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High-resolution analysis of submarine lobes deposits: Seismic-scale outcrops of the Lauzanier area (SE Alps, France)

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ABSTRACT

The Lauzanier area represents the northernmost extension of the Annot Sandstone series and contains deposits between 650 and 900 m-thick. This basin was active from upper Bartonian or lower Priabonian to early Rupelian. It is composed of two superposed units separated by a major unconformity. The sediment supply is due to channelled flows coming from the south. Flow processes include mass flow to turbidity currents. The size of the particles and the absence of fine-grained sediment suggest a transport over a short distance. The Lower Unit is made of coarse-grained tabular beds interpreted as non-channelled lobe deposits. The Upper Unit is made of massive conglomerates interpreted as the channelled part of lobes. These lobe deposits settle in a tectonically confined basin according to topographic compensation that occurs from bed scale to unit scale. The abrupt progradation between the lower and the upper unit seems related to a major tectonic uplift in the area. This uplift is also suggested by a change in the petrographic nature of the source and an abrupt coarsening of the transported clasts.

This field example allows providing high resolution analysis for depositional sedimentary sequences of terminal lobe deposits in a coarse-grained turbidite system. The outcrop analysis shows the lateral evolution of deposits and the system progradation allows a longitudinal analysis of facies evolution by superposing on the same outcrops the channelled lobe system and the non-channelled lobe system. These results of high-resolution outcrop analysis can be extrapolated to results obtained on sedimentary lobes in recent deep-sea turbidite system that are either restricted to cores, or with a lesser resolution (seismic).

1. Introduction

The Grès d'Annot (Annot Sandstone) has concentrated sedimentology field work in SE France for 150 years. The deposits were at the origin of the successful turbidite concept (Kuenen, 1952, 1953, 1959; Bouma, 1962; Lanteaume et al., 1967) and the development of early models of deep-sea sedimentation (Stanley, 1961a,b). In the 1980s the facies were used to understand the gravity processes on submarine slopes. Scaled experiments and conceptual models were developed to compare the deposits with those observed in the Annot Sandstone. This led to the emergence of the concepts of turbulent surge and sustained turbidity current (Lüthi, 1980; Ravenne and Beghin, 1983; Laval et al., 1988). The accessibility of outcrops and the amount of collected data over time make the Annot Sandstone outcrops a worldwide reference site both for academic institutions and industrial companies because these sandstones are considered as good analogs for hydrocarbon reservoirs. More recently, a scientific team led by the Institut Français du Pétrole (IFP) conducted work on the western part of the formation. They developed a sedimentation model integrating new data and concepts on geodynamic and structural evolution, stratigraphy, and sequence analysis. The results have been collected in Joseph and Lomas (2004b). The present paper focuses on a small sub-basin that has not been included in this study, the Lauzanier area (Fig. 1). It presents a model for spatial (lateral and

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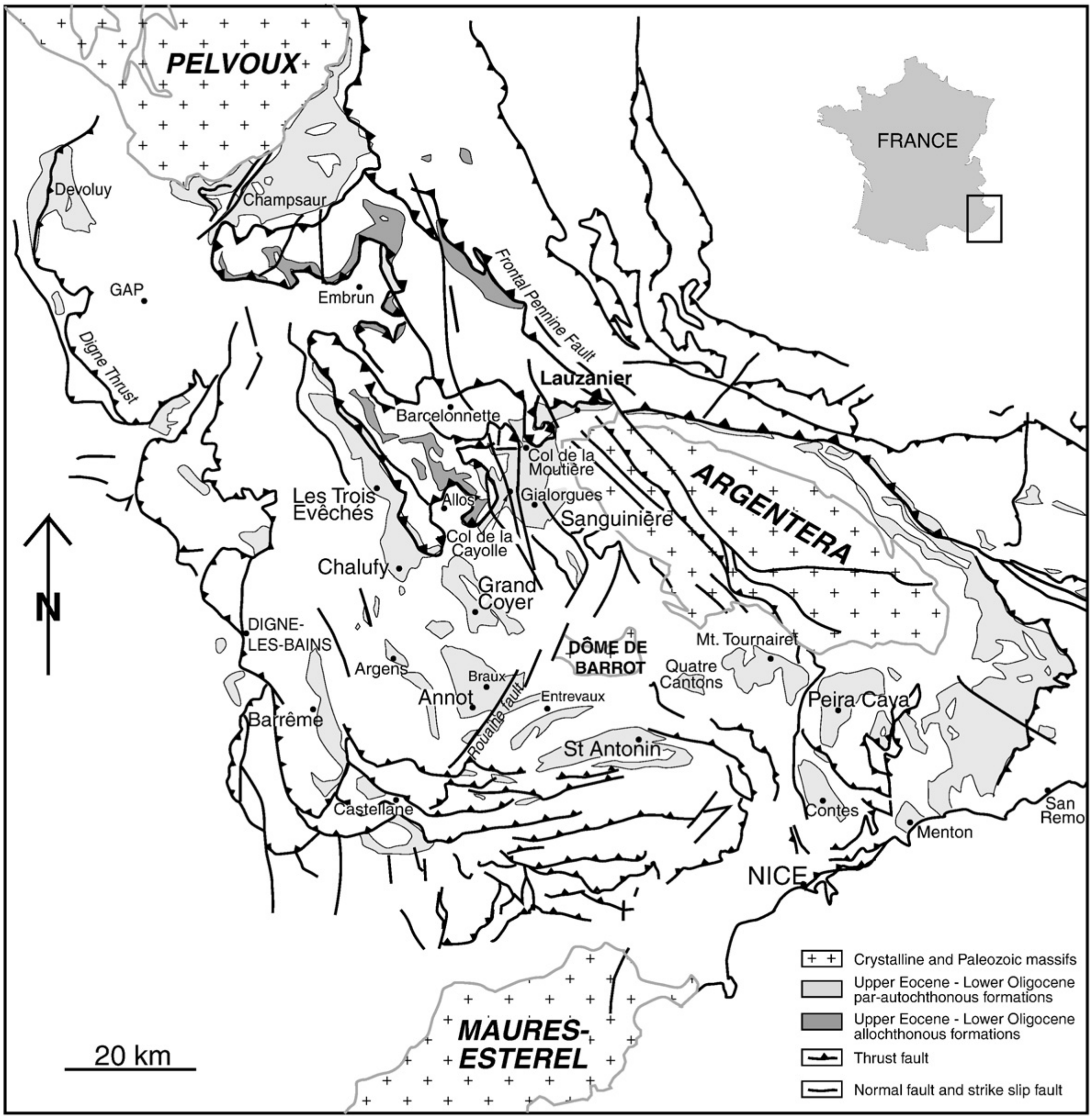

Fig. 1. Simplified geological map of the western Alps and location of the study area (From Joseph and Lomas, 2004a).

longitudinal) evolution of sedimentary facies in laterally confined lobe deposits.

2. Area descriptions

2.1. Regional geology and stratigraphic framework

The remnants of the Annot Sandstone and related systems formation are located in the Digne Thrust verging southward in the Castellane Arc (Fig. 1). The systems are bordered by crystalline massifs: the Argentera in the east that uplifted in Miocene and early Pliocene according to Apatite fission track dating (Bogdanoff et al., 2000; Bigot-Cormier et al., 2006), the Pelvoux in the north and the Maures-Esterel in the south. They are overlain by the Embrunais–Ubaye Thrusts (Autapie and Parpaillon) and thrusts from internal zones (Helminthoides Flysch; Figs. 1 and 2).

Five sub-basins (s–b) can be defined in the Annot system, from east to west: the eastern (1) Italian s–b, (2) the Contes–Peïra Cava s–b, (3) the Mont-Tournairet s–b eventually connected northward to the Lauzanier, (4) the Quatre-Cantons-Sanguinière s–b and (5) the Saint Antonin-Annot-Grand-Coyer s–b (Fig. 1).

The upper Eocene–lower Oligocene Annot Sandstone (SE France) represents the filling of the foreland Alpine basin. The infill Series is known as the *Trilogie Nummulitique* (Boussac, 1912; Faure-Muret et al., 1956; Figs. 2 and 3). The trilogy overlies a Mesozoic substratum and is constituted with three lithostratigraphic units: the Nummulitic Limestones (Calcaires Nummulitiques), the Blue Marls (Marnes Bleues) and the Annot Sandstone (Grès d'Annot; Figs. 2 and 3).

The transgressive nummulitic limestones are constituted of an alternation of shell-rich calcarenites, polygenic breccia and calcareous marls. The latter constitutes the transition towards the overlying Blue Marls. They rest unconformably on the Mesozoic substratum and locally on the ante nummulitic microcodium conglomerate. Infra nummulitic conglomerates (Bodelle, 1971; Besson, 1972) may locally fill incisions bordering topographic highs (Fig. 2).

The Blue Marls (or Globigerin Schists) are mainly constituted by mudstones with calcarenite and clay intercalation (Fig. 2). The marls contain an abundant planktonic fauna which are interpreted as slope or distal ramp deposits (Ravenne et al., 1987). Intercalation of fine-grained turbidites towards the top of this unit gives a brown colour to the marls and announces the overlying Annot Sandstone (Flysch Noir of Kuenen et al., 1957).

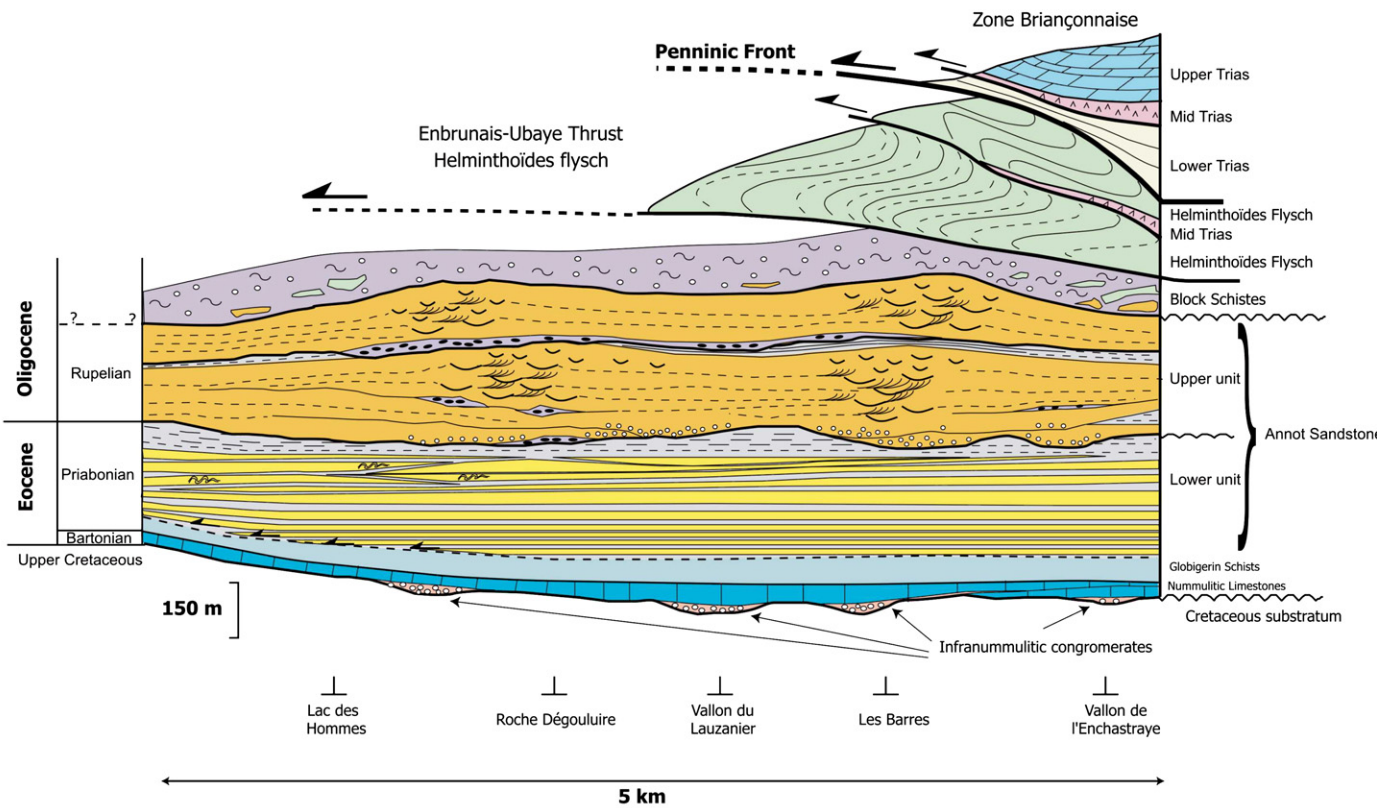

Fig. 2. Synthetic lithostratigraphic section of the early Tertiary foreland basin showing the "Nummulitic Trilogy".

