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A new conceptual model for the deposition process of homogenite: Application to a cretaceous megaturbidite of the western Pyrenees (Basque region, SW France)

Thierry Mulder [a,*], S. Zaragosi [a], P. Razin [b], C. Grelaud [b], V. Lanfumey [a], F. Bavoil [a]

[a] Université de Bordeaux, UMR 5805 EPOC, avenue des facultés, F-33405 Talence cedex, France
[b] Université de Bordeaux, Institut EGID, 1, allée Daguin, F-33607 Pessac cedex, France

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ABSTRACT

The north Pyrenean megaturbidite is a 19–63 m exceptional thick bed deposited during the Late Turonian and extending over more than 90 km in the Basque region Country (SW France). Its thickness varies from more than 63 m to about 19 m from east (Mauléon area) to west (Basque coast). It represents a total compacted volume of about 90 km^3 of carbonates. On the field, rare sedimentary structures are visible in the turbidite bed. They consist of laminar planar lamination and rare cross laminations in the eastern region and antidune-like structures in the western region. Five sites have been sampled with a vertical step of 50 cm to 1 m. Thin sections have been quantitatively analyzed for counting the terrigeneous fraction, the quartz grain size and the mineral orientation. The deposits fine westward, which suggests a source located in the east of the Mauléon Basin. This is consistent with the quartz grain orientation in the lower part of the megaturbidite. The deposits fine upward from medium sand to clayey-silt. This is consistent with the classical definition of homogenites and suggests that these kinds of deposits are turbidites. These observations also suggest that the term “megaturbidite” is appropriated for these deposits. The sedimentary analysis indicates that the deposit results from a single event. The volume of sediment involved in the process, as well as the quartz grain orientation indicating flow motion in the opposite direction of the initial flow and the antidune-like structure suggest the formation of reflected flows and the formation of standing waves over the complete water column in the Basque flysch sub-basins corresponding to a “Seiche effect”. The origin of the megaturbidite is probably an earthquake-generated collapse on the carbonate platform. This example allows providing a new conceptual model for the process of homogenite deposition. This model explains the deposition of thick, fine-grained, crudely-graded megaturbidites.

1. Introduction

Sediment mass flows are a frequent process of sediment transport along submarine slopes (e.g., Stow, 1994). This term includes very different processes such as laminar sediment flows and particle-laden turbulent flows named turbulent surges or turbidity currents. Laminar sediment flows can be subdivided into matrix-supported flows, grain-supported flow and water-supported flows (Middleton and Hampton, 1973). These natural processes represent a continuum of flow transformation described by Fisher (1983) and originating from a subaerial or submarine slope failure, slumping or sliding according to the shape of the failure surface (resp., rotational or translational, Skempton and Hutchinson, 1969). Sediment underflows can also originate as the continuation of a river flow during floods when the suspended sediment concentration is high enough to form a non-buoyant plume (hyperpycnal flows of Bates, 1953; Mulder and Syvitski, 1995).

Several classifications exist for mass flow deposits. They are either descriptive, based on sedimentary facies (Bouma, 1962; Piper, 1978; Stow and Shanmugam 1980; Pickering et al., 1989; Guibaudo, 1992), or genetic and include an interpretation of the original process of deposition (Mutti and Ricci Lucchi, 1975; Walker, 1978; Nardin et al., 1979, Mutti, 1992; Mulder and Alexander, 2001).

Within gravity flows, particle deposition can occur by (1) freezing, (2) traction and (3) suspension fall-out. (1) Freezing corresponds to an abrupt stop of the flow when the resistance exceeds the driving shear force. The internal resistance can be due either to matrix cohesion (cohesive freezing of Middleton and Hampton, 1973; Lowe, 1979, 1982) or to grain-to-grain interaction (Middleton and Hampton, 1973; frictional freezing in hyperconcentrated flows of Mulder and Alexander, 2001). (2) Traction corresponds to bedload transport and is responsible for all the dynamic (motion-related) sedimentary structures in deposits, particularly those related to concentrated flows deposition (Mulder and Alexander, 2001). (3) Suspension fall-out is at the origin of most of the vertical normal (fining-up) grading in sedimentary beds. It is dominant in dilute turbulent flows forming Te intervals. In this case, mixing of very fine turbidite deposition and

* Corresponding author.
E-mail address: t.mulder@epoc.u-bordeaux1.fr (T. Mulder).

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hemipelagic and pelagic fall-out generated the definition of hemiturbidites (Stow and Wetzel, 1990). Numerous additional terms have been used to describe flow processes and their deposits. An extensive review is proposed by Shanmugam (2006a).

Thick and extensive submarine mass flow deposits are frequently described both in recent and ancient environments. The slides of volcanic island flanks such as Hawaii destabilization occur under the form of a co-seismic initial rockslide (Moore et al., 1989, 1994; Takahashi et al., 2002) or large-scale rotational slides affecting oceanic island flanks. Parts of these large slides can collapse to form submarine debris avalanches such as on the flank of Piton de la Fournaise volcano in La Réunion (Ollier et al., 1998) or in Hawaii (Moore et al., 1995). Recently, the 10,000 km^3 mass flow deposit corresponding to the Ayabacas formation (Andean) was interpreted as the largest known submarine event. It occurred at the Turonian-Coniacian boundary (Callot et al., 2008).

Transformation of a slump into a turbidity current is a frequent process that is usually associated with intense erosion of the submarine floor. The 0.08 km^3 slump that occurred in October 1979 on the steep slopes seaward of the Nice Airport and the related turbidity current that travelled at about 20 $m.s^{-1}$ (72 $km.h^{-1}$) on the steep continental slope deposited a turbidite that reached 1 m in thickness in the upper submarine Var channel (Piper et al., 1992; Piper and Savoye, 1993; Habib, 1994).

Megaturbidite is a term used to describe a thick, extensive deposit from an exceptionally large mass flow. Its grain size can vary from large blocks to clay particles (Bouma, 1987). This author proposes to restrict its use when the deposit (1) is thick and differs in composition from the host rock; (2) has a large spatial extension, and (3) is not a part of a turbidite system.

In deep central-eastern Mediterranean, thick transparent units have been called homogenites by Kastens and Cita (1981), Cita et al. (1984) or unifites by Stanley (1981). They usually fill topographic lows and are related either to volcanic eruptions (e.g. Santorini, Cita and Aloisi, 2000) or earthquakes (seismoturbidites of Mutti et al., 1984). Cita et al. (1996) and Reeder et al. (1998) detail two types of homogenites: type (A) can be several decimetres to several metres thick with a thin sandy-silt sole overlaying a sharp basal contact. The bed rapidly fines up to clay without sedimentary structure. Type (B) has a thickness ranging from a few centimetres to about 20 m. It looks like type (A) except that the sandy base is more developed and the basal contact is erosive. The description of Reeder et al. (1998) suggests that homogenites are not homogeneous in texture which was already noted by Cita et al. (1996). For these authors, the term “homogenite” involves only a homogeneous nature of the deposits and is kept for consistency to their previous works. They propose to refer “homogenite” to the expression on a unique event with a definite stratigraphic position (Cita et al., 1996). This definition fits the “megaturbidite” definition of Bouma (1987). Some homogenites are considered to be tsunamogenic (Kastens and Cita, 1981; Cita et al., 1996; Cita and Rimoldi, 1997; Cita and Aloisi, 2000) because they rework a considerable volume of sediments and sometimes because coastal tsunami deposits could be related to the deep-sea deposits. For this reason they have been called tsunamites (review in Shanmugam, 2006b). However, as recommended by Shanmugam (2006b), the terms “seismoturbidites” and “tsunamites” should not be used. Seismoturbidites represent mass flow deposits, not turbidites, and tsunamites represent the association of several sedimentary and hydrodynamic processes. In addition, these terms mix facies description (data) and process interpretation and favour failures on process interpretation in the case of facies convergence (similar facies related to different processes).

