at La Moutonnière (46.2383° N, 6.3601° E) is also considered as a reference locality. This outcrop is easily accessible as it is situated along a forest road. Although the Fillinges quarry (46.1538° N, 6.3727° E) was described as the best outcrop of the Voiron Flysch (Lombard 1940), the quarry is now abandoned, and the exposure is obscured by growing vegetation.

5.1.3 History

The Voiron Sandstone is the most studied and documented unit of the Voiron Flysch. After an initial description by de Saussure (1779), the Voiron Sandstone was promptly linked to the Gurnigel Flysch and to the Macigno Alpin (Studer 1827, 1853). Fucoids (chondrites in modern terminology) have been reported in sandstones from the Voiron crest (de Beaumont 1828; de Mortillet 1858; Fischer-Ooster 1858). Favre (1867) retrieved nummulites from the upper sandstone layers, and therefore distinguished a lower, Mesozoic part (“flysch de base”) and an upper, Cenozoic part (“flysch supérieur” or nummulitic sandstone; Sarasin 1894; Gagnebin 1924; Pilloud 1936) in the Voiron Flysch. Lombard (1940) provided the first comprehensive dissertation on the Voiron Sandstone, and interpreted it as a marine deposit fed by rivers. The discovery of turbidity currents in the 1950s (Kuenen and Migliorini 1950; Kuenen 1950, 1957) resulted in a reinterpretation of these rocks as deep-marine turbidites (Kuenen and Carozzi 1953; Lombard 1963a, b). During the 1970s to 1980s, several biostratigraphic studies based on calcareous nannofossils and dinoflagellates were carried out on the Voiron Sandstone (Jan du Chêne and Gorin 1975; Jan du Chêne and Chateaufort 1975; Jan du Chêne et al. 1975; van Stuijvenberg 1980; van Stuijvenberg and Jan du Chêne 1980). van Stuijvenberg (1980) tentatively subdivided the unit into four layers based on lithologic criteria. Finally, in the 1990s and at the beginning of this century, planktonic foraminiferal biostratigraphy (Ujjetz 1996; Coppo 1999; Ospina-Ostios et al. 2013; Ospina-Ostios 2017) and petrography (Ragusa 2015; Ragusa et al. 2017) were applied to the study of the Voiron Sandstone.

5.1.4 Spatial distribution

The Voiron Sandstone (Fig. 6) is restricted to the Voiron and the Allinges Hills (Fig. 5). Major outcrops occur in quarries along the D 20 road, along the Voiron crest and in the streams of the eastern flank (e.g. Ruisseau de Curseille and Nant de Manant). The Voiron Sandstone might correspond to the layers 1 and 2a of the Allinges

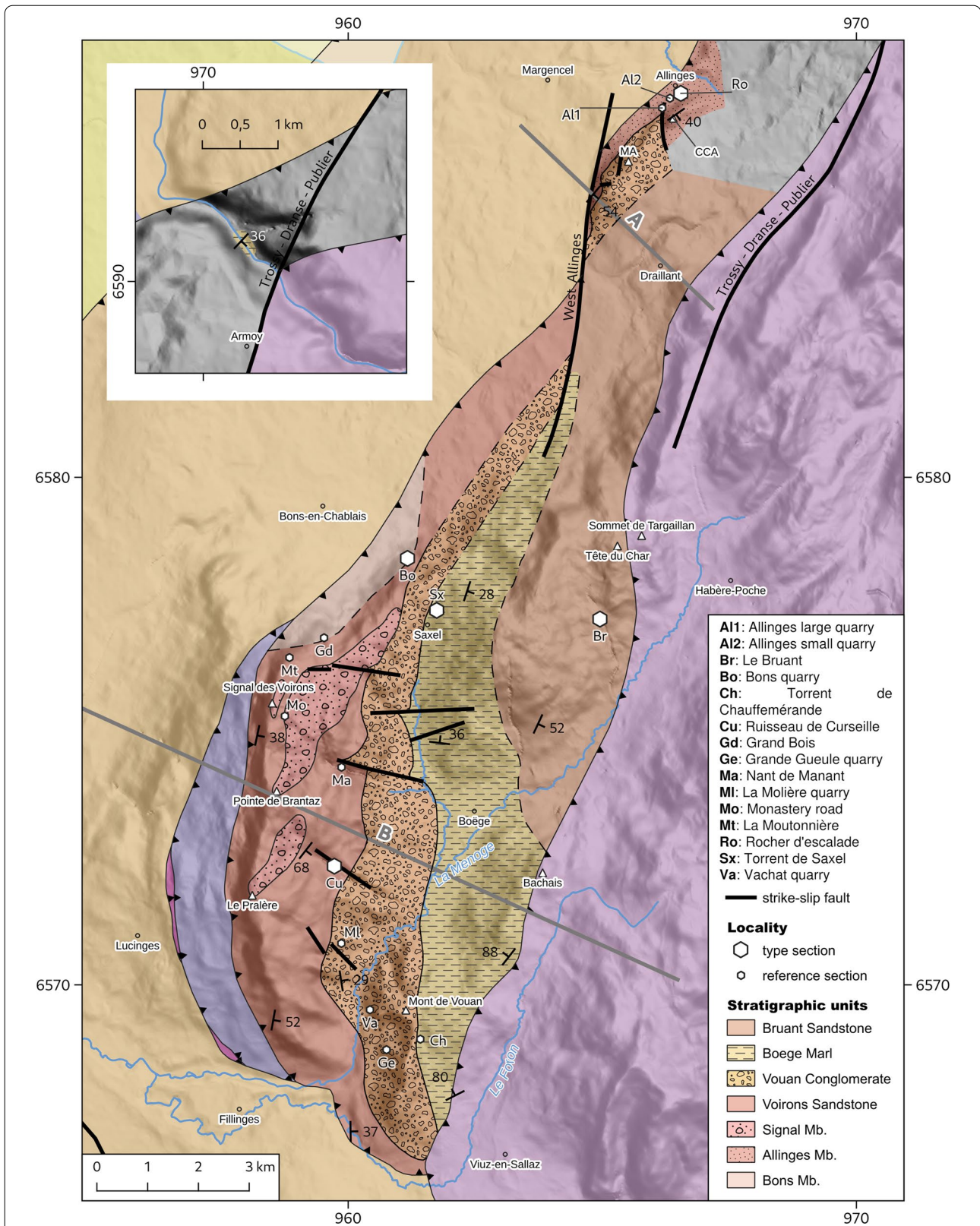


Fig. 5 Revised tectonic map of the Voiron Flysch between the Voiron and the Allinges Hills with the location of the type and reference sections. The northern portion beyond the Dranse River is not shown due to the lack of constraints. The geometry along the Allinges Hills is hypothetical in the absence of subsurface data. The Bruant Sandstone is interpreted here as a stratigraphic unit

cross-section (Fig. 3a) and is mainly exposed throughout the Allinges Mb. (Sect. 5.4).

5.1.5 Lithological characteristics and facies variations

The Voirons Sandstone mostly comprises tabular sandstone beds with marly interbeds in variable proportion, thus leading to important variations of the stratal pattern (Fig. 7). The sandstone beds are blue to grey on fresh surfaces with a brown corroded rim. Marls are of dark grey to greenish (Ospina-Ostios 2017). The basal layers comprise the predominantly marly interval of the Bons Member (Sect. 5.2; Figs. 4, 6a) which only includes cm- to dm-thick sandstone beds (“Niveau 1” of van Stuijvenberg 1980). They are organised in thinning-upward sequences beginning with a one m-thick, massive sandstone bed rapidly grading into a thin-bedded succession (Ragusa 2015). The formation evolves toward a massive and structureless sandstone accumulation forming the western cliff beneath the Voirons crest (“Niveau 2” to “Niveau 4” of van Stuijvenberg 1980) and the upper part of the eastern flank. The thickness of sandstone beds ranges between ca. 10 cm and 1 m. Marly interbeds are not regularly preserved leading to the amalgamation of sandstone beds in massive layers. Apart from the Bons Mb., cm-thick beds are rare and also occur in restricted intervals of the middle part (equivalent to the “Niveau 3” of van Stuijvenberg 1980). This accumulation is disrupted by patchy conglomeratic along the Voirons crest (Signal Mb.; Sect. 5.3; Figs. 2b, 3b, 4 and 6b). Towards the North, the Allinges Mb. (Sect. 5.4) is characterized by a predominantly sandy accumulation with rare marly interbeds and micro-conglomerates.

5.1.6 Sedimentological characteristics

The base of the sandstone beds is sharp and displays numerous bioturbations (Lombard 1940), as well as some flute casts and groove casts. Thick beds are mostly structureless, but locally show planar bedding and likely aggrading subaqueous dunes (i.e. La Moutonnière exposure and Saxel lower quarry, 46.2493° N, 6.3836° E). Thin beds display Bouma sequences and F8 to F9 facies (Mutti 1992). The important lithologic variability (conglomerate to fine-grained sandstone) and the fluctuating amount of marly intervals (Fig. 7) reflect a large diversity of depositional settings from channel to lobe (interlobe?) and accumulation by high-concentration density flows to turbiditic flows (Ragusa

and Kindler 2018). A single glauconite-rich sandstone bed (Fig. 6c) is also observed at the La Renardière locality (Ragusa and Kindler 2018; L6 petrofacies). Palaeocurrent directions fluctuate between N001 and N258 with a prominent group between N038 and N152 (Fig. 8).

