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Inversely graded turbidite sequences in the deep Mediterranean: a record of deposits from flood-generated turbidity currents?

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Abstract Turbidity currents generated during floods of small and medium rivers have been demonstrated to be an important process of sediment transport from continent to abyss. They produce fine-grained turbidite deposits. No deposit related to these flood-related turbidity currents has yet been described in the deep sea. In this paper, we present some unusual sandy to muddy turbidite beds cored in the Var turbidite system (NW Mediterranean). They show a coarsening-upward basal unit capped with a classical fining-upward unit which are related to the periods of increasing and decreasing discharge at the river mouth, respectively. The two units are separated by a contact which can be gradational to erosional. This intrabed contact is interpreted as resulting from erosion during peak flood conditions. This intrabed contact can be confused with classical basal contacts of turbidite beds. The frequency of hyperpycnal turbidite beds can be used to relate climatic changes inland to the deep-sea sedimentary record, as an increase corresponds to periods of enhanced flooding at the river mouth.

Introduction

One of the great unresolved problems in deep-marine sedimentology is understanding the frequency and triggering mechanisms of turbidity currents in different tectonic settings (Normark and Piper 1991). This is important if the linkage of long turbidite records to climate is to be resolved (Weltje and de Boer 1993), and the cyclicity in turbidite deposits is to be understood (Hiscott et al. 1997). Conceptual advances in recognising the importance of hyperpycnal flows from small- and medium-sized rivers (Mulder and Syvitski 1995) as well as technical advances in digital X radiography and image analysis (Migeon et al. 1999) can be used to distinguish different types of fine-grained turbidites in proximal sedimentation settings. These new techniques allow, in particular, very accurate definition of bed contacts and sedimentary structures within beds.

The occurrence of hyperpycnal turbidity currents in the world's ocean has been demonstrated statistically (Mulder and Syvitski 1995). Hyperpycnal turbidity currents have also been recorded at the mouth of the Huanghe River (China; Wright et al. 1986, 1988, 1990), which has the second highest mean yearly suspended sediment concentration (after the Haile River, China; Mulder and Syvitski 1995).

In this paper, we present turbidite sequences which differ from the classical Bouma sequence model (Bouma 1962; Lowe and Guy 2000). These non-Bouma sequences show a well-developed, inversely graded basal unit. We shall show how it can be related to hyperpycnal turbidity currents at the mouth of the Var River.

Regional setting and previous work

The Var turbidite system is located in the Ligurian Sea (NW Mediterranean; Fig. 1). The Var Canyon leads from the Var river mouth (Savoye et al. 1993) to an asymmetric fan valley with a high right-hand levee (the Var sedimentary ridge; Migeon et al. 2000) which debouches onto the Ligurian abyssal plain, west of Corsica. The canyon and upper fan valley are floored with gravel and sand units (Piper and Savoye 1993).

At present, the Var system shows an important turbiditic activity which can be classified into three main kinds of processes (Mulder et al. 1997b, 1998a).