Since these early studies, “homogenites” have been described in deep basins of Marmara Sea (Beck et al., 2007) or Gulf of Mexico (Tripdanas et al., 2004) and lakes (Chapron et al., 1996; Chapron, 1999).

In this paper, we aim at accurately describing the vertical and horizontal evolution of the north Pyrenean megaturbidite using quantitative analysis of thin sections in order to provide a process interpretation of this deposit and an explanation for the spatial facies variations. The results will allow providing a new conceptual model for deposition of thick, fine-grained, poorly-graded megaturbidites.

2. Geological context

To be consistent with previous studies, we use the French terminology for the lithostratigraphic units and sequences. When necessary, an English translation is provided.

The Basque Country (Fig. 1) is located at the boundary between the intracontinental chain of the Pyrenees and the North Spanish Margin (Boillot, 1984). The geological history of this region during the Mesozoic and Cenozoic is related to the motion between Iberia and Europe. During Aptian and Albian, the divergence of these two plates formed a complex intracratonic basin where rare gravity processes occurred before middle Albian (Curnelle et al., 1982). During Cenomanian and Turonian, sub-basins merged to form a single through limited by the South Aquitaine carbonate platform in the north and the North-Iberian carbonate platform in the south (Fig. 2). During the Late Senonian, Iberia began a sinister thrust-like motion against Europe reducing the extent of the flysch basin. The complete filling of the basin is diachronous from east to west. Turbidite sedimentation occurred from Albian to Coniacian in the eastern part, and from Vraconian to middle Eocene in the western part.

The whole turbiditic series is almost 4500 m thick. It accumulated in the Saint-Jean-de-Luz and Mauléon sub-basins (Fig. 1). Its history began during Albian with the deposition of the black flysch in the easternmost sub-basins (Deloffre, 1966). During Vraconian, the Saint-Jean-de-Luz Basin formed as a result of a westward extension of the Mauléon Basin. After a short episode of silico-clastic supply during Vraconian and Cenomanian (deposition of the *Brèche d'Amotz-Amotz Breccia-* and *Flysch de Mixe-Mixe Flysch*), carbonate sedimentation began during middle Cenomanian (deposition of the 1200-m thick Lower Calcareous flysch including the “Flysch à Silex inférieur” (*Lower flinstone Flysch*), the “Calcaires d'Ablaintz et de Villa Rosa” (*Ablaintz and Villa Rosa limestones*) and the “Brèche de Béhobie” (*Béhobie Breccia*; Fig. 3)). This period is characterized by an intense subsidence. In the Saint-Jean-de-Luz Basin, the Cenomanian-Campanian series forms “the carbonate turbidite complex of the Basque coast” (Razin, 1989; Fig. 3). Its thickness is about 3000–3500 m. Turbidite deposition formed small turbidite systems. The depositional environment corresponds to the “platform–slope apron” type of Mullins and Cook's (1986). The turbidite systems were mainly fed by destabilization of continental shelf deposits along the South Aquitaine Margin in the north. Supply from the south (shallow part of the North Iberia Margin localized in the Basque Massifs) was less active. During upper Cenomanian and Turonian, the Saint-Jean-de-Luz Basin progressively deepened eastward until Coniacian-Santonian (deposition of the 250–400 m thick “Calcaires de Béhobie” (*Béhobie limestones*), and 600–800-m thick “Flysch à Silex de Guéthary” (*Flinstone Flysch of Guéthary*; Feuillée and Sigal, 1965; Mathey and Sigal, 1976; Fig. 3). These formations consist of top-cut-out turbidites (Ta–c intervals) with rare coarse silico-clastic particles in Ta interval. Td interval is rare and Te is always absent. During the Coniacian, the basin abruptly deepens as a result of a tectonic collapse resulting in the formation of several superposed slumped beds (Erromardie slumps of Razin, 1989). The Aquitaine platform also deepens and a distal sedimentation occurs (deposition of the 350–400 m thick “Flysch Marno-calcaire of Socoa”—*Marly limestone of Socoa*; Fig. 3). Turbidites are mainly base cut-out turbidite with rare Ta intervals. They form several decimetre-thick beds with a well-developed Te interval made of carbonated mud. These turbidites are interpreted as lobe fringe deposits, i.e. deposited in a more “distal” environment than the *Flysch à Silex of*

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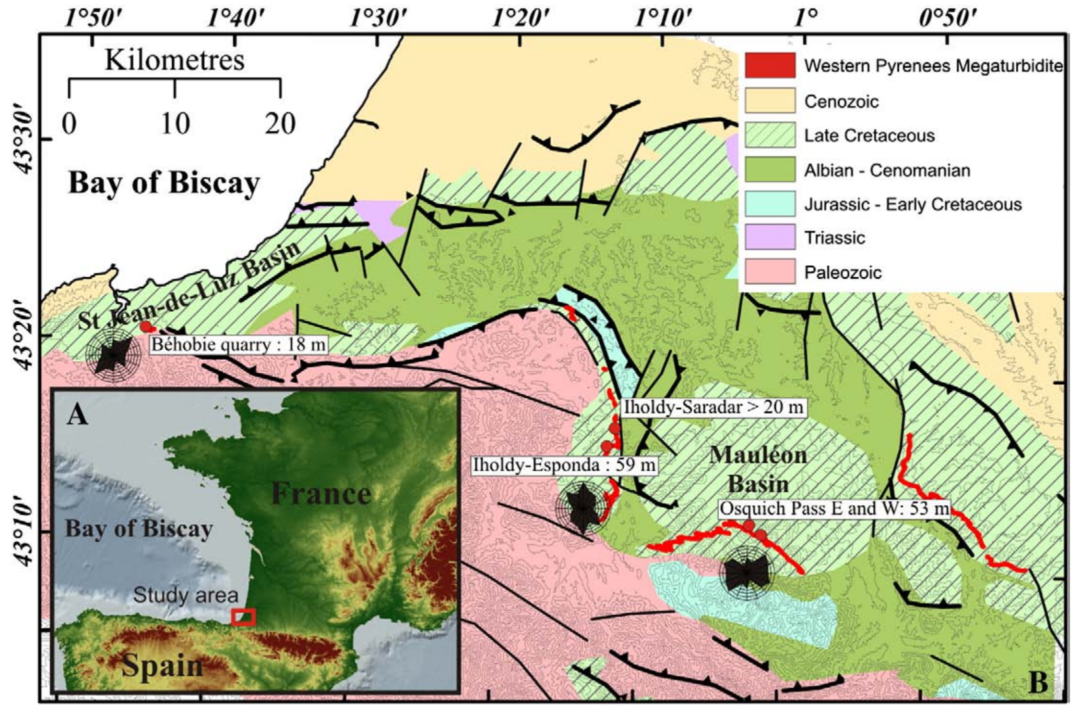

Fig. 1. A: Location of the study area. B: Geological map of the Basque Pyrenees (Razin, 1989) and location of the north Pyrenean megaturbidite, the studied outcrops and the thickness values of the megaturbidite. Rose diagram indicates flow direction deduced from quartz grain orientation. The geological map results of compilation of BRGM maps published by Casteras (1971) and Le Pochat (1974, 1976, 1978).

