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Planktonic foraminifer biostratigraphy as a tool in constraining the timing of flysch deposition: Gurnigel flysch, Voirons massif (Haute-Savoie, France)

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ABSTRACT

New biostratigraphic, sedimentological and petrographic data and a thorough review of existing literature modify existing knowledge on the age, the sedimentology, the petrography and the palaeogeographic origin of the Gurnigel flysch from the Voirons massif (Haute Savoie, France). Planktonic foraminiferal biostratigraphy assigns the flysch to the upper Middle Eocene (zones P12 to P14) through to Lower Oligocene (zones P16 to P20) stages. This result contrasts with previous work, which assigned the unit to the Lower Palaeocene to upper Middle Eocene on the basis of calcareous nannofossil and dinoflagellate assemblages. The following findings suggest that the Voirons massif comprises several stacked flysch units that do not have exactly the same palaeogeographic origin: (i) the occurrence of flysch exposures in reverse stratigraphic order combined with the lack of evidence for bed overturning; (ii) the variability of palaeo-depositional settings inferred from different flysch outcrops of similar age; (iii) the differences in the heavy mineral content; and (iv) the anomalous superimposition of distal turbidites and/or basinal contourites (Saxel Marls) over proximal turbidites (Vouan Conglomerates). The young age of these kilometre-sized flysch slices precludes their hitherto postulated locus of deposition in the South-Penninic Ocean, and rather indicates a provenance from the Ultrahelvetic and/or North-Penninic (Valais) palaeogeographical domains. Finally, none of the nannofossil assemblages are contemporaneous with the observed planktonic foraminifera associations, suggesting that they have been reworked, dissolved, or just simply diluted and not found by earlier researchers. This study from the Voirons massif shows that planktonic foraminifera associations are a highly reliable biostratigraphic tool for obtaining accurate ages of flysch successions.

Keywords Biostratigraphy, contourites, Eocene, flysch, France, Gurnigel, Haute-Savoie, Oligocene, planktonic foraminifera, Prealps, turbidites, Ultrahelvetics, Valais realm.

INTRODUCTION

Flysch deposition usually represents the last phase of sediment accumulation before basin closure and inversion (Kuenen & Carozzi, 1953; Homewood & Lateltin, 1988; Stampfli *et al.*, 2002). Precisely dating flysch series is therefore of prime importance for any geodynamic and kinematic reconstruction. However, dating flysch successions is a demanding task because the vast majority of constituent grains, including microfossils, are resedimented and may thus be substantially older than final sediment deposition. Along passive continental margins, turbidites usually remobilize shallow-water shelf sediment. Therefore, the age difference between the constituting material and the depositional event is likely to be small, possibly below stratigraphic resolution. Along convergent margins, however, turbidites commonly incorporate considerably older sediment exposed on the sea floor due to thrusting. In the latter scenario, the only method to obtain reliable biostratigraphic markers is that of sampling thin, hemipelagic beds. Unfortunately, such layers may be rare, especially in the case of proximal turbidites. Further, hemipelagic beds can easily be confused with the fine-grained division of Bouma sequences (T_e), which inevitably contains reworked material. A somewhat pessimistic, but also more secure, view is to consider all ages retrieved from flysch successions to be, at best, maximum ages.

Over the past 15 years, researchers from the University of Geneva (Ujetz, 1996; Coppo, 1999; Frébourg, 2006) have found microfossils in the Gurnigel flysch exposed in the Voirons massif (Haute-Savoie, France) that are considerably younger than the Palaeocene to Middle Eocene age previously given to this unit (Jan du Chêne *et al.*, 1975; van Stuijvenberg, 1980; Charollais *et al.*, 1998). At first, these anomalous ages were interpreted as resulting from contamination during sampling or laboratory processing. However, additional consistent findings were made by different researchers in various stratigraphic intervals of this flysch. Some of these discoveries were duplicated, suggesting that they are well-founded. The aim of this study is to review existing information and present new data on the sedimentology and biostratigraphy of the main lithological units forming the Gurnigel flysch in the Voirons massif, and to show that this flysch is likely to be younger and therefore of a more external palaeogeographic origin than proposed by some previous workers (e.g. Caron, 1976).

GEOLOGICAL SETTING

Located in Haute-Savoie, France, *ca* 15 km to the East of Geneva, the Voirons massif is bound to the south and east by the Menoge and Foron rivers, and to the north and west by the national road N206 and the departmental road D903 (Figs 1 and 2). It covers *ca* 100 km^2 and consists

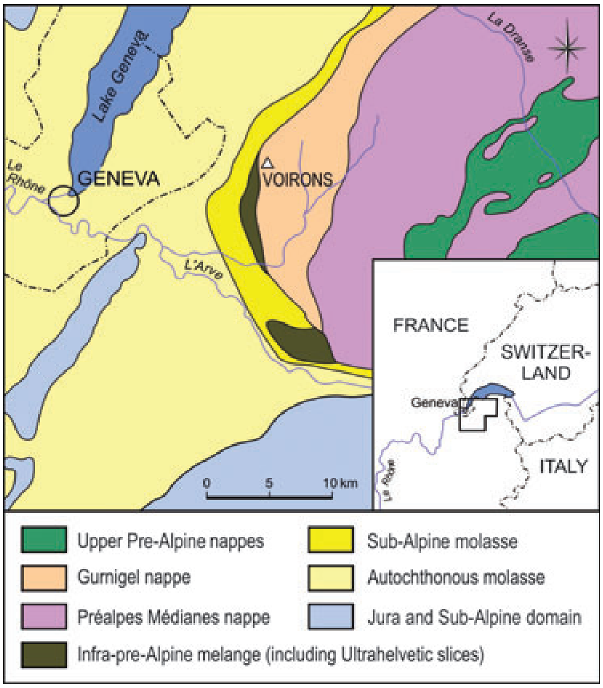


Fig. 1. Geographic situation and tectonic setting of the Voirons massif (Haute-Savoie, France).

of several moderate-elevation, north–south striking, wooded ridges separated by pasture-covered valleys. The only ridges to bear a name, and thus the most important ones, are 'Les Voirons', 'la Tête du Char' and 'le Mont de Vouan', which culminate at 1480 m, 1297 m and 978 m, respectively.