5.1.7 Petrographical characteristics

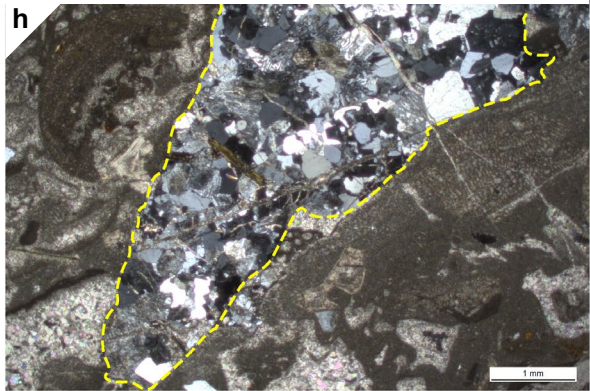
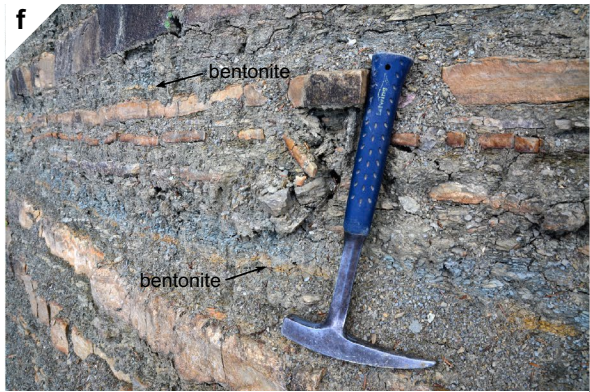
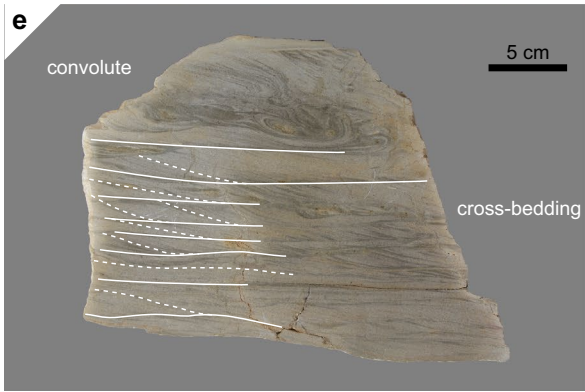
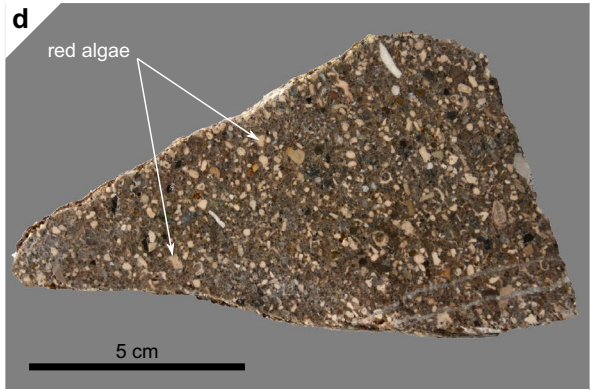
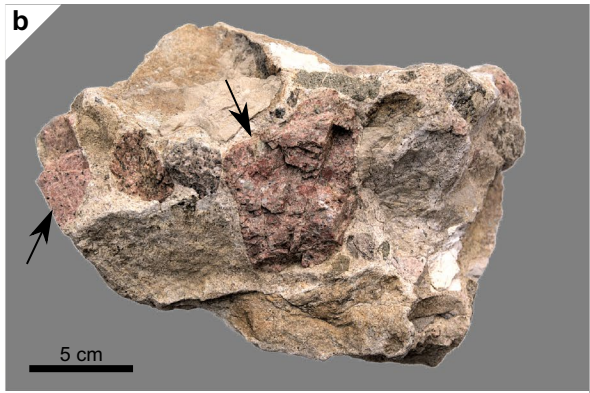
The petrographic composition essentially corresponds to the *Quartzose petrofacies* with a minor and random occurrence of the *Feldspathic petrofacies* (Ragusa et al. 2017). Pink granite fragments characterise coarse-grained layers (Fig. 6b). Several strata rich in red algae are observed locally (Fig. 6d; Charollais et al. 1998; Ragusa 2015). A single exposure of glauconite-rich sandstone bed is reported at La Renardière locality (Fig. 6c). Accordingly, Lombard (1940) wrote: “la diversité de composition semble être le seul caractère constant de ces grès” (p. 34). Amber was also observed by Pilloud (1936) along the Menoge river.

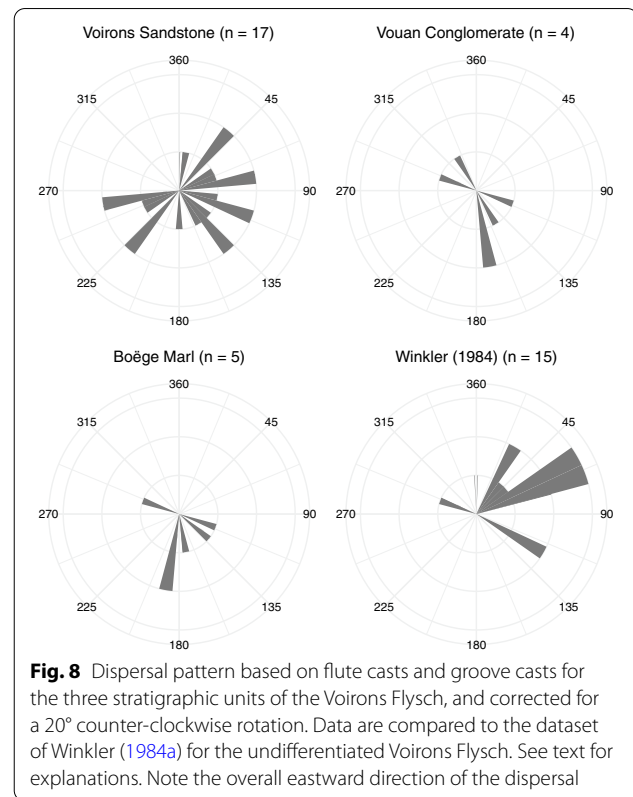
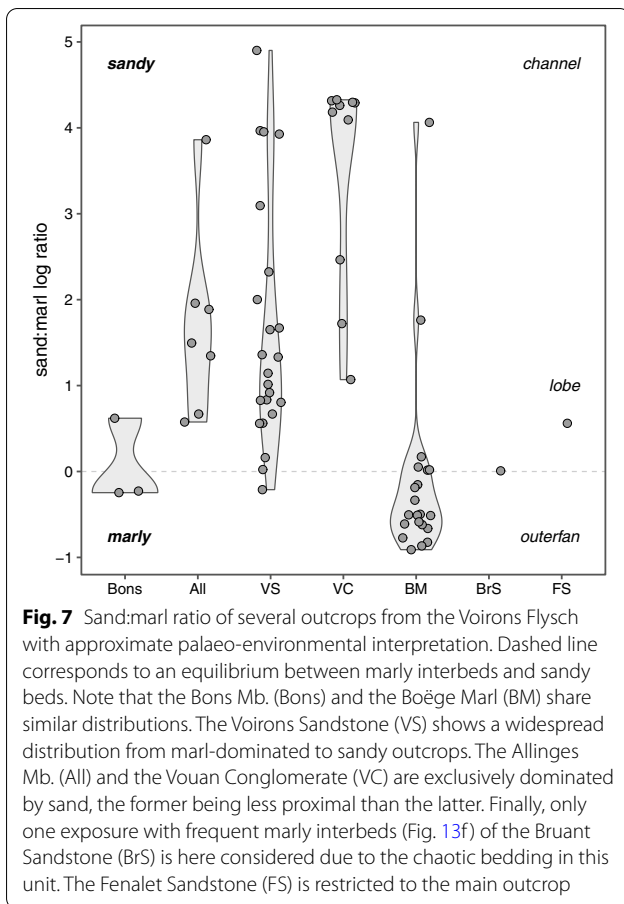
5.1.8 Lower boundary

The lower boundary of the Voirons Sandstone corresponds to the basal thrust of the Voirons Nappe over the underlying Infraprealpine Mélange (van Stuijvenberg and Jan du Chêne 1980; Carletti 1987; Ujetz 1996; Charollais et al. 1998), and is only exposed along the Voirons (Figs. 2, 3). Off-scraping along the thrust fault removed the oldest components, probably composed of a marly succession (Bons Mb.), which was possibly incorporated into the underlying mélange. Towards the South, the tectonic contact rises through the Voirons Sandstone (Fig. 9), progressively shifts within the massive sandstone accumulation along the NW cliff (van Stuijvenberg and Jan du Chêne 1980), and finally reaches its upper part, near the Fillinges quarry, close to the boundary with the Vouan Conglomerate. Furthermore, the lateral decrease in thickness of the Infraprealpine Mélange indicates that the Subalpine Molasse is also in contact with the Voirons Sandstone (Fig. 2) (van Stuijvenberg and Jan du Chêne 1980; Kerrien et al. 1998). Northward, the basal contact is covered by Quaternary slope deposits along the Allinges Hills (Fig. 3a) (Ospina-Ostios 2017). Electric prospects (Büchli et al. 1976) did not identify Paleogene tectonic slices, suggesting that the Voirons Nappe might locally thrust

(See figure on next page.)

Fig. 6 Major lithologic features of the Voirons Sandstone. **a** Marl-dominated section of the Bons Mb. (46.2552° N, 6.3911° E). **b** Block of the Signal Mb. from the Monastery road exposure with pink granite fragments (black arrows). **c** Glauconitic sandstone at the La Renardière outcrop (46.2239° N, 6.3679° E) (L6 lithofacies). **d** Polished section of the red-algae rich sandstone from the La Moutonnière exposure. **e** Polished section of cross-stratified bed from the Bons quarry (L5 lithofacies). **f** Bentonite layers from the Bons quarry. **g** Pink granite inclusions in a limestone block beneath the Pralère (46.1973° N, 6.3485° E). **h** Microphotograph of the limestone with pink granite fragments





directly over the molasse of the North Alpine Foreland Basin (Dray 1971; Vial et al. 1976; Dray 1993).

5.1.9 Thickness

Initially estimated at ca. 200 to 300 m (Charollais et al. 1998; Coppo 1999; Frébourg 2006), the thickness of the Voiron Sandstone is readjusted to about 750 m (Fig. 4) (van Stuijvenberg 1980; Ospina-Ostios 2017). However, this assessment does not consider the dismantling of the base of the Voiron Nappe during the subduction and incorporation into the sedimentary accretionary prism.

5.1.10 Geologic age

Revision of larger benthic foraminifera (Ospina-Ostios 2017) from previous studies (Pilloud 1936; Lombard 1940; Cogulu 1961, Rigassi 1966) provides an early to late Eocene age (P5-P16). Calcareous nannofossil biostratigraphy indicates an early Thanetian—early Bartonian interval (NP 5-NP 16) (Jan du Chêne et al. 1975). Charollais et al. (1998) assume a Danian—late Ypresian age. Revision of the planktonic foraminiferal biostratigraphy (Ragusa et al. 2018) constrains the age of the Voiron Sandstone between the Ypresian and the Lutetian (P7-P11).

5.1.11 Comparison with other regions

The diverse lithofacies described by Tercier (1928) in the eastern units of the Gurnigel Flysch are not recognised or occur only at local scale in the Voiron (Lombard 1940). Furthermore, the important lithological variations observed in these units contrast with the Voiron Sandstone where fluctuations are more subtle.

5.2 Bons member

5.2.1 Origin of the name

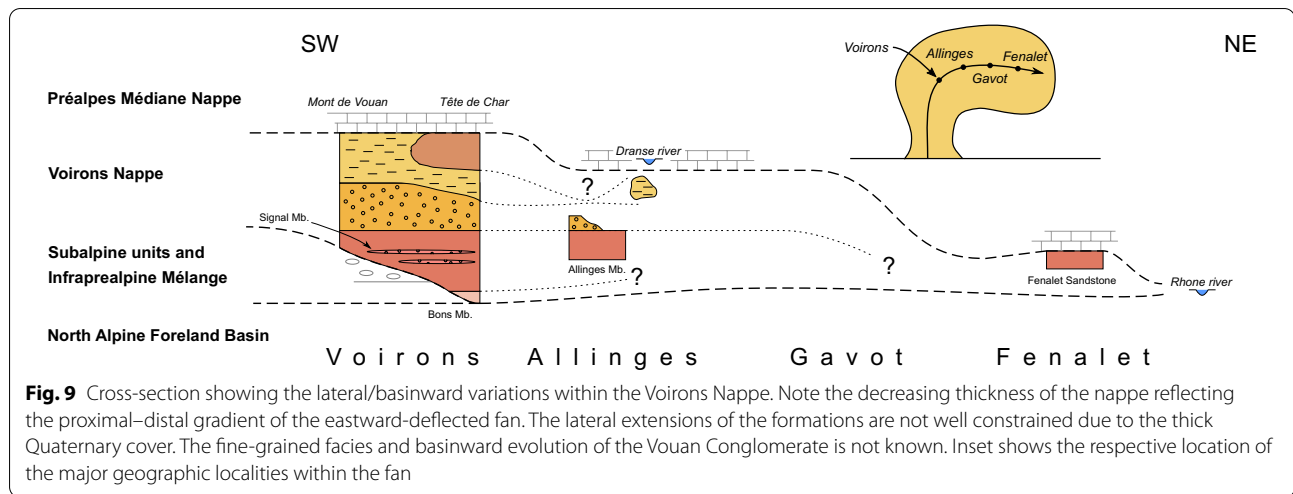
The name refers to the main outcrop of this unit: the Bons quarry (Fig. 5) (Ragusa 2015; Ospina-Ostios 2017) also named “Bois de Besson” (Winkler et al. 1985).