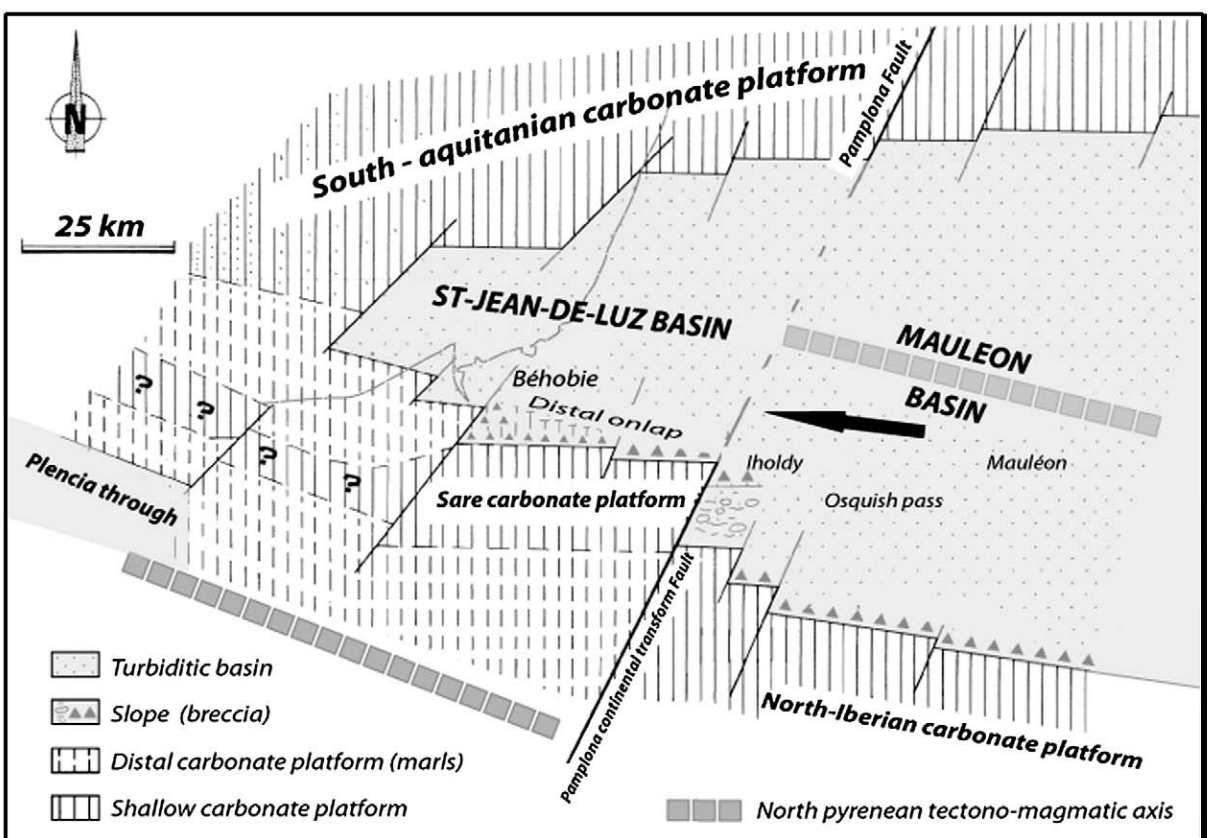

Fig. 2. Schematic paleogeographic reconstruction of the axial turbiditic basin and adjacent carbonate platforms in the western Pyrenees during the Cenomanian and Turonian (Razin, 1989). Arrow: direction of the north Pyrenean megaturbidite flow.

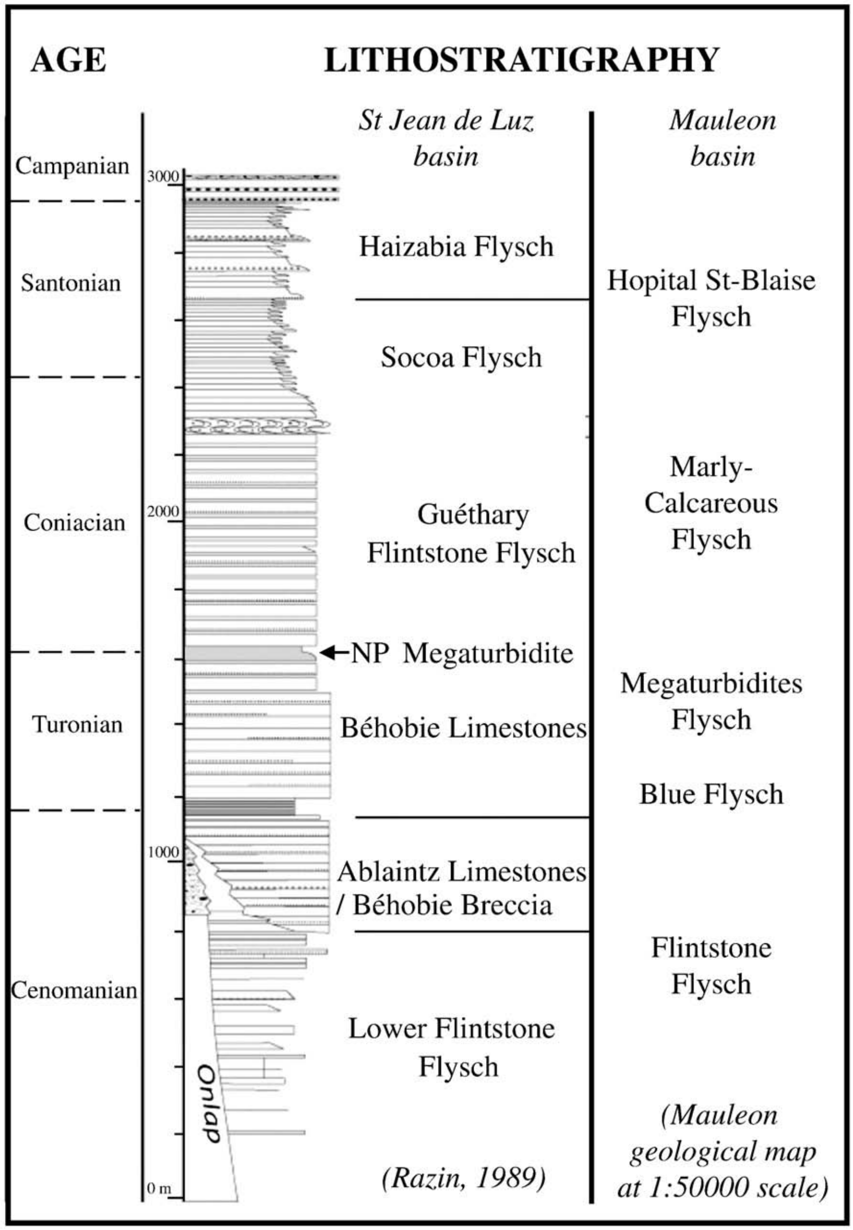

Fig. 3. Stratigraphy and basin evolution of the carbonate turbidite complex of the Basque coast in the Basque flysch basin in northern Pyrenees (modified from Razin, 1989). Stratigraphic correlations with units in the Mauleon Basin. NP: North Pyrenean.