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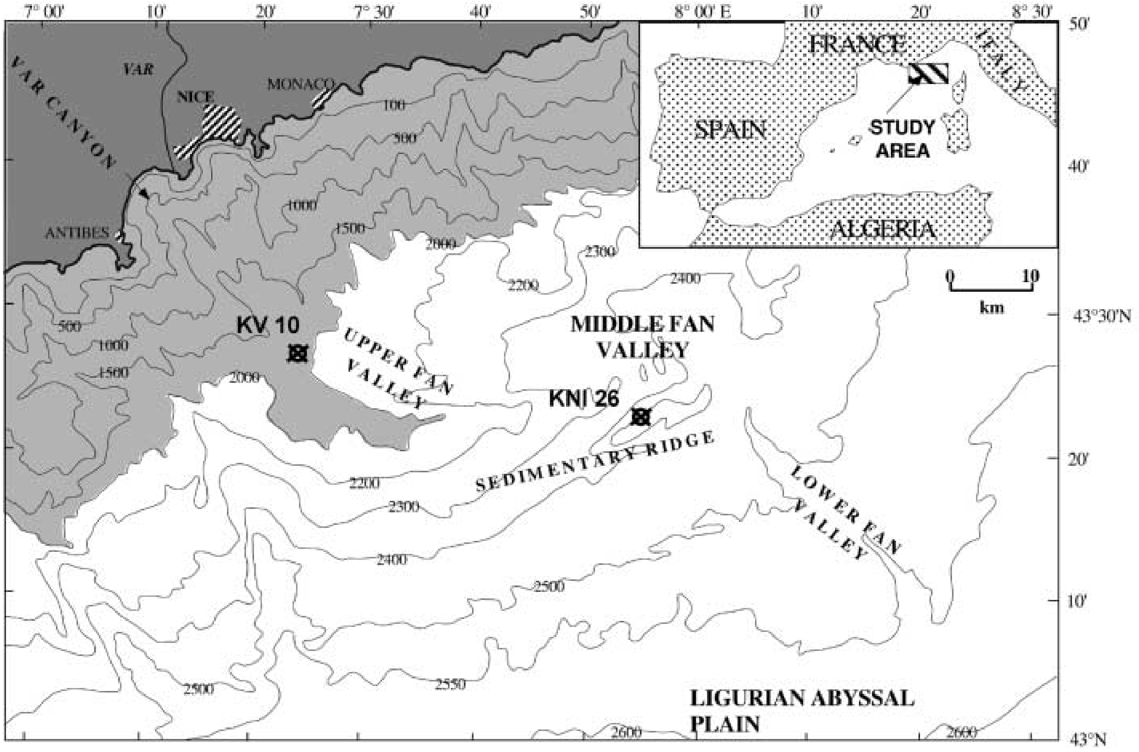

Fig. 1 Location of the Var deep-sea fan and the study area (*inset*). Studied cores are indicated with *crosses*

1. Large failure-induced turbidity currents, such as the event in 1979 when part of the Nice airport submerged (Gennesseaux et al. 1980; Malinverno et al. 1988). The process is a short-duration, catastrophic, fast turbiditic cloud (cf. surges of Laval et al. 1988). Inferred velocities can reach more than 30 m/s on steep slopes of the canyon (Piper and Savoye 1993; Mulder et al. 1997a). As a consequence, deeply incised scours can be formed on the canyon and upper valley floors. Cobbles and boulders can be transported as bed load. Coarse sand can be transported in suspension, as shown by the extensive turbidite related to this event (Piper and Savoye 1993).
2. Small turbidity currents supplied by retrogressive failure during periods of high sedimentation rate (Mulder et al. 1998a). Each individual failure creates a small turbidity current. Successive failures can generate a turbidity current lasting several days, similar to the processes recorded by Gennesseaux et al. (1971) in the Var Canyon and by Prior et al. (1987) and Bornhold et al. (1994) in west Canadian fjords.
3. Hyperpycnal turbidity currents triggered during floods. The Var River is a small, mountain-supplied river regularly experiencing violent storm-generated flash floods. Because a hyperpycnal turbidity current is related to flood magnitude at a river mouth, Mulder et al. (1997b) made a statistical analysis of river discharge at the Var river mouth. Using the rating curve for the Var River, they demonstrated that short-duration (several minutes to several hours) hyperpycnal turbidity currents can form every 2–5 years. Day-long hyperpycnal turbidity currents can form every 5–21 years.

Methods

Data used in this study come from two Kullenberg cores (Fig. 1). Core KNI 26 is from 2,365-m water depth on the Var sedimentary levee (Migeon 2000; Migeon et al. 2001). Core KV 10 is from 1,970-m water depth on a terrace located 30 m above the axis of the Var upper valley. Core position is based on GPS. Magnetic susceptibility and gamma density were measured, together with a visual description of the cores. Then, 1-cm-thick slabs of sediment from the whole length of the core were X radiographed using the new digital X-ray imaging system SCOPIX (Migeon et al. 1999). Digital images were processed using Optilab or Image SXM software. This image processing system allows a very accurate definition of bed boundaries and enhances the internal structures within the beds. Using these data as a guide, the slabs were subsampled for (1) measurements of carbonate content, using a Bernard calcimeter with samples being taken every centimetre, and (2) grain-size analysis of selected intervals, using a Malvern laser microgranulometer. In the latter case, steps for sampling were either every 2 cm or every lamina in interesting sequences.

Results

An important criterion to distinguish deposition from different kinds of turbidity currents is the grading trend (Middleton and Hampton 1973; Shanmugam and Moiola 1995). In the cores from the Var system, we have two types of sequences: fining-upward beds and beds showing a basal coarsening-upward unit.