5.2.2 Type and reference sections

Exposures are restricted to the Bons quarry (Fig. 6a; 46.2550° N, 6.3913° E) and to the Grands Bois locality (46.2397° N, 6.3719° E). The Bons quarry, the type section, is well preserved and has often been investigated (e.g. Jan du Chêne et al. 1975; Ujetz 1996), whereas the Grands Bois is mostly covered by slope deposits as it is located in a small valley.

5.2.3 History

Although the Bons quarry exposure was reported as “Niveau 1” by van Stuijvenberg (1980), the member was



first described by Ragusa (2015). The Bons quarry was previously sampled for the biostratigraphy of calcareous nannofossils and dinoflagellates (Jan du Chêne et al. 1975; Jan du Chêne and Chateaufort 1975), and planktonic foraminifera (Ujett 1996; Ospina-Ostios 2017).

5.2.4 Spatial distribution

The Bons Mb. is currently restricted to the NW flank of the Voiron Nappe (Fig. 5). A possible extension toward the South is missing probably due to the uprising of the basal thrust of the Voiron Nappe, whereas its northward extension is questionable: the marly layer 1 identified at the Maladière by electric prospect (Fig. 3a) might be correlated to the Bons Mb.

5.2.5 Lithological characteristics and facies variations

The Bons Mb. consists of a marly succession with mostly cm- to m-thick tabular sandstone beds (Fig. 6a). Beds show a yellow to creamy colour derived from their important carbonate content (Fig. 6e). The marly intervals rarely exceed 1 m in thickness. The sand:marl ratio is low, but slightly higher than that of the Boège Marl (Fig. 7; Additional file 1). Sandstone intervals are organized in thinning-upward sequences, grading from one discrete, m-thick, coarse tabular sandstone bed to a succession of dm- to cm-thin, fine-grained calcareous beds (Ragusa 2015).

5.2.6 Sedimentological characteristics

Sandstone beds frequently show the Tb–Td intervals of the Bouma sequence (Bouma 1962), and include upper-plane beds, ripples, and soft-deformation (convolute) structures (Fig. 6e). Bases are sharp and devoid of erosive features. Flute casts and groove casts are found at the

base of thicker beds. These layers describe a distal environment of outer-fan to inter-lobe deposits (Ragusa and Kindler 2018). The frequent occurrence of F8 to F9 facies (Mutti 1992) suggests deposition by a turbidity flow (Ragusa 2015).

5.2.7 Petrographical characteristics

The petrographic composition corresponds to the Quartzose petrofacies (Ragusa et al. 2017). The framework composition of thin beds includes calcareous laminae with abundant planktonic foraminifera that alternate with quartzo-glaucitic laminae (lithofacies L5; Ragusa and Kindler 2018).

5.2.8 Lower and upper boundaries

Both boundaries are not well constrained because of the limited exposures and the considerable vegetation cover. However, the lower boundary of the Bons Mb. likely corresponds to the basal thrust of the Voiron Nappe.

5.2.9 Thickness

The total thickness cannot be precisely measured because the base of the member has been likely dismantled, and its top is covered by vegetation. The apparent thickness is estimated at ca. 50 m.

5.2.10 Geologic age

The calcareous nannofossils initially indicated a Thanetian age (NP 9, Jan du Chêne et al. 1975), whereas planktonic foraminiferal biostratigraphy suggests an age between the Ypresian and the Lutetian (P7–P11; Ragusa et al. 2018). Two bentonite layers (Fig. 6f) from the upper part of the section (Ospina-Ostios 2017) did not provide any chronostratigraphic data (Winkler et al. 1985).

5.2.11 Comparison with other regions

The Bons Mb. presents similarities with the “Calcaire blond silto-argileux” of the Helstätt Fm. (Gurnigel Flysch; Tercier 1928; Kapellos 1973; Caron 1976), the “Kreideflysch am Satelpass” (Schlieren Flysch; Winkler 1983) and the “Basis des Wägital Flyschs” (Wägital Flysch; Winkler et al. 1985b). Furthermore, all of these calcareous sandstone beds are similar to the Alberese facies (Studer 1827; Mutti et al. 2009), and are typical of the basal portion of these flyschs.

5.3 Signal Mb.

5.3.1 Origin of the name

The name refers to the highpoint of the Voirons (1480 m; Fig. 2).

5.3.2 Type and reference sections

The type section at the Signal des Voirons (46.2280° N, 6.3543° E) provides a good exposure, and is of easy access. Reference sections comprise the Monastery road (46.2280° N, 6.3583° E) outcrop and the Pralère summit (Fig. 5; 46.1979° N, 6.3488° E). They both display facies variations from clast-supported to matrix-supported conglomerates, respectively.

5.3.3 History

Favre (1867) first mentioned these conglomerates (i.e. “poudingues”) when he found nummulites in the coarse sandstones below the Pralère summit (note that the spelling “Pralaire” was used in old publications and maps). Sarasin (1894) and then Pilloud (1936) listed several blocks embedded in these nummulitic poudingues. Lombard (1940) regrouped these deposits as the “Conglomérats du Pralairé”, and described them as local events of minor significance in the overall sedimentation of the Voirons Sandstone. van Stuijvenberg (1980) merged the “Conglomérats du Pralairé” with the Vouan Conglomerate (see below), although these two units occur in different tectonic positions. The name “Conglomérat du Signal” was also applied to this unit by Ujetz (1996). The “Conglomérats du Pralairé” were then re-attributed to the Voirons Sandstone by Kerrien et al. (1998) and Charollais et al. (1998). Ragusa (2015) described this unit as the “Conglomérat de la Crête”.

5.3.4 Spatial distribution

The Signal Mb. is made of at least three large rock bodies forming the three highpoints of the Voirons (Pralère, Brantaz and Signal), and extending over the eastern flank along a NE direction (Figs. 2b, 5).

5.3.5 Lithological characteristics and facies variations

The Signal Mb. forms discrete, lens-shaped conglomeratic successions distributed in the middle part of the Voirons Sandstone (Fig. 4). They mainly consist of

matrix-supported to clast-supported conglomerates (Monastery road exposure; Fig. 6b) and of microconglomerates (Signal des Voirons exposure). The matrix is made of medium- to coarse-grained sandstone, and includes pebble- to gravel-size lithoclasts. Larger blocks (maximum size=50 cm) are only reported from the Monastery road outcrop. The lateral extension is variable from several metres to ca. one kilometre (Figs. 2b, 5).

5.3.6 Sedimentological characteristics

The conglomerates are massive and devoid of internal organisation, but Frébourg (2006) tentatively described a convex lens of “Conglomerate remnant Facies” (Mutti 1992) at the Monastery road exposure. The dominant F2–F3 facies of Mutti (1992) identify the Signal Mb. as channel deposits accumulated by a high-concentration density flows or a debris flow. The clast-supported conglomerate of the Monastery road exposure might correspond to levee deposits or potentially be derived from a debris flow. The restricted location in the succession of the Voirons Sandstone indicates exceptional and isolated events, occurring during a short time span (Lombard 1940).

5.3.7 Petrographical characteristics

The sandy matrix is affiliated to the Quartzose petrofacies (Ragusa 2015). Pebble petrography was described by Sarasin (1894), Pilloud (1936), Lombard (1940) and Cogulu (1961). They show a wide variety of composition including Mesozoic limestones, quartzarenite, metamorphic and magmatic rocks (Ragusa 2015). Pink granite fragments are especially concentrated in these layers (Fig. 6b). The clast petrography is broadly similar to that of the Vouan Conglomerate (Lombard 1940), but proportions differ (e.g. pink granites are frequent and carboniferous sandstones are rare to absent). Metric blocks of limestone containing small fragments of pink granite occur at the Pralère exposure (Fig. 6g, h). They possibly originated from a carbonate platform overhanging the Voirons Flysch basin, while the granite fragments were derived from one large coastal cliff surrounding the carbonate platform.

5.3.8 Lower and upper boundaries

The contact with the encompassing sandstones and marls is poorly documented. It appears as a sharp transition at the Pralère exposure (Pilloud 1936) or as a slightly erosional limit, mostly hidden by vegetation, at the Monastery road outcrop.

5.3.9 Thickness

No accurate estimation of thickness can be provided for these rock bodies because their overall geometry is unclear. Individual lenses are likely several meters thick.

5.3.10 Geologic age

Jan du Chêne et al. (1975) identified a NP 6 (Thanetian) calcareous nannofossil association along the crest. Frébourg (2006) suggested a Bartonian age (P14 zone of planktonic foraminifera) with some reworking. However, this age is conflicting with recent biostratigraphic data on the Voiron Flysch (Ragusa et al. 2018), suggesting this nannofossil association has been reworked. An Ypresian to Lutetian age is more likely.

5.3.11 Comparison with other regions

Microconglomeratic to conglomeratic layers are widely reported throughout the Gurnigel Flysch (Weidmann et al. 1976) and the Schlieren Flysch (Winkler 1983, 1985b). They are described as discrete beds interspersed within the succession or as localised accumulations of coarse material within sandy beds.

5.4 Allinges member

5.4.1 Origin of the name

The name refers to the Allinges Hills to the NE of the Voiron. The expression *Grès des Allinges* was introduced very early (de Mortillet 1863).

5.4.2 Type and reference sections

The Rocher d'escalade exposure is defined as the type section (Fig. 5; 46.3353° N, 6.4663° E). This outcrop presents several facies including rare marly intervals and a m-scale microconglomeratic layer. Quarries along the D 233 road (Lombard 1940; Cogulu 1961; Jan du Chêne et al. 1975) constitute the reference sections. They comprise one small quarry (46.3346° N, 6.4634° E) and one large quarry (Fig. 10a; 46.3329° N, 6.4613° E), and consist of a stack of amalgamated m-thick sandstone beds devoid of marly intervals.

5.4.3 History

During the second part of the XIXth century, the sandstones of the Allinges Hills were either included in the upper part of the flysch or *Macigno Alpin* (Favre 1867; Jaccard 1892; Sarasin 1894; Douxami 1904), or in the molasse (de Mortillet 1863; Renevier and Lugeon 1892).

These rocks were then neglected because they seemed uninteresting compared to the Voiron Sandstone (Lombard 1940, p. 1). Considering their coarse grain-size, Lombard (1940) and Cogulu (1961) correlated them with the Vouan Conglomerate, but Jan du Chêne et al. (1975) related them to the Voiron Sandstone based on biostratigraphic criteria. van Stuijvenberg (1980) thus considered these sandstones as a coarser facies of the Voiron Flysch, and associated them to his "Niveau 2". The Voiron Sandstone affiliation was used by Vial et al. (1989) in the Douvaine map of the French geological survey, whereas Olive et al. (1987) placed these rocks into the Vouan Conglomerate following the interpretation of Lombard (1940) (see Fig. 2b). Finally, recent petrographic investigations (Ragusa 2015; Ragusa et al. 2017) confirm the similarities with the Voiron Sandstone.