Guéthary during a period of intensified carbonated mud supply from the Aquitaine carbonate platform (Razin, 1989). Tectonic convergence between Iberia and Europe began during Campanian and induced the transition from an extensive to a compressive tectonic regime. The *Flysch d'Hayçabia*, formed during this period, is composed of two superposed series: the *Makila series* and the *marly limestone of Loya* (Fig. 3). The Makila series shows the progressive increase of the average grain size of deposits and the siliceous/calcareous, hemipelagite/turbidite ratios. Development of polygenic microbreccias and coarse-grained sandstones composed of abundant Paleozoic clasts suggest local erosion of the shallow Paleozoic substratum along the slope apron. The marly limestone of Loya is a hemipelagic unit in which gravity flow deposits are only represented by exceptional beds (Razin, 1989). This facies evolution indicates a transition from deep basin to continental slope depositional environment. This change is interpreted as resulting from the southward progradation of the Aquitaine slope towards the basin. The "Flysch d'Hayçabia"(*Haizabia Flysch*) corresponds to the last phase of carbonate turbidite sedimentation in the Saint-Jean-de-Luz Basin before the development of the Upper Campanian to Middle Eocene siliciclastic turbidite systems, always in a convergent geodynamic context but with a southward shift of the main turbidite through (Razin, 1989).

Exceptional mass flow deposits are rare before the Haizabia Flysch. One has been identified in the Mixe Flysch, four in the Béhobie Limestone and one in the Flinstone Flysch of Guéthary in addition to the Erromardie slump and the Béhobie megaturbidite (Razin, 1989). In the Haizabia Flysch, exceptional mass flow deposits are frequent (Lagier et al., 1982; Lagier, 1985). Razin (1989) described nine of these deposits including debrites, grain-flow deposits, and Lowe sequence (hyperconcentrated flows of Mulder and Alexander, 2001). These beds are metre to decameter thick. They occur as acyclic processes in the background sedimentation (turbiditic for the Béhobie Limestone, the Flinstone Flysch of Guéthary, the marly limestone of Socoa and the Makila series, hemipelagic for the marly limestone of Loya). They correspond to megaturbidite beds defined by Bouma (1987). Most of these beds show a vertical evolution towards classical turbidites (Bourrouilh and Offroy,

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1983; Offroy, 1984; Bourrouilh, 1987; Bourrouilh et al., 1987; Razin, 1989) suggesting a longitudinal flow transformation during motion (Fisher, 1983). The north Pyrenean megaturbidite was described by Viers (1960) and called the "Grande Barre Calcaire" (*Thick Calcareous Bed*) or the Béhobie megaturbidite. It was recognized later as a thick mass flow deposit (Debroas et al., 1983). Its thickness varies from 63 m in the Mauléon Basin to 19 m in Béhobie-Biriatou (Offroy, 1984) in the Saint-Jean-de-Luz Basin. This exceptionally-thick bed extends over more than 90 km from Oloron to Béhobie and is an excellent lithostratigraphic marker between the two basins. It marks the Turonian-Coniacian boundary. Considering the lithological units, it separates the Béhobie Limestone from the Flinstone Flysch of Guéthary. This "out of system" deposit (Razin, 1989) completely fits the definition of Bouma (1987) for a megaturbidite and we will keep this terminology in this paper. In addition, this terminology is consistent with previous literature and geological maps.

The age of the flysch has been determined using planktonic foraminifers (*Rotalipora*, *Dicarinella*, *Globotruncana*). Their presence and an ichnofauna assemblage made of more than 90% by Planolithes, Granularia, Helminthopsis and Fucoides suggest a mid to lower bathyal environment (800–2000 m; Mathey, 1987; Razin, 1989).

3. Data and methods

The north Pyrenean megaturbidite has been sampled in details in five locations (Fig. 1): (1) the Iholdy-Saradar Quarry (Fig. 4A; N 43° 16′ 21″; W 01° 12′ 21″); (2) the Iholdy-Esponda Quarry; (N 43° 15′ 49″; W 01° 12′ 27″); (3) the eastern flank of the Osquich Pass anticline (N 43° 11′ 49″; W 01° 01′ 24″), (4) the western flank of the Osquich Pass anticline (N 43° 11′ 47″; W 01° 01′ 27″), and (5) the Béhobie Quarry (N 43° 20′ 43″; W 01° 45′ 06″). Six additional samples have been collected in the Hoqui Quarry. The historical Béhobie-Biriatou quarries along the Bidassoa River (Fig. 4B and C) could not be sampled because of prohibited access. For each outcrop, samples have been collected in the underlying Béhobie limestones and in the overlying Flinstone Flysch of Guéthary. These outcrops have been selected according to the BRGM geological maps of Iholdy (Le Pochat, 1974), Mauléon-Licharre (Le Pochat, 1976), Tardets-Sorholus (Casteras, 1971) and St-Jean-Pied-De-Port (Le Pochat, 1978).

In the five outcrops, a rock sample has been collected approximately every 50 cm to 1 m on a vertical log. Thin sections have been made for each sample for enabling a semi-automatic image analysis on a Leica DM 6000B microscope with a Leica DFC 480 camera. After identification, carbonate and quartz have been analyzed. Grain count for each component was automatically performed using the Leica Qwin V3 software and the method developed by Johnson (1994). A grain has been defined as a particle larger than 10 µm. Fragments below this size belong to undifferentiated rock carbonated mud matrix. Each grain was contoured using an optical pen to calculate automatically its size and shape parameters. The density of each component per surface unit could thus be calculated. In addition, grain orientation has been measured to estimate flow direction.

Fold have an axis orientation = N110 (Pyrenean direction), i.e. identical to regional deformation at different scale. Consequently folds have not been rotated and do not need restoration.