Classical fining-upward beds

Several beds are made of a normally graded, fine- to medium-sand facies overlaid by a silty clay facies (Fig. 2). Bed thickness varies between several centimetres and two decimetres. The sandy facies is bounded by sharp or erosive contacts at both base and top. The sandy facies can be structureless, poorly to well laminated (Fig. 2) or cross laminated (Migeon et al. 2001). Above the basal contact, the sequence can show a millimetre- to centimetre-thick inverse grading resulting from the incorporation of eroded mud clasts or flame-load structures (Migeon et al. 2001).

Beds with a basal coarsening-upward unit

Numerous beds show the vertical succession of two units: a well-developed coarsening-upward basal unit, and a fining-upward top unit (Mulder et al. 1998b; Figs. 3 and 4). Bed thickness typically varies between 2 and 20 cm. Median grain size corresponds to fine to medium sand. The basal unit is commonly thicker than the top unit. Beds are commonly bounded by gradational to sharp contacts at the base, although an erosional contact is observed in some cases (Fig. 4). The upper contact can be sharper than the basal contact.

Both the upper and lower units can contain thin horizontal parallel laminations or well-developed cross bedding. Climbing ripples are common. The basal unit can also be structureless (Fig. 3). The contact between the two units can be erosive, sharp or gradational (Figs. 3 and 4).

Beds of this type represent 80% of the sedimentary sequences in core KV 10, and 30% in core KNI 26.

Discussion

Origin of classical fining-upward beds

The normally graded sequence classically constitutes a typical deposit of waning flow (Komar 1985; Kneller 1995). The constant deceleration of flow with time produces a succession of sedimentary facies (Ta, Tb, Tc, Td and Te) above a sharp or erosive contact. This succession is called the Bouma sequence (Bouma 1962). The whole sequence represents rapid fallout of coarse particle (Ta), and interaction of suspended particle deposition and traction (Tb, Tc, and Td). The progressive decrease in flow regime combined with a progressive increase of traction explains the upward change in sedimentary structures occurring in the sequences (Walker 1965). Alternation of burst and sweep events in the basal boundary layer may explain the alternation of silt and clay laminae (Hesse and Chough 1980). Facies Te corresponds to the distal deposit of the turbidite mixing progressively with hemipelagic fallout. According to the morphology of a turbid cloud (Middleton and Hampton 1973), the sharp basal contact would result from the erosive waxing head of the flow. Facies Ta–d result from the deposition of the waning flow body. Facies Te represents both deposition of the flow tail and hemipelagic background sedimentation. The absence of one or several facies within the Bouma sequence can result either from the proximal or distal location of the deposits or to