The Voirons massif is located at the western edge of the Chablais Préalpes Médianes of Subbriançonnais and Briançonnais palaeogeographical origin (Fig. 1) and consists of four vertically stacked tectonic units, from bottom to top (Fig. 2; Charollais *et al.*, 1998): (i) the autochthonous molasse; (ii) the sub-Alpine (thrusted) molasse; (iii) an infra-pre-Alpine melange ('Wildflysch'); and (iv) the so-called Gurnigel nappe (Caron, 1976). This latter unit essentially consists of flysch deposits (shales, sandstones, conglomerates and subordinate fine-grained limestones). It is found in the same structural position and contains similar lithologies as those found in the Niremont, Berra and Gurnigel massifs in front of the Swiss Préalpes Médianes (Tercier, 1928; van Stuijvenberg, 1979; Morel, 1980; Winkler, 1984a). The palaeogeographic origin of the Gurnigel nappe is controversial. At first, it was attributed to the Ultrahelvetic realm (e.g. Lombard, 1940; Hsü & Schlanger, 1971; Trümpy, 1980). However, since the work of Caron (1976), a South-Penninic to even South-

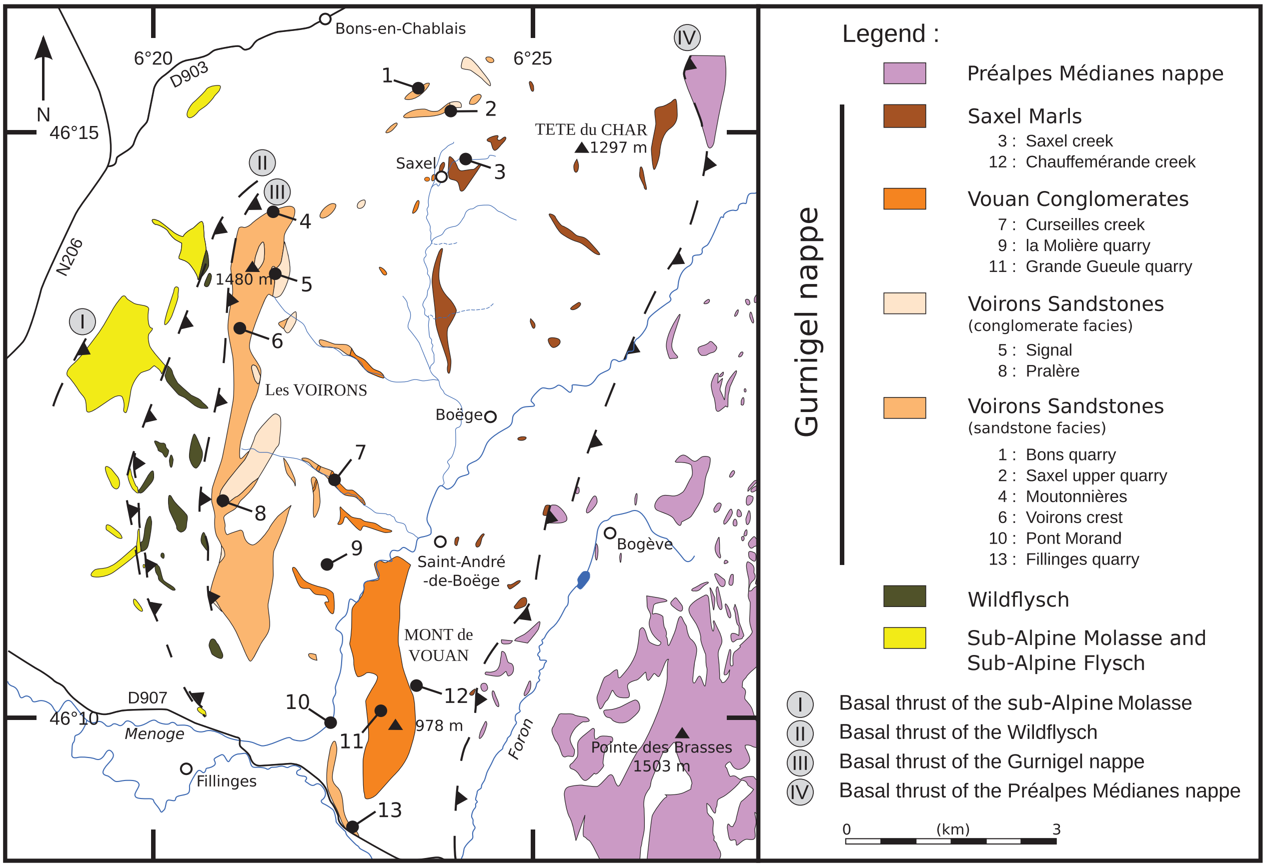


Fig. 2. Geological map of the Voirons massif showing the location of exposures mentioned in the text.

Alpine origin was advocated by most Alpine geologists (e.g. Caron *et al.*, 1980, 1989; Gasinski *et al.*, 1997; Stampfli *et al.*, 2002), except for Hsü (1994). Recently, based on a study of the Iberg Klippen in north-east Switzerland, Trümpy (2006) argued that the Gurnigel flysch occurrences in this study area originated from the Valais domain, and suggested that the same may be true for the lateral equivalents of this flysch in the Gurnigel, Berra and the Voirons regions.

In the Voirons massif, the Gurnigel flysch includes the following three main formations that have been previously interpreted as Lower Palaeocene to upper Middle Eocene (Bartonian) or Upper Eocene (Priabonian) units (van Stuijvenberg, 1980; van Stuijvenberg & Jan du Chêne, 1981; Charollais *et al.*, 1998): (i) the Voirons Sandstones; (ii) the Vouan Conglomerates; and (iii) the Saxel Marls, originally described as the Boëge Marls (van Stuijvenberg & Jan du Chêne, 1981). The tectonic structure of the Gurnigel nappe in the Voirons massif is contentious. According to Lombard (1940) and Jan du Chêne *et al.* (1975), all formations form one large monocline roughly dipping to the east, whereas van Stuijvenberg (1980), relying on biostratigraphic (nannoplankton) mapping and lithostratigraphic criteria, identified a stack of three tectonic slices (Branta, Saxel and Tête du Char slices). This interpretation has been questioned by Charollais *et al.* (1998) because of: (i) the thick vegetation cover; (ii) the overall poor quality of exposures; and (iii) the petrographic resemblance to other formations exposed in this area.

METHODS

Thirteen exposures, all previously described in the literature (eight in the Voirons Sandstones, three in the Vouan Conglomerates and two in the Saxel Marls; Fig. 2; Table 1), were revisited, examined in detail and logged at a decimetre scale. Sedimentological analysis was performed in the field using the approach and terminology of Mutti (1992) and Mutti *et al.* (2003) for characterizing turbidite deposits. Sandstone samples were thin-sectioned, examined with a petrological microscope and point-counted (200 points

Table 1. Geographic coordinates of studied exposures.