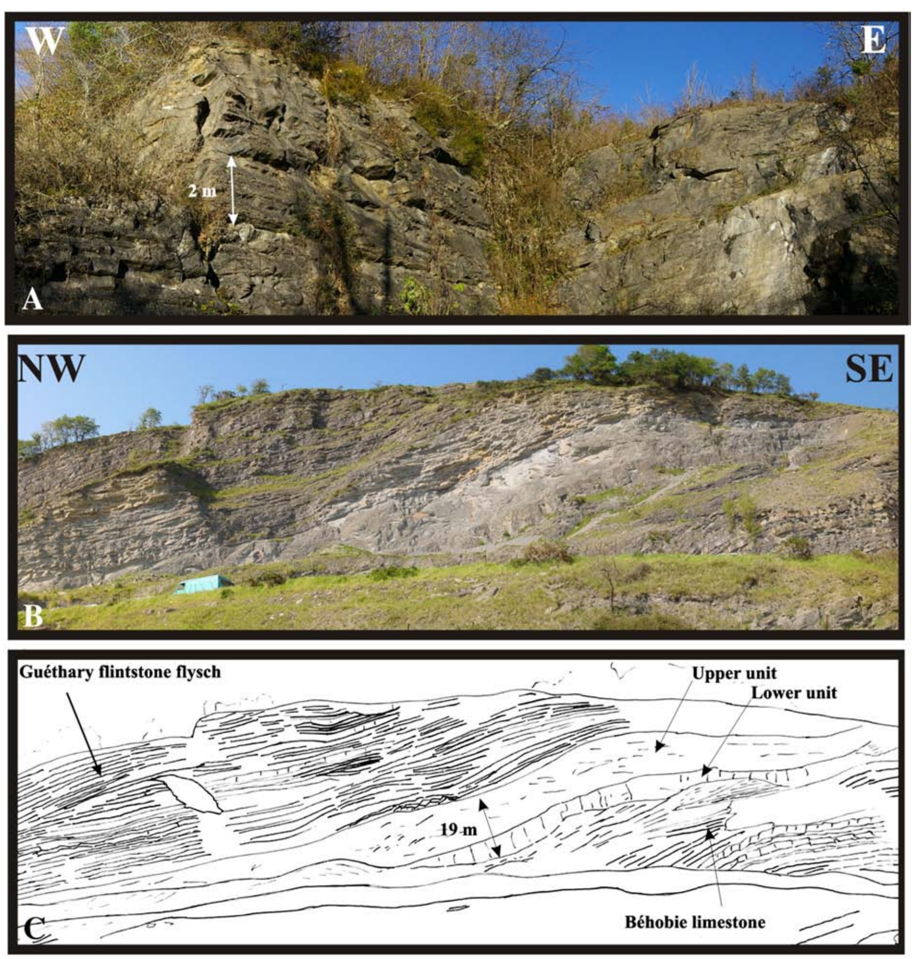

Fig. 4. Pictures of the north Pyrenean megaturbidite. A, Proximal facies in Iholdy-Esponda Quarry B: Photograph and C: line drawing of distal facies in Béhobie-Biriatou Quarry.

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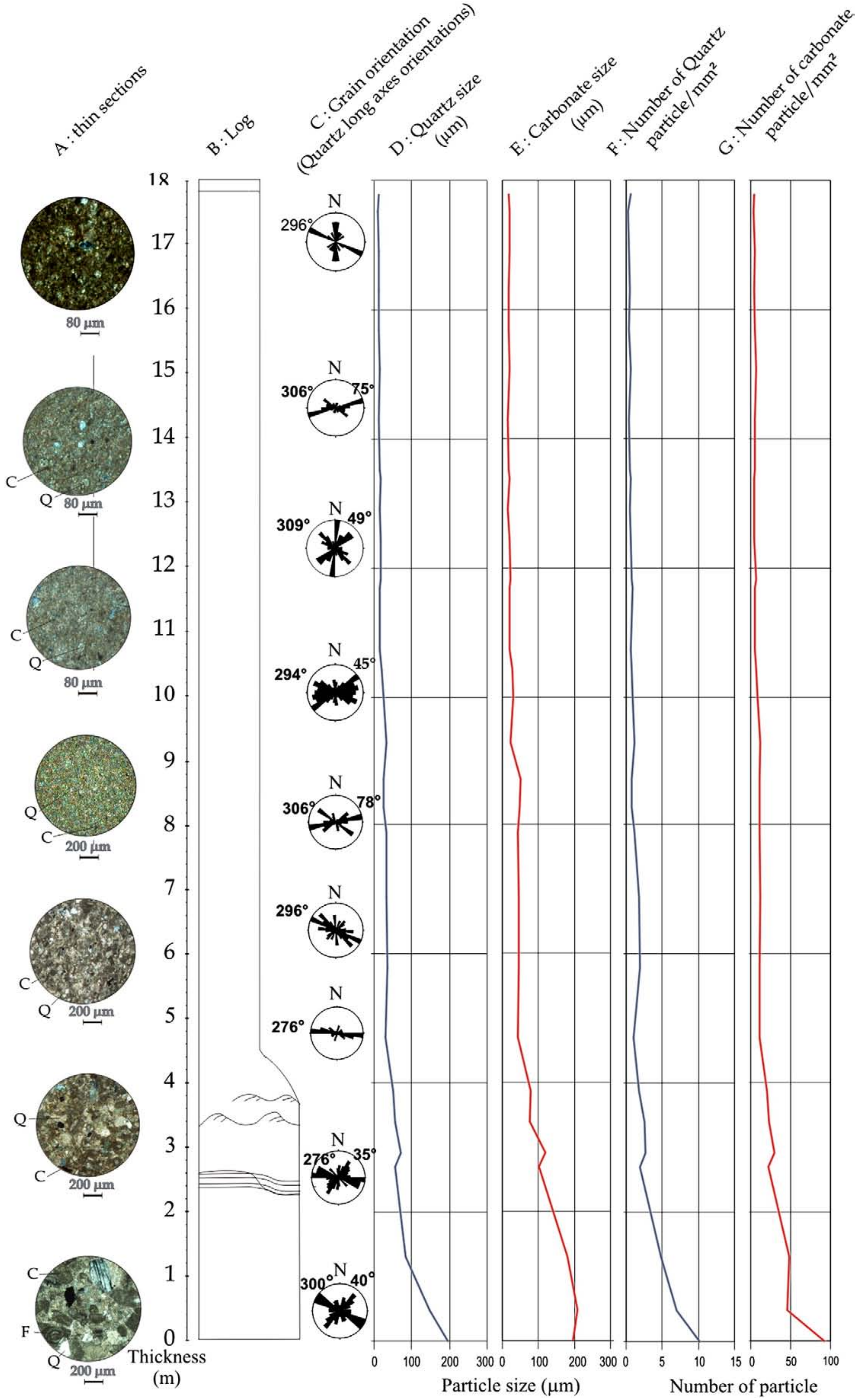

Fig. 5. Example of a complete dataset of analyses on a sampled outcrop in Béhobie Quarry. A: Thin sections of rock samples using cross-polarized lighting; B: sedimentary log; C: particle orientation measured on long axes; D: quartz particle size; E: carbonate particle size; F: quartz particle concentration; G: carbonate particle concentration.