5.4.4 Spatial distribution

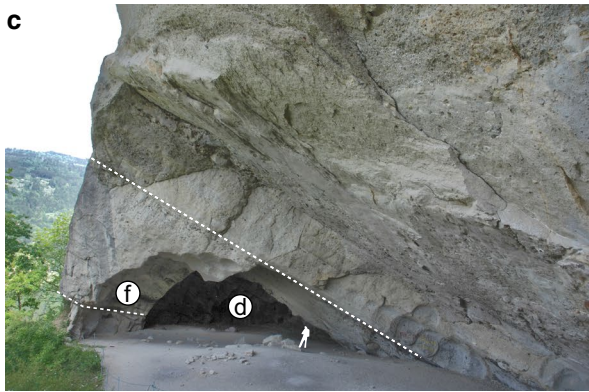
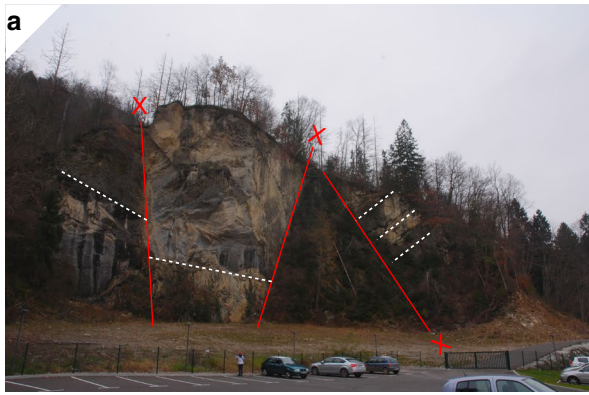
Exposures are located to the NE of the Voiron between the villages of Lully and Allinges (Fig. 2b). Outcrops comprise several small prominences (Lully, La Rochette Castle) and the Allinges Hills. The subdued relief as well as the low structural position led to an overall covering by glacial deposits of Quaternary age (Fig. 3a) limiting the exposition of the Allinges Mb. Furthermore, the frequent occurrence of glacial erosion features (Coutterand 2010) at the Allinges Hills shows that glacial activity has probably removed most of the southern connexion with the Voiron (Fig. 3a).

5.4.5 Lithological characteristics and facies variations

Based on electric prospects (Büchli et al. 1976) which determined three distinctive layers at the Maladière (Fig. 3a), Layer 2a would correspond to the Allinges Mb. The exposed Allinges Mb. is a massive stack of fine- to coarse-grained sandstones (Fig. 10a), locally interspersed by cm-thick marly interbeds (Rocher d'escalade exposure). Conglomerates are rare (Fig. 10b) and clasts are mainly of gravel size (Lombard 1940; Cogulu 1961). The homogeneity of this rock body precludes any internal subdivisions.

(See figure on next page.)

Fig. 10 Major lithologic features of the Allinges Mb. (a, b) and of the Vouan Conglomerate (c–h). **a** Massive sandstone accumulation at the large quarry of Allinges. **b** Erosive microconglomerate overlying a laminated coarse sandstone at the Rocher d'escalade exposure. **c** The Grande Gueule millstone quarry exposure. Letters refer to close-up views depicted in next sub-figures. **d** Remnants of millstone extraction from the Grande Gueule quarry. Note the homogeneous lithology of the excavated section. **e** The Grotte aux Loups exposure (46.3172° N, 6.4445° E) at the Maladière is the easternmost outcrop of the Vouan Conglomerate. **f** Pinch out and variable pebble size and distribution at the Grande Gueule quarry. Note the large block floating into the sandy matrix and the fining-up grain-size (black triangle). **g** Clast of black conglomerate of Paleozoic age characterising the Vouan Conglomerate from the Grande Gueule exposure. White circle: lens cap (72 mm). **h** Marly interval (sequence 3) of the Ruisseau de Curseille (46.2° N, 6.3712° E)



5.4.6 Sedimentological characteristics

The low marly content, the frequent amalgamation of beds, and the occurrence of F5 to F9 facies (and scarce F2) (Fig. 10b) indicate an intermediate depositional setting characterized by high- to low-concentration density flows. Furthermore, the rare conglomeratic inputs suggest a more distal depositional environment than that of the Vouan Conglomerate or of the Signal Mb.

5.4.7 Petrographical characteristics

The framework composition of the Allinges Mb. is affiliated to the Quartzose petrofacies (Ragusa 2015; Ragusa et al. 2017). This result corroborates the suggestion of Jan du Chêne et al. (1975) and Vial et al. (1989), and excludes an affiliation with the Vouan Conglomerate as postulated by Lombard (1940), Cogulu (1961) and Olive et al. (1987). The occurrence of amber, locally called *Allingite* (Decrouez and Maquignon 2018; Maquignon and Decrouez 2019), is reported by de Mortillet (1863) and Renevier and Lugeon (1892). Similar occurrences have been also reported throughout the Gurnigel Flysch (Tercier 1928).

5.4.8 Upper and lower Boundaries

The lower and upper boundaries cannot be defined since most of the Allinges Mb. is covered by Quaternary deposits (Fig. 3a). Moreover, uncertainties concerning the lateral extension of the upper stratigraphic units (Vouan Conglomerate and Boège Marl) along the Allinges Hills preclude accurate mapping of this member.

5.4.9 Thickness

Based on electric prospect (Büchli et al. 1976) (Fig. 3a), a thickness of ca. 100–200 m can be estimated for the Allinges Mb. (layer 2a).

5.4.10 Geologic age

The scarcity of marly interbeds hampers reliable dating. Jan du Chêne et al. (1975) described a Thanetian age based on calcareous nannofossils which is not consistent with more recent planktonic foraminiferal data ranging from the Ypresian to the Lutetian for the Voiron Sandstone (Ragusa et al. 2018), and would suggest reworking of the nannofossil association.

5.4.11 Comparisons with other regions

No lateral correlation is currently available for the Allinges Mb. as it mostly corresponds to a lateral extension of the Voiron Sandstone.

5.5 Vouan Conglomerate

5.5.1 Origin of the name

The name refers to the Mont de Vouan (Fig. 2). Although conglomerates do not represent the major lithology, this term is maintained since (1) it has a historical significance, and (2) conglomeratic layers and widespread floating pebbles are the most prominent features.

5.5.2 Type and reference sections

The most important millstone quarry of the Mont de Vouan, the Grande Gueule quarry (Fig. 10c; 46.1681° N, 6.3806° E), is defined as the type section of the Vouan Conglomerate (Fig. 5). The reference sections include the Vachat quarry (46.1752° N, 6.3768° E) and the Molière quarry (Fig. 5; 46.1873° N, 6.3702° E).

5.5.3 History

Favre (1867) discovered nummulites at the Mont de Vouan, and considered this conglomerate-rich succession as stratigraphically capping the Voiron Sandstone. He further reported the occurrence of large blocks similar to those observed at Habkern. De Mortillet (1858) questioned the origin of the pebbles found in these “puddingstones”. Later, Renevier and Lugeon (1892) rejected the presence of the nummulites reported by Favre (1867), and attributed the Vouan Conglomerate to the molasse. Douxami (1901) considered these rocks as a nummulitic conglomerate occurring between two similar sandstone series. The Vouan Conglomerate was first described as a distinct unit by Lombard (1940). Cogulu (1961) listed the pebble population, and Frébourg (2006) provided a catalogue of the limestone pebbles. Frébourg (2006) further suggested that the Vouan Conglomerate represents an incised channel complex similar to those of the Corsica system. The petrographic analysis of these rocks (Ragusa 2015; Ragusa et al. 2017) revealed a distinct detrital composition (i.e. the Feldspathic petrofacies) suggesting a different source than that of the Voiron Sandstone.

5.5.4 Spatial distribution

The Vouan Conglomerate is exposed at the Mont de Vouan, along the lower part of the eastern flank of the Voiron, and continues north-eastward, toward the Saxel pass (Fig. 2b). Most outcrops consist of millstone quarries (Fig. 10c). These exposures are well preserved, large and easily accessible. However, most of them are now protected as *Monuments historiques* (e.g. French national heritage sites), and sampling is thus restricted. They represent one of the most important millstone quarry site in the Alps, and were also investigated by archaeologists (Fig. 10d) (Belmont and Anderson 2011; Belmont 2012). Several m-scale collapsed blocks are reported to the north of the Mont de Vouan (46.1842° N, 6.3803° E). These are

not protected, and comprise thick conglomeratic successions available for sampling. The Vouan Conglomerate is also reported along the northern flank of the Grande Combe on the Douvaine geologic map (Badoux 1965b). However, the important vegetation cover in this area renders any confirmation difficult. Beyond the Voirons, the Vouan Conglomerate is only exposed along the SW crest of the Maladière (Figs. 5, 10e; the Grotte aux Loups outcrop), and likely represents the layer 3a of the geological transect through the Maladière (Fig. 3a).

5.5.5 Lithological characteristics and facies variations

The Vouan Conglomerate consists of an amalgamation of coarse pebbly sandstone and of polymictic, matrix-supported conglomerate with a coarse sandy matrix (Fig. 10f) (Charollais et al. 1998; Frébourg 2006). The thickness of the amalgamated beds varies between 0.1 and 10 to 15 m (Charollais et al. 1998; Frébourg 2006; Ragusa 2015). Beds exhibit pronounced lateral variations with pinch-outs and erosive surfaces preventing lateral correlation (Fig. 10f) (Frébourg 2006). Exposed rocks show a yellow colour and frequent vertical sheet-like foliations resulting from meteoric weathering. Marly interbeds are scarce, and mostly found as reworked mud pebbles (Frébourg 2006; Ospina-Ostios et al. 2013; Ragusa et al. 2018).

