Flood Deposits in Continental and Marine Environments: Character and Significance

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ABSTRACT

This chapter focuses on the processes, character, and significance of hyperpycnal floods and their deposits (hyperpycnites) in the geologic record based on selected examples from modern environments, outcrops, sediment cores, and seismic reflection profiles.

For bed-load- or suspended-load-dominated hyperpycnites, the rating curve of a flood event can be predicted and is represented by a power-law relationship between discharge and load. Because of reconcentration processes in marine waters, rivers other than those considered dirty (high sediment concentration) may form hyperpycnal flows over long distances on the sea floor. Hyperpycnal floods generally have a meteorologic origin, but catastrophic hyperpycnal floods can also occur because of dam outburst in the catchment area of a river. In some cases, catastrophic floods are associated with earthquakes or volcanic activity. Both in marine and lacustrine environments, frequent and powerful hyperpycnal flows develop meandering channel levee systems and more distal basinal fan lobes.

Hyperpycnites are characterized by a coarsening-upward basal sequence formed during the rising limb of the flood (waxing flow) and a fining-upward upper sequence formed during the falling limb of the flood (waning flow). The lower sequence is not always preserved, so hyperpycnites may be difficult to distinguish from classical turbidites. The common occurrence of organic debris of continental origin at the base of deposits is an indicator of hyperpycnites.

In glacial valleys of mountain ranges, a large amount of clastic material can be deposited in large valley lakes or in fjords by frequent hyperpycnal flows. Both in lacustrine and marine environments, large hyperpycnal floods, which are sometimes catastrophic, are documented in association with significant environmental changes such as deglaciation of the continent or volcano-glacier interactions (jökulhlaup).

INTRODUCTION

Submarine turbidity currents can be initiated by ocean currents of various types, including the transformation of a submarine slide into a laminar and then turbulent flow or the direct flux from continental rivers to submarine environments (Normark and Piper, 1991; Piper and Normark, 2009). The latter case is an important issue because rivers represent the main entry point for terrigenous material provided by erosion on the continents toward sedimentation areas such as lakes or marine sedimentary basins.

Forel (1885, 1892) observed direct transfer from the Rhone River to Lake Geneva (Switzerland), but it was a half century before a real improvement in knowledge of sedimentary processes was made, with the recognition of en masse sediment transfer and the discovery of turbidity currents (Heezen and Ewing, 1952; Kuenen, 1952). The cable failures related to the earthquake-triggered 1929 Grand Banks (eastern Canada) turbidity current demonstrated the existence of energetic submarine gravity processes able to play a part in shaping continental margins. Graded deposits were related to turbidity currents (Kuenen and Migliorini, 1950; Kuenen, 1953). Bouma (1962) defined a sequence (turbidite) consisting of a series of fining-upward sedimentary facies (Ta–Te) that could be related to a waning (velocity decreasing with time) flow (Kneller, 1995; Kneller and Branney, 1995), in which bed-load transport and fallout transport act simultaneously. Hydrodynamically, this turbidity current is a water-sediment mixture, in which particles are maintained in suspension mainly by the upward component of the fluid turbulence (Middleton and Hampton, 1973). Such a mechanism occurs only for low-concentration flows (volume concentration, <9%; Bagnold, 1962). Low concentration allows particle fallout and grain-size sorting. Bed-load transport generates sedimentary structures of the sedimentary facies superposed in the Bouma sequence.

Flow transformation toward a turbidity current (e.g., Heezen and Ewing, 1952; Bourrouilh and Offroy, 1983; Bourrouilh, 1987; Piper et al., 1992) is a concept that includes threshold in flow velocity and concentration

(see “ignition” in Parker, 1982). Flow transformation includes different phases from the initial mass failure: debris (cohesive) or hyperconcentrated (granular) density flow (Mulder and Alexander, 2001) including the Lowe sequence (Lowe, 1982), in which bed-load transport dominates; concentrated flow leading to the deposition of the Ta facies of the Bouma sequence; and finally suspension fallout (Tb–Te facies of the Bouma sequence).

The importance of intense sediment transport at river mouths is demonstrated, for example, by Heezen et al. (1960) in the Gulf of Corinth (Figure 1), who compared the frequency of submarine cable failures with the locations of the river mouths, which represent a natural depocenter for terrigenous sediment eroded on the continent. No evidence is seen in the Heezen et al. (1960) article that cable failures are directly related to long-duration flows originating from river floods, instead of the transformation of submarine slides triggered by high sedimentation rates. However, this study indicates the relationship between rivers, sediment flux, and gravity processes. A pioneer study of Houbolt and Jonker (1968) on the Rhone delta in Lake Geneva combined seismic reflection profiling and coring to provide a clear identification of sedimentary facies, channels, levees, and fan lobes in a river-supplied deep basin. In a stratified alpine lake (Lake Thun, Switzerland), Sturm and Matter (1978) further documented with cores the influence on the basin fill of river-borne sediment, which developed either hypopycnal flows (overflows), mesopycnal flows (interflows), or hyperpycnal flows (underflows; Figure 2). Lambert and Giovanoli (1988) used moorings (current meters and thermistor chains) in the active channel of the Rhone delta in Lake Geneva to provide the first identification in a lake of both river-borne dense turbidity underflows (i.e., hyperpycnal flows) and turbidity currents triggered by the remobilization of delta deposits. A similar and quantitative study by Bornhold et al. (1994) used current meter measurements at the mouth of the Homathko and Klinaklini rivers (British Columbia, western Canada) to record turbidity currents related to river floods. However, the measurements of very low suspended-matter

FIGURE 1. Map of the Gulf of Corinth showing the location of cable failures between Corinth and Patras during the period from 1884 to 1939 and the small rivers discharging in the Gulf. Note the clusters of failures located seaward of the river mouth (modified after Heezen et al., 1960).

concentration at these two river mouths showed that these turbidity currents were related to sediment failures generated by mouth-bar progradation instead

of the direct transformation of a river flow into a subaqueous sediment flow (hyperpycnal process; see Itirbilung Fjord in Syvitski and Hein, 1991).