4. Results

The maximum thickness of the megaturbidite measured on the studied outcrops is up to 59 m in the Mauléon Basin: 53 m at Osquich Pass and 59 m in Iholdy-Esponda Quarry (Fig. 1B). In Iholdy-Saradar, the base of the turbidite could not be sampled but the megaturbidite is thicker than 20 m. In Béhobie, its thickness is 19 m but only 18 m has been sampled. Everywhere, the megaturbidite is formed by the superposition of two units: a lower unit and an upper fine-grained unit (Fig. 4). The turbidite has an E–W extent of 90 km and a N–S extent of 27 km which represents a total surface of 2430 km^2 and a compacted volume of approximately 90 km^3 (Fig. 1). In all outcrops, the upper unit is thicker than the lower unit. The thickness of the lower unit varies from 6.5 m in Béhobie Quarry to 17 m in Osquich Pass East. The thickness of the upper unit varies from 12.5 m in Béhobie Quarry to 49 m in Iholdy-Esponda Quarry. The lower unit is a calcarenite showing facies variations from east to west between two end-members. In the eastern part, it is formed by the superposition of up to nine beds bounded by sharp surfaces and a small grain size shifts (Iholdy-Esponda and Saradar quarries, Fig. 4A). Each bed is approximately 1 m thick. Erosion at the megaturbidite base remains small in all outcrop locations. Planar laminations are rarely observed in the lower unit but more frequently in the upper unit. In the western part (Fig. 4B, C), the lower unit has a sharp basal contact and shows a constant fining-up (Figs. 5, 6). The top of the lower unit shows antidune-like sedimentary structures (Béhobie), oscillation structures (Hummocky-Cross Stratification or HCS-like structures (Prave, 1986; Prave and Duke, 1990; Mulder et al., 2009), and climbing megaripples with a SE–NW transport in cross-sections (Razin, 1989)). The lower unit contains lithoclasts and bioclasts derived from the Cenomanian-Turonian carbonate platform including Orbitolins, Prealveolins, Cuneolins, Dicyclins, Miliolids, Textulariid, bryozoans, bivalves,

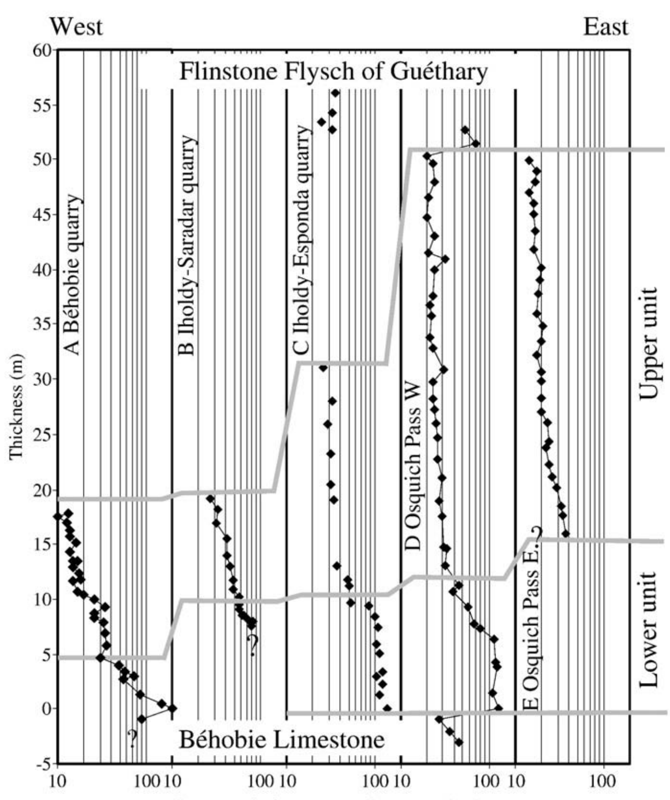

Fig. 6. Vertical quartz grain size evolution on studied outcrops. From west to East: A: Béhobie Quarry; B: Iholdy-Saradar quarry; C: Iholdy-Esponda quarry; D, E: east and west flanks of Osquich Pass anticline.

echinoderms and algal fragments (Debroas et al., 1983; Lagier, 1985; Razin, 1989). Extraclasts from Paleozoic substratum can be found locally in the coarsest sole (quartz and schist fragments). The upper unit is more homogeneous. Only rare undulating beds are observed in the Iholdy-Esponda Quarry. It contains only echinoid spines, Pithonels, and calcispheres. The megaturbidite also contains terrigeneous glauconite (Debroas et al., 1983; Lagier, 1985; Razin, 1989).

Fig. 5 shows the complete collected dataset in Béhobie Quarry. It highlights that along a vertical section, the size of grain particle (carbonate and quartz) and the particle concentration within the matrix both decrease upward. In Béhobie Quarry, quartz particle content decreases from 10 particles/mm^2 to 2 particles/mm^2 in the lower unit and from 2 particles/mm^2 to <1 particle/mm^2 in the upper unit. Carbonate particle content decreases from 100 particles/mm^2 to 20 particles/mm^2 in the lower unit, and from 20 particles/mm^2 to <5 particles/mm^2 in the upper unit. Size of carbonate and quartz particles evolves similarly. Grain size of quartz particle decreases from 200 μm to 50 μm in the lower unit and from 50 μm to 10 μm in the upper unit. Carbonate particle content decreases from 200 μm to 70 μm in the lower unit, and from 70 μm to 15 μm in the upper unit.

Fig. 6 shows only the data related to measurements of quartz grain sizes for the five outcrops. These grain sizes remain constant (200 μm) at Osquich Pass West and Iholdy-Esponda quarry and are finer in Iholdy-Saradar Quarry (100 μm) where the base of the lower unit has not been sampled. However, at the top of the lower unit (base of the upper unit), the quartz grain size is larger in the eastern outcrops (70 μm, Osquich Pass West and Iholdy-Esponda quarry) than in the western outcrop (50 μm, Béhobie). At the top of the upper unit the grain size is larger in the outcrops located in the east (10 μm in Osquich Pass West, 13 μm in Iholdy-Esponda Quarry) than in those in the eastern part (1 μm in Béhobie quarry).

Flow directions measured from particle orientations show a clear E–W or SE–NW trend in the lower unit and at the base of the upper unit. Scattering is more important in the upper half of the upper unit with a level still showing an E–W flow orientation but also levels showing clearly an opposite (W–E) flow direction.

5. Discussion

5.1. Source of the megaturbidite

The north Pyrenean megaturbidite thins westward, from 59 m in Mauléon to 19 m in Béhobie. Particles are slightly coarser in the eastern part than in the western part (in Béhobie), both at the top of the lower unit (70 μm and 50 μm, resp.) and at the top of the upper unit (13 μm and 1 μm, respectively). The quartz grain direction in the lower unit also clearly shows a westward or northwestward orientation which is consistent with a SE towards NW direction provided by the climbing ripples in the lower unit in Béhobie. The only change in flow direction in the lower unit occurs in the Iholdy-Saradar Quarry (Fig. 1B) where the flow direction is S towards N. This change is related to the presence of the Basque Massif punch that formed a topographic high during Cenomanian and that deflected the turbidite flow at this location (Razin, 1989). All these results are consistent with a source located in the eastern part of the study area, in the Mauléon Basin. This is also consistent with the presence of breccia in the Oloron-Mauléon area that is interpreted as a debrite representing the proximal part of the megaturbidite. The breccia contains limestone blocks with Pithonels limestone suggesting that the transported limestone was deposited in an environment with a water depth corresponding to the outer shelf (Lagier et al., 1982; Lagier, 1985; Offroy, 1984).

Erosion at the base of the megaturbidite bed is low and restricted to sharp contacts in the most eastern part. This suggests that the initial volume at the source was at least identical to the volume of the

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deposited turbidite (90 km^3) multiplied by a decompaction parameter, assuming that no erosion of the upper part of the megaturbidite occurred after deposition. This important volume of carbonate mud involved in the flow triggering suggests that the megaturbidite is the result of the collapse of a large area of a carbonate platform and not a restricted (point-source) slide.