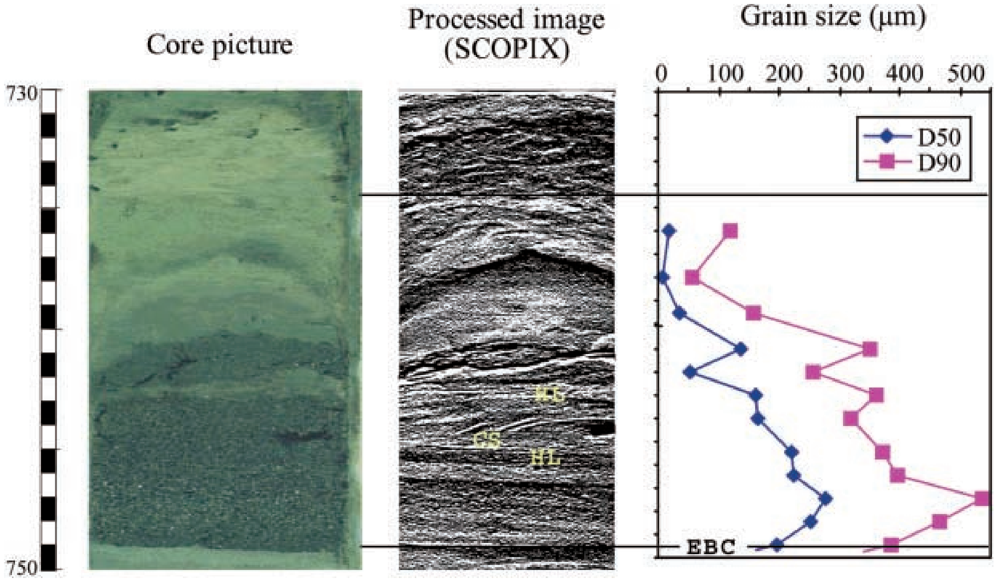

Fig. 2 Fining-upward turbiditic sequence in core KNI 26 (Bouma sequence) formed by the deposits of suspended particles within a turbiditic surge. Hemipelagic deposits lie on the top of the sequence. *EBC* Erosional basal contact; *CS* ripple cross lamination; *HL* horizontal laminations. Vertical scale in centimetres