The Annot Sandstone shows a cumulated thickness of more than 600 m in the Annot Basin, and between 650 and 900 m in the Lauzanier area, in which the unconformity between the Blue Marls and the Annot Sandstone is of 2–3° in dip and 10–30° in direction (dip angle is between N60, 30°NW and N90, 30°N in Blue Marls and N95–N100, 30–32°N in the Annot Sandstone). They contain siliciclastic gravity flow deposits including classical turbidites (Bouma sequences; Bouma, 1962), grain-flow deposits and slurry-flow deposits and debrites. The largest slurry-flow deposits and debrites may be used as correlative beds within a given sub-basin. In the Lauzanier area, the Annot Sandstone is organised into two units (Figs. 2 and 3): (1) A Lower Unit showing alternation of massive homolithic bars separated by heterolithic intervals and (2) an Upper Unit dominated by homolithic very coarse-grained bars with little heterolithic intervals.

2.2. Biostratigraphy

The five sub-basins have a decreasing age from east to west, following the westward migration of the Alpine deformation front (Bodelle, 1971; Callec, 2001; du Fornel et al., 2004; Fig. 4).

The eastern Italian s–b was filled during the Bartonian (P14 foraminiferal zone).The Contes–Peïra-Cava s–b was active during early Priabonian. The Mont Tournairet s–b was active during the whole Priabonian (P15 sup-NP19 zone). The Sanguinière s–b and the Saint-Antonin-Annot s–b became active during the late Priabonien (P16-NP19/20 zone) to early Rupelian (P18–NP21 zone). In our paper, the preliminary dating and stratigraphic framework has been based on the work of Sztrákos and du Fornel (2003).

3. Method and material studied

Sedimentology descriptions have been done on 13 sections with lengths varying from 100 to 650 m at the scale of 1:50. Samples dedicated to biostratigraphy have been selected in heterolithic levels separating sandstone and silt beds or transported mud clasts. Blues marls at the base of the Annot Sandstone series have been systematically sampled. Samples have been cleaned of organic matter using oxygenated water. They have been sieved at 150 µm for nannofauna analysis. Foraminifer analysis has been done on the full sediment.

Samples for source analysis have been selected in homolithic levels (sandstones or granule beds). For the petrographic analysis of the Lauzanier sediments, 27 thin sections have been cut from the terrigenous sandstones of the Lower (10 samples) and Upper (17 samples) units. Samples were selected in sandstones with similar grain sizes from the base of turbidite beds or granule and coarse sandstone massive beds (FA1.3 and FA5). Modal analysis has been carried out with a petrographic binocular microscope and a James Swift® electronic point counter at Henri Poincaré University, Nancy (CNRS-UMR 7566 "G2R"). For each sample, 1000 points were counted at a spacing of 0.5 mm. Counting procedure in classical provenance studies suggests that 600 points per sample should be counted (Dickinson, 1970; Graham et al., 1975; Ingersoll and Suszek, 1979; Ingersoll et al., 1984). In this work, 1000 points were counted for each sample, because of relatively poor sorting of the Lauzanier sandstones, and to gain better statistical results on low amount phases (Van der Plas and Tobi, 1965). In order to control the accuracy and reproductibility of the counting, some samples were counted twice. From point-counting data, 13 recalculated parameters (Ingersoll and Suszek, 1979; Dickinson and Suczek, 1979; Dickinson et al., 1983; Ingersoll et al., 1984) to plot ternary diagrams to delineate the provenance of the sandstones (Dickinson, 1985, 1988). The recalculated mean values of Qt–F–Lt (Qt: total quartz; F: total feldspar; L: total polycrystalline lithic fragments) and Qp–Lvm–Lsm (Qp: polycrystalline quartz; Lvm: volcanic–metavolcanic lithic fragments; Lsm: sedimentary–metasedimentary lithic fragments) parameters of sandstone samples were plotted in corresponding diagrams (Fig. 6A and B).

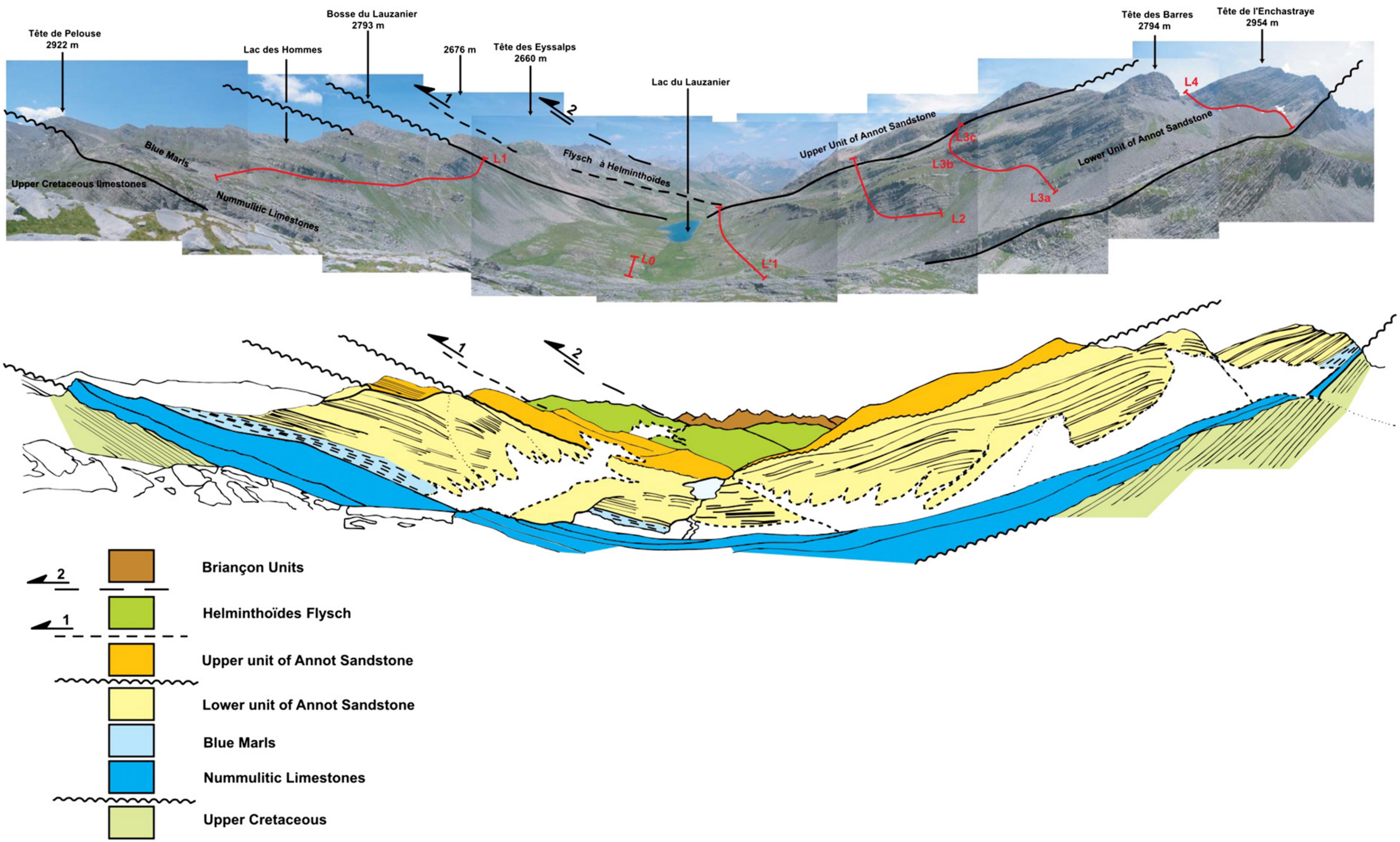

Fig. 3. Panoramic pictures showing a view southward of the Lauzanier area. The lake is approximately 300 m long.

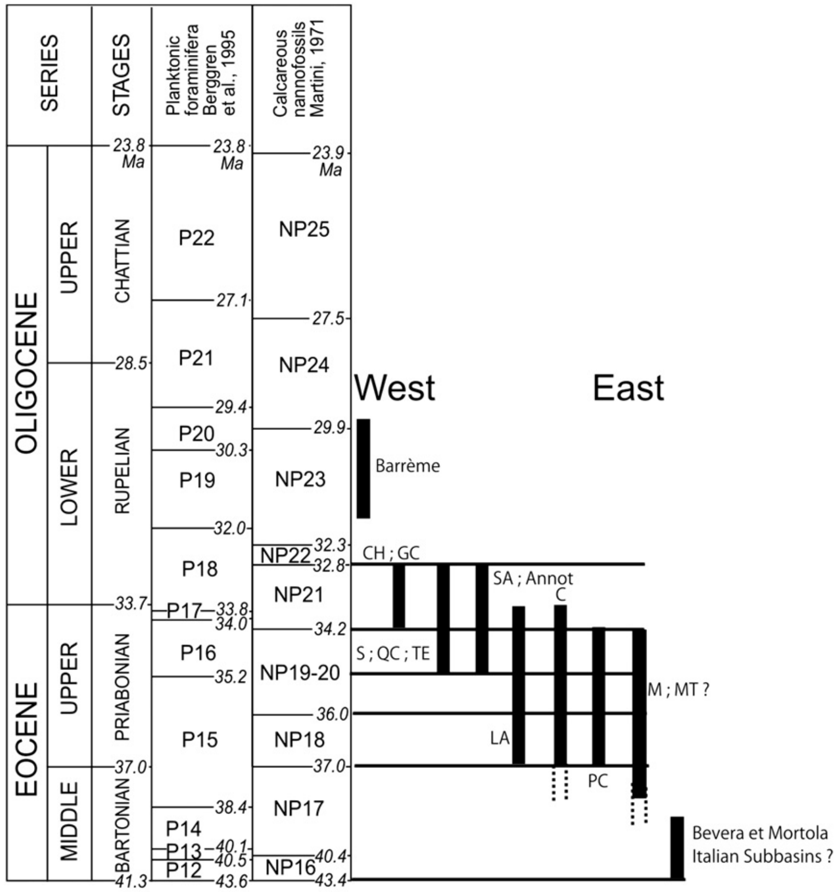

Fig. 4. Stratigraphic table showing the westward decreasing age of the sub-basins in the Annot Sandstone. GC: Grand Coyer; C: Contes; CH: Chalufy; L: Lauzanier; M: Menton; MT Mont-Tournairet; PC: Peïra Cava; QC: Quatre Canton; S: Sanguinière; SA: Saint-Antonin; TE: Trois-Évêchés (modified from Joseph and Lomas, 2004a).

Aerial orthophotographs have been collected by the *Institut Geographic National* (IGN) using a 1:25,000 scale and an extended Lambert 2 projection. The pixel resolution is 50 cm.

4. Results and analyses

4.1. Biostratigraphy

The age of the outcrops is an important point to support the paleogeographic reconstruction of Joseph and Lomas (2004a) and the potential connection of the Annot Sandstone in Lauzanier with a more proximal outcrop (Mount Tournairet, Peïra Cava, Contes). 29 Samples have been collected in marly and shaly intervals between sandstone beds. They have been processed using the procedure described by du Fornel (2003). The samples have been sieved between 0.1 and 2 mm for both nannofauna and foraminifers determination. Results are presented in Table 1. They show that Blue Marls have an age ranging from lower to middle Priabonian (*Globigerina* cf. index; *Turborotalia* cf. *cerroazulensis*). The presence of *Nummulites variolatus* shows that sedimentation of sandstone in the lower unit began either in the upper Bartonian or in the lower Priabonian. In the upper unit, the presence of *Bathysiphon taurinensis* shows that the sedimentation continued during the upper Priabonian or lower Rupelian in an oxygen-poor environment close to anoxia as shown by the presence of frequent pyritized burrows.

4.2. Flow directions and sources

Flow directions are provided by sole marks. Most of them are located at the base of massive coarse-grained bars. The sedimentary structures in the Annot Sandstone were described by Lanteaume et al. (1967). They mainly correspond to groove casts, flute casts and prod marks. Long axes of elliptic scours have also been measured. Results are synthetised in Fig. 5. The results are homogeneous suggesting confined flow with a direction towards NNW.

Sandstones of the Lower and Upper units are poorly sorted litharenites. Samples in the Upper Unit are coarser than in the Lower Unit. The fine-grained matrix, which grades up to 10% (volume) in the studied samples, is constituted of clay minerals with minor carbonates. Only some cracks display calcite-fillings. Pore space is partly filled with peripheral secondary idiomorphic quartz.

The litharenites mainly contain quartz (mono- and polycrystalline), alkali feldspar and plagioclase crystals and lithic particles of magmatic and metamorphic origin, with very minor carbonate fragments. Crystal and lithic grain shapes range from angular to rounded. Quartz occurs as individual crystals, or as polycrystalline quartzite fragments. Quartz constitutes 35% to 80% of total framework grains of the litharenites. Average percentages of monocrystalline and polycrystalline quartz are 29% to 50% and 9% to 24%, respectively in the Lower Unit, and 17% to 57% and 3% to 32%, respectively in the Upper Unit. Feldspar crystals, the second most abundant constituent, are present in similar amounts in both Units (18% to 31%). They are mainly alkalic and display perthitic textures (5% to 20%), and plagioclase (5% to 15%) is often sericitized.