5.2. Process of deposition

The north Pyrenean megaturbidite shows at all locations a fining-upward trend from medium to fine sand to clay (Figs. 5 and 6). This fining-up trend and the range of particle size clearly suggest particle fall-out in a low concentration flow. Rare sedimentary structures suggest particle transport by traction, in particular at the base of the lower unit. Consequently, this exceptional thick bed corresponds clearly to the turbidite definition *sensu* Middleton and Hampton (1973). The term "megaturbidite" is then justified. In details, the grain size trend varies between the lower and the upper units. The grain size clearly fines up in the lower unit and decreases still progressively. In the upper units, the grain size also fines up but the fining-up is very progressive and the range of particle size variation is very small. This feature explains the confusing use of the term "homogenite" when such megabeds are observed at the seismic scale or without accurate quantitative measurement of the grain size.

Although the quartz grain orientation clearly shows an E towards W flow direction in the upper unit and at the base of the upper unit, reverse flow directions (W towards E) are clearly recorded in the upper half of the upper unit (Fig. 5). Considering the spatial extent of the turbidite that covers the whole Saint-Jean-de-Luz and Mauléon Basins and considering the considerable time to deposit a fine-grained particle (using simply the Stokes law and excluding particle aggregation, a 10 µm particle needs 13 days to settle in a 100-m thick flow with a density of 1050 kg/m^3 (clay particle density = 1450 kg/m^3) and a 2 µm particle needs 83 days to settle in a similar flow), the total deposition of the whole megaturbidite probably took weeks. This thick flow could be reflected several times on the western side of the Saint-Jean-de-Luz Basin and then the eastern side of the Mauléon Basin before the deposition of the finest particle. Secondary reflections on the topographic high separating the Saint-Jean-de-Luz and Mauléon Basins also occurred and generated complex flow interactions that slowed down the particle fall-out, restrained the grain size sorting and formed complex sedimentary structures including antidune-like structures.

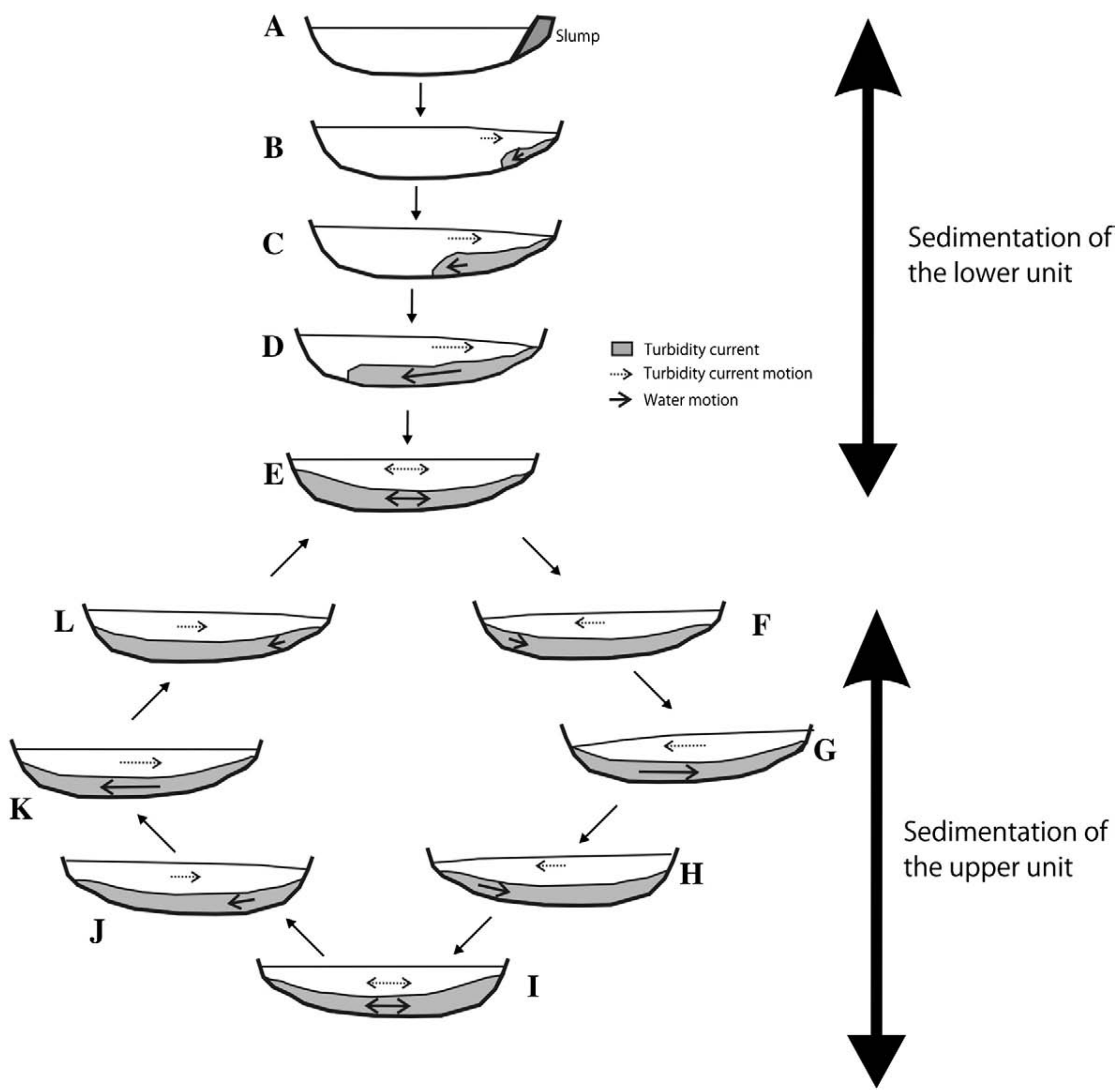

Fig. 7. Application of the Seiche effect to explain the emplacement of the megaturbidite (modified from Lemmin, 1995). A to E: Deposition of the fining-up lower unit by a classical failure-induced turbidity current. F to L: deposition of the upper unit by a flow moving in an oscillatory basin.

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5.3. Depositional model

To explain how the upper part of the turbidite deposit can be made of almost homogeneous particles with a grain size thinning of a few micrometers over several decametres in the eastern Mauléon Basin and over a few metres in the Saint-Jean-de-Luz Basin, we use the analogy with the Seiche effect frequently observed in lakes (Lemmin, 1995, Fig. 7). The Seiche effect (Forel, 1892) results of a complete oscillation with a very long wavelength (standing wave) of a restricted or semi-restricted basin under the action of any natural event producing waves including wind, tsunamis, earthquakes or submarine slides.

This model is constrained by two criteria before being applied.

(1) It necessitates a restricted basin. The Seiche effect was initially defined in the Swiss Lakes (Geneva and Bourget lakes, Chapron et al., 1996; Chapron, 1999; Chapron et al., 1999). It was then applied to eastern and occidental Mediterranean sub-basins. The set of the two Basque basins (Mauléon and Saint-Jean-de-Luz) fits this first criterion.

(2) The Seiche effect involves the motion of a very large volume of water to initiate. Consequently, the initial volume of failed sediment usually needs to exceed several cubic kilometres. The non-decompacted volume of the western Pyrenean (about 90 km^3) fits this second criterion.