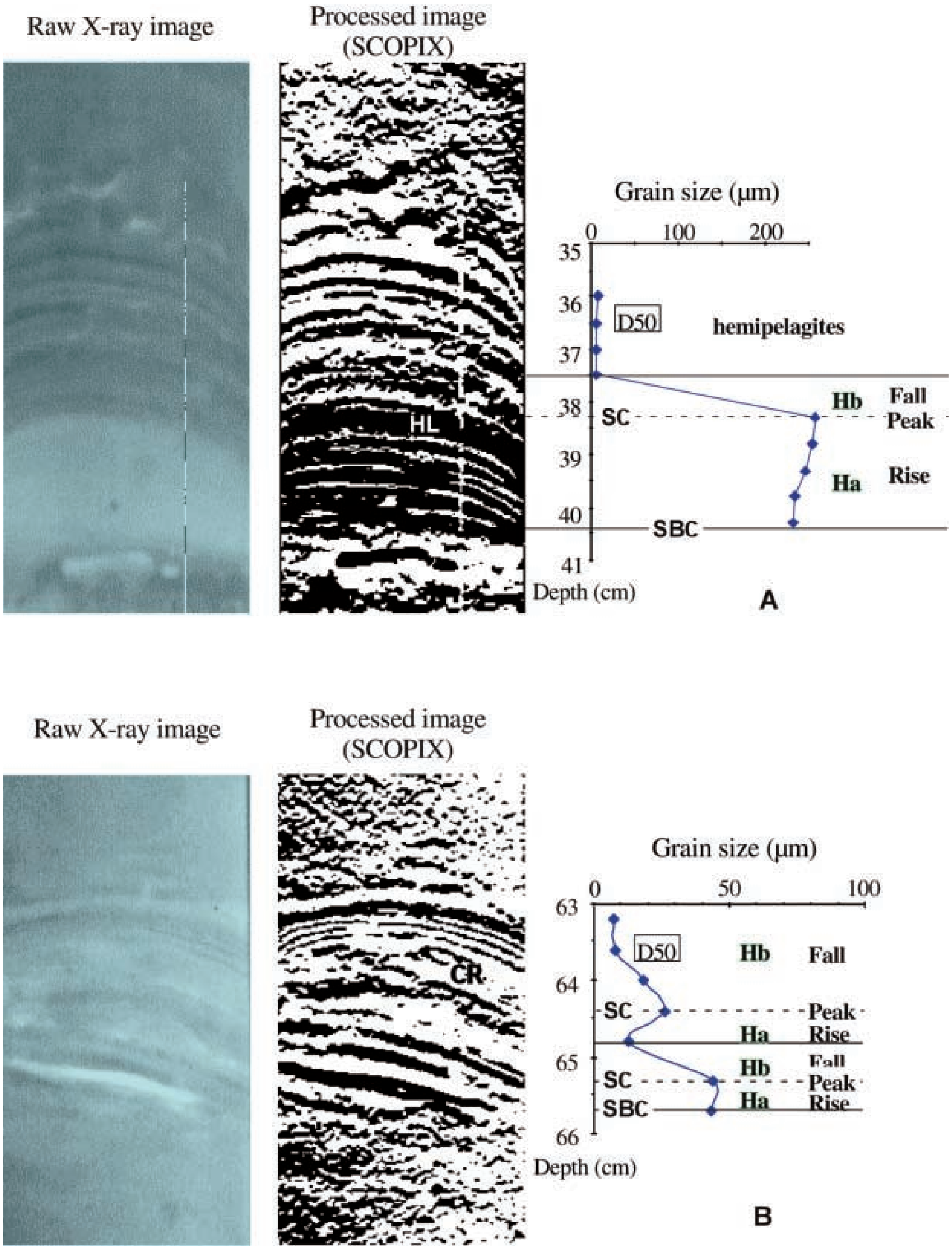

Fig. 3A, B Hyperpycnal turbidite sequences in core KV 10. **A** The basal contact is sharp (*SBC*). The basal unit (*Ha*) is coarsening-upward and capped with a fining-upward top unit (*Hb*). Contact between Ha and Hb is sharp (*SC*). Sequence contains sandy horizontal laminae (*HL*). **B** Two sequences with the identical grain-size trend as in **A**. Both contain silty clay laminae and climbing ripples (*CR*) which reflect a process in which particle load is larger than particle transport. Vertical scale in centimetres

the size of particles transported. These normally graded beds are the result of short-duration, unsteady turbid surges (Laval et al. 1988). The sharpness of the basal contact, the intensity of erosion of the underlying sequences, and the size of the transported grains depend on the energy of the event.

In this scheme, the Var sequences similar to the one presented in Fig. 2 correspond to complete or truncated Bouma sequences, i.e. classical turbidites.

Origin of beds with a basal coarsening-upward unit

Coarsening-upward units can have several origins: (1) incorporation of mud clasts at the base of a turbid cloud, (2) freezing of a laminar boundary layer, and (3) a constant flow acceleration with time.

1. Incorporation of mud clasts at the base of erosive turbid surges is a common phenomenon described in the Var sequences (Migeon et al. 2001). These clasts contribute to a local decrease of the mean grain size. This constitutes an artefact in the grain-size trend of the Bouma sequence, by generating a millimetre- to centimetre-thick inverse grading. This subunit never shows any structure. In the beds we described with a basal coarsening-upward unit, mud clasts are never observed, neither visually nor on X-ray images.