FIGURE 2. Types of flows according to density differences between the effluent and the receiving basin: hypopycnal, homopycnal, mesopycnal, and hyperpycnal flows.

DEFINITION AND TYPES OF RIVER-BORNE FLOWS AND RELATED DEPOSITS

Definition and Types of River-borne Flows

Hyperpycnal flows (Bates, 1953; Mulder and Syvitski, 1995; Nakajima, 2006) are defined in this chapter as sediment-laden subaerial flows entering a subaquatic basin containing either fresh water or salt water. The flow forms a continuum between the subaerial environment and the subaquatic environment. The flow is maintained along the basin floor because of the excess density in the water effluent when compared with the density of the river. Using this definition, hyperpycnal flows differ strongly from turbidity currents resulting from the transformation of sediment failures. Three major differences between hyperpycnal flows and flow resulting from the transformation of a sediment failure can be listed:

- 1) In a submarine environment, the initial interstitial fluid in a hyperpycnal flow is fresh water. Denser salt water is progressively incorporated through entrainment (e.g., Garcia and Parker, 1993) from the ambient surrounding fluid. In the marine environment, dense fluid entrainment in the moving flow maintains density in excess of the surrounding water and prevents flow lofting. In the submarine environment, seawater entrainment is necessary to maintain the hyperpycnality because initial flow density tends to decrease as a result of sediment deposition, unless ignition occurs. In lakes, entrainment is not necessary. Cold river flows can plunge over a lake floor only because of the difference in temperature between the river water and the lake water. However, lakes frequently are stratified, and a suspended-sediment load is necessary in the river water to plunge through the pycnoclines.
- 2) Except when related to a catastrophic dam break, hyperpycnal flows are long-duration (range, days to weeks) processes always corresponding to sustained turbidity currents (Lüthi, 1981; Ravenne and Beghin, 1983; Laval et al., 1988). Dam-break hyperpycnal flows and other subaerial flows entering a subaquatic basin, although related to a direct input of fresh water from a river system, can also be considered as turbulent surge.
- 3) Because of the long duration of hyperpycnal events, bed-load transport can occur over long distances even if the flow is dominated by suspended load and the volume of the bed-load-transported material is small.

Flood deposits of this kind are called “hyperpycnal flows” in the rest of the chapter. They form hyperpycnal flood deposits. The other deposits are related to buoyant (hypopycnal) and partially buoyant (mesopycnal) flows that can form deposits either by simple particle fallout or by reconcentration processes. In the chapter, these are called “hypopycnal flows” or “mesopycnal flows,” respectively. Both can also be considered as “flood deposits.”

Hyperpycnal flows can be turbulent, and thus correspond to the hyperpycnal turbidity currents of Mulder and Syvitski (1995), or nonturbulent, and thus correspond to the inertia flows of Bates (1953) or the hyperpycnal flows of Mutti et al. (1996).

In terms of origin, floods are dominantly related to climatic events: rainfalls or snowmelt. Rainfall-producing floods are usually seasonal. They can be related to short-duration (range, hours to days) events (thunderstorms, hurricanes) or long-duration (range, weeks to months) events (monsoon, spring snowmelt, or glacier melt). At the geologic scale, global inlandsis melt (combining of a large number of glacier melts) generates larger floods. Geothermal activity can locally and temporarily increase glacier melt. The intensity of discharge during the flood is related to the storage of water by a natural or artificial dam along a stream related to riverbank failure. In the case of a classical climatic event (without damming), the flood intensity is close to steady. The sediment load is mainly suspended load and can be predicted using a rating curve. In the case of a dam break, the flood is unsteady (surge-like or outburst). The discharge and sediment flux (mainly bed load) is not predictable. In both cases (climatic event or dam break), the sediment load can be increased by riverbank and channel-bed erosion.

Suspended-load-dominated Hyperpycnal Flows

The nature of transported particles is fundamental to explain the type of transfer to the river mouth (bed load or suspended load). Syvitski (2003), using a worldwide database, showed that river load represents 89% of the total terrigenous load toward the ocean (Table 1). Seventy-two percent of the transport is represented by suspended load, and 8% is represented by bed load. The remaining 20% is composed of dissolved load that can play an important part in biologic and diagenetic subaquatic processes. Figure 3 illustrates the importance of suspended load in generating surface hypopycnal plumes during flooding at the mouth of a large river draining the Himalayas in Southeast Asia (Ganges-Brahmaputra River; Figure 3A)

Table 1. Transport mechanism for particles attaining the world ocean (modified from Syvitski et al., 2000 and Syvitski, 2003).

<i>Transport Mechanism</i>	<i>Global Flux Estimate, % (10^{12} kg/yr)</i>	<i>Reference</i>
Rivers, suspended load	64 (18)	Milliman and Syvitski, 1992
Rivers, bed load	7 (2)	Milliman and Syvitski, 1992
Rivers, dissolved load	18 (5)	Summerfield and Hulton, 1994
Glaciers, sea ice, icebergs	7 (2)	Hay, 1994
Wind	2.5 (0.7)	Garrels and Mackenzie, 1971
Coastal erosion	1.5 (0.4)	Milliman and Syvitski, 1992

and a small temperate mountainous river draining the southern Alps (Var River, southeastern France; Figure 3B).

This analysis of the sediment delivery at a river mouth suggests that two types of flood-related flows can occur at a river mouth: Hyperpycnal turbulent flows are mainly dominated by suspended load, and nonturbulent hyperpycnal flows are dominated by bed load.

The flood magnitude depends mainly on two parameters: (1) the climatic event at the origin of the flood and (2) the shape of the drainage basin.