5.5.6 Sedimentological characteristics

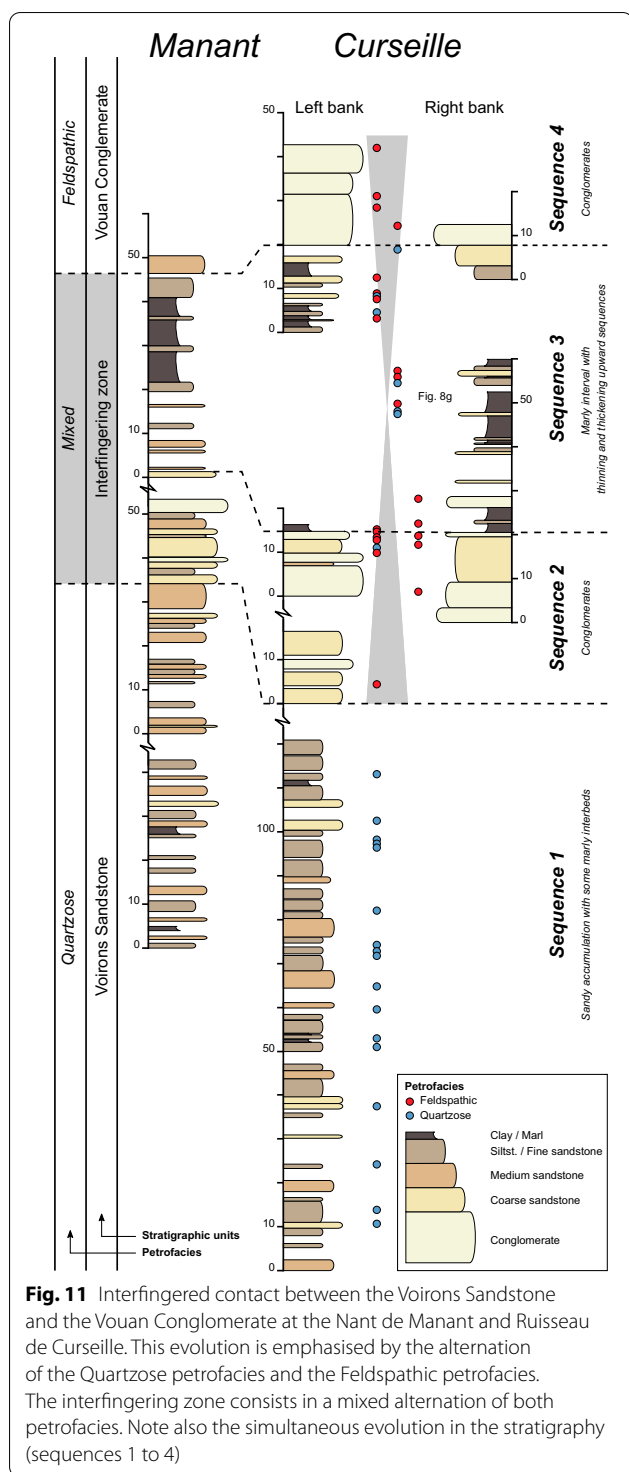
Clasts are sub- to well-rounded, pebble to block size, and can be several meters wide (Fig. 10f). They exhibit both normal and reverse grain-size grading, and locally form accumulations embedded in sandstones. Their distribution throughout the succession frequently highlights internal subdivisions in the amalgamated beds (Fig. 10f). Lombard (1940) saw rhythmic oscillations in the alternation of sandstones and conglomerates, and estimated about 15 cycles in the cliff near Mijouet. Palaeocurrent directions reported from the Vouan Conglomerate are rare (Frébourg 2006) because the bases of beds are either not exposed, correspond to erosion surfaces, or are entirely bioturbated (Vachat quarry). The few data originate from the Saxel upper quarry (46.2523° N, 6.3960° E) which is considered as the base of the unit in the Voirons (Ragusa 2015). Palaeocurrent direction varies from N113 to N332 (Fig. 8), which differs from that of the Voirons Sandstone as Frébourg (2006) already suggested. The dominant F2–F5 Mutti facies and the stack of coarse-grained deposits (Frébourg 2006; Ragusa 2015) support a proximal depositional setting dominated by high-concentration density flows and debris flows. A cross section of channel deposits is well exposed at the Vachat quarry (Ragusa 2015). F6–F9 facies are also found intercalated between massive beds, possibly indicating overbank or levees deposits.

5.5.7 Petrographical characteristics

The Feldspathic petrofacies is diagnostic of the Vouan Conglomerate (Ragusa et al. 2017). Among the pebble population listed by several authors (Cogulu 1961; Frébourg 2006; Ragusa 2015), the most characteristic pebbles are black sandstones of Paleozoic age (Fig. 10g) that possibly originate from the Zone Houillère (Ospina-Ostios et al. 2013; Ragusa et al. 2017), and that are almost totally missing in the Voirons Sandstone (Lombard 1940; Cogulu 1961). By contrast, the pink granites fragments that frequently occur in this unit are absent from the Vouan Conglomerate. This important modification of the detrital supply and the radical change in depositional setting between the Voirons Sandstone and the Vouan Conglomerate represents the first major disruption in the Voirons Flysch.

5.5.8 Lower boundary

The contact with the underlying Voirons Sandstone is a stratigraphic boundary (Lombard 1940; Cogulu 1961; van Stuijvenberg 1980). Frébourg (2006) saw an erosional contact with an angular discontinuity, but this has not been confirmed by more recent surveys (Ragusa 2015; Ospina-Ostios 2017). The transition consists in a complex interfingering exposed along the Ruisseau de Curseille and the Nant de Manant (Fig. 11) (Ragusa 2015). The sandy accumulations of the Voirons Sandstone (sequence 1) are interrupted by the thick amalgamated, matrix-supported conglomerates of the Vouan Conglomerate (sequence 2). The overlying strata comprise a thinning-upward sequence (sequence 3) followed by a thickening-upward sequence grading to the conglomerates (sequence 4). The transition between sequences 3 and 4 corresponds to a m-thick marly interval with scarce cm-thick sandy beds (Fig. 10h). Both the Quartzose and the Feldspathic petrofacies (Ragusa et al. 2017) are randomly distributed in this marly interval, whereas the other sequences display the dedicated petrofacies. The transition zone has a limited lateral extension emphasizing that the Vouan Conglomerate initiated in a constrained channel, and progressively spread over the pre-existing fan (Fig. 12). Northward, the contact is covered by vegetation between the Saxel lower quarry (Voirons Sandstone) and the Saxel upper quarry (Vouan Conglomerate). To the south, the contact might be located at Pont Morand (Ospina-Ostios 2017), and may correspond to a marly succession (outer fan setting?) covered by meadows above the Fillinges quarry (Voirons Sandstone) and beneath the outcropping rocks of the Vouan Conglomerate (Lombard 1940; Cogulu 1961; Frébourg 2006).



5.5.9 Thickness

This homogeneous unit is estimated to be ca. 500 m thick at the Voiron (Fig. 4) (Ospina-Ostios 2017) and might be reduced to 100 m at the Maladière (Fig. 9).

5.5.10 Geologic age

The scarcity of marly intervals prevents the sampling of non-reworked microfossils. Several authors (Favre 1867; Pilloud 1936; Lombard 1940) found nummulitids in the coarse sandstones of the Vouan Conglomerate. A revision of these forms by Dr. U. Menkveld-Gfeller (Naturhistorisches Museum, Bern) indicates an early to late Eocene age (P5-P16; Ospina-Ostios 2017). However, this interpretation must be taken with care since the isolated specimens of Lombard (1940) were not found in the collection. Charollais et al. (1998) considered a late Ypresian to Lutetian age because of the late Lutetian to Bartonian age attributed to the overlying Boège Marls. Based on calcareous nannofossil data from the underlying Voiron Sandstones and the Boège Marls, the age of the Vouan Conglomerate was constrained between the late Lutetian and the Bartonian (NP15–NP16 to NP17 biozones, Jan du Chêne et al. 1975; van Stuijvenberg 1980). Recent studies focusing on planktonic foraminifera confine the Vouan Conglomerate to the Lutetian (P12; Ragusa et al. 2018).

5.5.11 Comparisons with other regions

It is well known that the Vouan Conglomerate has no equivalent in the Gurnigel Flysch to the Wägital Flysch (Caron et al. 1989). A few discrete conglomeratic layers have nonetheless been reported from the eastern flyschs, but none of them forms a distinct stratigraphic unit. For example, Weidmann et al. (1976) described frequent microconglomeratic layers in the “Flysch 5 à microconglomérats siliceux” (Gurnigel Flysch) that are coeval with the Vouan Conglomerate (Lutetian), but only comprise gravel-size clasts.

5.6 Boège Marl

5.6.1 Origin of the name

Although the type section is located along the Torrent de Saxel, van Stuijvenberg and Jan du Chêne (1980) used the village of Boège as the formation name to prevent confusion with the outcrops of the Saxel quarries which belong to the underlying units. The name is kept, and the denomination “Saxel Marl” (Charollais et al. 1998; Coppo 1999; Frébourg 2006) should be avoided.

5.6.2 Type and reference sections

The Torrent de Saxel (46.2456° N, 6.3982° E) remains the type section (Fig. 5) (van Stuijvenberg and Jan du Chêne 1980) as it provides the longest exposure of the Boège Marl. Equivalent successions can also be found along parallel streams southward. Although, its total thickness is restricted, the reference section of the Torrent de Chauffémérande (46.1697° N, 6.3893° E) is of prime

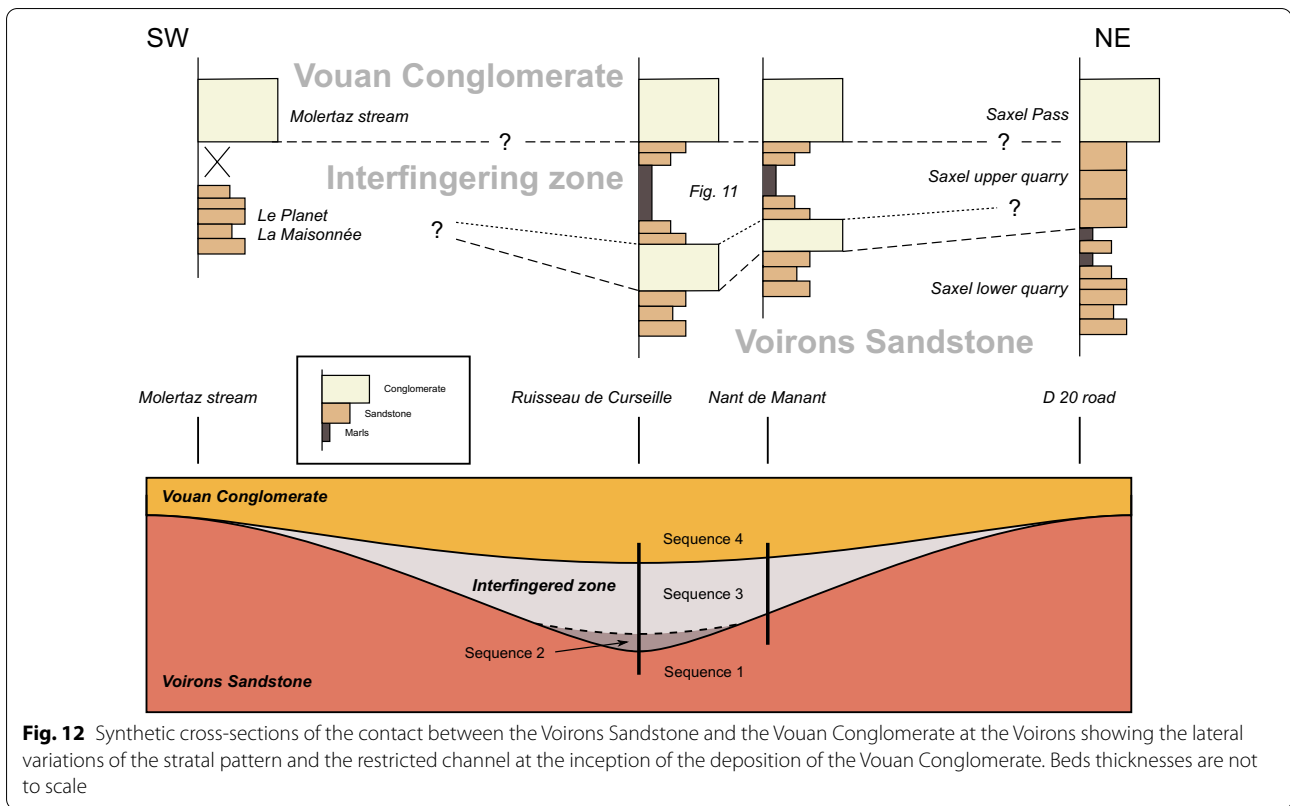


Fig. 12 Synthetic cross-sections of the contact between the Voiron Sandstone and the Vouan Conglomerate at the Voiron showing the lateral variations of the stratal pattern and the restricted channel at the inception of the deposition of the Vouan Conglomerate. Beds thicknesses are not to scale

importance because it exposes the stratigraphic contact with the underlying Vouan Conglomerate, and further includes conglomeratic layers (Fig. 13a). However, the Chez Musard exposure (46.2242° N, 6.4118° E) is removed because of its chaotic nature, and its uncertain origin (see Sect. 5.7.8).