Lithic fragment composition is variable. Fresh to strongly weathered granitoid clasts (K-felspar + plagioclase + quartz) dominate. Some granite particles contain muscovite indicating an aluminous composition. The presence of aluminous granite (leucogranite) fragments is confirmed by gravels of similar composition at the base of some of the coarsest turbiditic sequences of the Lower

Table 1
List of Foraminiferal and nannofauna occurrence. Foraminifer determination has been done par K. Sztrákos. Nannofauna stratigraphy has been done by C. Muller. See Fig. 15 for sample location. Sample location is indicated in metre from the base of each section.

Section no.-sample no. (location in m)	Unit	Lithology	Species (nannofauna and foraminifers) and remarks
–Italian side (Puriac valley)	Blue Marls	Calcareous marl, Black shale	*Turborotalia* cf. *cocoaensis* (Cushman); *Subbotina* sp. *Globigerna* sp.?; *Chrysalogonium* sp.; Piritized fill of burrow. Middle to Upper Priabonian.
L0a-01 (0²m)	Base Blue Marls	Grey micaceous shale	*Subbotina* sp; Piritized fill of burrow.
L1-06 (0 m)	Blue Marls	Calcareous marl	*Globigerinatheka* cf. index (Finlay); *Turborotalia* cf. *cerroazulensis* (Cole); *Subbotina linaperta* (Finlay); *Subbotina eocaena* (Gümbel); *Chrysalogonium* sp.?; *Siphonodosaria* gr. *camerani* (Dervieux); *Gyroinoides* sp.?; *heterolepa* sp.; Piritized fill of burrow. Lower to middle Priabonian.
L1-02 (44 m)	Annot Sandstone, Lower Unit	Black shale	*Bathysiphon taurinensis*
L1-04 (184 m)	Annot Sandstone, Lower Unit		Nannofauna. Upper Eocene or Lower Oligocene
L'1-02 (32 m)	Blue Marls	Calcareous marl	*Globigerinatheka* sp.; *Turborotalia cerroazulensis* (Cole); *Subbotina eocaena* (Gümbel); *Chrisalogonium tenuicostatum* (Cushman and Bermudez); *Lenticulina* sp.; Piritized fill of burrow. Lower to Middle Priabonian.
L'1-04 (55 m)	Blue Marls		Undetermined Rotaliinae.
L2-01 (10 m)	Annot Sandstone, Lower Unit	Black micaceous shale	*Bathysiphon taurinensis.*
L3b-02 (14 m)	Annot Sandstone, Lower Unit	Black micaceous shale	*Bathysiphon taurinensis;* Piritized fill of burrow.
L3b-03 (33 m)	Annot Sandstone, Lower Unit	Black shale	*Bathysiphon taurinensis.*
L4-02 (10 m)	Blue Marls	Black carbonated sandstone	Frequent Nummulites ex gr. *Variolatus* (Lamarck); *Operculina* sp.; *Pyramidulina* sp.; *Globulina gibba* (d'Orbigny). Bartonian.
L4-06 (51 m)	Annot Sandstone, Lower Unit		*Bathysiphon taurinensis (Sacco);* Lignite fragments.
L4-02b (66 m)	Annot Sandstone, Lower Unit	Black micaceous shale and silt	Piritized fill of burrow, *Bathysiphon*? sp; Probable Upper Eocene?
L4-03b (120 m)	Annot Sandstone, Lower Unit	Black micaceous shale and fine sandstone	Piritized fill of burrow, *Bathysiphon*? sp.
L4-012a	Blue Marls in Schistes à Blocs		*Subbotina eocaena* (Gümbel); Priabonian to Rupelian
L9-02 (7.5 m)	Annot Sandstone, Upper unit	Black micaceous shale	Piritized fill of burrow.
L9-03 (10 m)	Annot Sandstone, Upper unit	Black micaceous shale	Piritized fill of burrow.
L21-02 (198 m)	Sandstone, upper unit	Black micaceous shale	*Bathysiphon*? sp.
L22-04 (13 m)	Annot Sandstone, Upper unit	Black micaceous shale	*Ismolithus recurvus; Dictyococcites dictyodus; Reticulofenestra umbilica; Helicosphaera compacta; Coccolithus pelagicus; Cyclococcolithus formosus; Cribrocentrum reticulatum; Lanternithus minutus*; Large species. NP1; Uppermost Eocene.
L22-06 (442 m)	Annot Sandstone, Upper unit	Black micaceous shale	*Nummulites* ex gr. *Striatus.* (Reworked). Upper Bartonian and Lower Priabonian.
L22-07 (528 m)	Schistes à Blocs	Shale	*Dictyococcites dictyodus; Reticulofenestra umbilica; Helicosphaera compacta; Coccolithus pelagicus; Cyclococcolithus formosus; Cribrocentrum reticulatum; Lanternithus minutus;* Probable Upper Eocene? + reworked upper cretaceous nannofauna.
L22-08 (530 m)	Schistes à Blocs	Shale and Black micaceous shale	Probable Upper Eocene? + reworked upper cretaceous nannofauna.
L24-08 (87 m)	Annot Sandstone, Upper unit	Black micaceous shale	Piritized fill of burrow.
L24b-13 (215 m)	Annot Sandstone, Upper unit	Black micaceous shale and silt	*Ismolithus recurvus; Dictyococcites dictyodus; Reticulofenestra umbilica; Cribrocentrum reticulatum; Coccolithus pelagicus; Cyclococcolithus formosus*, Very large species; NP19.
L24b-17 (350 m)	Annot Sandstone, Upper unit	Black micaceous shale	*Chiasmolithus oamaruensis; Dictyococcites dictyodus; Reticulofenestra umbilica; Cribrocentrum reticulatum; Coccolithus pelagicus; Cyclococcolithus formosus*; NP18(Late Eocene).
L25-05 (102 m)	Annot Sandstone, Upper unit	Black micaceous shale	*Bathysiphon*? sp.
HOM 1 (23 m)	Annot Sandstone, Upper unit	Black micaceous shale	Piritized fill of burrow.
HOM 3 (84 m)	Annot Sandstone, Upper unit	Black micaceous shale	Piritized fill of burrow.
HOM 4 (652 m)	Schistes à Blocs	Black micaceous shale	*Dictyococcites dictyodus; Reticulofenestra umbilica; Helicosphaera compacta; Coccolithus pelagicus; Cyclococcolithus formosus; Cribrocentrum reticulatum; Lanternithus minutus;* Probable Upper Eocene? + reworked upper cretaceous nannofauna.

Unit. The anatectic origin of some fragments is confirmed by the occurrence of clasts, which display micrographic and/or granophyric textures (Fig. 6C), indicating eutectic crystallization. Volcanic clasts are present in various amounts. They range from 1% to 7% of the total framework of the Lower Unit, whereas their content is significantly higher and reaches up to 28% in the Upper Unit (1% to 28%). Volcanic particles are mainly of rhyolitic composition, and display felsitic to spherolitic textures (Fig. 6D) with a large amount of alkali feldspar and euhedral embayed quartz. Isolated euhedral quartz of rhyolitic origin are absent in the litharenites. Very rare ignimbritic clasts (with eutaxitic texture) of rhyolitic composition, and rare dark coloured microlitic clasts (andesite?) were observed. The content of fragments of metamorphic origin, including polycrystalline quartz, reaches up to 35%. This is mainly represented by polycrystalline quartzite showing undulatory extinction of quartz crystals and interfingered crystal contacts related to pressure solution during metamorphic processes. Gneiss and phyllite remain very minor (up to 5%). These elements are present in similar amounts in both the Lower and Upper Units. The sedimentary clasts (mainly fine-grained sandstone), the less abundant constituent (<8%) in the whole section, reach 13% in only one sample of the Upper Unit. Bioclasts represented by foraminifer fragments are very minor (<3%).

4.3. Facies description

Facies has been classified according to facies associations (FA) defined by Broucke et al. (2004) and Guillocheau et al. (2004). The progradational facies association (FA2) has not been observed as well as the homolithic to slightly heterolithic tabular, shallow erosional to

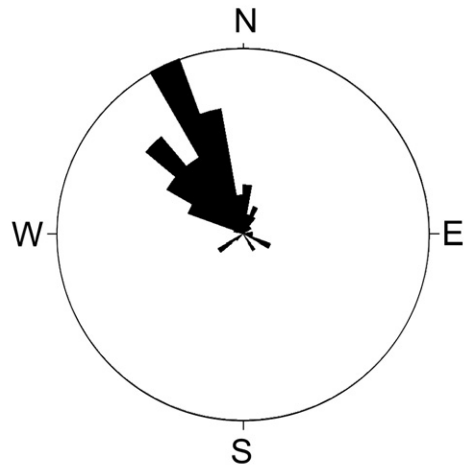

Fig. 5. Synthesis of the flow direction measurements in the Lauzanier sections (Lower and Upper Units). 100 measurements including flute and groove casts, clasts imbrication, megaripples and ripples).

by-pass facies association (FA3). The absence of FA2 facies could be due to the extent of outcrops. Progradational trends sometimes need hectometre-long outcrops to be observed. In this case, some facies interpreted as FA1.3 could be FA2 of Guillocheau et al., 2004). A correlation has been attempted with classical facies classification (Mutti and Ricci Lucchi, 1975; Mutti, 1992) and process-related classification (Mulder and Alexander, 2001; Fig. 7).

4.3.1. Heterolithic, tabular facies (FA1)

This facies is composed of alternating mudstone and fine- to coarse-grained sandstones.

4.3.1.1. Facies FA1.1. Base-missing Bouma sequences (Tde) or fine-grained turbidites. This facies is composed of centimetre- to several centimetre-thick beds. The base of the beds is made of fine or very fine sandstones with planar horizontal laminations and fading ripples, grading up to siltstone and mudstone. They are commonly found in heterolithic intervals and at the base of the Annot Sandstone unit. There, they alternate with Blue Marls and progressively replace them. They are interpreted as the final fall-out deposition of turbulent surges (FA1.1 of Guillocheau et al., 2004, fine-grained turbidites of Stow and Shanmugam, 1980 and distal part of facies F9 of Mutti, 1992).

4.3.1.2. Facies FA1.2. Base and top-missing (Tbc) Bouma sequences. This facies is a compound of several centimetre- to decimetre-thick fining-up beds made of fine to medium sand and silt with various sedimentary structures (horizontal planar to subplanar, climbing lamination, cross bedding) and synsedimentary deformations (convolutes). They correspond to classical Tbc units of the Bouma sequence (Bouma, 1962). They are deposited by mostly turbulent flows (FA1.2 of Guillocheau et al., 2004, turbidites *sensu stricto* of Mulder and Alexander, 2001 and facies F9 of Mutti, 1992).

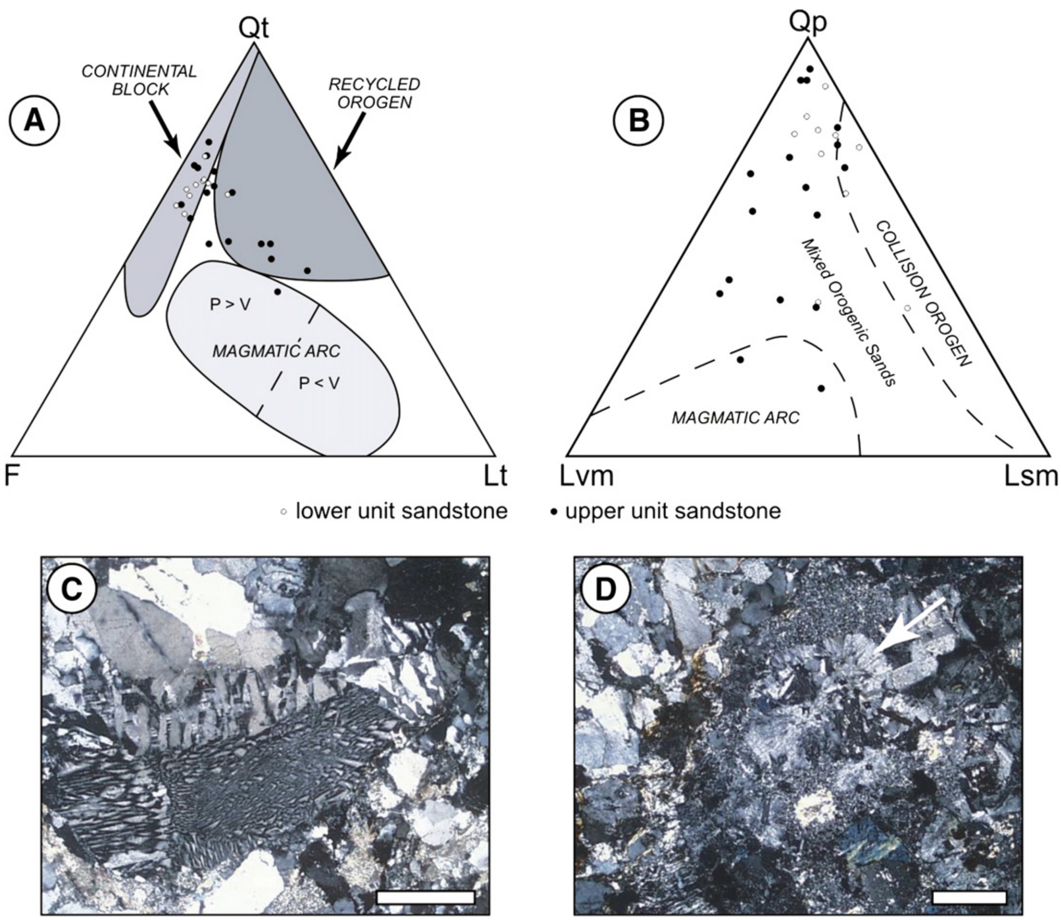

Fig. 6. A, B: Ternary diagrams for source analysis using petrography of litharenites and lithic fragments (Ingersoll and Suszek, 1979; Dickinson and Suczek, 1979; Dickinson et al., 1983; Ingersoll et al., 1984): Qt: total quartz; F: total feldspar; L: total polycrystalline lithic fragments; Qp: polycrystalline quartz; Lvm: volcanic–metavolcanic lithic fragments; Lsm: sedimentary–metasedimentary lithic fragments. C: clasts showing micrographic and/or granophyric textures. D: Volcanic particles with rhyolitic composition, displaying felsitic to spherolitic textures. Scale bar represents 0.5 mm in C and 1 mm in D.