1) If the climatic event is of short duration (e.g., storm, thunderstorm, hurricane), the increase in water discharge is sudden. This is the case for the Var River floods related to the Mediterranean climate (thunderstorms in autumn). This is also the case for floods related to tropical cyclones in Southeast Asia (Warrick and Milliman, 2003; Milliman and Kao, 2005). Erosion on the drainage basin can be intensified, significantly increasing the concentration of suspended matter. In addition, during a flow, erosion of the riverbank increases. Bank failures can occur in places along the river course and transform rapidly into sediment flows that are rapidly diluted and provide soft material mixed with the river water. In that case, the flood hydrograph is sharp, the peak flood condition is attained shortly after the beginning of the flood, and the flood duration is short. The shape of the hydrograph resembles the hydrograph related to a catastrophic event (dam break), but with a peak of lesser magnitude and a less abrupt phase of increasing discharge. This kind of flood hydrograph is observed in arid-dry climates. Sporadic streams called “oueds” (e.g., Djer and Isser rivers in Algeria) can have sudden catastrophic floods after long periods of drought. How-

ever, the river experiencing such flood hydrographs tends to produce high-energy floods with high transport competency that favors bed-load instead of suspended-load transport (flow competency represents the maximum grain size transported by a flow and is related to flow velocity). If the climatic event is seasonal (e.g., monsoon), the flood hydrograph is flatter and the flood can last several weeks to several months. This is the case of the Yellow River (Huang He) in China for which long-duration hyperpycnal turbidity currents have been recorded (Wright et al., 1986; Liu et al., 2004). These long seasonal floods lead to very high yearly average concentrations, making Chinese and Taiwanese rivers among the dirtiest rivers in the world (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995).

2) The shape of the drainage basin also has a big influence on the shape of the flood hydrograph (Figure 4A). A long or large drainage basin for rivers flowing on flat continental areas (e.g., Precambrian shields) tends to flatten the flood hydrograph by distributing the water discharge over a long time. In addition, a concentration time ([CT] Figure 4A) can exist between the beginning of the rainfall and the peak flood conditions. For very large rivers, this is emphasized by the fact that the drainage basin might be only partially affected by rainfall during a rainy event. A very large drainage basin can cross different climatic areas, limiting the climatic impact of rainfalls. Conversely, on a rounded drainage basin, the time for a drop of water to reach the river mouth is approximately the same where every point on the drainage basin is where the drop falls. No concentration time before the beginning of the flood is seen, and the flood hydrograph is not flattened. This is typically the case for small drainage basins of rivers in mountainous environments.

FIGURE 3. Subaerial photograph of the hypopycnal plume generated at the Ganges-Brahmaputra River mouth during monsoon floods (A) and a map of the Var River mouth (B). (C) Flooding Choshui River in Taiwan showing the very high turbidity caused by a high suspended-sediment load.

FIGURE 4. Example of flood hydrographs. (A) Importance of the size and shape of the drainage basin for classical climatic-related floods. CT = concentration time (modified from Lefèvre and Schneider, 2002). (B) Hydrograph of 1934 and 1954 jökulhlaups related to Grimstvötn eruptions in Iceland (modified from Björnsson, 1992). (C) Relationship between the total number of suspended-matter fluxes carried more than 2% of the time (Ms2) and the size of the drainage basin (modified from Dang, 2007).

Hypopycnal Flows and Reconcentration Processes

The critical concentration of 35 to 40 kg/m³ for initiation of hypopycnal flows, which was initially given by Mulder and Syvitski (1995), can be considerably reduced by convective instability that occurs in a surface plume (Chikita, 1991; Hoyal et al., 1999; Maxworthy, 1999). Hypopycnal flow with a suspended-sediment concentration at the river mouth as low as 1 kg/m³ could produce hypopycnal flows. During the experiments of Parsons et al. (2001), convection took the form of millimeter-scale sediment-laden fingers descending from the base of the surface (hypopycnal) flow. Finally, convective instability can transform most hypopycnal plumes into hyperpycnal flows. Ducassou (2006) and Ducassou et al. (2008) applied this concept to explain very fine-grained ungraded sequences cored on the Nile deep-sea fan. The sequences form contemporaneously with sapropels and during monsoon-related wet (pluvial) periods in the Nile drainage basin. During these periods, the discharge of the Nile River increased, leading to the formation of large low-density hypopycnal plumes and to the intensification of the water stratification in the eastern Mediterranean Basin, where the stratification is normally already larger than in the western Mediterranean Basin. Ducassou (2006) and Ducassou et al.

(2008) suggest that several successive convective reconcentration processes occurred at the base of the surface hypopycnal plume and successively at the base of each mesopycnal plume forming along each pycnocline that separates each water mass. The process was repeated until the deepest plume reached the Mediterranean sea floor and formed a very low-density turbidity current.

Flood Events and Lake Stratification

In lakes, the development of river-borne flows, related deposits, and the construction of specific clastic sedimentary environments depend, respectively, on the existence of stratification in the water column during the flood event, the duration and intensity of the event, and the size of the basin.

Four types of flows can form in a lake (hypopycnal, mesopycnal, hyperpycnal, and homopycnal flows; Figure 2) depending on the density contrast between inflowing water and lake waters, density here being chiefly controlled by water temperature and suspended-sediment load. Hypopycnal flows in lakes generally supply very little sediment, and no reconcentration processes of hypopycnal flows have been documented. Thus, only three main types of flood deposits are

documented in lakes: mesopycnal, hyperpycnal, and homopycnal flood deposits. In stratified lakes, essentially two types of river-borne flows may develop contrasting deposits: mesopycnal and hyperpycnal flows (Sturm and Matter, 1978; Schröder et al., 1998; Van Rensbergen et al., 1998, 1999; Chapron et al., 2002, 2005). Although mesopycnal flow deposits result from suspended-sediment fallout in the water column, hyperpycnal flows follow the basin-floor morphology. When the basin is large enough, the hyperpycnal flows develop channel levee systems in proximal environments and feed fan lobes in deep distal environments. In nonstratified lakes, river-borne hyperpycnal flows can form, but homopycnal flows are as common, especially in proglacial lakes (Brodzikowski and Van Loon, 1991). During homopycnal flood events, sediment plumes expand in three dimensions from the tributary mouth (Bates, 1953). They can be associated with significant currents and can develop contrasting deposits in proximal and distal basins (cf. Chapron et al., 2006, 2007).