5.6.3 History

Renevier and Lugeon (1892) first reported sandstone beds above the Vouan Conglomerate. He included them in the Flysch, and depicted a syncline fold connecting these beds to the Voiron Sandstone. Lombard (1940) and Cogulu (1961) described the “Chauffemérande marls” capping the Vouan Conglomerate. Later, van Stuijvenberg and Jan du Chêne (1980) formally defined the Boège Marl, and hypothesized this unit was duplicated tectonically to account for its important thickness (ca. 1000 m). Up to now, the Boège

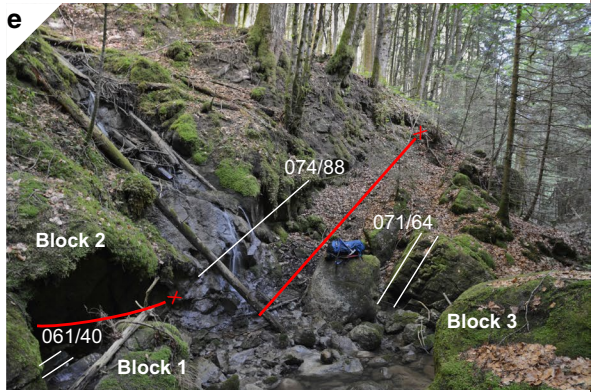
Marl was the only unit formally described in the Voiron Flysch (van Stuijvenberg and Jan du Chêne 1980). Coppo (1999) suggested to consider it as a separate tectonic unit, but this hypothesis was refuted by Ospina-Ostios (2017).

5.6.4 Spatial distribution

The Boège Marl mostly crops out in the Ludran Hills and the Grande Combe (Fig. 2). Exposures are generally of poor quality due to the significant proportion of marls. Reliable, extensive outcrops are concentrated along streams, especially along the western flank of the Grande Combe (Fig. 2). Exposures along the Ludran Hills are smaller, but show a tectonic contact with the overlying Préalpes Médiannes Nappe at the Bachais. To the North, outcrops are mostly covered and restricted to the Dranse River (Figs. 2, 5) (Jan du Chêne et al. 1975; Dupuy et al. 2014). Marly intervals are missing from the upper part of

(See figure on next page.)

Fig. 13 Major lithologic features of the Boège Marl (a–d), of the Bruant Sandstone (d–f) and of the Fenalet Sandstone (g). **a** Clast-supported conglomerate of the basal layers of the Boège Marl along the Torrent de Chauffemérande (46.1701° N, 6.3839° E). **b** Sandstone bed with current ripples from the Dranse outcrop (46.3594° N, 6.5207° E). **c** Small-scale fault-propagation fold along the Chez le Merizier stream (46.2237° N, 6.3991° E). **d** Chaotic structure along the stream at the Chez Musard (46.2234° N, 6.4136° E). This outcrop might correspond to the contact between the Boège Marl and the Bruant Sandstone. The nature of the chaotic structure (fault or slump) is not resolved. **e** Exposure of the Bruant Sandstone along the Bruant stream displaying faulted block (46.2435° N, 6.43967° E). Note the different dip directions. **f** Marly interval in the Nant de Carraz (46.2297° N, 6.4162° E). **g** Tectonic contact between the Préalpes Médiannes Nappe and the Voiron Nappe at the Fenalet quarry



the Allinges Hills (Fig. 3a) indicating a discontinuous lateral extent of the formation.

5.6.5 Lithological characteristics and facies variations

The Boège Marl consists of a stack of dm- to m-thick marly intervals interspersed by cm-thick sandstone beds (Figs. 7, 13b). Pristine marls are grey, and weathered layers are brownish (van Stuijvenberg and Jan du Chêne 1980; Charollais et al. 1998). Most of the marls are relatively indurated, and contain between 21 and 40% of carbonate (van Stuijvenberg and Jan du Chêne 1980; Ospina-Ostios 2017). Thin black laminations are locally observed in marly intervals. Sandstone layers do not exceed 50 cm in thickness. They are tabular, fine- to medium-grained, rarely coarser (Ragusa and Kindler 2018). Rare dm-thick, matrix-supported conglomerates (Figs. 3b, 4 and 13a) are exposed at the base of the formation in the Torrent de Chauffemérande (van Stuijvenberg and Jan du Chêne 1980).

5.6.6 Sedimentological characteristics

The sandstone beds within the Boège Marl present numerous sedimentary features including upper-plane beds, ripple laminations, convolute bedding, and current ripples (Fig. 13b) (Ospina-Ostios et al. 2013; Ragusa 2015). Flute casts and groove casts are rare since their development is positively correlated to the grain-size (Allen 1968, 1971; Pett and Walker 1971a, 1971b; Peakall et al. 2020). Consequently, flute casts are narrow, and can be confused with bioturbations. The base of beds is sharp. Palaeocurrent measurements range from N111 to N291, and most of them are concentrated between N111 and N191 (Fig. 8). The occurrence of F8 to F9 facies (Mutti 1992) indicates that turbiditic flows were predominant. However, the lack of lithofacies L6 (Ragusa and Kindler 2018) suggests a deposition by surge-like turbidity currents (Mulder and Alexander 2001) in a continental slope setting (van Stuijvenberg and Jan du Chêne 1980; Winkler 1984a). Conglomerates found at the base of the formation are probably related to upstream channel collapses (Ragusa 2015; Ragusa et al. 2018). A dm- to m-scale faulted fold has been recognised along the Chez le Merizier and the Chez Rollin streams (Fig. 13c) (Ragusa 2015; Ospina-Ostios 2017), and extends possibly up to the Torrent de Saxel. Slumps occur also in several places (Fig. 13d; e.g. Chez Musard exposure and the Dranse outcrop). These features suggest unappreciated and frequent internal deformations.

5.6.7 Petrographical characteristics

The Boège Marl is characterised by the Quartzose petrofacies (Ragusa et al. 2017). The fine-grained texture

involves a large depletion of lithoclasts and an increase in mica, skeletal grains and calcite cement (Ragusa and Kindler 2018).

5.6.8 Lower boundary

The boundary between the Vouan Conglomerate and the Boège Marl represents the second major break in the sedimentation of the Voiron Flysch. The massive sedimentary flux of the Vouan Conglomerate abruptly stopped, and was replaced by the starved marly succession of the Boège Marl (Fig. 4) (van Stuijvenberg and Jan du Chêne 1980; Charollais et al. 1998). The best exposure is located along the upper part of the Torrent de Chauffemérande (46.1713° N, 6.3886° E). The Boège Marl overlies the Vouan Conglomerate with a slight angle (Fig. 3b) (Ospina-Ostios 2017). The contact is further characterised by the occurrence of discrete conglomeratic beds at the base of the formation (Figs. 4, 13b) (van Stuijvenberg and Jan du Chêne 1980; Ragusa 2015; Ospina-Ostios 2017).

5.6.9 Upper boundary

The Boège Marl is overlain by both the Bruant Sandstone and the Préalpes Médiannes Nappe. The boundary with the Bruant Sandstone is described below (Sect. 5.7.8). The tectonic contact with the dolomitic breccia (Triassic) at the base of the Préalpes Médiannes Nappe crops out in the southern part of the Voiron area (Fig. 2b) (Coppo 1999; Ragusa 2015; Ospina-Ostios 2017). Beds are steeply dipping in the vicinity of the contact (Torrent de Chauffemérande: 46.1607° N, 6.3967° E; Les Chaix hamlet: 46.1928° N, 6.4175° E), indicating important internal deformations (Fig. 3b). The thrusting of the Préalpes Médiannes Nappe may thus have promoted the development of a folded structure such as that depicted in the Ludran Hills (Ujetz 1996; Coppo 1999; Ospina-Ostios 2017). This contact can be broadly followed to the North, but beyond the Voiron, it is covered by thick Quaternary deposits (Fig. 3a).

5.6.10 Thickness

van Stuijvenberg (1980) estimated the total thickness of the Boège Marl to ca. 1000–2000 m (Fig. 4), which is equivalent to the thickness of the Gurnigel Flysch, but within a more restricted timespan (van Stuijvenberg 1980). Coppo (1999) imagined one large folded structure within the Boège Marl to explain their important thickness. However, no evidence of such a fold was found (Ospina-Ostios 2017), but minor internal deformations including small-scale folds and thrusts (Fig. 13c) (Coppo 1999; Ospina-Ostios 2017) may have increased the thickness of the Boège Marls, such as at the Ludran Hills (Coppo 1999). Consequently, we consider a thickness of about 400 m for this formation.

5.6.11 Geologic age

van Stuijvenberg (1980) constrained the age of the Boège Marl within one calcareous nannofossil zone (NP 18) corresponding to the late Bartonian. The micropalaeontological content is rich (dinophyceae, scolecodonts, pollens, spores, calcareous nannofossils), but does not contain any diagnostic form of the NP 19 association (van Stuijvenberg and Jan du Chêne 1980). A Priabonian age (NP 18–NP 20) was attributed to the Dranse exposure (Jan du Chêne et al. 1975). Based on planktonic foraminifera, Coppo (1999) constrained the age of the formation between the P12 and P17 biozones (late Lutetian/early Bartonian to late Priabonian) and eventually to the early Oligocene. However, ages based on planktonic foraminifera remain uncertain (Ragusa et al. 2018), and provide a Lutetian age for the base of the formation. Additionally, this age may correspond to that of reworked material from the Vouan Conglomerate as shown by the occurrence by discrete conglomerate layers at the base of the formation (Fig. 13b). A younger age extending up to the Priabonian has to be considered regarding the low sedimentation rate and thus the time needed to accumulate such a thick marly succession.

5.6.12 Comparisons with other regions

As previously noted by van Stuijvenberg and Jan du Chêne (1980), the “Flysch 4 à turbidites silteuses” observed in the Gurnigel Flysch (Weidmann et al. 1976) shows the same stratal pattern as the Boège Marl, and also dates from the Lutetian. However, it underlies the Flysch 5 which can be considered as an equivalent of the Vouan Conglomerate. The stratigraphic succession of the Voiron Flysch would thus be reversed compared to that of the Gurnigel Flysch.

5.7 Bruant sandstone

In contrast to Ragusa (2015), no stratigraphic rank is attributed to the Bruant Sandstone because of the uncertain nature of this unit (discrete stratigraphic unit capping the Boège Marl or tectonic slice of Voiron Sandstone thrust over this formation). Furthermore, this unit cannot be interpreted as a *mélange* (Kerrien et al. 1998) or as a broken formation due to the absence of a block-in-matrix fabric as well as boudinage following the common definition (Hsü 1974; Festa et al. 2010).