	Exposure	Formation	Long. E	Lat. N
1	Bons quarry	Voirons Sandstones	6·3910	46·2560
2	Saxel upper quarry	Voirons Sandstones	6·3958	46·2522
3	Saxel creek	Saxel Marls	6·4097	46·2481
4	Moutonnières	Voirons Sandstones	6·3602	46·2382
5	Signal	Voirons Sandstones	6·3552	46·2304
6	Voirons Crest	Voirons Sandstones		
7	Curseilles creek	Vouan Conglomerates	6·3710	46·2004
8	Pralère	Voirons Sandstones	6·3488	46·1979
9	Molière quarry	Vouan Conglomerates	6·3701	43·1872
10	Pont-Morand	Voirons Sandstones	6·3711	46·1648
11	Grand Gueule quarry	Vouan Conglomerates	6·3805	46·1680
12	Chauffemérande creek	Saxel Marls	6·3893	46·1685
13	Fillinges quarry	Voirons Sandstones	6·3727	46·1538

per thin section) to determine the proportions of quartz, feldspar and lithoclasts. Percentages were plotted in ternary diagrams following the methodology of Folk (1974). Weakly indurated samples gathered from the uppermost part of shaly intervals (to minimize the sampling of reworked material) were disaggregated with gasoline, washed and wet-sieved through 90 μm sieves for planktonic foraminiferal analysis. Selected specimens were coated with gold, and photographed with a JEOL 6400 scanning electron microscope (SEM, JEOL Ltd, Tokyo, Japan) at 15 to 30 kV accelerating voltage and 20 to 50 nm spot size. The planktonic foraminiferal biozonations of Tourmarkine & Luterbacher (1985), Premoli-Silva *et al.* (2003), Sztrákos & du Fornel (2003) and Pearson *et al.* (2006), as well as the Palaeogene time scale of Luterbacher *et al.* (2004) and the chronostratigraphic scale of Berggren *et al.* (1995) were used in this study. Thirty-eight out of 77 shaly samples contained planktonic foraminifera. Fractions of six relevant samples were examined for calcareous nannofossils.

RESULTS

The Voirons Sandstones

Forming the crest and most of the eastern flank of the Voirons ridge (Fig. 2), this formation is between 200 m and 300 m thick, and mainly consists of decimetre-thick to metre-thick beds of sandstone with subordinate calcareous shale, conglomerate and calcilutite. The sandstone beds are grey, with a brown alteration colour, and usually show sharp contacts with the surrounding shales. Grain size in the sandstone ranges from silt to very coarse sand. These rocks can be classified as calcite-cemented arkoses (Fig. 3) with a variable content of bioclasts and lithoclasts. Bioclasts primarily include red-algae fragments, clasts of larger benthic foraminifera (nummulitids and discocyclinids), planktonic foraminifera, bryozoans and rare echinoid debris. Winkler (1984a) found similar compositions in the Gurnigel–Schlieren Flysch group from Central Switzerland to the Lake of Geneva. Shaly intervals are grey to brown; green shale interbeds, very common in the Gurnigel flysch from other areas (Hubert, 1967; Winkler, 1984b), are missing in the Voirons. Metre-thick conglomerate layers mainly occur at localities near the top of the Voirons ridge (Pralère and Signal sections) and are typically clast-supported. The Voirons Sandstones contain igneous, metamorphic and sedimentary lithoclasts. The former include characteristic pink-coloured granite and red porphyry fragments, the parent rocks of which are presently only cropping out in the southern Alps and the Austro-Alpine zone (Sarasin, 1894; Cogulu, 1961). However, they also contain a small percentage of andesite and diabase (Fig. 4) that seem very similar to those found in greater quantities in very external (Helvetic and sub-Alpine) flysch formations (Taveyannaz Sandstones and Val d'Illiez Formation; Martini, 1968; Sawatzki, 1975). The sedimentary lithoclasts, of possible north-Alpine affinity, include micritic limestones with calpionellids, Urgonian-type biosparites, globotruncanid-rich mudstones and spiculites similar to those found in the Helvetic/Ultrahelvetic Wang beds (Villars, 1988). Note that *Globotruncana*-bearing biomicrite was also observed in the

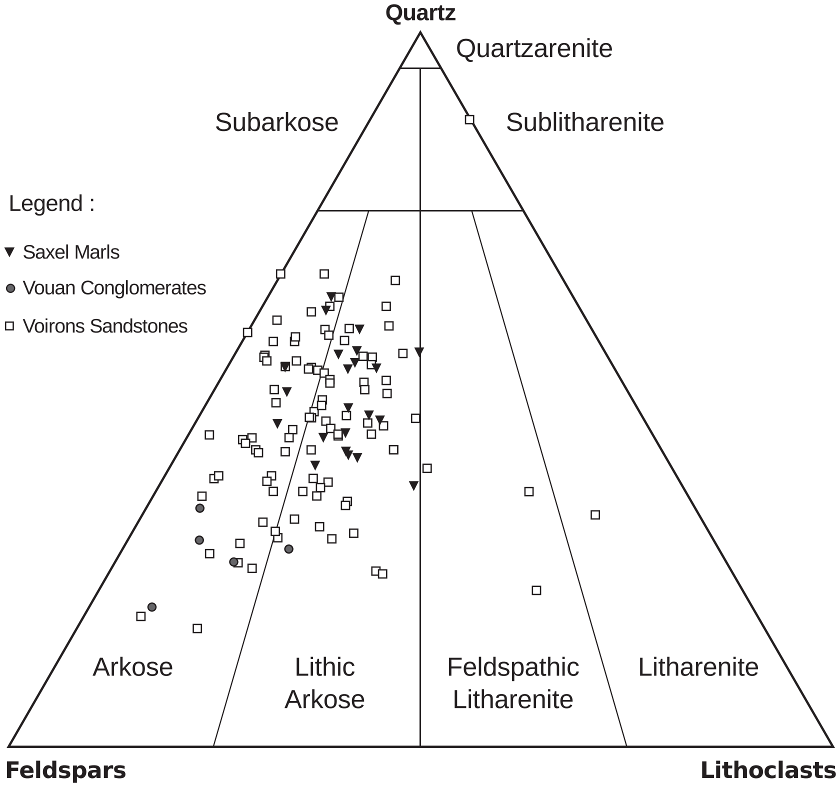


Fig. 3. Comparative petrography and mineralogy of the sandstone beds from the Voirons Sandstones, the arenitic matrix of the Vouan conglomerates and the coarsest sandstone beds in the Saxel Marls.

Schlieren flysch (Winkler, 1983). Preliminary heavy-mineral analyses (Table 2; Ragusa, 2009; Ospina *et al.*, 2009) show that some exposures (for example, the Moutonnières section) are characterized by the occurrence of garnet, whereas others (for example, Fillinges quarry) contain a much lower quantity of this mineral.