THE RATING CURVE

The formation of flood deposits is directly related to the flux of suspended sediment in the fresh river-water flux. The rating curve is the curve that relates sediment concentration (or the sediment discharge) to the water discharge. Thus, knowledge of this rating curve is a key issue in predicting the frequency of hyperpycnal flows and their magnitude and in quantifying the volume of sediment they transport toward sedimentary basins.

The rating curve is also indispensable in predicting the type of sediment transport at a river mouth. For suspended load, the rating curve is a power law. Its shape induces the major conclusion that during low-discharge periods, sediment transport is very reduced, and most particles (either bed load or suspended load) are transported during high-discharge periods (floods). A quantitative example is provided for the Red River (Hong He) by Dang (2007). A total of 23 to 27% of the annual suspended sediment flux is carried more than 2% of the time (Figure 4C). Only 5% of the annual water discharge occurs during the same period. The analysis shows also that 97% of the annual suspended flux is carried along during precisely half the year. For the Red River, the variation in amount of suspended load carried more than 2% of the time is stable, just as it is for other rivers with their sediment loads dominated by suspended matter, in-

cluding the Mississippi (United States), Isle, and Adour (France; Meybeck et al., 2003; Coynel et al., 2004; Coynel, 2005). Only 75% of the annual water flux occurs during the same period. Meybeck et al. (2003), Coynel et al. (2004), and Coynel (2005) showed that small mountainous streams in which bed-load transport is important such as in the Mad, Siuslaw, and Iowa rivers (United States) or in the Isère, Nivelle, and Nive rivers (France) have a very high amount of suspended load carried more than 2% of the year, but with large variations (50–70%).

Using the simple rating curve and a worldwide database, Mulder and Syvitski (1995) showed that 71% of the world's rivers discharging into the world's oceans could generate hyperpycnal flows with a frequency of one event every year (dirty rivers) to one event every 100 yr (moderately clean rivers). Parsons et al. (2001) showed that this number could be potentially increased by considering processes such as convective sedimentation, leading to the reconcentration of a surface (hypopycnal) plume. In that case, 84% of the world's rivers could generate hyperpycnal plumes in the submarine environment.

A small number of rivers can have a naturally high concentration of suspended matter (Mulder and Syvitski, 1995, use the term “dirty rivers”). High suspended-matter concentration can also occur exceptionally in clean rivers because of the noncatastrophic erosion along the river's course or because of a temporal natural dam made of fine-grained sediments. This occurs frequently in areas of moderate (Saguenay Fjord in western Quebec, Saint-Onge et al., 2003) to high (Choshui River in Taiwan, Milliman and Kao, 2005; Figure 3C; Golgol River in Chile, Chapron et al., 2006) seismicity, coupled with the presence of fine-grained poorly consolidated sediments (quick clays in Saguenay Fjord, eolian loess in Taiwan, and andosols in Chile). An earthquake produces subaerial sediment failures. Some of the slides might dam the river. The dam is later eroded by snowmelt-related floods in Quebec and in Chile, as well as the typhoon-related flood in Taiwan. In the Saguenay Fjord, for example, the formation of a hyperpycnal flow is demonstrated by the superposition of a graded Bouma sequence (contemporaneous with the earthquake) and a hyperpycnite (contemporaneous with the hyperpycnal flows generated by erosion of the natural dam during the spring snowmelt flood). In the world, only 10 rivers out of more than 200 can be considered as dirty (Mulder and Syvitski, 1995). The other 71% (84% in Parsons et al., 2001) of rivers generates hyperpycnal flows solely during floods. This

strong relationship between hyperpycnal flows and flooding conditions and the shape of the rating curve suggests that terrigenous sediment flux from continent to sedimentary basins, and particularly oceans, is very restricted both in space (river mouth) and time (flood periods). In general, rating curves are robust laws and can be used for sediment delivery prediction when established using daily data or measurement made with a higher frequency (Mulder and Syvitski, 1995).

Although a classical rating curve can be a simple power law, a significant number of rivers might show a curve with a more complex shape (Syvitski and Alcott, 1993, 1995) that takes the form of an ortho-grade or retrograde hysteresis. Usually, this particular shape suggests that the erosion rate varies in the drainage basin according to the period of the year. For example, Mulder et al. (1997) showed that the Var River has a rating curve with higher sediment load for floods occurring in autumn when strong thunderstorm-related rainfalls erode very dry soils and sediments (Figure 5A). A similar conclusion is suggested for the Cointzio Lake in Mexico (Figure 5B) (Susperregui, 2008). The rating curve for this freshwater reservoir has a high concentration of suspended matter corresponding to floods that occur at the beginning of the wet season. Erosion is enhanced by strong rainfall onto dry soil after intense soil remolding by agriculture. Conversely, at the end of the wet season, the suspended-matter concentration decreases because of the dilution effect and the consumption of the material available for erosion.

This analysis of the rating curve suggests that monitoring of sediment load at a river's mouth is a key issue for improving the accuracy of quantification of sediment transfer from erosional areas to the sedimentary basin. However, this monitoring is very difficult to perform for three main reasons: (1) monitoring needs a long time series that covers a large number of major floods; (2) monitoring must be concentrated during major floods (this is not an easy task because major floods are commonly related to inhospitable weather conditions); (3) intensification of artificial damming during recent decades has considerably reduced the sediment load (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Farnsworth and Milliman, 2003; Guyard et al., 2007) and suggests that even if a large monitoring is performed, it is presently impossible to measure the natural (= previous to damming) sediment delivery at a river's mouth. This suggests that predicting rating curves is a good alternative to measuring them.