Lower unit

Nomenclature

Guillocheau et al. (2004)	FA6 Condensed interval	FA7.3	FA5.3	FA5.2	FA1.3	FA1.2	FA1.1
Mutti (1992)	F9		F3	F7-F8	F8	F9 proximal	F9 distal
Mulder et Alexander (2001)	Hemipelagites (Teh)	Slump deposit	Frictional flow deposit	Hyperconcentrated and liquefied flow deposit	Concentrated flow deposit (Ta)	Base-missing Bouma sequence (Tbe)	Fine-grained turbidites (Tdet) /hemipelagites (Teh)

Upper units

Nomenclature

Guillocheau et al. (2004)	FA5 deformed (small scour and fill with fluid escape structures)	FA4.2 (large scour and fill)	FA4.1 Megaripples	FA7.2	FA7.1	FA1.3/FA1.2	FA1.2
Mutti (1992)	F7-F8	F5	F6	F1	F3	F8/F9 proximal	F9 proximal
Mulder et Alexander (2001)	Hyperconcentrated and liquefied flow deposit	Hyperconcentrated flow deposit	Hyperconcentrated flow deposit	Cohesive flow deposit	Frictional flow deposit	Concentrated flow deposit Base-missing Bouma sequence	Base-missing Bouma sequence

Fig. 7. Facies classification, terminology and equivalences.

4.3.1.3. Facies FA1.3. Top-missing (Ta) Bouma sequences. This facies is made of massive, poorly sorted, medium to coarse sandstone. Bed thickness varies from one to a few decimetres. Planar laminations are rare and crude. These beds correspond to Ta unit of Bouma (1962), F8 facies of Mutti (1992) and to concentrated flow deposits of Mulder and Alexander (2001). Because of their small thickness, they are equivalent to FA1.3 beds of Guillocheau et al. (2004).

4.3.2. Homolithic, tabular facies with oblique lamina set and large scours (FA4)

Facies FA4 is made of granules (rare pebbles) and coarse sands with large-scale erosional structures. Frequency of scouring suggests intense by-passing. This facies is frequent in the Upper Unit and rare in the Lower Unit.

4.3.2.1. Facies FA4.1. Megaripples with granules and coarse sandstone. Lamina sets fill large (decametre-size) scours. They are made of several metre-long and decimetre-thick fining-up beds. This facies is rare in the basal unit and frequent in the upper unit. They are interpreted as foreset progradation within a gravel bar under the action of thin hyperconcentrated flows. This corresponds to facies F6 of Mutti (1992).

4.3.2.2. Facies FA4.2. Large scour and fill structures. This facies is made of alternating erosional structures (scouring) and filling by laminaset deposition. Scours are several to one metre-sized with a curved base and a rounded or slightly elongated shape (Flood, 1983). The frequent erosional scours in these beds suggest a five-step deposition (Guillocheau et al., 2004) (1) initial erosion (scour formation); (2) deposition of a several centimetre-thick granule and sand beds potentially showing traction carpets and local inverse grading (hyperconcentrated flow of Mulder and Alexander, 2001; coarse-grained turbidite of Lowe, 1979, 1982); (3) erosion of the coarse bed by multiple high energy turbulent surges; (4) deposition of fine-grained turbidite or hemipelagites (mud drape) (5) deposition of a new granule or sand bed overpressuring the underlying, under-consolidated beds and generating fluid escape structures. This set corresponds to facies F5 of Mutti (1992).

4.3.3. Homolithic, tabular facies with tabular lamina set and small scours (FA5)

Facies FA5 is made of mainly coarse sand with small-scale erosional structures. Frequency of scouring suggests intense by-passing.

4.3.3.1. Facies FA5.1. Coarse grained planar beds. Sub-planar coarse-grained sandstones with granules. This is made of massive metre- to decametre-thick massive beds overlying an erosion surface with common erosion figures (groove, flute and prod casts). The beds are made of gravels with a diameter ranging from 0.4 to 1 cm and coarse sandstone. Gravels are constituted with quartzite and clasts of magmatic rocks (mainly granite with muscovite). Mud clasts are sometimes found. Grading and laminations crude and sometimes absent. When grading exists, the gravels at the base pass to coarse and medium sandstone. FA5.1 usually forms the base of massive FA5.2 facies. This set corresponds to facies F4 of Mutti (1992).

4.3.3.2. Facies FA5.2. Coarse sandstones with granules and small scour and fill structures. This is the most common facies association in the lower unit of the Lauzanier outcrops. Several decimetre-large scours are frequent. Scour size tends to decrease upward. Sometimes, scours are draped with fining-up gravel lenses. It corresponds to facies F7 and F8 of Mutti (1992).

In the upper part of this facies, coarse-grained massive beds of FA5.1 or 5.2 are frequently mixed by fluid escape structures (dishes), frequently underlined by a fine muddy laminae that mimics crude flaser bedding. These structures give a hummocky appearance at the bed surface (FA5 deformed).

4.3.3.3. Facies FA5.3. Coarse sandstones and granules beds with mudclasts. These beds are made of coarse to medium sandstones and several centimetre-long flat mud clasts. They usually cap FA5.2 facies. The presence of mud clasts indicates erosion of the substratum and suggests intense bypassing. This facies thins laterally and fills topographic depressions.

4.3.4. Condensed facies (FA6)

Facies FA6 is generally a few centimetres thick. It is made of organic matter-rich dark mudstone with intense bioturbation dominated by post depositional *Planolites* burrows that affect the top of the homolithic bed below the condensed facies. It corresponds to permanent particle fall-out in the water column (samples for nannofauna and foraminifers were collected in this facies). It is interpreted as a condensation interval and could correspond to the top of facies F9 of Mutti (1992).

4.3.5. Facies related to event deposition (slump, slides, slurry-flow deposits, debrite; FA7)

Facies FA7 shows internal deformation indicating short (slide/slump) or important (flow) transport. They show fast variation in thickness and fill topographic lows. They are isochronous deposits and can be good stratigraphic markers for log correlation within the Lauzanier s.b. Three subdivisions can be made in this facies.

4.3.5.1. Facies FA7.1. Grain flow deposits. This facies corresponds to a conglomerate showing rounded sandstone pebbles with a diameter ranging from one to several centimetres. Pebbles can be connected or separated by a sandy matrix. It corresponds to frictional flow deposits (Mulder and Alexander (2001), slurry-flow deposits (Nardin et al., 1979) and to F3 facies of Mutti (1992).

4.3.5.2. Facies FA7.2. Debrite. This facies usually shows a fine-grained mudstone with decimetre- to metre-large sandstone or mudstone blocks. It corresponds to cohesive flow deposits (Mulder and Alexander (2001) and to F1 facies of Mutti (1992).

4.3.5.3. Facies FA7.3. Slumped beds. This facies shows deformed metre-thick beds made of medium to fine sandstone and siltstone. Fluid injection might also be found.

5. Discussion

5.1. Depositional environment

The beds deposited in the Annot Sandstone basin are essentially gravity flow deposits dominated by turbidity current deposits (Bouma sequences; Kuenen et al., 1957; Bouma, 1962). The controversy related to the existence of deltaic deposits inside the Annot system (Sinclair, 1993, 1997, 2000) is now closed. In the Lauzanier area, there is no evidence of continental shelf sedimentary structures such as true HCS or sigmoidal cross-bedding. Some scour and fill deposits (facies FA4 and FA5) might sometimes mimic HCS/antidune-like structures but their internal geometry and size are very different from those of HCS formed on a shallow environment by storms or tidal currents. In deep-sea environments, HCS-like structures can result from antidune formation (Hand et al., 1972; Hand, 1974; Mulder et al., 2009), oblique reflection of turbidity currents on sidewalls (Kneller et al., 1991; Kneller and McCaffrey, 1999) or fault scarp, internal solitary waves (Kneller et al., 1997).

The clastic system that developed in the Lauzanier area is characterized by:

- Coarse to very coarse deposits (conglomerates), particularly in the Upper Unit.
- The poor development of channelling in the Lower Unit.
- The development of shallow channels forming conglomeratic lenses in the Upper Unit. Some of them could correspond to elongated scours rather than to true channels.
- The intense avulsion (and short lifetime) of channels in the Upper Unit.
- The absence of levee deposits and geometry.
- The importance of scouring, and dipping laminaset facies in the Upper Unit.
- The low longitudinal and lateral extensions (less than 3 km) of the outcropping sedimentary bodies.

Two main classifications are preferentially used for clastic depositional environments: (1) classical classification of global systems according to fan morphology and sedimentary facies (Reading and Richards, 1994), and (2) architectural elements (Stow and Mayall, 2000). The most recent classification system is the one developed by Reading and Richards (1994). The classification is matrix-like with rows defining the type of source (point, line or multiple) and the column defining the grain size from mud to gravel. In this classification, the sedimentary deposits of the Lauzanier area would correspond to the lobe of a coarse sand-(granule-) rich submarine fan for the Lower Unit and to the lobe of a gravel-rich slope apron for the Upper Unit. In the architectural element concept, it would correspond to isolated stacked lobes for the Lower Unit and to clustered lobes for the Upper Unit (Stow and Mayall, 2000). The lack of depression channelling the flows at the base of the Lower Unit (marker beds 1 to 7 in Fig. 11) suggests that deposition occurs on a non-channelled lobe. Appearance of small channelling at the top of the Lower Unit (marker beds 8 to 16 in Fig. 11) suggests that deposition occurs at the transition between non-channelled and channelled lobe. In the Upper Unit, the importance of channelling suggests that deposition occurs in the channelled (proximal) part of the lobe. By analogy with the Annot–St Antonin system (du Fornel, 2003, 2004; Joseph and Lomas, 2004a), the source area would be an alluvial fan located southward of the deposits for the Upper Unit. In the two units, the main sediment supply would be provided by hyperconcentrated flows (granule beds and conglomerates) corresponding to the avalanching and inertia flows of Reading and Richards (1994). In the Lower Unit, turbidity (turbulent) flows could form by longitudinal differentiation of hyperconcentrated and concentrated flows. The confinement of the system (Amy, 2000; Joseph and Lomas, 2004a) explains the lack of levee deposits in the Lower Unit. In the Upper Unit, the lack of levee is also explained by the absence of fine particles at the source. In addition, the flow restriction prevents flow spreading and allows hyperconcentrated flow to travel over longer distances (>100 km) than suggested by Reading and Richards' model (1994). In addition, hydroplaning could help hyperconcentrated and debris flows to travel over long distances (Mohrig et al., 1999). The presence of fluid escape structures at the top of coarse-grained hyperconcentrated flow deposits (conglomerates and granule beds) suggests interstitial fluid is an important component of particle support and flow motion.

5.2. Elementary depositional sequence

Facies analysis allowed us to define elementary stratigraphic facies association (sequence) for both lower and upper units of the Annot Sandstone.