Fig. 7 shows the initiation of the original slump in the eastern part of the Mauléon Basin and the early westward propagation of the resulting turbidity current in the basin (Fig. 7A). The volume of the initial failure and the volume of displaced water generate an oscillatory motion of the water in the whole Mauléon and Saint-Jean-de-Luz Basins. The turbidity current deposits the fining-up lower unit (Fig. 7 A to E). Most of the coarse particles (sand and silt) settle during this phase (Fig. 8). The bedload transport of particles is demonstrated by the formation of sedimentary structures. When the turbidity current reaches the side of the basin opposite to its source, the oscillatory motion slows down and the deposition of the fine-particle-laden turbid cloud and the winnowing of particles begin (Fig. 7 F to L). At the stage where only fine silt and clay remain in suspension, the turbid cloud made of carbonate mud forms a thick nepheloid layer that oscillates during several days to several weeks and progressively forms the upper unit with a very subtle fining-up. Few sedimentary structures can form in this upper unit because the process of deposition is almost exclusively dominated by particle fall-out (without traction) and because the size of particle is very fine (less than 20 μm; Fig. 8). The thickness of this upper unit suggests that the volume of carbonate mud in the initial failure was very important and that the initial failure corresponds to the collapse of a carbonate platform.

The north Pyrenean megaturbidite appears as an isolated bed in the sedimentary series (Fig. 3) although thinner (a few metres thick) and massive carbonated beds exist in the Béhobie Limestone. It occurred during the extensional phase of the Basque flysch basin. Most of the other exceptional beds in the Saint-Jean-de-Luz Basin occurred during Santonian and Coniacian, when the tectonic regime in the area changed from extensional to compressional.

The north Pyrenean megaturbidite also differs from other thick gravity deposits in the Saint-Jean-de-Luz and Mauléon Basins by both its extension to the whole basin (other beds are restricted to one basin or to the other) and its exceptional thickness. It is several decametres thick when other thick beds related to gravity flow deposits have usually a thickness that does not exceed 10 m. Consequently, the extent of the north Pyrenean megaturbidite, the active tectonic setting of the basin and the non-cyclicity of all the thick gravity flow deposits strongly suggest that these exceptional beds are the result of transformation or earthquake-triggered slumps on the upper slope of the basin.

6. Conclusions

The north Pyrenean megaturbidite represents an exceptional bed of about 90 km^3 marking the boundary between Turonian and Coniacian at the scale of the whole French Basque Country. It is composed of two superposed units. The lower unit shows a clear

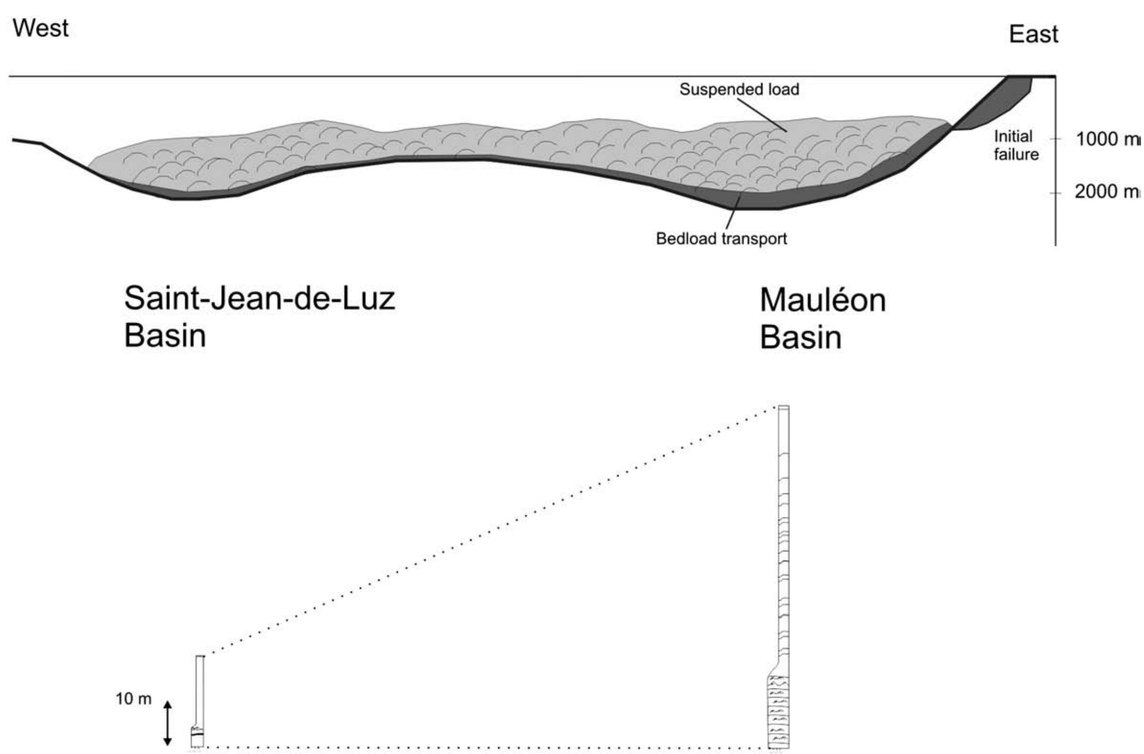

Fig. 8. Longitudinal section showing the initiation of the megaturbidite flow in Mauléon and Saint-Jean-de-Luz Basins and the resulting log correlation.

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fining-up and the upper unit, a light fining-up. The vertical grading of the whole deposits suggests particle fall-out. Sedimentary structures in the lower unit suggest bedload transport. These characteristics and its spatial extents fit well with the megaturbidite concept. Its source located in the eastern part of the Flysch basin is suggested by the westward thinning of the bed, from 59 to 19 m. This is consistent with the westward fining of the coarse particles in the turbidite and the orientation of particles in the lower unit and the base of the upper unit that clearly indicates an E–W flow. However, the vertical and spatial extent of the megaturbidite and the measurement of reverse flow directions in the upper part of the megaturbidite both suggest that the flow reflected several times on the west side of the Saint-Jean-de-Luz Basin and possibly on topographic highs in the Mauléon Basin. This probably slowed down the particle deposition and generated a complete oscillatory motion in the Mauléon and Saint-Jean-de-Luz Basins known as the Seiche effect.

The Seiche effect is used as an analog to explain the process at the origin of the megaturbidite. A large initial volume of unconsolidated fine-grained carbonates failed on the eastern part of the basin, on the upper margin, probably due to earthquake shaking. The volume of the initial slide was close to 90 km^3 and probably corresponds to a large collapse of a carbonate platform. It generated the formation of an oscillatory motion in the two basins. It rapidly transformed into a turbidity current that crossed over Mauléon and Saint-Jean-de-Luz Basins. It deposited the fining-up, coarse part forming the lower unit. When reaching the western side of the Saint-Jean-de-Luz Basin, the turbidity current was slowed down by the oscillatory motion and the fine particles contained in the turbid cloud were winnowed and deposited very slowly, forming the upper part of the megaturbidite (homogenite). This new conceptual model correctly explains the thickness of the deposits, the deposition of the two units, the crude but real grading of the fine-grained upper unit and the presence of unusual primary sedimentary structures (antidunes). This conceptual model also explains the deposition process of fine-grained mega-turbidites in a confined, closed or partially closed sedimentary basin and made of fine-grained and crudely-graded sediments that justified the usual term of homogenite.

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