FIGURE 5. Example of rating curves: (A) Var River (modified from Mulder et al., 1997); (B) Retrograde hysteresis, Cointzio Reservoir, Mexico (modified from Susperregui, 2008). June to mid-August: Beginning of wet season and activation of the hydrologic network. Intense rainfall eroded soils too easily after the dry season generated a high sediment load. Mid-August to end of November: Maximum and end of wet season; sediment load decreased because the particles that eroded easily were transported during the preceding period. The load comes from the cohesive particles eroded along the streambed. Q = water discharge; C_s = suspended-sediment concentration.

Morehead et al. (2003) proposed a general relationship to estimate sediment load ($\bar{Q}_S$) using morphometric and climatic parameters:

$$\bar{Q}_S = \alpha H^{3/2} A^{1/2} e^{k\bar{T}}$$

where H is river basin relief (m), A is river basin area (km^2), $\bar{T}$ is mean surface temperature of the drainage basin ($^{\circ}\text{C}$), and α is a dimensionless constant ($2 \cdot 10^{-5}$), as is k (0.1331).

This relationship suggests that elevation of the drainage basin is important: sediment load is higher

for small mountainous rivers (Milliman and Syvitski, 1992) and rivers with a small drainage basin (Mulder and Syvitski, 1995, 1996). Drainage basins with a cold mean temperature (and lesser vegetal cover) are subjected to more intense erosion, particularly if the small mean temperature is related to relief elevation instead of to a location at a high latitude.

Regional parameters can influence the rating curve such as the geology of the area. In the Var River drainage basin, the Terres Noires (black shale) formation that mostly extends into the western Alps provides a large amount of easily eroded material, producing mudflows during intense rainfalls. For rivers discharging in the Tanganyika Lake in the East African rift (Tanzania), the suspended load is provided by the presence of easily eroded volcanic material such as ashes and pumice (Tiercelin et al., 1987, 1992). In China and Taiwan, the loess cover is intensively eroded during the monsoon rains, generating unusual suspended-sediment concentrations after typhoons, particularly if sediment has been remobilized by earthquakes (Dadson et al., 2004; Milliman and Kao, 2005). The picture of the flooding Choshui River (Figure 3C) illustrates this high sediment load. For the Nile River, the easily eroded material comes essentially from the Blue Nile tributary and the alteration (clay transformation) of basaltic rocks on the Ethiopian highlands. Similarly, in the Ogooué (Gabon) and Zaire basins, the fine particles are coming from the intense alteration of Precambrian shields in tropical climates (Giresse and Kouyoumontzakis, 1973; Séranne et al., 2008).

The geologic and climatic environment and the mean elevation of the drainage basin not only influence the volume of sediment delivery at the river mouth, but also control the nature of the particles that are carried at the river mouth. Using the Reading and Richards (1994) classification of submarine deep-sea fans, rivers located in nonglaciated mountainous environments will have a drainage basin with a small surface area and high relief. The sediment transported at the river mouth will be coarse (pebbles and sands) because the mean slopes on the basin are steep and the river's length is too short to form fine-grained particles. These rivers will preferentially generate bed-load-dominated hyperpycnal flows that develop alluvial fans that preferentially generate suspended load, where the river length is long enough to produce small particles; that is, when the mean slope of the drainage basin is low and the steep slopes where alluvial fans are concentrated are located far away from the river mouth. In glaciated mountainous en-

vironments, a significant part of the sediment load supplied to the marine realm through drainage basins also comes from glacier erosion that produces fine-grained particles (glacial flour). These clayey and silty particles are exported from subglacial and proglacial environments by glacier melt water pulses and transported downstream as suspended material in proglacial meltwater streams (Dhal et al., 2003). Glacier meltwater streams can develop large flood events in fluvio-glacial outwash plains, proglacial lakes, and fjords (Figure 6).

Lake Type and Basin Size

Lakes in a catchment area can either trap or filter sediment during a flood event, depending on its stratification and size. For example, Lake Saint-Jean in Quebec acts as a trap for particles on the Saguenay River course. Thus, when entering the Saguenay Fjord, the Saguenay River is very clean (Syvitski and Schafer, 1996). As shown in Figure 2, large homopycnal and mesopycnal flows in small lakes can reach the outlet and export downstream fine-grained suspended sediment load, either in stratified or in nonstratified lake basins. Hyperpycnal flows will therefore be deposited in smaller lakes, whereas most of the flood-related sediment plumes will be trapped in large lakes (e.g., lakes Geneva, Houbolt and Jonker, 1968; Tanganyika, Tiercelin et al., 1992; or Baikal, Back et al., 1998). In glaciated catchment areas, for example, glacier melting (related to climate change or increased heat flux by geothermal or volcanic activity) results in the formation of numerous small proglacial lake basins, where large volumes of sediment can be exported with glacial meltwaters by the development of homopycnal flows (Figure 6). In mountain belts, during flood events, a wide range of lakes formed by glacier erosion, frontal moraines, landslides, lava flows, or tectonic basins can occur in valleys and will influence the amount of clastic particles delivered to the ocean.

Continental Shelf

The presence of a narrow continental shelf is important for the longitudinal persistence of a submarine hyperpycnal flow and its ability to reach the continental slope, canyons, and finally, the deep-marine environment. Suspended-load-dominated hyperpycnal flows are low-concentration flows in which particles are mixed with fresh water when entering the sea. If the nonbuoyancy is not rapidly maintained by fluid entrainment, the flow rapidly collapses. Particles are then mixed with pelagic sediment to form classical hemipelagites. The intensity of water entrainment

FIGURE 6. Development of hypopycnal flows in Baie de la Table Fjord (49°32'S/69°13'E; Kerguelen Island) in relation with Ampère glacier (Cook ice cap) melting (A). The historical glacier snout positions, (1) Little Ice Age, (2) 1962, (3) 1995, and (4) 2008, were redrawn from the studies of Vallon (1977) and Frenot et al. (1997). Development of homopycnal flows in recent proglacial lakes and in the Ampère outwash plain (B). Picture of a hypopycnal flow in Baie de la Table Fjord in March 2009 (C).

is defined by the Richardson number, Ri (inverse of squared Froude number, Fr). When Ri is small (<0.25 , meaning Fr is large), the velocity shear is large enough to produce turbulent mixing. When Ri is large, no turbulent mixing occurs (Turner, 1973). On steep slopes, such as along canyon floors, hyperpycnal flows rapidly accelerate and become supercritical ($Fr > 1$), generating a high entrainment rate. Conversely, on a flat continental shelf, hyperpycnal flows remain subcritical, no entrainment occurs, and the hyperpycnal flow stops and eventually lofts (Sparks et al., 1993; Hesse and Khodabakhsh, 2006).