For the Lower Unit (Fig. 8), the elementary sequence is typically 5 to 8 m thick. It begins with base-missing turbidites followed by top-missing turbidites (FA1.1, FA1.2, and FA1.3). This association is both

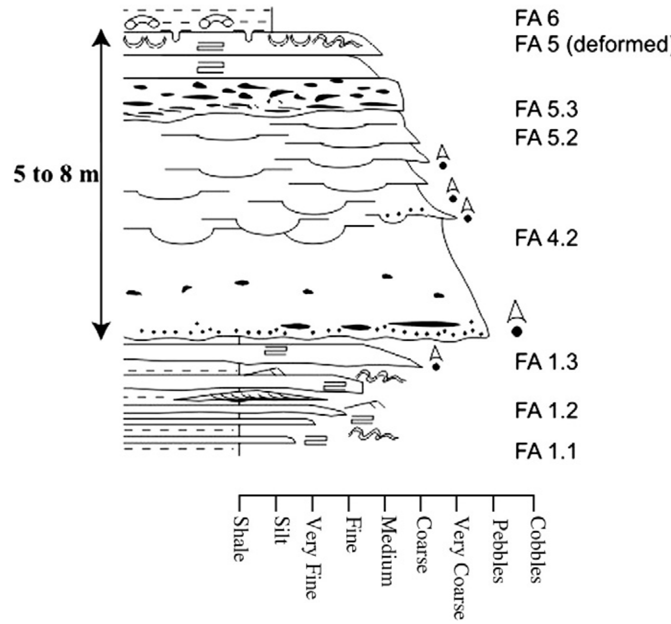

Fig. 8. Facies association constituting the elementary stratigraphic sequence model in the Lower Unit.

coarsening and thickening-up suggesting a global progradational trend but without geometric evidence at the bed scale (lack of the FA3 facies of Guillocheau et al., 2004). In terms of processes, the sedimentation is dominated by turbulent surges (FA1.1 and FA1.2) with a more or less developed concentrated flow at its base (FA1.3). The surge flows show a more and more proximal trend. This facies association is capped by an erosional surface separating them from massive coarse-grained beds (FA4.2) with a crude grading and numerous small-sized erosional surfaces (scours) underlined by grain-size changes. Such features suggest that these beds record the stack of a large number of sedimentary events and represent intense bypass. Bypass intensifies towards the top of the beds as suggested by the presence of numerous small-size scours (FA5.2) and mud-clasts (FA5.3) facies. The crude fining upward and the decreasing size of scouring towards the top of the beds suggest aggradation in FA5.2 and slight retrogradation in FA5.3. The sedimentary processes at the origin of these massive beds are hyperconcentrated flows of Mulder and Alexander (2001). The frequency of fluid escape structures at the top of a massive bed (FA5 deformed) suggests that the emplacement of most of these massive beds is fast. The top of the coarse grained-beds is capped by the condensed facies with intense burrowing (FA6). It also corresponds to the maximum mud content suggesting a maximum flooding surface. The synthetic sequence in the lower subunit shows little lateral evolution (Fig. 10). Sequence thickness remains identical and the only noticeable change is the disappearance of mud clast facies, both at the base and at the top (FA5.3) of the massive beds and the lateral decrease in size of the scours (facies FA4.2 passes laterally to facies 5.2).

The elementary sequence in the Upper Unit is typically 10 to 20 m thick (Fig. 9). It begins with coarse grained top-missing turbidites (FA1.2 and FA1.3) showing a clear coarsening and thickening-up trend suggesting progradation. This prograding part of the sequence in the Upper Unit is thinner than for the elementary sequence in the Lower Unit. Deposition is dominated by concentrated flows (FA1.3) and less frequent turbulent surges (FA1.2). Very fine-grained turbidites (FA1.1) are absent. The top of these beds is capped by an erosional surface. Above the surface, very massive (more than 10 m-thick) beds appear. The erosional surface is filled with debrites/slurry flow deposits (FA7.2). The debrite/slurry flow thickness deposit ranges from a few decimetres to 1 m with a

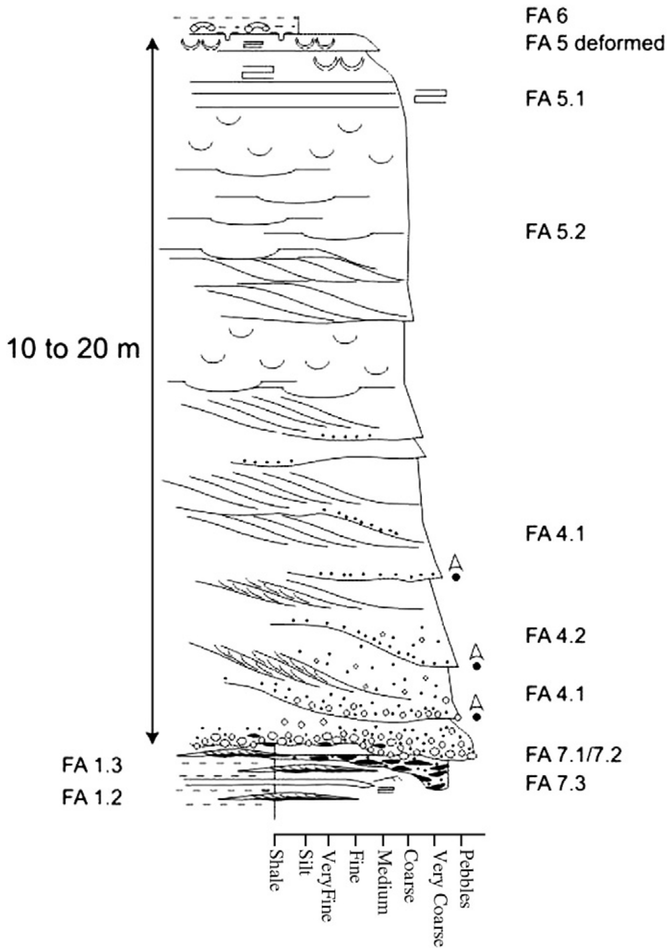

Fig. 9. Facies association constituting the elementary stratigraphic sequence model in the Upper Unit.

longitudinal extent of a few decametres to a few kilometres, respectively. The three largest debrite/slurry flow deposits can be correlated in the whole Lauzanier area. Debrites/slurry flow deposits are themselves capped by one or several erosional surfaces filled by conglomerates with a thickness in the range of 1 dm to 1 m (FA7.1). No fabric is visible in the gravel constituting the conglomerates but the gravels are frequently in contact. This suggests rapid deposition ("en masse" deposition or flow freezing) by mass flows over a short distance, including cohesive matrix-supported flows (debris flows) of Mulder and Alexander (2001) and frictional flows (slurry flows or grain flows of Nardin et al., 1979). These mass flow deposits are capped by several meters of coarse-grained deposits showing megaripples with laminasets having a dip of several degrees (FA4.1). The metric packets of laminasets are separated by decametric erosional scours (FA4.2). Grain size changes are frequent and the massive bars show no grain size trend or, in rare cases, a very crude fining-up. The top of the massive beds is made of facies with small scours (FA5.2). The depositional processes at the origin of these massive beds are hyperconcentrated flows. Grain size changes and erosional scours suggest that numerous events are stacked. However, the development of fluid escape structures (FA5 deformed) at the top of the massive beds again suggests a fast emplacement for these beds. The beds fine-up at their very top and are capped by an intensely bioturbated condensed interval (FA6) with the highest mud content of the whole sequence (maximum flooding surface).

Both lower and upper units show a decrease in thickness laterally. However, the facies of the Upper Unit shows an important lateral variation. Conglomerates and debrites (FA7) are thick in the transport axis and pinch out perpendicularly (Fig. 10) suggesting that channelling is important in this unit. This increased thickness allows the main transport axis to be located just east of the lake. In this axis, the development of facies with megaripples (FA4.1) suggests that the coarse-grained megaripples develop within a channel. The dipping foresets suggest rapidly prograding gravel bars similar to those described in anastomosed shallow channels with a high amount of bedload transport including deep-sea canyons (e.g. the Var Canyon, Parize et al., 1989; Piper and Savoye, 1993). Laterally, megaripples (FA4.1) pinch out and correlate with large scours (FA4.2; Fig. 10).

The lateral evolution of the elementary stratigraphic sequence in the Upper Unit is very similar to the sequence in the Lower Unit (Fig. 10). Assuming that both the energy of the depositional environment and the deposition rate decreases downstream, this suggests strongly that the elementary sequence in the lower unit represents a longitudinal evolution of the upper elementary sequence. In such an interpretation, the Upper Unit would represent a general progradation of the system when compared to the Lower Unit. However, the presence of a strong erosion surface and the unconformity between Upper and Lower Units suggest that the progradation between the two units occurs as a consequence of an increase of tectonic activity.

5.3. Sediment source

The petrographic data provide information about the terrigeneous sources of the Lauzanier litharenites. The high content of quartz and perthitic K-feldspar crystals strongly suggests a provenance from a granite source. This source is confirmed by the presence of abundant granitoid clasts. Moreover, the texture and mineralogical composition of the granite fragments suggest that the source was partly constituted of aluminous granites (anatexis). The influence of a sedimentary cover is more discrete and attested by the presence of volcanic and minor sedimentary clasts.

Although there is an overlap of the data, the litharenite compositions differ in the Lower and Upper units of the Lauzanier sandstones. The Lower Unit samples mainly fall in the continental block field of the Qt–F–Lt diagram (Fig. 6A). Similarly, the Lower Unit samples also fall in and close to the collision orogen field of the Qp–Lvm–Lsm diagram (Fig. 6B). Components of plutonic origin dominate. The Upper Unit sandstones fall in both continental block and recycled orogen fields of the Qt–F–Lt diagram, with only one sample in the magmatic arc field (P>V). They mainly fall in the mixed orogenic sands field of the Qp–Lvm–Lsm diagram with two samples in the magmatic arc field. This repartition reflects the presence of more abundant volcanic clasts, mainly of rhyolitic composition, in the Upper Unit sandstones compared with the Lower Unit, and a mixing of clastic material from contrasted sources. Consequently, the sandstones of the Upper Unit are relatively enriched in volcanic elements in comparison to the Lower Unit. The rhyolitic elements could derive from the Permian volcanic formations of Southeast France. These data suggest that the composition of the source changes with time, from a basement dominated by plutonic rocks to a source in which the sedimentary and volcanic formations of the cover are more influent on basin sedimentation. This composition change probably records the effects of tectonic movements affecting the basement and its cover located to the south of the Lauzanier depositional area. The large increase in grain size and sediment supply in the Upper Unit when compared with the Lower Unit suggests an intensification of the erosion of the source related to an uplift.

The provenance of the sandstones of the Grès d'Annot system is classically considered to be from the Corsica–Sardinia block (Stanley and Mutti, 1968; Jean et al., 1985; Jean, 1985; Garcia et al., 2004). In the Lauzanier turbiditic succession, the paleocurrent measurements

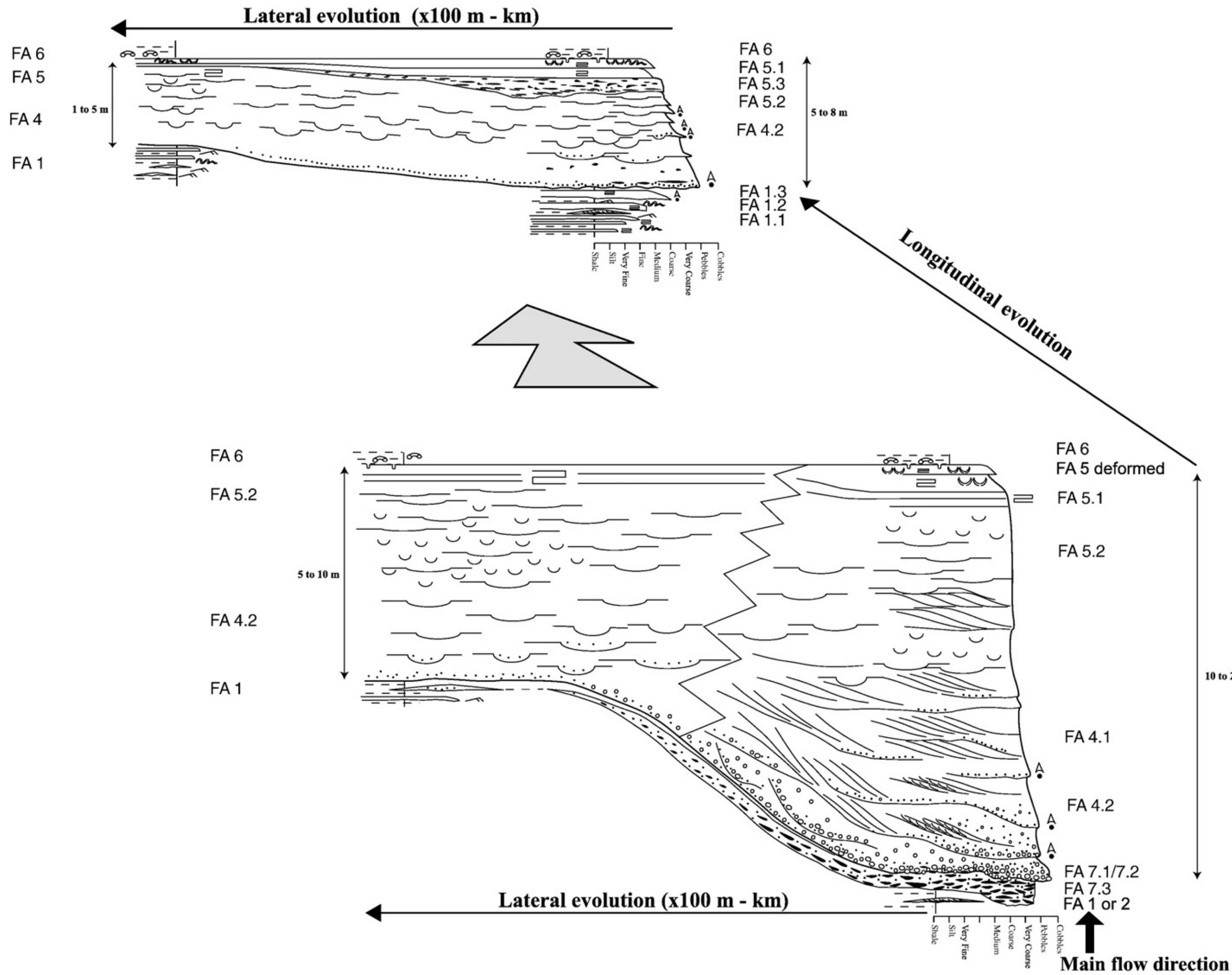

Fig. 10. Spatial correlation between elementary stratigraphic sequence models in upper and lower units.

indicate a very homogeneous orientation of the detritic flux toward the NNW (Fig. 5) and, consequently, a southern terrigenous source. Provenance studies in progress indicate that the composition of the Lauzanier sandstones is different from those of the Mont Tournairet sandstones that also belong to the Grès d'Annot system of the French Southwestern Alps (Joseph and Lomas, 2004a). This is consistent with the facies analysis. Mont Tournairet shows more distal facies with a smaller grain size than those located in the Lauzanier area. Moreover, the litharenites at Lauzanier are coarser and more poorly sorted than their southern stratigraphic equivalents. These arguments strongly suggest contrasted sources for Lauzanier and Mont-Tournairet turbidites and a possible local source for the Lauzanier outcrops. Characteristics and paleogeographic location of the potential sources remain to be identified.