5.7.1 Origin of the name

The name refers to the Bruant, a stream flowing west of the Habère-Lullin village and a tributary of the Menoge River.

5.7.2 Type and reference sections

Outcrops along the Bruant (46.2428° N, 6.4398° E) represent the type section (Fig. 5). However, the large occurrence of fault planes disrupting strata precludes appropriate logging (Fig. 13e).

5.7.3 History

This unit was diversely interpreted in the past. Lombard (1940) first reported sandstone beds capping the Vouan Conglomerate at the Mont Macheret (i.e. the Grande Combe) and at the Targaillan peak. These beds were described as scattered and weathered. Van Stuijvenberg (1980) interpreted this succession as a tectonic slice, the Tête du Char slice, which comprised a lower part made of Voiron Sandstone capped by the Boège Marl. Kerrien et al. (1998) reinterpreted this unit as a *mélange*, whereas Charollais et al. (1998) described a “*Série à prédominance gréseuse (Priabonien?)*” (Figure 2b). Recently, Ragusa (2015) refuted the *mélange* hypothesis, but the tectonic interpretation remains questionable as discussed below.

5.7.4 Spatial distribution

The Bruant Sandstone is currently restricted to the Grande Combe and the Tête du Char (Fig. 7). The northern extension is unclear due to the lack of exposures along the north flank of these landforms. However, layers 2b and 3b at the Allinges Hills (Fig. 3a) could be a lateral equivalent of the Bruant Sandstone (see also Sect. 6.1 for further discussion). The S-SE limit broadly follows the Menoge River. This unit is characterised by sporadic outcrops between the Chez les Roch hamlet and the Tête du Char (Charollais et al. 1998; Kerrien et al. 1998).

5.7.5 Lithological characteristics and facies variations

The lithology is broadly similar to that of the Voiron Sandstone. There is no evidence of a chaotic organisation or of muddy matrix as postulated by Kerrien et al. (1998). Some beds are folded as observed along the stream at the Chez Gagne hamlet (46.2325° N, 6.43° E). Most outcrops consist in a stack of tabular and massive dm- to m-thick sandstone beds (Fig. 13e). They are interspersed by some cm-thick marly intervals. No conglomeratic layers have been reported (van Stuijvenberg 1980). A marly outcrop with cm-thick sandstone beds is located along the Nant de Carraz (Figs. 7, 13f).

5.7.6 Sedimentological characteristics

Sedimentary features are also comparable to those of the Voiron Sandstone with predominant structureless sandy beds. Because of the variable dips, no palaeocurrent direction is reported from this unit.

5.7.7 Petrographical characteristics

The framework composition is similar to that of the Voirons Sandstone with a dominant Quartzose petrofacies (Ragusa et al. 2017). Charollais et al. (1998) reported more frequent red-algae and bioclastic horizons than in the Voirons Sandstone. van Stuijvenberg and Jan du Chêne (1980) further noticed a darker colour and a lower calcite content in the marly intervals. Recently, a small sandy block with amber fragments has been discovered north of Burdignin (Dr. André Piuz, pers. com. 2020).

5.7.8 Lower boundary

The unit overlies the Boège Marl in the NE part of the Voirons (Fig. 5). The gradual increase in sandstone beds at the Granges Sauthier exposure (46.2334° N, 6.4086° E; Ragusa 2015) emphasizes the probable stratigraphic nature of this boundary (Fig. 4). This might be confirmed by the undocumented units (layers 2b and 3b) overlying the Vouan Conglomerate at the Maladière (Fig. 3a). However, a tectonic contact cannot be totally excluded, and the Bruant Sandstone would then correspond to a tectonic slice of the Voirons Sandstone following an out-of-sequence thrust as postulated by van Stuijvenberg (1980). Likewise, the chaotic bedding observed at the Chez Musard outcrop (Fig. 13d) is suspicious. This section could either correspond to a slump, confirming the stratigraphic contact and the occurrence of minor internal deformations within the Boège Marl, or could be related to the thrusting of the tectonic slice.

5.7.9 Upper boundary

The variable dip orientations reported from the Bruant Sandstone (Ospina-Ostios 2017) emphasise that this unit is tectonically deformed by several faults related to the overthrusting of the Préalpes Médiannes Nappe. Despite its proximity to this nappe, the contact with the latter is hidden by a dense vegetation cover. This brittle deformation contrasts with the prevailing soft deformation observed in the Boège Marl.

5.7.10 Thickness

The Bruant Sandstone was initially included in the Boège Marl. Kerrien et al. (1998) and Charollais et al. (1998) did not provide any measurement of the thickness of their alleged mélange, and the pronounced tectonic deformation, as well as the dismantling from the thrusting, prevents an accurate estimation. The current thickness of the deformed unit is roughly evaluated at about 500 m (Fig. 4).

5.7.11 Geologic age

Due to the scarcity of marly intervals, no age determinations have been performed. Charollais et al. (1998)

suggested a Priabonian age for this unit because it overlies the Boège Marl (Bartonian). Based on foraminiferal biostratigraphy, Ragusa et al. (2018) postulated a Lutetian or a Priabonian age for this formation. Dating this unit will clarify its nature.

5.7.12 Comparisons with other regions

Since the nature of the Bruant Sandstone is unresolved, comparisons remain uncertain. A potential equivalent could be the “Flysch 5 à microconglomérats siliceux” (Gurnigel Flysch; Weidmann et al. 1976), highlighting the re-establishment of a sandy sedimentation on top of a marly succession (i.e. the Boège Marl) before the accretion of the Voirons Flysch.

5.8 Fenalet Sandstone

There is no stratigraphic rank currently attributed to the Fenalet Sandstone because its current stratigraphic position remains uncertain, and lacks lateral continuity with the rest of the Voirons Flysch (Fig. 9).

5.8.1 Origin of the name

The name refers to the Fenalet quarry (46.3873° N, 6.8201° E) situated along the state road 21 near Saint-Gingolph (Fig. 2).

5.8.2 Type and reference sections

The ca. 50 m-high excavation front of the Fenalet quarry, capped by the Triassic sole (cornieule) of the Préalpes Médiannes Nappe (Fig. 13g), constitutes the largest outcrop of the Voirons Flysch, and the best-preserved exposure of a tectonic contact between nappes in the Chablais Prealps. A secondary exposure forms a small bulge bounding the quarry from the railway.

5.8.3 History

Blanchet (1844) initially included the sandstone from the Fenalet quarry in the Flysch, while Favre (1867) placed it within the *Macigno Alpin*. Favre (1867) further correlated these sandstones with the Cenozoic rocks quarried at Bonneville (i.e. *Grès de Bonneville*). The Fenalet Sandstone was also merged with the red molasse deposits of the Bouveret section, and related to the *Ralligensandstein* (Studer 1853). Lugeon (1901) included these sandstones in the upper part of the Flysch, and Schardt (1906) confirmed their relationship with the *Préalpes bordières* (External Prealps). The sandstones of the Fenalet quarry were then affiliated to the Ultrahelvetic realm (Gagnebin 1944; Badoux 1953, 1962; Rigassi 1966) as reported on the Montreux sheet of the Swiss Geological Atlas (Badoux 1965a) and on

the Thonon–Chatel sheet of the French Geological map (Badoux 1965b). Badoux (1965b) mentioned some analogies of these rocks with the Voirons Sandstone. However, Caron (1976) did not include the Fenalet quarry within the former Gurnigel Nappe, and suggested affinities with the Ultrahelvetic realm or the Submédiane Zone. Badoux (1996) took over this interpretation. Nevertheless, subsequent biostratigraphic data (Ujetz 1996) showed that the Fenalet Sandstone might be coeval with the Voirons Flysch. This led Dupuy et al. (2014) to modify their structural interpretation, and to suggest a correlation of this exposure with the Voirons Flysch, which was corroborated by the occurrence of garnet in the heavy-mineral composition (Ragusa 2015; Ragusa et al. 2017).

5.8.4 Spatial distribution

The Fenalet Sandstone constitutes the easternmost exposure of the Voirons Flysch. Two tectonic slices occur along the state road 21 between Saint-Gingolph and Le Bouveret (Gagnebin 1924; Badoux 1996; Dupuy et al. 2014), the most important of which is the Fenalet quarry (Fig. 13g).

5.8.5 Lithological characteristics and facies variations

The Fenalet Sandstone presents a peculiar and monotonous stratal pattern comprising an alternation of dm-thick, tabular, fine- to medium-grained dark sandstone beds interspersed by cm-thick marly intervals (Figs. 7, 13g). Such a stacking pattern is unique in the Voirons Flysch. Indeed, the marly interbeds are thinner than those of the Bons Mb. and of the Boège Marl for a similar range of sandstone bed thickness, and their thickness does not vary up section.

5.8.6 Sedimentological characteristics

The laminated, fine- to medium-grained, tabular sandstone beds correspond to the F9 facies (Mutti 1992). They commonly show upper-plane bed laminae and current ripples. No palaeocurrent direction could be measured from the Fenalet Sandstone because of the scarcity of features at the base of beds and the very thin interbeds. Blanchet (1844) and Favre (1867) reported fucoids from this exposure. The frequent occurrence of thin sandstone beds suggests deposition from surge-like turbidity currents (Mulder and Alexander 2001). Furthermore, the low lithic content and the high proportion of mica confirm deposition in the distal part of a deep-sea fan (Ragusa and Kindler 2018).

5.8.7 Petrographical characteristics

Beds consist of well-cemented micaceous sandstones (Peterhans 1923; Badoux 1962, 1965b). The framework composition comprises chert and various limestone fragments (Badoux 1953, 1962). Abundant skeletal grains include red-algae fragments, bryozoans, *Asterocyclina* sp., *Discocyclina* sp., *Heterostegina* sp., and shell fragments (Badoux 1953). Badoux (1953) also noticed the occurrence of authigenic quartz within red-algae fragments. Recent quantitative petrographic analysis affiliated the Fenalet Sandstone to the Quartzose petrofacies (Ragusa et al. 2017).

5.8.8 Lower boundary

The lower boundary of the Fenalet Sandstone corresponds to the tectonic contact of the Voirons Nappe with the underlying Infrapréalpine mélange (Fig. 2a). This contact is indiscernible as it is covered by Quaternary deposits, and situated beneath the Léman (Lake Geneva). Additionally, the lateral continuity of the Fenalet Sandstone is interrupted by dextral strike-slip faults (Fig. 2a) (Dupuy et al. 2014).

5.8.9 Upper boundary

The upper limit of the Fenalet Sandstone corresponds to the basal thrust of the Préalpes Médiannes Nappe (Fig. 13g). The uppermost layers have been softly deformed by the overlying nappe, and no mélange is observed.

5.8.10 Thickness

Only the upper part of this unit is visible at the exposure (ca. 50 m). The seismic profile of Dupuy et al. (2014; Fig. 17) indicates that at least 150 m of undifferentiated flysch are buried below glacial to glaciolacustrine deposits off the Fenalet quarry. Moreover, potential dismantling of the upper part of the unit by the overriding Préalpes Médiannes Nappe has to be considered.