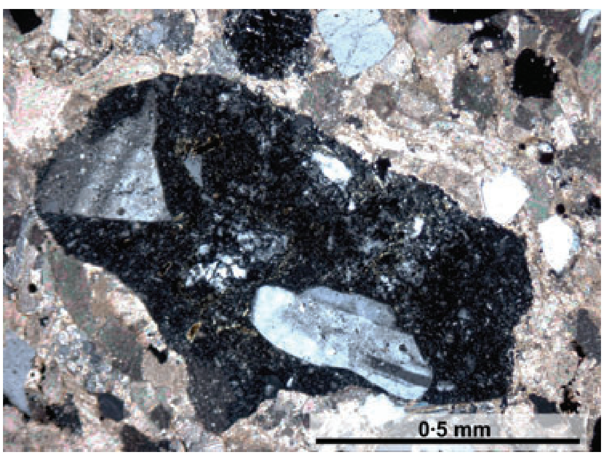


Fig. 4. Sample LMO 037, Pont Morand exposure. Microscopic view (cross-polarized light) showing a basaltic rock with a porphyric texture. Similar clasts are common in north-Helvetic flyschs (Taveyannaz and Val d'Illiez Sandstones; Martini, 1968; Sawatzki, 1975).

The common occurrence of sole marks (flute and groove casts) and Bouma sequences indicate that the Voirons Sandstones were deposited by gravity-driven mass flows. The thick, flat-based, massive sandstone beds (Fig. 5A) and clast-supported conglomerates exposed along the crest of the Voirons can be assigned to Facies F5 and F3 (Mutti, 1992; Mutti *et al.*, 2003), respectively, whereas the rhythmic alternations of laminated sandstone and shale found in other exposures (for example, Bons quarry; Fig. 5B) appear to be typical of Facies F8 to F9.

The planktonic foraminiferal assemblages retrieved from the samples gathered for this study are generally poorly preserved and contain a considerable amount of reworked specimens, including Upper Cretaceous globotruncanids, and Palaeocene and Lower Eocene globigerinids. Providing an accurate age for this formation is thus problematic, as is also the case for the other formations comprising the Gurnigel flysch in this area. The oldest assemblage obtained from one sample collected near the top of the Voirons massif (Signal exposure) includes *Acarinina bullbrooki*, *Acarinina collactea*, *Acarinina primitiva*,

Table 2. Heavy mineral percentages in investigated sandstone samples (from Ragusa, 2009).

Sections	Amphibole	Apatite	Grenat	Pyroxene	Rutile	Staurolite	Talc	Titanite	Tourmaline	Zircon	ZTR
Fillinges	8·10	16·48	4·06	0·41	5·10	3·65	0·00	1·27	0·00	16·43	21·52
Samoëns	25·67	5·21	1·21	0·24	9·88	1·45	0·24	7·05	0·00	11·41	21·29
La Moutonnière	15·65	10·75	12·24	1·70	10·70	13·66	0·63	4·84	0·32	21·93	32·94
La Molière	8·90	24·87	26·85	0·44	17·66	3·85	1·15	10·03	0·00	7·29	24·94

ZTR = zircon, tourmaline, rutile.

Acarinina echinata, *Subbotina yeguaensis*, *Subbotina linaperta*, *Globigerina officinalis*, *Truncorotaloides topilensis ?*, *Turborotalia* aff. *ampliapertura* (Fig. 6H and I), *Turborotalia* aff. *cerroazulensis* s.s. (small), *Turborotalia frontosa*, *Turborotalia* aff. *increbescens*, *Dentoglobigerina ?* (crushed), *Morozovella spinulosa* and small *Catapsydrax* sp. indicating a Middle Eocene age (planktonic foraminiferal zones P12 to P14).

The youngest assemblage, retrieved from one thin shaly layer on the west flank of the Voirons (Moutonnières exposure), contains well-preserved, partial internal moulds with fragile, finely preserved remnants of foraminifer walls of *Subbotina* cf. *praeturritilina* (Fig. 6A), *Subbotina* cf. *linaperta* (Fig. 6D), *Catapsydrax* aff. *unicavus* (juv.; Fig. 6E), *Globoturborotalita ouachitaensis* s.s. (Fig. 6J) and *Globoturborotalita* cf. *ouachitaensis gnaucki* (Fig. 6K). This assemblage is consistent with planktonic foraminiferal zones P14 to P19, or younger, indicating that the unit is Upper Eocene to Lower Oligocene. Overall, the planktonic foraminiferal data constrain the deposition of the Voirons Sandstones to between the Middle Eocene and the Early Oligocene. By contrast, nannofossil assemblages obtained from the same samples are Upper Palaeocene to Lower Eocene and, hence, are considered reworked (calcareous nannoplankton zones NP6 to 8, to NP10, corresponding to planktonic foraminiferal zones P4 to P6).

The Vouan Conglomerates

Between 300 m and 400 m thick, the Vouan Conglomerates occur along the eastern flank of the Voirons ridge, but are best exposed in the western cliffs of the Mont Vouan along the Menoge River (Figs 2 and 5C), where they have been mined for millstone. These cliffs consist of plurimetric beds of matrix-supported conglomerates (cobbly and pebbly sandstones) that are occasionally highly weathered and friable, probably due to poor cementation (Frébourg, 2006). Shaly intervals are extremely rare in this formation. The conglomerate matrix is a feldspar-rich arkose (Fig. 3). The centimetre-sized to metre-sized lithoclasts are angular to well-rounded and derive from sedimentary, metamorphic and igneous rocks. The former include Triassic dolostones, crinoidal-rich, bryozoan-rich and oolite-rich limestones of possible Late Jurassic age (Frébourg, 2006), and orbitolinid limestone dating to the Aptian (Cogulu, 1961). Metamorphic blocks comprise dark schists, sandstones