Bed-load-dominated flows are typically nonturbulent. As in the case of frictional flows, in which the particle support is maintained by the dispersal pressures because of grain-to-grain collisions (Middleton and Hampton, 1973), bed-load-dominated flows re-

quire steep slopes to remain in motion. On an even narrower continental shelf, the flow rapidly freezes (Mulder and Alexander, 2001, use the term “frictional freezing”).

Bed-load-dominated Hyperpycnal Flows

Bed-load transport in rivers is very difficult to measure and predict (Inbar and Schick, 1979). Bed-load transport in coarse-grained alluvial channels can vary from flood to flood, depending on flood frequency (Reid et al., 1985). Bed-load transport is less important than suspended-load transport and occurs with a lower frequency (Syvitski, 2003). In addition, monitoring is very difficult, particularly in large catchment areas.

Hyperpycnal flows with bed load as the dominant transport mechanism are commonly generated by

catastrophic (outsized) events. The examples are essentially related to natural or artificial dam breaks, to the entering of a mass flow in a subaquatic basin, or to flash floods. Even during flood conditions, major bed-load transport in rivers is restricted to small rivers draining mountainous basins and to high-magnitude floods (Inbar and Schick, 1979; Mao and Lenzi, 2007).

The Icelandic jökulhlaup is typical of the sudden drainage of a subglacial lake; it represents the sudden drainage of a subglacial reservoir filled by ice melting during the eruption of a subglacial volcano (Björnsson, 1992). Jökulhlaups occur with a frequency of one event per year to one event every 10 yr. For example, in 1996, the Grimsvötn volcano drained a 3.2-km^3 (0.77-mi^3) lake in 40 hr and produced a jökulhlaup with a peak discharge of $50,000\text{ m}^3/\text{s}$ (Björnsson, 1998). Generally, the ice breakage occurs beneath the glacier with the formation of an ice tunnel. A mixture of dark volcanic rock fragments and ice boulders are deposited on a Skeidarársandur (Grönvold and Jóhannesson, 1984; Einarsson et al., 1997; Gudmunsson et al., 1997). Other events produced hyperpycnal flows with concentrations reaching 200 kg/m^3 when entering the Atlantic Ocean (Mulder et al., 2003). Jökulhlaups also occur in Alaska (Baker, 1995). For example, Lake Russell at the front of the Hubbard Glacier was drained by a Jökulhlaups burst in 1986, producing a discharge of $10^5\text{ m}^3/\text{s}$ (Krimmel and Trabant, 1992).

At geologic scale, similar triggering can occur at the end of glacial cycles but with a higher magnitude by the drainage of proglacial lakes (moraine-dammed lakes). Brunner et al. (1999) and Zuffa et al. (2000) described deposits related to a hyperpycnal outburst of glacial Lake Missoula (Utah) during the late Pleistocene (17–12 ka). The dam height reached 610 m (2001 ft). The lake that reached a surface area of 7770 km^2 (3000 mi^2) and maximum volume of 2100 km^3 (503 mi^3) was drained 40 to 80 times by the breaking of the moraine front during the melting of the North American ice sheet. Each episode of drainage generated an individual flood with an estimated peak discharge of $10^7\text{ m}^3/\text{s}$. The floods, associated with the Columbia River drainage system, eroded 210 km^3 (50 mi^3) of volcanic rock and sediment and transported the eroded products downstream (Richmond et al., 1965; Mullineaux et al., 1978; Baker and Bunker, 1985; Waite, 1985).

Lake Bonneville is a pluvial lake that formed 32,000 yr ago when the climate in the western United States was wetter. It occupied a surface of $51,000\text{ km}^2$

($19,690\text{ mi}^2$) at the location of the present Great Salt Lake in Utah and had an estimated water volume of 1583 km^3 (379 mi^3) (Gilbert, 1878). The lake probably emptied and filled several times because of alternation of wet-dry cycles. However, its final drainage 14,500 yr ago was catastrophic and produced a flood through the Snake River system, with an estimated peak discharge of $425\text{ }10^3\text{ m}^3/\text{s}$ (Malde and Powers, 1962; Malde, 1968).

Barber et al. (1999) and Lajeunesse and Saint-Onge (2008) suggested that the outburst flood of the Agassiz-Ojibway subglacial lake, 8.47 ka ago, which resulted from the melting of the Laurentide ice sheet, produced a flux of fresh water into the Atlantic Ocean high enough to perturb its thermohaline circulation and produce the cold climatic event at 8.2 ka (Broecker et al., 1989; Clarke et al., 2004; Broecker, 2006). The flood produced large scours because of iceberg transport by the high energy flow and hectometer-large sand waves in the Hudson Bay.

During the last glacial period, the presence of glacial lake sediments in the area of the Dogger Bank, North Sea (Laban, 1995), suggests that the European ice sheet produced probably a large marginal lake by damming the drainage system of western Europe (Toucanne, 2008). After ice melted, the Manche River drained the lake and the river system before the last Holocene sea level rise. If this lake existed, no evidence for either a quick (outburst) or a steady drainage and the production of hyperpycnites similar to what happened in the North American margin were seen.

Two characteristics of flood hydrographs related to dam breaks or jökulhlaups are the magnitude of the peak flood and the shortness of the increasing discharge period (Figure 4B). The two characteristics show that the flow is unsteady and resembles a surge-like event with a very high sediment concentration instead of a classical flood.