5.4. Regional correlations

Synthetic logs are presented in Figs. 11 and 13. The best outcrop (l'Enchastraye) with the most continuous series was chosen as the reference log (Fig. 12B). In the Lower Unit, 16 massive beds were chosen as marker beds (Figs. 11 and 12). These marker beds were used for visual correlation on panoramic views (Fig. 12). In the Upper Unit, at least 15 major massive conglomeratic beds could be identified (Fig. 13). In this unit, correlations were not as easy as in the Lower Unit because of the lack of heterolithic intervals and bed amalgamation in conglomerates, and beds have not been numbered. Correlations were made using three major slurry flow deposits/debrites covering most of the area and the thickest heterolithic interval that occurs in the upper part of the unit. Using these lithologic markers, four sedimentary members (A, B, C and D) were defined and are present in the whole area (Fig. 14). Correlations have been made at the scale of the outcrop using the aerial photograph (Fig. 14).

Member A extends from a major marker debrite/slurry flow deposit over the erosion surface at the top of the Lower Unit (yellow marker in Fig. 14) to a second major debrite/slurry flow deposit (pink marker in Fig. 14). Member B is between the second major debrite/slurry flow deposit and the heterolithic interval. Member B contains several minor debrites and frictional (slurry) flow deposits (respectively FA7.2 and FA7.1) with a limited spatial extent. The heterolithic interval is not isopach. Its thickness varies from several decimetres to usually several meters and is compounded mostly of heterolithics with rare intercalated fine-grained turbidites (FA1.1 and 1.2 facies) and condensed levels (FA7). Member C is between the heterolithic interval and the third major debrite/slurry flow deposit (green marker in Fig. 14). The coarsest deposits in these debrites/slurry flow deposits

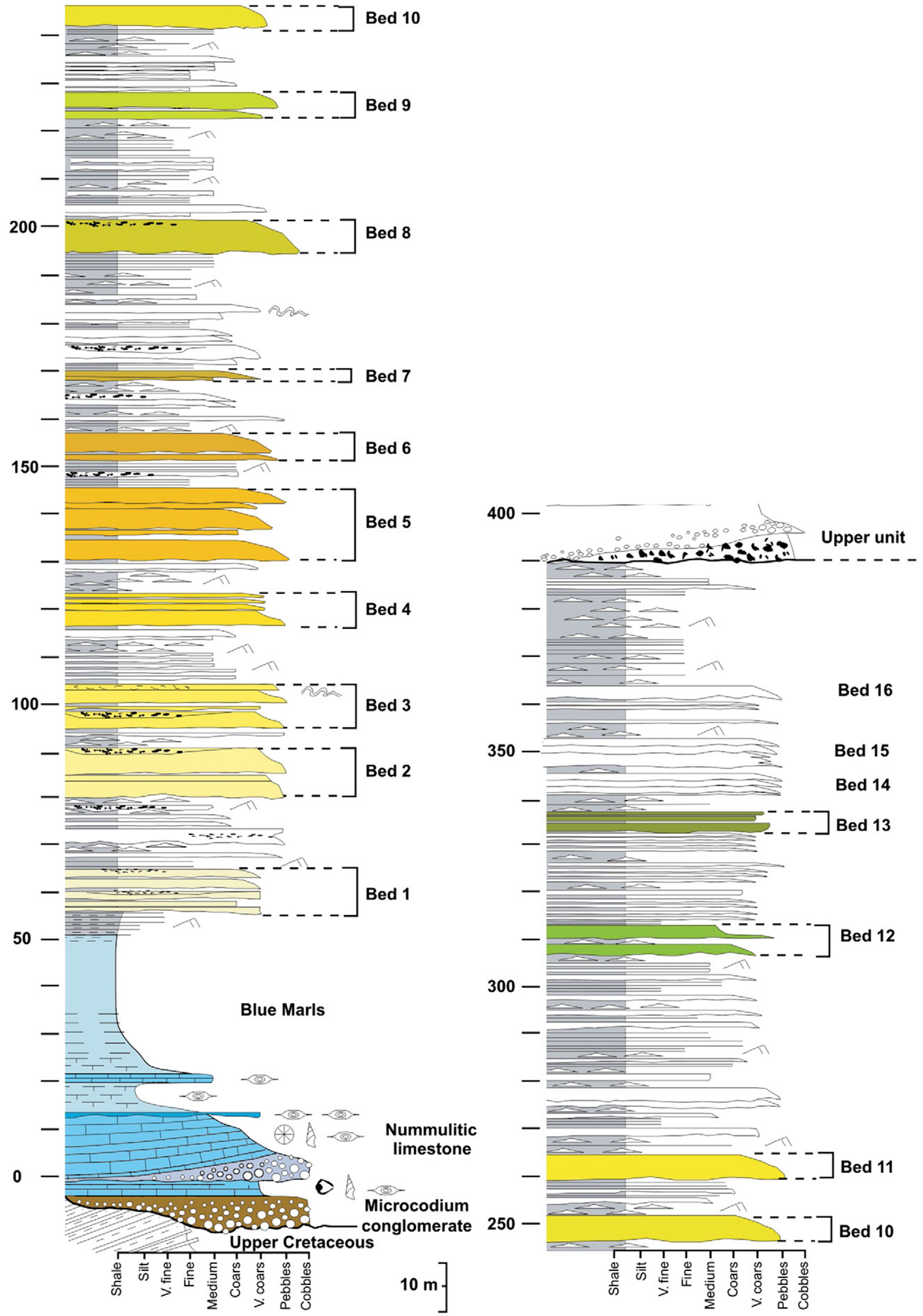

Fig. 11. Synthetic log in the Lower Unit of the Annot Sandstone showing the 16 massive marker beds.

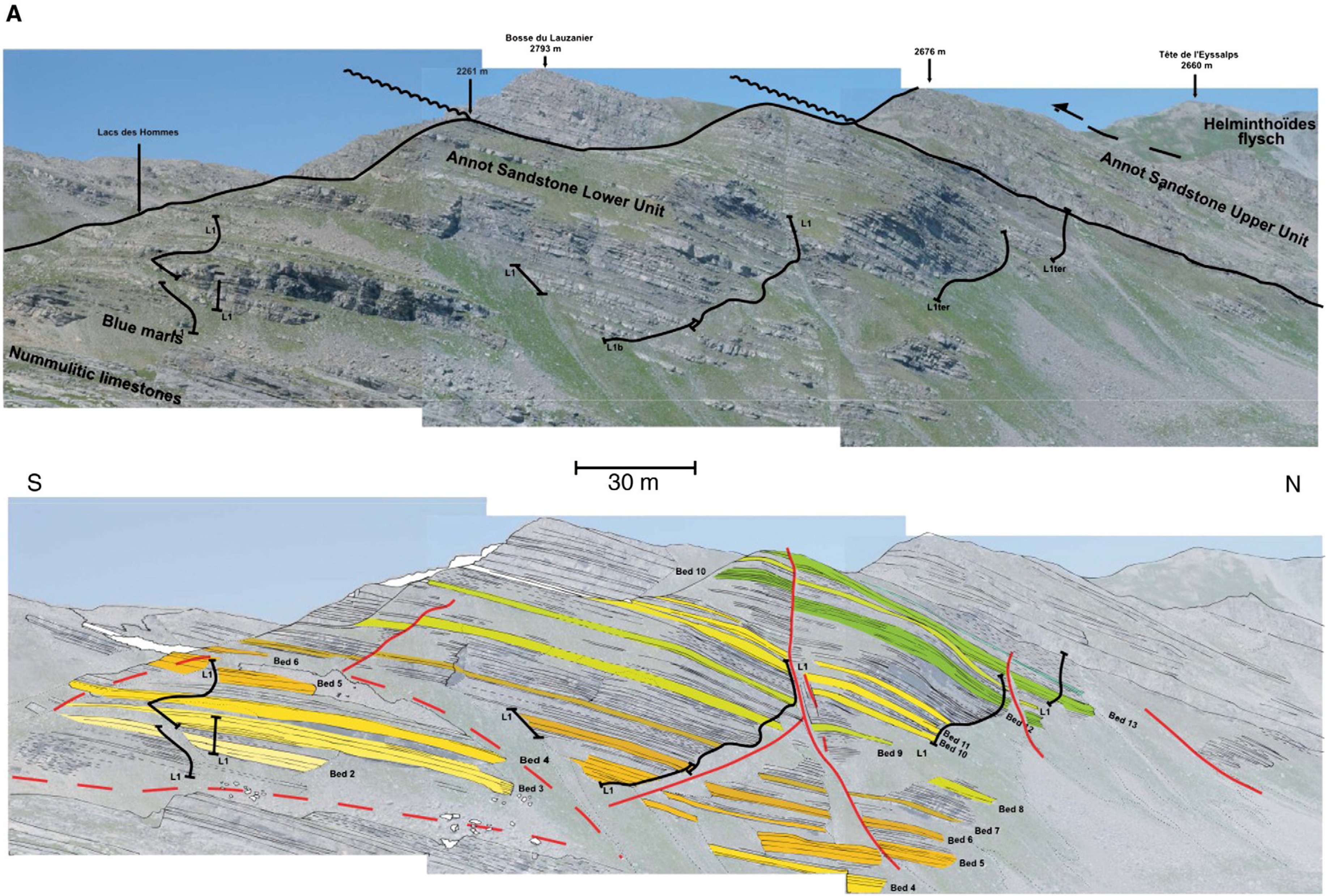

Fig. 12. Pictures of the outcrops in the Lower Unit showing the marker beds and the position of logs. (A) Western side of the Lauzanier Lake; (B) Eastern side of the Lauzanier Lake (Enchastraye log).