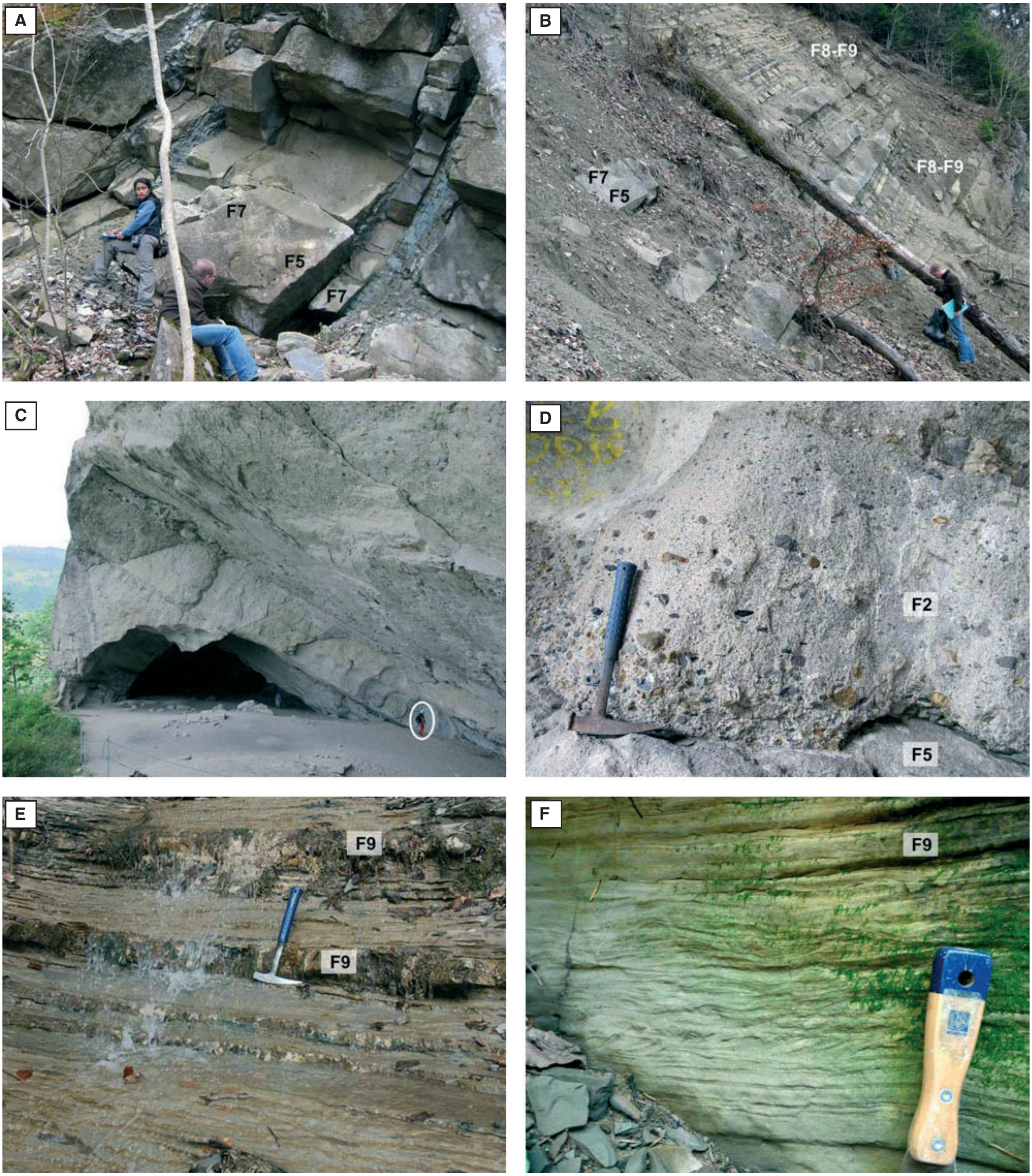
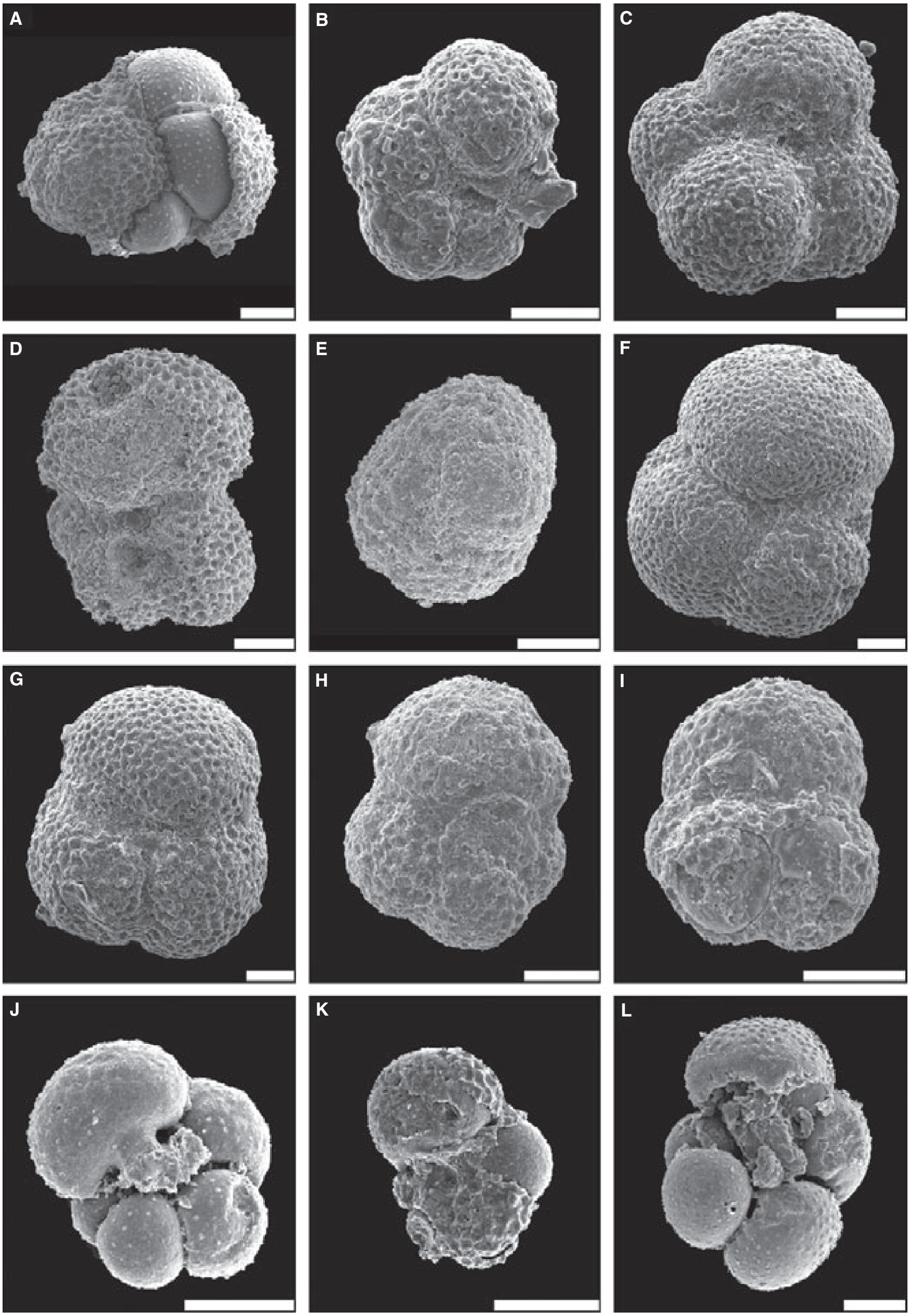