Subglacial meltwater can occur without a lake outburst. Piper et al. (2007) described a large amount of gravel and sand from the Laurentian Rise to the Sohm Abyssal Plain (offshore southern Newfoundland) that seems to be unrelated to North Atlantic Heinrich events and large melting periods of the Wisconsinan ice sheet. Deposition can occur through either rare large bed-load-dominated hyperpycnal flows or hypopycnal flows and lofting hyperpycnal flows. Similarly, for the Orphan Basin (offshore eastern Newfoundland), Tripsanas and Piper (2008) described eight major meltwater events preserved as red layers (plumites). Three of them produced hyperpycnal flows

FIGURE 7. Longitudinal distal-proximal facies evolution of hyperpycnites: from left to right. (A) Base-truncated hyperpycnites similar to Bouma sequence. Example of several stacked sequences in Les Scaffarels outcrops, Annot Sandstone in Annot, southeastern France. (B) Truncated hyperpycnite with partial truncation of the basal unit. Example of one sequence (arrow) in Les Scaffarels outcrops, Annot Sandstone in Annot, southeastern France. (C) Complete coarse-grained hyperpycnite. Example in Saint-Antonin outcrop, southeastern France. (D) Fine-grained hyperpycnite. Example in Oman Sea (Bourget et al., 2010a, b). Ha = basal coarsening-up unit; Hb = top fining-up unit (from Mulder et al., 2003).

that deeply imprinted the channel system and transported sand into the distal part of the system.

Dromart et al. (2007) reported steep clinoforms in Valles Marineris on Mars that could be related to outburst flows formed during Hesperian times (3.5 Ga) when the Martian atmospheric pressure was high enough to temporarily allow ice melting. These deposits can be interpreted as fan deltas formed by the sporadic outbursts of floods related to the temporary melting of the Martian ice and deposition in sub-aquatic basins, similar to what happens on outwash plains, such as Skeidarársandur in Iceland.

TYPES OF FLOOD DEPOSITS

Establishing links between initiation processes (flood or ice melting, in this chapter) and the resulting deposits is not an easy exercise, as pointed out by Piper and Normark (2009), who noted a lack of simple relationship between both and other sedimentary or hydrodynamic processes, as well as with sea-

floor morphology that can interact with the hyperpycnal flow. We thus provide lengthy descriptions for the interpretation of these deposits.

SUSPENDED-LOAD-DOMINATED HYPERPYCNITES

Suspended-load-dominated hyperpycnal flows are turbulent flows (turbidity currents) with velocities that reflect variations of the flood hydrograph at the river mouth. Their deposits are traction-fallout mixed hyperpycnal deposits, and the variations in flow velocity are recorded in the hyperpycnites (Mulder et al., 2002). The typical sequence shows a coarsening-up interval deposited during the increasing discharge period and a fining-up interval deposited during the decreasing discharge period (Figure 7).

Such sequences can be very fine grained and millimeter-to-centimeter thick when deposited in an unconfined environment, for example, on a deep sea fan such as the Var Fan (Mulder et al., 2001a, b)

and Toyama (Nakajima, 2006) or be several meters thick when the flow is laterally confined, such as in the Saguenay Fjord (Mulder et al., 1997; Saint-Onge et al., 2003).

For fine-grained hyperpycnites generated by suspended-load-dominated hyperpycnal flows, hyperpycnites with the vertical grain size recording both the waxing and waning phases of the flood hydrograph can be preserved in very deep-sea environments. In ancient systems, such as the Annot Sandstone, the water depth is from shoreface to deeper than storm-wave base (Joseph et al., 2005). In modern environments, hyperpycnites have been recognized in water depths of 2000 m (6560 ft) at the mouth of the Var Canyon and at 3200 m (10,500 ft) in the Arabian Sea (Bourget et al., 2010a, b). Nakajima (2006) described hyperpycnites in the Toyama deep-sea fan, more than 700 km (435 mi) from the river mouth. Ungraded beds related to reconcentration processes during Nile floods have been collected between 1000 m (3280 ft) and greater than 3000 m (9840 ft) water depth (Ducassou, 2006; Ducassou et al., 2008). In these beds, organic particles are observed up to 300 km (186 mi) from the river mouth. Cores collected in central Hudson Bay and western Hudson Strait show a decimeter-thick red silt bed with a reverse to normal grading, which is interpreted as the hyperpycnite related to the final outburst of Lake Agassiz-Ojibway (Lajeunesse and Saint-Onge, 2008).

For high-magnitude floods, sediment forming the basal unit can be eroded during the peak flood conditions, generating a base-absent hyperpycnite resembling a classical Bouma sequence (Figure 7A) (Bouma, 1962; Mulder et al., 2001b; Mulder et al., 2002). The Saint-Antonin outcrops are interpreted as the proximal part of the turbidite system supplying the Annot Sandstone in the main outcrop of Annot Station (du Fornel, 2003; Joseph and Lomas, 2004). It was supplied by small river systems eroding the Corsica-Sardinia massifs during the Eocene and Oligocene. Saint-Antonin outcrops show complete hyperpycnites (Figure 7C), deposited mainly in a shallow-water environment (above the lower limit of wave action). Les Scaffarel outcrops in the Annot Sandstone are located distally of Saint-Antonin outcrops. These outcrops show complete hyperpycnal sequences, including base-truncated hyperpycnites that could be related to shallow conglomerates (bed-load-dominated hyperpycnal deposits) in the Saint-Antonin outcrops.