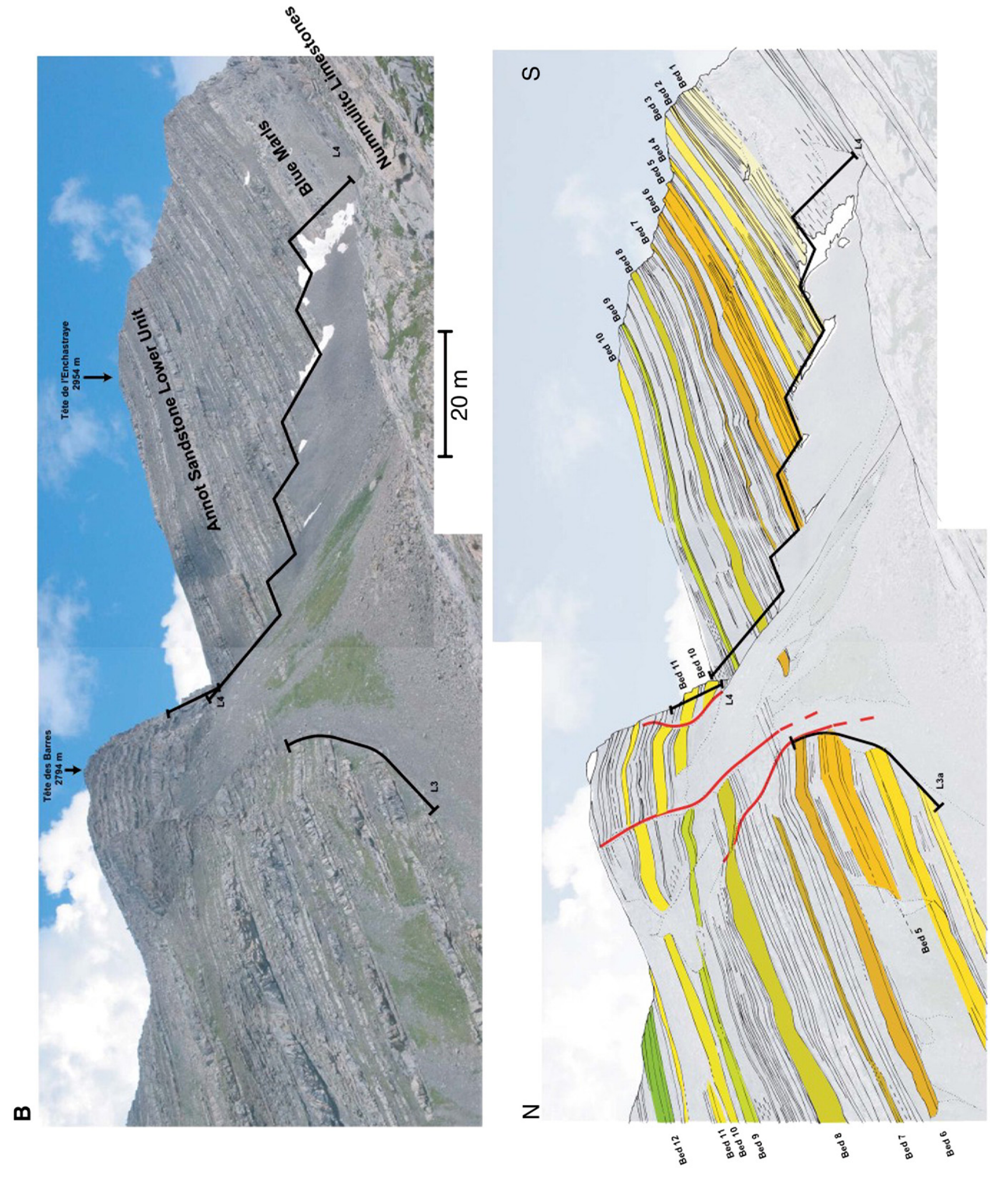

Fig. 12 (*continued*).

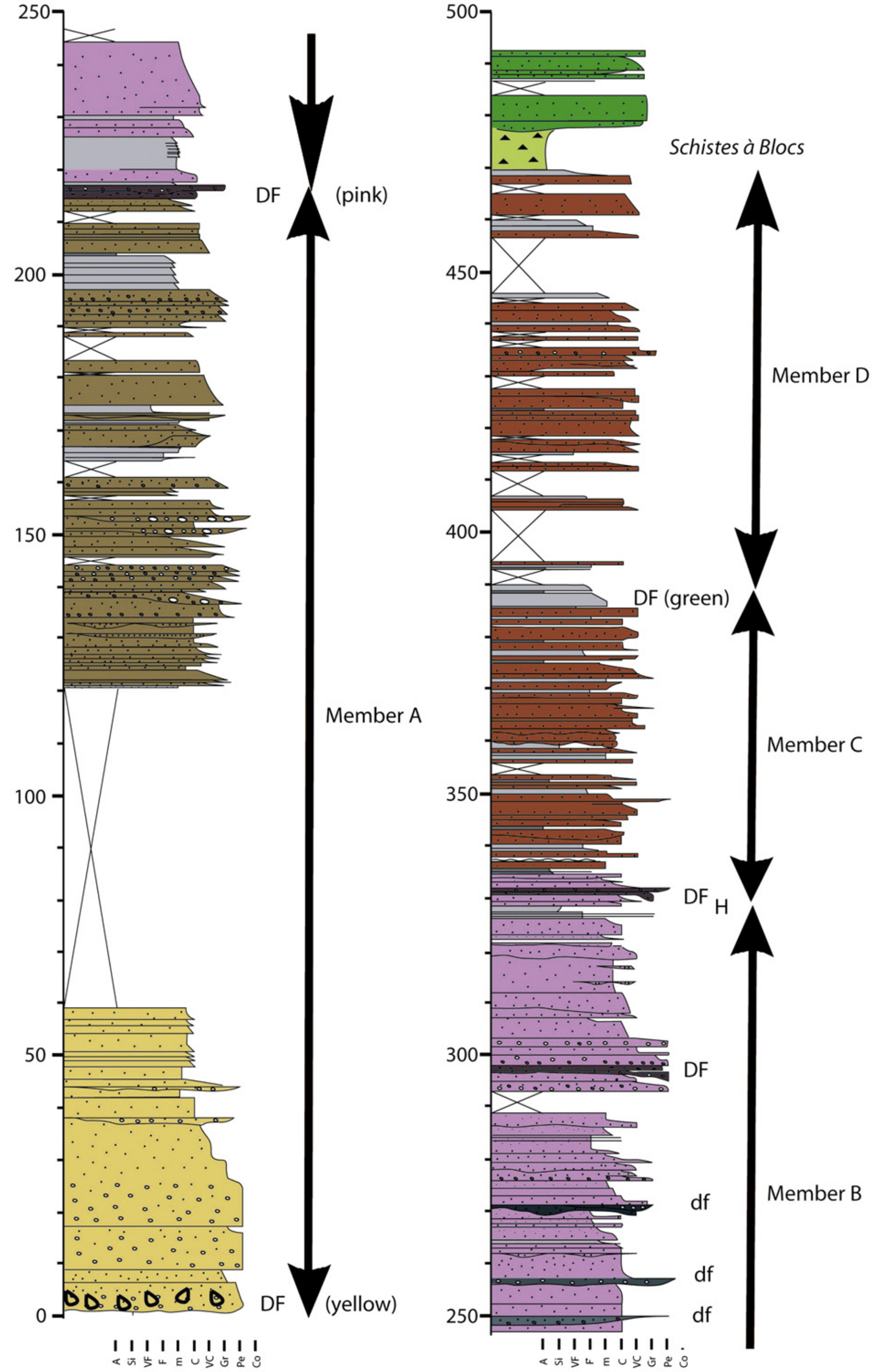

Fig. 13. Synthetic log of the Upper Unit of the Annot Sandstone. DF: Major marker debrites or slurry flow deposits. df: minor debrites/slurry flow deposits with a small spatial extent. H: Marker heterolithic interval.

are observed in deposits located on the eastern side of the lake (decimetre-large boulders). They are interpreted as the location of the feeding axis during the deposition of B and C members (black arrow in Fig. 14). Member D is between the third major debrite/slurry flow deposit and the Schistes à Blocs Formation.

The main axis of transport is hard to define in the Lower Unit because of the lack of channelling and the small grain size variation at the bed scale. In the Upper Unit, the axis of transport is marked by the maximum grain size in the conglomeratic beds and by the maximum thickness of the deposits.

The Lower Unit is very isopach (Fig. 15). Its thickness varies from 340 to 375 m. At the scale of the stratigraphic sequence, isopacity is also observed. Decimetre-thick beds can be correlated on the whole outcropping area. Beds are perfectly isopach over the whole area until marker bed 7. From marker bed 8 to 16, isopacity is slightly perturbed. A conglomeratic channel is observed above marker bed 6 on the east of

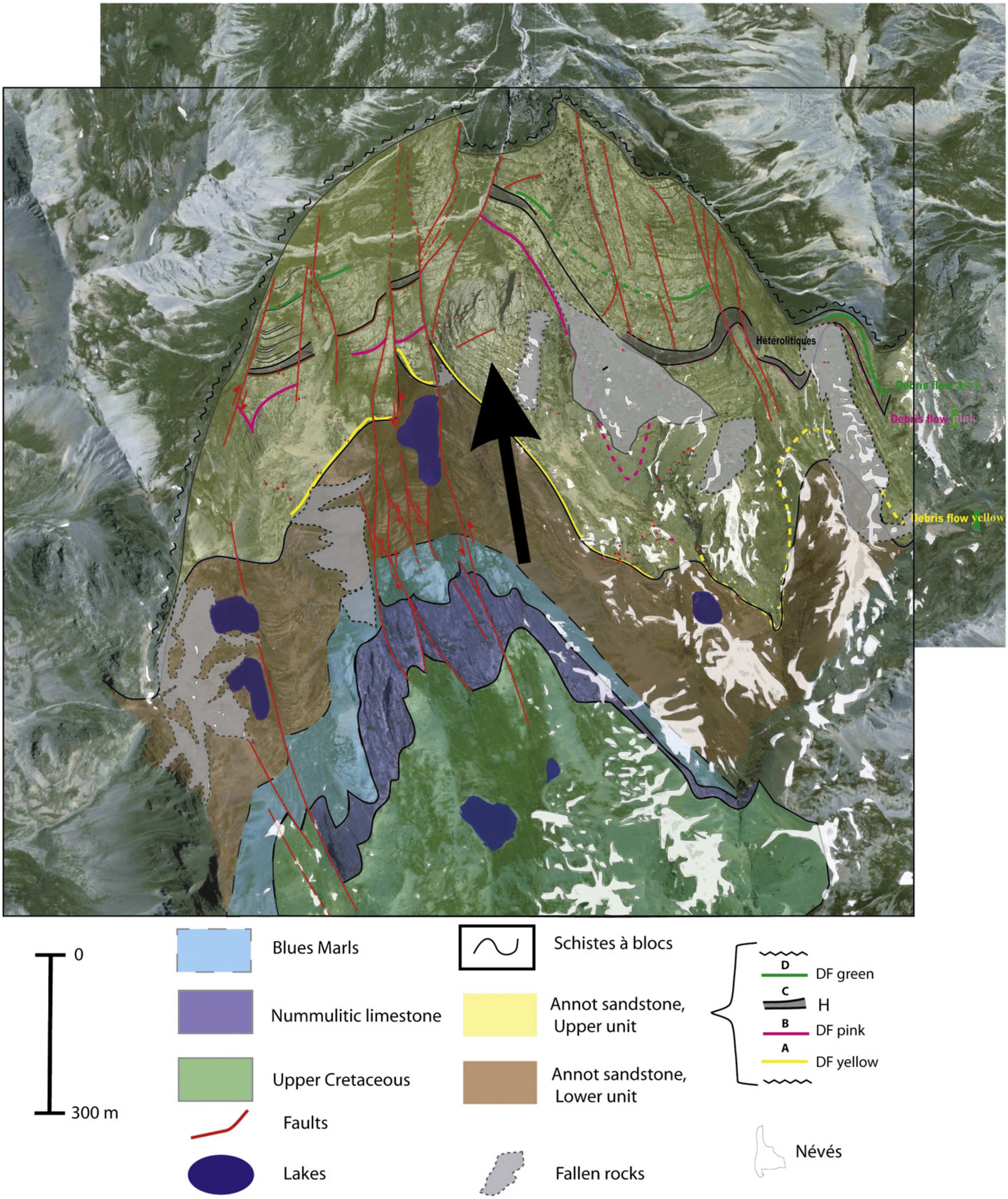

Fig. 14. Aerial photograph showing the extension of the units (upper and lower), members (A to D) in the Upper Unit and marker beds (debrites/slurry flow deposits and heterolithics) in the Lauzanier area. The lake is approximately 300 m long. The north is located at the top of the photograph. The black arrow represents the axis of transport (coarsest observed boulders) during deposition of members B and C in the Upper Unit. Published with the permission of IGN: ©IGN - 2005 - BD ORTHO® - licence n°2005CUBX0061.