5.8.11 Geologic age

Badoux (1962, 1965b) inferred a probable Priabonian age from the skeletal grains in the sandstones. van Stuijvenberg and Morel failed to date the section with dinoflagellates and calcareous nannofossils (R. Morel, comm. pers. 2005 in Dupuy et al. 2014). Finally, Ujetz (1996) found upper Paleocene planktonic foraminifera in the marls which are probably reworked considering the presence of nummulitids and discocyclinids in the sandstones.

5.8.12 Comparison with other regions

The Fenalet Sandstone shares a similar petrographic composition (Quartzose petrofacies) with the Voirons Sandstone and the Bruant Sandstone, and could be a downslope counterpart of these units. The marly intervals present some similarities with the Boège Marl. However, because its sand:marl ratio is higher, the Fenalet Sandstone cannot be considered as a distal equivalent of this latter unit. Intermediate inputs from the surrounding shelf are not excluded, and would explain the abundance of turbiditic episodes, as well as this peculiar stratal pattern. Exposures of the Schoni Sandstone in the Schlieren Flysch (Fig. 44 in Winkler 1983) show a similar stratal pattern.

6 Discussion

6.1 Northern extension of the Voirons Nappe and of the underlying units

Figure 5 depicts the reviewed tectonic map of the Voirons Flysch deep-sea fan between the Voirons and the Allinges Hills. Beyond the Voirons, the extensive Quaternary cover hinders accurate mapping of the Voirons Flysch and obscures stratigraphic correlations. Fortunately, electric prospects (Büchli et al. 1976) and boreholes (Table 2) (Dray 1971; Blavoux 1988) performed between Bons-en-Chablais and Évian-les-Bains, as well as a recent seismic survey over Lake Geneva (Dupuy et al. 2014) provide some information on this part of the Voirons Flysch.

The low elevation of the Allinges Hills contrasts with that of the Voirons. This difference could be related to the accretion of the tectonic slices and of the Infraprealpine Mélange beneath the Voirons (Figs. 2, 3) which may persist as a thinned layer along the Allinges Hills where only a ca. 80 m-thick limestone interval has been identified in the Mapad 1 core (Fig. 2a; Table 2) (Dupuy et al. 2014). This interval is tentatively related to the Infraprealpine Mélange (Charollais et al. 1998) whose seismic profiles confirm its continuation eastwards beneath Lake Geneva and along the Fenalet quarry where it is interrupted by several dextral strike slip faults (Dupuy et al. 2014).

Although Quaternary deposits are locally up to 500 m thick (Blavoux 1988), a subsurface continuity between the Voirons and the Allinges Hills is preserved (Fig. 3a). The restricted outcrop of the Dranse River also confirms the continuation of the Voirons Flysch in this direction. However, the subsurface occurrence of the Ultrahelvetetic Flysch in this area next to the Voirons Flysch remains questionable since all flysch-type deposits have a similar seismic signature (cf. the “undifferentiated flysch” of Dupuy et al. 2014). Nannoplankton dating carried out on some borehole samples (Fig. 2a) gave a late Eocene age (Table 2) which is consistent with both the age of the

Ultrahelvetetic Flysch (Charollais et al. 1993) and that of the Voirons Flysch (van Stuijvenberg and Jan du Chêne 1980, e.g. Boège Marl). Hence, due to the lack of reliable petrographic data, the flysch deposits of Late Eocene age identified in the subsurface in the Gavot Plateau area cannot be attributed with certainty to the Voirons Flysch.

The northern prolongation of the stratigraphic units is also hampered by Quaternary deposits. The boundary of the Allinges Mb. cannot be constrained southward within the Voirons Sandstone Fm. We have arbitrarily defined the limit by the strike-slip fault to the West of Allinges in Fig. 5. As stated above, Layer 1 at the Allinges Hills (Büchli et al. 1976) might correspond to the Bons Mb. with regard to their common marly content (Fig. 3a). Its occurrence at the Allinges Hills would suggest a larger extension than expected. However, the absence of exposures precludes any definite correlation, and Layer 1 is by default affiliated to the Allinges Mb. As explained above, the downslope extension of the Vouan Conglomerate is missing, and the lack of exposure beyond the Maladière hampers to determine its overall geometry. The Vouan Conglomerate is currently interrupted by a sinistral strike-slip fault separating the Maladières from the Collines des Châteaux (Figs. 2, 5). Despite field evidence for the extension of the Boège Marl to the Dranse River and the uncertainties regarding the status of the Bruant Sandstone, we suggest that the local pinch-out of the Boège Marl can be due to an erosional event preceding or associated to the deposition of the Bruant Sandstone and emphasising the progradation of the reactivated fan in outer-fan settings. This local disappearance could be alternatively linked to the occurrence of a thrust fault if the tectonic origin of the Bruant Sandstone is corroborated.

6.2 Geometry of the Voirons Flysch deep-sea fan

Assuming a lack of internal tectonic subdivisions, except for regional-scale, post-nappe deformation by several strike-slip faults (Dupuy 2006; Dupuy et al. 2014; Ospina-Ostios 2017), the Voirons Flysch is considered to behave as an integrated system. Furthermore, based on subsurface data, and despite the discontinuity of the exposures between the Voirons, the Allinges Hills and the Fenalet quarry, we assume they represent the same geological body (Fig. 2a). The geometry of the Voirons fan reconstructed in this paper shows a more restricted geographic extension, spatially separated from the adjacent Gurnigel fan. The Voirons fan is estimated to have been ca. 50 km length, whereas its width cannot be accurately constrained since an undetermined portion of the Voirons Flysch remains rooted beneath the Préalpes Médiannes Nappe.

the Voirons and the Allinges Hills. Finally, the lithologic and sedimentary features suggest that the Fenalet Sandstone constitutes the fringe of the deep-sea fan, i.e. an outer fan setting (Figs. 9, 14), although a lateral supply from the adjacent shelf is also plausible considering the high frequency of depositional events.

As turbidity currents can transport sediment along great distances (Ricci-Lucchi and Valmori 1980; Tyson and Follows 2000; Stow and Smillie 2020), the possibility that very fine-grained sediments from the Voirons Flysch were deposited in the vicinity of the Gurnigel fan, located only about 60 km to the east, and then in between the deep-sea fans cannot be excluded. Hence, although both fans might have been spatially separated, we cannot rule out intricate detrital exchanges.

6.3 Sedimentary evolution of the Voirons Flysch

Figure 14 depicts a model of the geometry of the Voirons Flysch deep-sea fan. We propose the following model to describe the sedimentary evolution of the Voirons Flysch:

1. The inception of the detrital supply might have started earlier than the Ypresian (Paleocene?). The subordinate thinned sandy beds of the Bons Mb. were wrapped in hemipelagic marls and suggest that direct connection between the shoreline and the deep-marine basin through a submarine canyon was not yet effective. Considering the confined lateral distribution of the Bons Mb., we hypothesize that a restricted immature trench fan (Underwood and Bachman 1982) was developing at that time.
2. The nascent fan graded to a mature fan of the Voirons Sandstone with the increasing frequency of density flows during early Eocene. Punctually, river floods or earthquakes lead to the local deposition of coarse detritus (Signal Mb.). In the meantime, repetitive tectonic events changed the terrestrial drainage system, and intermittently modified the detrital composition to the Feldspathic petrofacies.
3. A first major disruption in the sedimentation occurred during the Lutetian. The tectonic deformation may have been sufficiently pronounced to reduce detrital inputs (sequence 3; Fig. 11), and, simultaneously, to increase the shed of metamorphic lithoclasts (Feldspathic petrofacies). The acme of this stage corresponds to a short starvation period marked by the deposition of a thin (ca. 30 m) marly sequence (van Stuijvenberg 1980).
4. The turbiditic system was quickly reactivated and deposited a thickening- and coarsening-upward succession, the Vouan Conglomerate (sequence 4; Fig. 11). The previous sediment routing (*Quartzose petrofacies*) disappeared and was replaced by the

Feldspathic petrofacies. The channel deposits of the deep-sea fan (Vouan Conglomerate) prograded over the previously deposited lobes of the Voirons Sandstone. Frébourg (2006) reports an upward increase in block size suggesting an increasing energy of density flows with time. Detrital influx remained stable throughout the Lutetian. The homogeneous composition of the Vouan Conglomerate contrasts with the great variability of the Voirons Sandstone.

5. The occurrence of the Boège Marl during Lutetian/Bartonian corresponds to the second major disruption in the sedimentation of the Voirons deep-sea fan. The abrupt transition from massive, coarse-grained deposits to a thinly bedded, predominantly marly succession describes a long period of starvation (Ragusa et al. 2018). The latter locally induced channel collapses, as reported at the base of the Boège Marl (Ragusa 2015; Ospina-Ostios 2017; Ragusa et al. 2018). The *Feldspathic petrofacies* was replaced by the *Quartzose petrofacies*. Furthermore, the occurrence of soft-sediment deformations (slump) may correspond to the establishment of an upper slope-basin environment (Underwood et al. 2003).
6. Considering that the Bruant Sandstone is a stratigraphic unit, the deep-sea fan was reactivated around the middle-late Eocene boundary. The proportion of sand increased again, and a new fan system corresponding to the Bruant Sandstone was established. Sedimentation ended with the introduction of the Voirons Flysch within the sedimentary accretionary prism during the late Eocene (Bartonian or Priabonian?, Ragusa et al. 2018).

7 Conclusions

The present study provides a revision of the lithostratigraphic scheme of the Voirons Flysch with the following main results (Table 1):

- The Voirons Flysch is subdivided into three formations: the Voirons Sandstone, the Vouan Conglomerate, the Boège Marl. Each of these units is defined by lithological, sedimentological and petrographic criteria. The Voirons Flysch is capped by an additional unit, the Bruant Sandstone, the nature of which remains uncertain (youngest stratigraphic unit or tectonic slice).
- The Bons Mb., the Signal Mb. and the Allinges Mb. are recognised within the Voirons Sandstone with characteristic lithological and sedimentological features.
- The geographical extent of the Vouan Conglomerate has been refined. This formation has been identified

in the southern part of the Allinges Hills (e.g. Grotte aux Loups) and in a few exposures previously attributed to the Voirons Sandstone (e.g. the Saxel upper quarry).

- The lithostratigraphic succession comprises two major disruptions in sediment supply during the Lutetian at the Voirons Sandstone–Vouan Conglomerate and at the Vouan Conglomerate–Boège Marl boundaries.
- The Voirons Flysch was an eastward deflected deep-sea fan. Exposures located in the Voirons correspond to the channel-levee system and to the inner fan, whereas outcrops at the Allinges Hills and at the Fenalet Quarry represent the inner and the outer fan, respectively.
- The Voirons Flysch consists of a distinct deep-sea fan, separated from the the Gurnigel Flysch to the east. This raises questions about sedimentary exchanges between fans of the former Gurnigel Nappe, their correlations and more generally about their palaeogeographic relationship.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s00015-020-00383-1>.

Additional file 1. Major features of the Voirons Flysch stratigraphic units. Thicknesses in brackets are decompacted.

Additional file 2. Type and reference sections of the Voirons Flysch. Geographic coordinates are based on WGS84 system. T type section, R reference section. Location of outcrops is also available in Fig. 6.

Additional file 3. Flute cast and groove cast measurements for palaeocurrent directions in the Voirons Flysch (Ragusa 2015; Ospina-Ostios 2017; and recent additions by JR).

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Authors' contributions

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Availability of data and materials

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Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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