Fig. 5. Photographs of various sedimentary facies observed in the Voirons flysch. (A) Upper Saxel quarry: proximal facies of the Voirons Sandstones; note thin to thick, flat-based, stuctureless sandstone beds separated by thin shaly interbeds. Standing person is 1·6 m tall. (B) Bons quarry: distal facies of the Voirons Sandstones predominantly. Note the occurrence of some metre-thick, channelized sandstone beds (F5 to F7). Standing person is 1·7 m tall. (C) Grande Gueule quarry: western part of exposure showing thick beds of Vouan Conglomerates; circular structures near circled person are scars left by millstone extraction. Person is 1·6 m tall. (D) Grande Gueule quarry (Vouan Conglomerates): close-up on matrix-supported conglomerate interpreted as Facies F2 (Mutti, 1992). Note the erosional bed base. (E) Saxel creek: typical facies of the Saxel Marls showing thick shaly layers comprising thin sandstone beds; hammer for scale is 320 mm. (F) Chauffemérande creek (Saxel Marls): close-up on sandstone bed from the Saxel Marls showing both planar and ripple laminations. Spatula handle is 100 mm long.



and conglomerates, possibly derived from Carboniferous-age strata from the Zone Houillère (Lombard, 1940) which are generally absent in the Voirons Sandstones. In contrast, the pink granite clasts, so typical of the coarse-grained lithologies observed in the Voirons Sandstones, are missing in the Vouan Conglomerates. Preliminary analyses (Table 2; Ragusa, 2009) show that the heavy-mineral assemblage is dominated by garnet.

Fig. 6. SEM views of the most representative planktonic foraminifera retrieved from shaly samples (umbilical views if not specified). Scale bars = 50 μm. (A) *Subbotina* cf. *praeturritilina* (Blow & Banner), lateral view, Voirons Sandstones, LMO003, (Fillinges). (B) *Tenuitellinata angustiumbilicata* (Bolli), Voirons Sandstones, LMO104, (Saxel sup. Quarry). (C) *Globigerina officinalis* Subbotina, Saxel Marls, LMO135, (Super Saxel Rd.). (D) *Subbotina* cf. *linaperta* (Finlay), Voirons Sandstones, LMO011; (Moutonnières). (E) *Catapsydrax* aff. *unicavus* Bolli, Loeblich & Tappan, (juv.), Voirons Sandstones, LMO011; (Moutonnières). (F) *Subbotina utilisindex* (Jenkins), Saxel Marls, LMO135, (Super Saxel Rd.). (G) *Subbotina utilisindex* (Jenkins), Saxel Marls, LMO135, (Super Saxel Rd.). (H) *Turborotalia* aff. *ampliapertura* (Bolli) (small form), Voirons Sandstones, LMO015 (Signal des Voirons). (I) *Turborotalia* aff. *ampliapertura* (Bolli) (small form), Voirons Sandstones, LMO015 (Signal des Voirons). (J) *Globoturborotalita* cf. *ouachitaensis ouachitaensis* (Howe & Wallace) (internal mould), Voirons Sandstones, NPK184 (Moutonnières). (K) *Globoturborotalita* cf. *ouachitaensis gnaucki* (Blow & Banner) (partly internal mould), Voirons Sandstones, NPK184 (Moutonnières). (L) *Globoturborotalita* cf. *ciperoensis* (Bolli) (small form), Vouan Conglomerates, NPK212, (Curseilles creek).

The thick cobbly/pebbly sandstone beds are massive and commonly show erosional bases and load casts. Normal and inverse grading occur, but clasts are, in general, randomly distributed within beds. Facies F1 to F7 of Mutti (1992) have been observed in the Vouan Conglomerates, Facies F1, F2 (Fig. 5D) and F5 being the most frequent ones.

As mentioned above, shaly intervals are scarce in the Vouan Conglomerates and only one sample from the Curseilles creek has so far yielded a sizeable planktonic foraminiferal assemblage. It includes *Acarinina* sp., *A.* cf. *bullbrooki* (reworked), *Globigerina* cf. *officinalis*, *Globoturborotalita ouachitaensis* s.s., *Globigerina* cf. *praebulloides*, *Globoturborotalita* cf. *ciperoensis* (Fig. 6L) and *Globoturborotalita ouachitaensis gnaucki* indicating a Late Eocene to Early Oligocene age (planktonic foraminiferal zones P15 to P19).

The Saxel Marls

This formation is exposed on the eastern flank of the Vouan ridge and on the Tête du Char (Fig. 2). The Saxel Marls are predominantly composed of metre-thick layers of greenish-grey marls, displaying a light brown alteration colour, and separated by centimetre-thick to decimetre-thick beds of fine-grained sandstone (Fig. 5E). The $CaCO_3$ content of these marls varies between 21% and 31%, but values up to 40% have been reported by van Stuijvenberg & Jan du Chêne (1981). Mica, pyrite and glauconite were observed in washed sediment fractions. The sandstone beds are rather homogenous and consist of calcite-cemented lithic arkose (Fig. 3) characterized by the occurrence of numerous fragments of micritic limestone. Beds of arenaceous limestone are also common, but conglomerate layers are missing in this succession, except near its base. This succession is over 1000 m thick, but might be affected by tectonic folding (Coppo, 1999).

The thin sandstone beds exhibit sharp upper and lower contacts, and are commonly laminated (Fig. 5F). Flute casts, ripple laminations and convolute bedding have been observed at the base and within sandstone beds, respectively. However, complete Bouma sequences are uncommon. These beds could be interpreted as Facies F9 (Mutti *et al.*, 2003).

Most samples collected from the Saxel Marls yielded poor planktonic foraminiferal assemblages spanning the Middle to Upper Eocene stages. However, the best preserved assemblage contains *Catapsydrax globiformis*, *Catapsydrax martini*, *Catapsydrax howei*, *Catapsydrax unicavus*, *Turborotalia cerroazulensis cerroazulensis*, *Tenuitellinata angustiumbilicata* (Fig. 6B), *Globigerina officinalis* (Fig. 6C), *Pseudohastigerina micra*, *Subbotina linaperta*, *Subbotina angiporoides*, *Subbotina utilisindex* (Fig. 6F and G), *Subbotina eocaena*, *Acarinina echinata*, *Acarinina mcgowrani ?*, *Acarinina rotundimarginata*, *Acarinina spinuloinflata*, *Globorotaloides suteri*, *Globigerinatheka rubriformis* and *Globotruncana* (reworked). This well-preserved assemblage corresponds to the upper Middle Eocene to Lower Oligocene stage (planktonic foraminiferal zones P13 to P20).