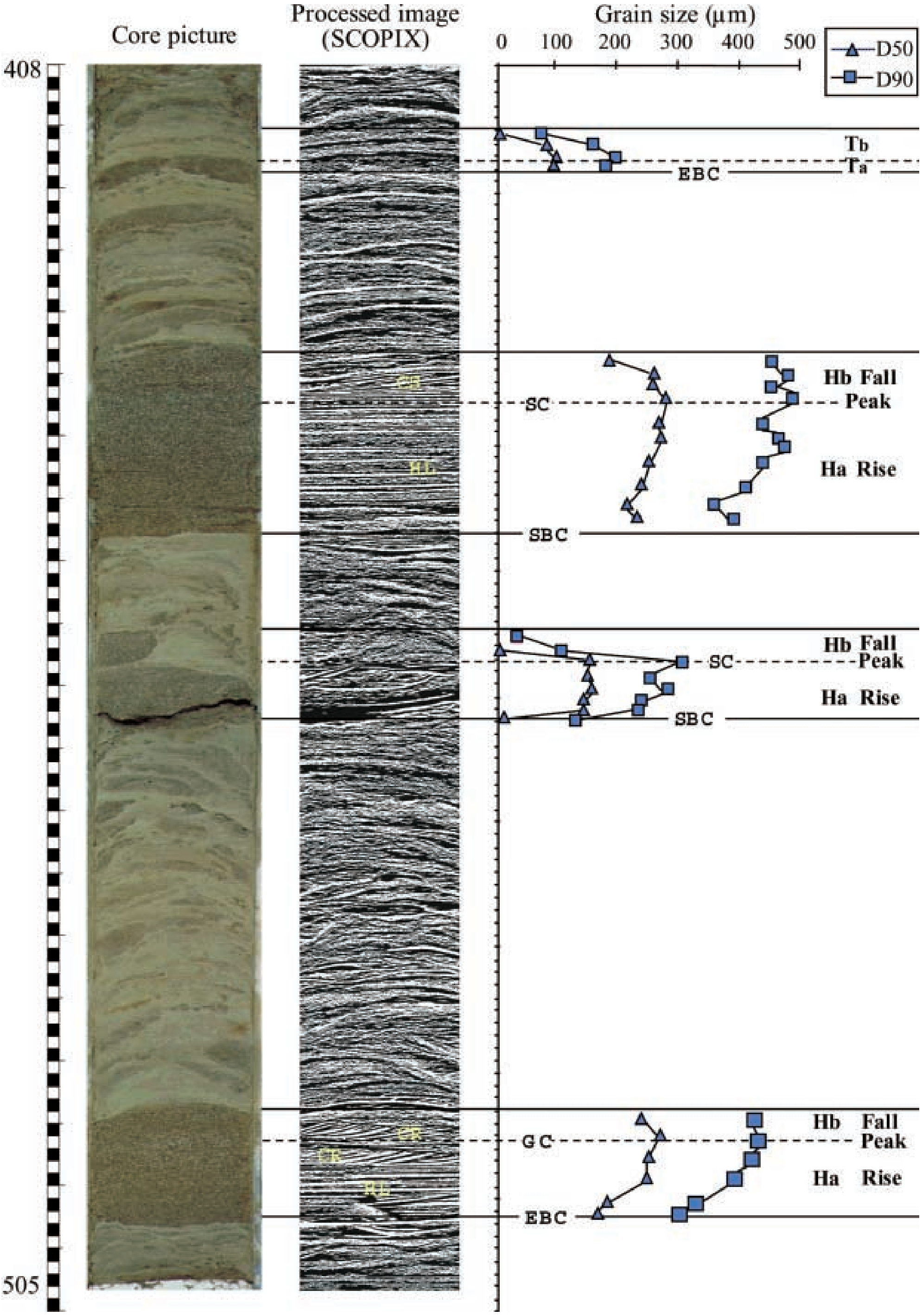

Fig. 4 Hyperpycnal turbidite sequences in core KNI 26. The basal contact can be gradational (*GBC*), sharp (*SBC*) or erosional (*EBC*). Contact between *Ha* and *Hb* can be gradational (*GC*), sharp (*SC*) or erosional (*EC*). The kind of contact is related to the flow energy during peak flood conditions. Sequences contain silty clay laminae, ripple cross lamination (*CS*) and climbing ripples (*CR*) which reflect a process in which particle load is larger than particle transport. Vertical scale in centimetres

2. A basal coarsening-upward unit can be deposited by a two-layered flow. In this scenario, a basal laminar boundary layer moves below a turbulent top layer. In the basal layer, the velocity increases from the bottom (where the friction is maximum) to the top. The size of the carried particles is proportional to the velocity, which induces an inverse grading within the flowing basal layer (Lowe 1982). The basal layer can partially freeze when its concentration locally increases because of particle fallout from the upper layer. This repetitive process leads to the deposition of several stacked coarsening-upward lenses which constitute the unit R_2 of the Lowe sequence (Lowe 1982). These coarsening-upward layers are always structureless. They usually contain coarse particles (gravels are common). These two features do not correspond to the observed sequences we present here.
3. A basal coarsening-upward unit can be deposited by a depletive (decelerating with distance) waxing (accelerating with time) flow (Kneller 1995). Because the

slope profile off a river mouth is concave-up, we can assume that the currents flowing through the Var canyon and valley are depletive (Kneller 1995). A waxing flow can be generated by the steadily increasing discharge at a flooding river mouth. Mulder and Syvitski (1995) showed that, if the concentration at the river mouth is high enough (42 kg/m^3), a particle-laden fluvial flow can be maintained along the seafloor, creating a hyperpycnal turbidity current. The current remains waxing as long as the discharge increases at the river mouth. According to Kneller and Branney (1995), the waxing flow should deposit a coarsening-upward facies as long as the flow velocity is below the erosion threshold. Particles in such flows are smaller than coarse sand, as they are carried in suspension. As these flows combine suspension fallout and traction, sedimentary structures can be formed. These structures are asymmetrical ripples if the ratio between velocity and sediment load is high, or climbing ripples if this ratio is low.