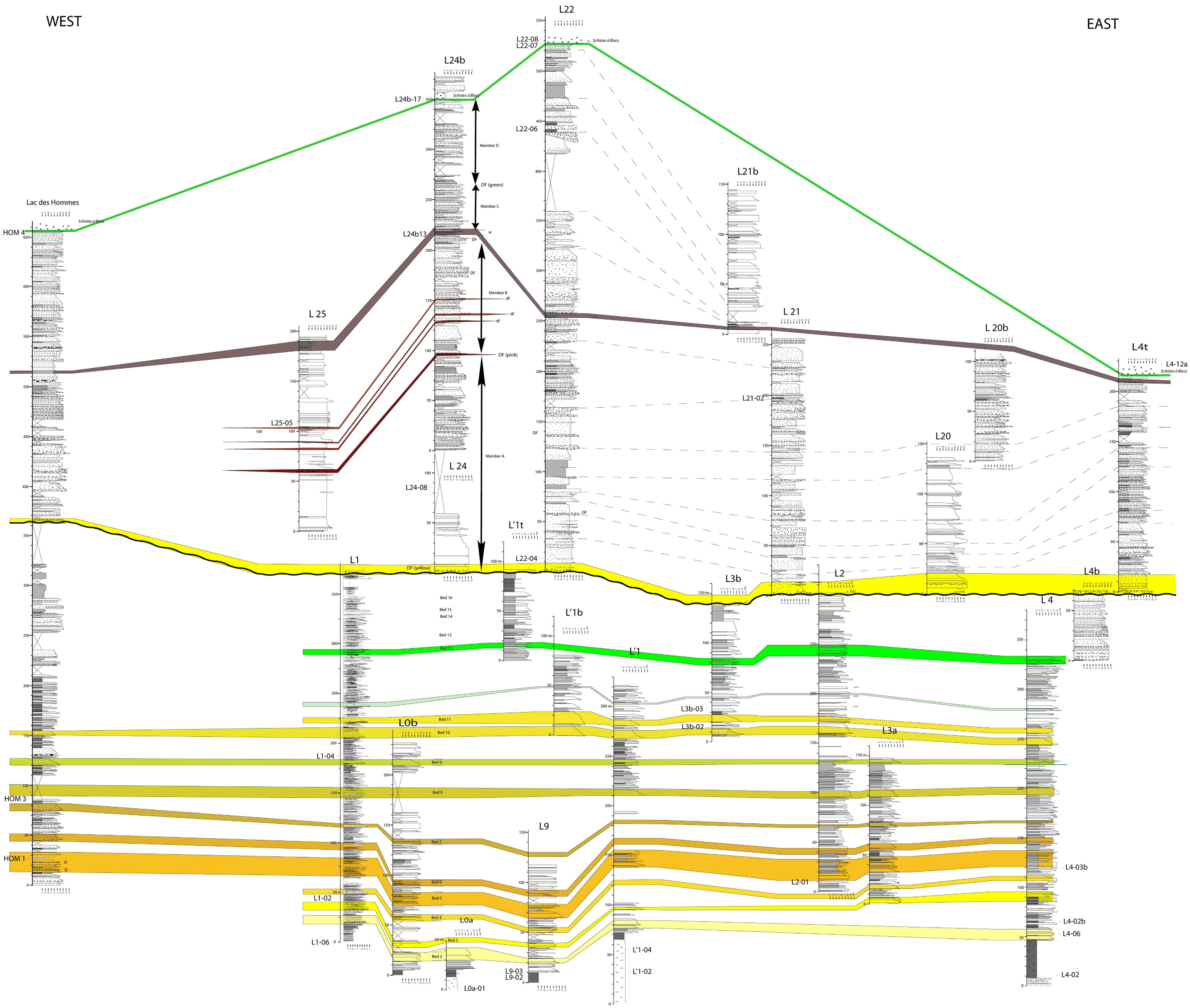

Fig. 15. Correlation panel in the Annot Sandstone in the Lauzanier area and location of samples used for stratigraphic analysis (see Table 1). A. Lower Unit; B. Upper Unit. DF: Debrite/slurry flow deposits. Same abbreviations as in Fig. 13. Bed 9 is used as a datum.

the lake. Anisopacity intensifies in beds 9—16. This suggests that a shallow depression (scour) formed at this location.

The Upper Unit is not isopach (Fig. 15). Thickness varies from 310 m to 525 m. The change in thickness is clear on the aerial photography map (Fig. 14).

5.5. Depositional model for the Lauzanier Series

Using the set of results, a synthetic model for sediment deposition in the Lauzanier sub-basin can be done. During all the depositional stages, the facies seems to be very proximal (coarse grain size and angular particles) suggesting that the flow occurs on a proximal submarine depositional environment following an alluvial fan plunging directly in the sea and spreading to form a lobe shape (coarse-grained slope apron from Reading and Richards, 1994). The initial deposition of gravity deposits above the Nummulitic Limestone and the Blue Marls in the Lauzanier area begins in the late Bartonian–early Priabonian (Fig.16). It begins by deposition of sheet sands corresponding to the progradation of coarse-grained non-channelled lobes (lower part of the Lower Unit). Unlike what happens in the Peïra Cava area where Blue Marls progressively enrich with silt to form the Flysch Noir (Black Flysch of Kuenen et al., 1957), in the Lauzanier area massive sandstone and gravel beds quickly prograde on the Blue Marls. Deposits are constituted by sheet sands and granules deposited by concentrated to differentiated turbulent flows initiated on a slope. Beds have a very good lateral continuity. Lobes are onlapping towards the west on the Blue Marls following the westward migration of the deformation front of the Alps. Channelling develops slightly in the upper part of deposition of the Lower Unit, suggesting that the sediments are deposited in the very distal part of the channelled lobe (Fig. 16B). Lateral continuity of beds is not as good as in the lower half of the unit. This suggests that channelling formed during the end of lower unit formation and can be interpreted as a progradational trend of the system.

A drastic change in the depositional environment occurs between the Lower and Upper units. This change is underlined by an unconformity between the two units. The depositional environment is more proximal in the Upper Unit than in the Lower Unit. This is suggested by the coarser grain size and less-sorted material and by the importance of channelling in the Upper Unit. In addition, mineralogical analysis suggests a change in the source between the deposition of lower and upper units. However, the channels remain shallow and channel migration by avulsion is frequent suggesting that deposition occurs in proximal channel lobes. No levee deposits are observed. In the whole Upper Unit the feeding is mainly made by cohesive, frictional flows and hyperconcentrated flows with very little differentiation.

The Upper Unit settles in two main phases (Fig. 16C and D). The two phases begin with the deposition of debrites/slurry flow deposits with a large spatial extent suggesting that migration is forced by tectonics. The unconformity at the base of the Upper Unit and the increase in grain size suggests that a major tectonic event occurred between the depositions of the two units. The mineralogical change of the source and the deposition of more proximal facies suggest that a topographic high began to denudate in the neighbouring area of the depositional zone. In the Upper Unit, a first phase corresponds to the deposition of members A and B. This deeply erodes the Lower Unit forming a supply axis. Member B of the Upper Unit piles-up eastward of member A, suggesting that topographic compensation occurs at the unit scale (Fig. 16C). This phase ends with the deposition of the heterolithic interval corresponding either to the deepening of the basin and/or to a decrease of the terrigeneous supply. The second phase corresponds to the deposition of members C and D. The feeding axis and main depocenter in members C and D (Fig. 16D) are located on the eastern side of the depocenter of members A and B suggesting once again topographic compensation. Deposition in the Lauzanier sub-basin continued until Early Rupelian. Consequently, the Upper Unit deposited simultaneously to the beginning of deposition in the St Antonin–Annot sub-basin.

The Annot Sandstone was then deeply incised by the canyon deposits of the Schistes à Blocs Unit and recovered by the Autapie and Briançon thrusts (Fig. 16E). The Schistes à Blocs deeply eroded the eastern part of the deposits in the Lauzanier area suggesting that the main axis of transport during deposition of the Schistes à Blocs was at a similar location as the transport axis during deposition of the Upper Unit.

6. Conclusions

The depositional environment in the Lauzanier area is dominated by lobe deposits in a point-source or ramp coarse-grained clastic system. The Lower Unit corresponds to non-channelled lobes and the distal part of channelled lobes. The Upper Unit corresponds to the proximal part of channelled lobes.

The Upper Unit is compounded of four members deposited by two phases. Each of these phases begin or contain debrites/slurry flow deposits suggesting that migration at the unit scale is forced by tectonics. The unconformity that occurs between the lower and upper units could be of importance for this part of the Alps. It suggests that an important tectonic event corresponding to an uplift happened close to the depositional area, and affected the area during the deposition of the Lauzanier series.

The apparent progradation between the lower and upper units thus corresponds to an important change in the source. The petrographic analysis is consistent with the sedimentary facies suggesting that no horizontal correlation exists with the outcrops of Mont Tournairet located southward. This analysis also suggests that the Lauzanier outcrops could be supplied by a local source. Topographic compensation occurs at all the scales from bed to unit. The Lauzanier sub-basin continued to fill during early Rupelian. It was active simultaneously to the St Antonin–Annot sub-basin, west of the Lauzanier area.

This outcrop example allows providing high-resolution analysis of depositional sedimentary sequences in terminal lobe deposits of a coarse-grained turbidite system. This analysis provides a facies association model for lateral evolution of deposits at the seismic scale. In addition, the progradation between lower and upper units allow the outcropping of both the channelled lobe system and the non-channelled lobe system. Consequently, the studied Lauzanier outcrops provide also a facies association model for longitudinal evolution of lobe deposits. These results are important for the interpretation of marine studies in recent submarine turbidite systems. They will allow extrapolating results obtained on these recent systems that are either with a poor spatial resolution because restricted to cores, or with a lesser resolution (acoustic data).

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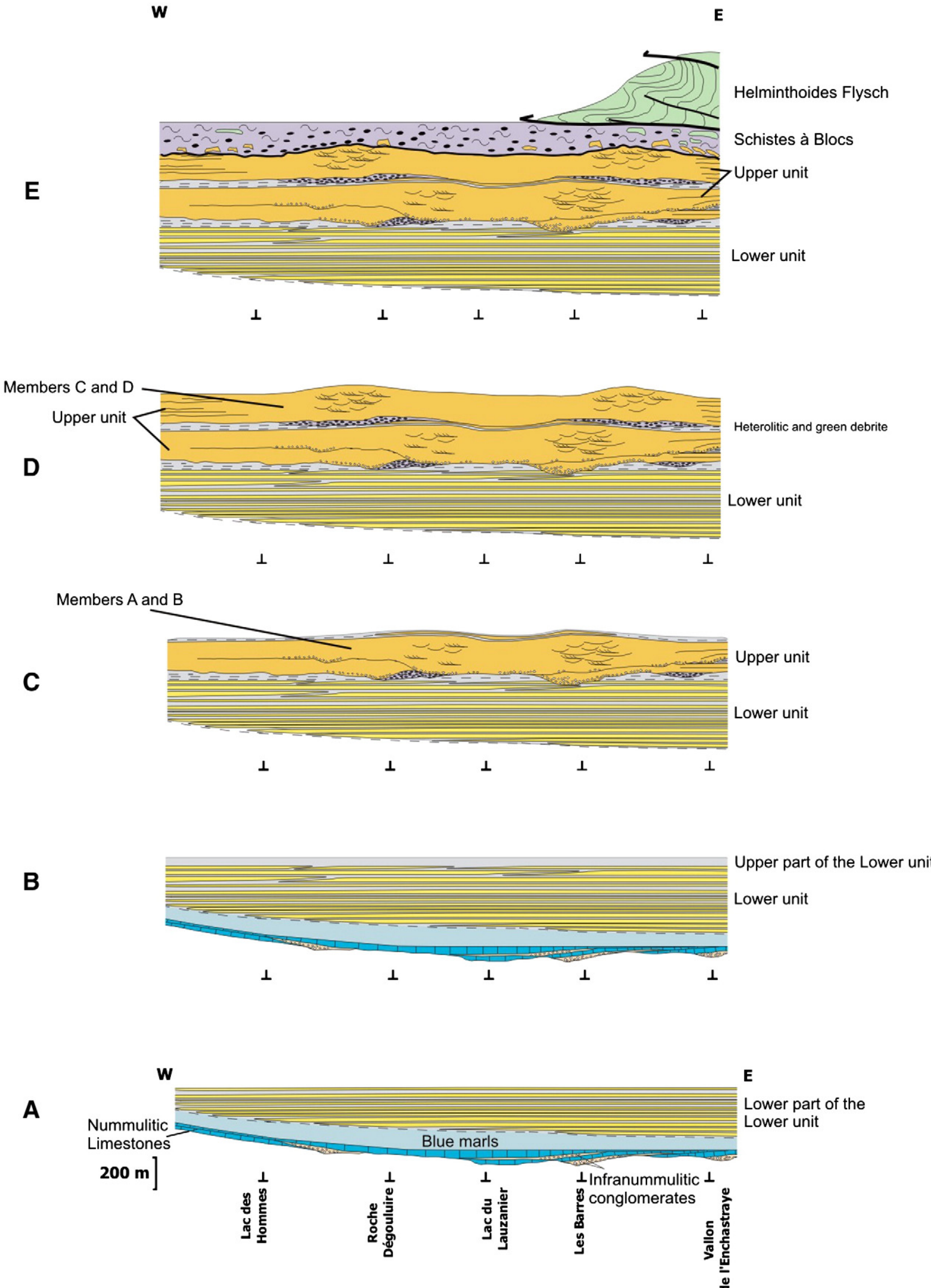

Fig. 16. Interpretation of the evolution of the Lauzanier area sub-basin during Priabonian. A: Deposition of the lower part of the Lower Unit of Annot Sandstone (sheet sand of the non-channelled lobes over the Nummulitic limestone and Blue Marls. Deposits have an excellent grain-size continuity and little lateral thickness variation. B: Deposition of the upper part of the Lower Unit of Annot Sandstone. Lateral continuity is lesser than in the lower part and topographic compensation begins to occur. C: Deposition of members A and B of the Upper Unit of the Annot Sandstone (conglomerates corresponding to channelled lobes). D: Deposition of member C and D of the Upper Unit of the Annot Sandstone. Important topographic compensation occurs E: Erosion of Annot Sandstone and deposition of the Schistes à Blocs.

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