DISCUSSION

Sedimentology and depositional environments

The Voirons Sandstones reflect a variety of sedimentary environments that occur in the middle to lower part of submarine fans, in a relatively deep setting, as inferred from the lack of hummocky cross-stratification (Mutti *et al.*, 2003). Channel (Fig. 5A) and levée deposits have been identified along the crest of the Voirons ridge. Depositional lobes, commonly showing upwards thickening sequences of beds, occur at both the Bons (Fig. 5B) and the Fillinges quarries. The sharp contacts between thin sandstone beds and shaly interbeds could be related to reworking by bottom currents (Stanley, 1993). The existence of such currents during the sedimentation of the Gurnigel–Schlieren flysch has already been identified by Hubert (1967) and Winkler (1983) in the Swiss Prealps. Using benthic foraminiferal assemblages, Ujetz (1996) attempted to provide more information on the palaeo-ecology of the Voirons Sandstones. Hemipelagic shales collected by this author from the Moutonnières section (corresponding to the Signal des Voirons A exposure in the study by Ujetz) yielded a *Rhabdammina*-type fauna, similar to assemblages retrieved from the Gurnigel flysch in other regions (van Stuijvenberg *et al.*, 1976; Winkler, 1984b) and indicating dysaerobic abyssal conditions. In contrast, benthic foraminiferal assemblages recovered from the Bons and Fillinges sections suggested a shallower and a more oxygenated setting than at the Moutonnières (Ujetz, 1996). Interestingly, in the present study, the biostratigraphic data show that, despite these differences in water depth and oxygenation, these three sections which were formerly assigned to the Upper Palaeocene, the Middle Eocene and the Upper Eocene by Ujetz (1996) can now be considered as more or less coeval.

The rather homogenous, coarse-grained succession of the Vouan Conglomerates (Fig. 5C and D) is interpreted as a series of debris-flow deposits accumulated in the proximal part of a submarine fan. The high proportion of amalgamated beds and the near absence of shaly intervals further support this interpretation. These beds probably represent the filling of major turbiditic channels, and not an ancient canyon (Frébourg, 2006). The lack of hummocky cross-stratification suggests a rather deep depositional environment (Mutti *et al.*, 2003), but this has yet to be confirmed by benthic foraminiferal analysis.

The sharp contacts, fine grain-size, overall good sorting, and widespread occurrence of parallel and ripple lamination (Fig. 5F) that characterize the Saxel Marls all suggest that these sediments could represent distal, fine-grained turbidites partly reworked by bottom currents (Stanley, 1993) and/or sandy and muddy contourites (Bouma, 1972; Stow *et al.*, 1998). These observations, and the abundance of marly lithologies, indicate that the Saxel Marls accumulated in a basinal setting in the vicinity of a submarine fan. Based on the benthic foraminiferal assemblage, Ujetz (1996) inferred a poorly oxygenated, middle to upper bathyal setting for this formation.

Age of the Gurnigel flysch in the Voirons massif

The Middle Eocene to Late Eocene–Early Oligocene age obtained for the Voirons Sandstones during this study confirms and complements the results of Ujetz (1996) and Coppo (1999). These authors also retrieved Middle Eocene to Upper Eocene to Lower Oligocene (P17 to P20) assemblages from the Fillinges and Pont-Morand sections, respectively. However, based on foraminiferal data from the Signal sections (western flank of the Voirons ridge), Ujetz (1996) claimed that flysch deposition began during the Early Palaeocene (planktonic foraminiferal zones P1d to P2), and Coppo (1999) interpreted the flysch exposed in the Pont Morand section as a large block in the underlying Wildflysch.

In contrast, the results from this study differ strongly from ages obtained from assemblages of larger benthic foraminifera (Pilloud, 1936; Lombard, 1940), planktonic foraminifera (Rigassi, 1958), calcareous nannofossils and dinoflagellates (Jan du Chêne *et al.*, 1975; van Stuijvenberg, 1980; van Stuijvenberg & Jan du Chêne, 1981), which assigned a Danian to Early Lutetian age to the Voirons Sandstones (NP2 to NP14, corresponding to foraminiferal zones P1b to P10). Note that a revision of the Lombard list of larger benthic foraminifera (mostly nummulitids) constrains the age of this formation between the Early and the Late Eocene, corresponding to planktonic foraminiferal zones P5 to P16.

The age retrieved for the Vouan Conglomerates from the Curseilles creek confirms the Late Eocene to Early Oligocene age (P16 to P20) obtained by Frébourg (2006) from the Molière millstone quarry. Fractions of the Frébourg samples, examined during the course of this study, produced an older assemblage of calcareous nannofossils indicative of the upper Lower Eocene (calcareous nannoplankton zones NP13 to NP14a, corresponding to planktonic foraminiferal zones P8 to P9). Note that Lombard (1940) assigned this succession to a time interval spanning the late Middle Eocene and the

Late Eocene (Lutetian to Priabonian) based on an assemblage of poorly preserved nummulitids. This poor preservation state indicates reworking and, thus, possibly a younger age.

The upper Middle Eocene to Lower Oligocene range obtained for the Saxel Marls encompasses the results of previous authors using various micropalaeontological tools (van Stuijvenberg, 1980; van Stuijvenberg & Jan du Chêne, 1981; Ujetz, 1996; Coppo, 1999). Van Stuijvenberg (1980) suggested that the entire succession of the Saxel Marls (>1000 m in thickness) could have been deposited during one short time interval in the Late Eocene (NP18), which was corroborated by Ujetz (1996). The Coppo (1999) data show, however, that some exposures, located near the (topographic) base of the succession, date from the latest Eocene (planktonic foraminiferal zones P16 to P17, corresponding to calcareous nannoplankton zones NP20 to the base of NP21), whereas others, located higher up in the succession, date from the late Middle Eocene (Bartonian, planktonic foraminiferal zones P13 to P14, corresponding to the lower part of calcareous nannoplankton zone NP17).

In summary, a review of the existing literature, combined with the new biostratigraphic data, constrains the age of the Gurnigel flysch in the Voirons area to between the lower Middle Eocene (planktonic foraminiferal zones P12 to P14) and the Lower Oligocene (planktonic foraminiferal zones P16 to P20). This succession could have thus been deposited in a time interval ranging from 3 to 13 Ma.

Mixed microfossil assemblages

Most of the authors working on turbidites in general, and on the Gurnigel flysch in particular, have been aware of the phenomenon of faunal reworking within sandstone beds (e.g. Lombard, 1940) and also in turbiditic pelites (the T_e division of Bouma; Rigassi, 1958; Hubert, 1967; Winkler, 1984b). The present study expands that of Ujetz (1996), who showed that the hemipelagic interbeds of the Voirons Sandstones contain calcareous nannofossil and dinoflagellate assemblages that produced an older age (up to 20 Ma) than the planktonic foraminiferal assemblage retrieved from the same samples. The same is also the case for the Vouan Conglomerates, but interestingly not for the Saxel Marls that yielded consistent nannofossil and foraminiferal assemblages. Several explanations, which are not mutually exclusive, are presented below.