In the beds described from the Var system (Figs. 3 and 4), the coarsening-upward unit is laminated or exhibits dynamic structures indicating that they were deposited by a turbulent flow in which traction acts simultaneously with suspension fallout. The presence of asymmetrical and climbing ripples supports the fact that sedimentation occurs continuously with a suspended particle load sometimes larger than particle transport, and that the flow has a high suspended particle concentration. This is consistent with the flow originating during floods. The substantial thickness (several centimetres) of the basal unit suggests that acceleration is progressive, and the gradual change in grain size suggests that velocity increases gradually. The flow energy increases progressively with time. Bourcart (1964, p. 150) already described cores from the Var system containing similar beds with grain size first increasing from silt to sand and then decreasing to silt. In addition, this author noted that the beds contained abundant organic matter, including *Chara oogonia* well as abundant leaves of *Phragmites* (a reed species from Provence*)* and *Arundo donax* (the common reed). These occurrences suggest a continental source for much of these sediments. The observations of Bourcart (1964) and our examples do not support the deposition of the sequence with a basal inverse grading by a turbidity surge related to an erosive head (slide-induced turbidity surge). Gradational or sharp basal contacts were more common than erosional basal contacts, suggesting that waning flow began from a relatively low-energy flow. In some cases, the sharp or erosive bottom contact suggests erosion of the thin underconsolidated sediments which drape the seafloor. The erosion of this underconsolidated drape can occur at the beginning of the flood even under the action of a low-energy flow.

A key feature of the flood-related sequences described in this paper is the existence of a sharp intrabed contact separating the basal coarsening-upward unit and the top fining-upward unit (Figs. 3 and 4). This sharp contact suggests that, in some cases, the flow is energetic enough to prevent deposition or even to erode the particles which have just been deposited. In the frame of a flood event, this would correspond to the period of highest energy, i.e. the period of peak discharge during a major flood. During a flood of lower magnitude, energy developed during peak flood period is insufficient to erode, and the transition occurs progressively. Sedimentary structures are continuous between the basal and top units.

Overall, the nature of the beds described from the Var system strongly suggests that hyperpycnal turbidity currents deposited these beds with a well-developed coarsening-upward basal unit. The currents are generated at the Var river mouth during floods. A high particle load is necessary to keep the current moving along the seafloor because the interstitial fluid is freshwater. Progressively, seawater entrainment contributes to maintain the flow along the seafloor, despite particle deposition (Mulder et al. 1998b). The coarsening-upward basal unit, Ha, is deposited by the waxing part of the flood event at the Var river mouth. The fining-upward top unit, Hb, is deposited by the waning part of the flood event. The Ha-Hb transition corresponds to the maximum grain size and marks the peak of the flood, i.e. the period of maximum energy (discharge) at the river mouth.

In the case of a low-magnitude flood but with a sufficient discharge to create a hyperpycnal turbidity current (curve 2 in Fig. 5), the transition between Ha and Hb is gradational. The flow energy and the maximum size of transported particles increase slowly, pass through a peak and then decrease slowly. There is no change in the sedimentary structures deposited before, during and after peak flood conditions. In this case, the deposited hyperpycnal turbidite can be mistaken with the contourite sequence defined by Faugères et al. (1984). The difference between the hyperpycnal turbidite and the contourite can be made according to the abundance of bioturbation. The contourite sequence is bioturbated, the hyperpycnal turbidite is not.

During higher magnitude flood conditions (curve 3 in Fig. 5), the discharge and velocity reached during the flood peak can be high enough to prevent deposition. Deposition occurs only when the velocities drop during the period of fall of discharge, and the change in grain-size trend is associated with a sharp contact. During peak conditions of a high-magnitude flood, the Ha unit can be eroded and the contact between Ha and Hb is erosive. During floods of exceptionally high magnitude (curve 4 in Fig. 5), erosion of Ha can be complete. Then, the hyperpycnal sequence is only constituted by a fining-upward unit, Hb, which can be easily mistaken for a classical Bouma sequence. If discharge and related sediment concentration are insufficient to generate a hyperpycnal turbidity current (curve 1 in Fig. 5), sediment accumulation just off the river mouth can generate slide-induced turbidity surge generating Bouma sequences.