Adverse water conditions
As suggested by Ujetz (1996), the absence of young (i.e. Upper Eocene to Oligocene) dinoflagellates and calcareous nannoplankton could be due to turbid waters and/or plumes of fresh surface water originating from river discharge in the sedimentary basin of the Gurnigel flysch. Such conditions would be detrimental to these phytoplanktonic micro-organisms, and could thus explain their absence in the accumulating hemipelagic deposits. In contrast, (rare) planktonic foraminifera would have been able to adapt to such an environment, and be preserved in the stratigraphic record. Areas where productivity of phytoplankton is considerably lower than that of planktonic foraminifera are common in modern oceans (e.g. Belyaeva & Burmistrova, 1985).

Selective dissolution could also explain the lack of calcareous nannofossils, which are less resistant to acidic waters because they settle more slowly than planktonic foraminiferal tests and are not protected by an organic film (Ujetz, 1996). This second hypothesis, however, does not explain the absence of young dinoflagellates in the studied samples.

Bottom and contour currents
Bottom and contour currents circulate in most ocean basins today, and probably did so in the past (Stow & Holbrook, 1984). The presence of such currents may have prevented the deposition of feathery nannofossils, but allowed heavier planktonic foraminifera that would have been incorporated in the mud layer on the ocean floor. Alternatively, sluggish bottom currents may have re-suspended nannofossils, leaving the 'heavy' planktonic foraminifera behind. The homogenous microfossil assemblage characterizing the Saxel Marls (Ujetz, 1996; this study) suggests that this formation comprises substantial intervals of true hemipelagic deposits (that were sampled), despite the strong sedimentological evidence for bottom currents during deposition.

Dilution
The fine fraction of turbiditic and contouritic deposits is characterized by the large preponderance (>98%; Ujetz *et al.*, 1994; Kindler *et al.*, 1995) of reworked microfossils over autochthonous specimens. The latter can thus easily be missed during palaeontological examination. This was demonstrated by Ujetz (1996) who retrieved a nannofossil assemblage of Middle to

Upper Eocene age (calcareous nannoplankton zones NP16 to NP19), and found it to be consistent with foraminiferal data, from the Fillinges section (Voirons Sandstones) that was previously dated, with the same method, as Upper Palaeocene (calcareous nannoplankton zones NP7; Jan du Chêne *et al.*, 1975).

CONCLUSIONS

The following conclusions and hypotheses can be derived from the data presented in this study:

1 The planktonic foraminiferal data assign the Gurnigel flysch in the Voirons massif to between the upper Middle Eocene and the Lower Oligocene. These data corroborate and complement the results of other authors (Ujetz, 1996; Coppo, 1999; Frébourg, 2006). However, due to problems related to faunal reworking, they conflict with previous studies (Jan du Chêne *et al.*, 1975; van Stuijvenberg & Jan du Chêne, 1981) that assigned this unit to the Lower Palaeocene and the base of the Upper Eocene. This flysch is thus younger and its deposition began significantly later than previously thought.

2 The Voirons massif probably consists of a stack of kilometre-sized flysch units of different palaeogeographic origin. This is supported by: (i) the occurrence of young (i.e. Upper Eocene) exposures near the topographic base of the Gurnigel nappe that are overlain by older (i.e. Middle Eocene) outcrops, none of these beds being overturned; (ii) differences in the heavy-mineral content between exposures (Table 2; Ragusa, 2009); (iii) contrasts in the palaeoceanographic conditions (oxygenation and depth; Ujetz, 1996) between different outcrops of more or less identical age; and (iv) the anomalous superimposition of basin-plain turbidites and/or basinal contourites (Saxel Marls) over proximal turbidites (Vouan Conglomerates) and evidence of recumbent folds in the former unit (Coppo, 1999). Further work is needed to delineate the precise boundaries of these slices.

3 The age range obtained for the Gurnigel flysch in the Voirons area indicates that it was probably not deposited in a remnant South Penninic (Piémont) Ocean, despite the fact that a large proportion of its constituents (lithoclasts and detrital zircons; Caron *et al.*, 1980; Winkler, 1983; Bütler *et al.*, 2011) probably originate from the southern margin of the Alpine Tethys, since the incorporation of the South-Penninic domain to the Alpine accretionary prism took place during the Middle Eocene or earlier (Bartonian; Stampfli *et al.*, 2002; Handy *et al.*, 2010). Hence, the South Penninic Ocean was closed before the onset of the sedimentation of this flysch. Therefore, although the red granite clasts, for example, are indicative of a detrital source area on the Adria margin (Sarasin, 1894; Caron *et al.*, 1980; Winkler, 1983; Bütler *et al.*, 2011), they are not at all diagnostic for the palaeogeographic locus of deposition of the flysch that contains such granites. The granites need not have been eroded from the substratum of the flysch basin exposed at its margin, but may have been shed from a higher, previously stacked, nappe complex of Adriatic origin.

Some exposures of the Voirons Sandstones (for example, Fillinges) probably originate from the Ultrahelvetic realm because of their pronounced similarities with the lithologies (Lombard, 1940; Kindler, 1988), heavy-mineral content (Table 2; Ragusa, 2009) and age (Wernli *et al.*, 1997) of flysch successions known to be derived from this palaeogeographic domain. The Vouan Conglomerates and the Saxel Marls could possibly represent the non-metamorphic equivalents of the Pierre Avoi Unit (Sion-Courmayeur Zone, internal Valais domain) that yielded an assemblage of planktonic foraminifera of upper Middle Eocene to possibly Lower Oligocene age (Bagnoud *et al.*, 1998), similar to the assemblages found in the younger units of the studied flysch, and likewise contains schist and sandstone blocks derived from the Zone Houillère (Bagnoud *et al.*, 1998). This assignment of a part of the Gurnigel flysch from the Voirons massif to the Valais domain supports the conclusions of Trümpy (2006) pertaining to the palaeogeographic origin of the north-east continuation of the Gurnigel nappe. Whether the central portion of this nappe between Lake Luzern and Lake Geneva should also be considered as North-Penninic, as suggested by Handy *et al.* (2010), is beyond the scope of this study. It must be noted, however, that van Stuijvenberg *et al.* (1976) obtained, but discarded, a $43{\cdot}5 \pm 1{\cdot}4$ Ma radiometric age (i.e. Middle Eocene) measured on a glauconite-rich sandstone bed from the base of Quarry I at Les Fayaux that was dated as Middle Palaeocene based on coccolith and dinoflagellate associations (calcareous nannoplankton zone NP5). If confirmed, this age would also preclude a South-Penninic origin for this exposure.

4 This study illustrates the difficulties and pitfalls in dating flysch deposits with calcareous nannofossils and dinoflagellates and suggests that planktonic foraminifer assemblages provide the most reliable biostratigraphic tool to achieve this endeavour.

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