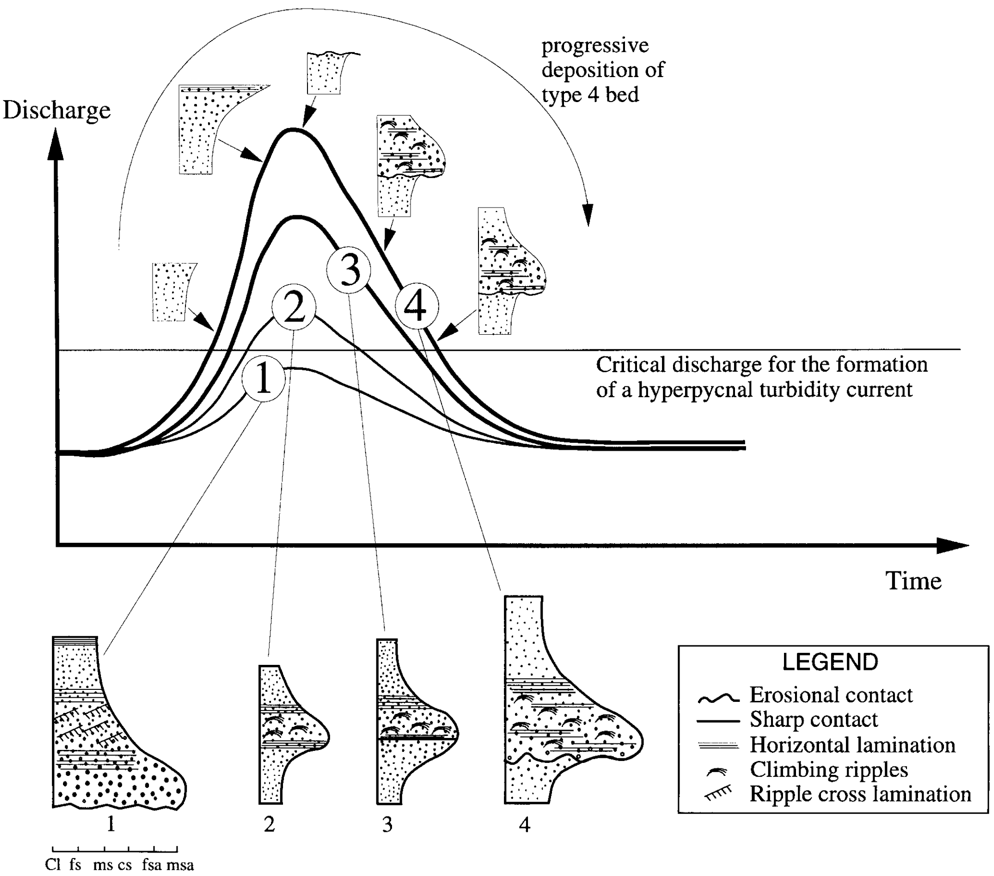

Fig. 5 Facies and sequences deposited as a function of the magnitude of the flood at the river mouth. *1* Low-magnitude flood. The maximum discharge is less than the critical discharge to produce hyperpycnal turbidity current. Failure-induced turbidity currents are generated. *2* Low-magnitude flood. The maximum discharge is more than the critical discharge to produce hyperpycnal turbidity current. Hyperpycnal turbidity current is created. A complete sequence with a transitional boundary between inversely graded unit Ha and normally graded unit Hb is deposited. *3* Mid-magnitude sequence. Identical to *2* but grain size can be coarser and sequence thicker. Sharp contact between Ha and Hb. *4* High-magnitude flood. Same as *3* but particles deposited are coarser. Erosional surface exists between Ha and Hb. Ha may have been completely eroded during peak flood conditions. *Cl* Clay; *fs* fine silt; *ms* medium silt; *cs* coarse silt; *fsa* fine sand; *msa* medium sand

Conclusions

The results of the present study convincingly demonstrate that beds which can be related to hyperpycnal turbidity currents are found in continental margin deposits of the Var turbiditic system. These beds begin with a gradational or sharp basal contact. They consist of a basal coarsening-upward unit capped with a fining-upward unit and commonly contain a continental flora. Structures commonly encountered in these beds are horizontal laminations and ripple cross lamination, frequently including climbing ripples. Some of the beds contain an intrabed contact separating the two units. The progressive transition or the erosion between the two units can be related to the magnitude of peak flood conditions. The existence of an intrabed erosional surface can generate a confusion between the top unit and a Bouma sequence, and can lead to an important re-interpretation of some fine-grained turbidites in river-related turbiditic systems. The frequency of hyperpycnal turbiditic sequences could be underestimated if we consider that a part of classical fining-upward failure-related turbiditic sequences (fine-grained turbidites) are, in fact, base cut-out hyperpycnal sequences, and hyperpycnal turbidity currents can be then a major process for sediment deposition in marine basins. Hyperpycnal turbidites can be a valuable sedimentological tool to link deep marine beds to terrestrial climatic changes through flood frequency and magnitude.

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