Sedimentary structures in modern marine hyperpycnites are rare, even when deposits are fine grained. The Saguenay hyperpycnites show only rare horizon-

tal lamination in their basal part corresponding to the waxing phase of the flood hydrograph. Ancient outcrops in the Annot Sandstone (du Fornel, 2003; Joseph and Lomas, 2004; Joseph et al., 2005) or in the Apennines (Mutti et al., 1996; Mavilla, 2000) show classical sedimentary structures (planar lamination, cross-bedding). Soyinka and Slatt (2009) described beds with diffuse lamination and coarsening/fining-up trends interpreted as hyperpycnites in mud-rich prodeltaic deposits from the Cretaceous Seaway in western North America. However, it seems that climbing ripples are more frequent in hyperpycnites than in classical slide-related turbidites (Mutti et al., 1996). In addition, the nature of sedimentary components includes continental species such as *Chara oogonia* (Bourcart, 1964). The very good preservation of organic matter is also observed in ungraded clastic beds related to reconcentration processes during Nile floods (Ducassou, 2006; Ducassou et al., 2008). Some wood fragments still show the preservation of the woody texture, suggesting a very short period between the death of the vegetation and its final burial.

In clastic lakes, modern suspended-load-dominated hyperpycnites can be millimeter-to-centimeter thick sharp-based deposits with the typical vertical grain-size signature of the waxing and waning phases of the flood hydrograph (Guyard et al., 2007). In-situ measurements in Kluane Lake (Yukon Territory, Canada) (Crookshanks and Gilbert, 2008) show the correlation between increasing/decreasing flow velocity and deposition of coarsening/fining-up units, respectively. High-magnitude flood events also frequently do not preserve the typical coarsening-upward sequence associated with a waxing flow (Guyard et al., 2007); instead, they are characterized by graded silty deposits in proximal environments (Figures 8, 9), and by very fine-grained (clayey-silt) sharp-based deposits in the deeper distal basin (Figure 9) (Chapron et al., 2002). A common feature of these hyperpycnites is the occurrence of organic debris at their base (Chapron et al., 2005).

Catastrophic Floods and Bed-load-dominated Hyperpycnal Flows

Bed-load-dominated hyperpycnal flows are drastically different from suspended-load-dominated hyperpycnal flows. Because of their high energy, the catastrophic flows can produce substantial onland erosion. The Missoula floods transported several meter-size basalt boulders (Malde and Powers, 1962) and the Bonneville flood carried meter- to house-size rounded

FIGURE 8. Illustration of homopycnal and hyperpycnal flows in Lake Puyehue (Chile) and related deposits on radiography (PU-II) and photography (PU-I). Line drawings and interpretation of seismic profiles previously published by Moernaut et al. (2006), Chapron et al. (2007), and Charlet et al. (2008) highlight the typical geometry of lacustrine sedimentation resulting from the contribution of authigenic and clastic supply in the upper seismic unit of this basin fill. Although homopycnal flows are affecting the whole lake basin and developing finely laminated sediments at coring site PU-II, sporadic hyperpycnal flows are only developing sharp-based graded beds at site PU-I in the proximal basin facing the Golgol delta. These sandy-silt graded beds were formed by riverbank incision after the deposition of a catastrophic hyperpycnal flood event resulting from the outburst in 1960 of an earthquake-induced landslide-dammed lake further detailed in Chapron et al., 2006, 2007.

blocks called “melon gravels.” Blocks of volcanic rocks with a similar size were transported by the 1996 Grimstvötn jökulhlaup and deposited along the Skeidarársandur.

Brunner et al. (1999) and Zuffa et al. (2000) described submarine deposits related to hyperpycnal outbursts of glacial Lake Missoula (Utah) in the Astoria deep-sea fan (Figure 10). The related deposits were cored during the Integrated Ocean Drilling Program (IODP) leg (Shipboard Scientific Party, 1998a, b, c; Brunner et al., 1999; Zierenberg et al., 2000). They show two types of deposits: (1) several meter-thick massive sand beds with no grading and (2) massive sand beds with a crude grading occurring at the top (Figure 10A). These beds correspond to either (1) hyperconcentrated flow deposits or (2) concentrated flow deposits (Mulder and Alexander, 2001) equivalent to Ta facies of the Bouma sequence (Bouma, 1962).

The deposits related to individual drainage of Lake Missoula are particularly easy to identify on 3.5-kHz seismic records. The top of the massive sand beds (top

of the hyperpycnal layer or limit between ungraded and crudely graded sand; Figure 10A) forms a good contrast in acoustic impedance and so provides good seismic reflectors. Deposits of the Malpasset Dam break (located along the Reyran/Argens River, south-eastern France) in the Fréjus Bay have been cored and provide a good example of a surgelike hyperpycnal flow (Figure 10B) (Mulder et al., 2009). They also show a few decimeter-thick, organic-rich, fining-up sandy-silt layers, with no grading or with crude grading developing at the top of the deposits. The sand component includes rock fragments and minerals eroded along the drainage basin of the Reyran/Argens River. The material is mixed with broken mollusk and foraminifer shells coming from the beach area and the shoreface. The deposits form a sediment wedge extending from the shore area pinching seaward down to the 30-m (98-ft) isobath. Characteristics of the deposit strongly suggest behavior corresponding to an inertia-dominated flow. This behavior of the flow and the type of deposits are explained by the short

FIGURE 9. Illustration of mesopycnal and hyperpycnal flow deposits in Lake Le Bourget (northwestern Alps, France). Short coring, side scan sonar, subbottom profiling, and long coring in this marginal valley lake (Chapron et al., 1996, 2002, 2005) allow mapping specific sedimentary environments associated with mesopycnal and hyperpycnal flood deposits associated with the different tributaries. Since the early Holocene, only major Rhone River floods are entering the lake and developing either mesopycnal or hyperpycnal flood deposits. In proximal environments (LDB04), Rhone River mesopycnal and hyperpycnal flood deposits are coarser, and the latter is characterized by a sharp base rich in organic debris. In distal environments, Rhone River mesopycnal flood deposits (B10) are producing finely laminated clastic facies, whereas hyperpycnal flood deposits (B16) are producing sharp-based thick clayey-silt layers rich in organic debris. The three flood layers shown in B16 correspond to a historical flood during the Little Ice Age (Chapron et al., 2002). Also shown is the location of a Chirp seismic profile presented in Figure 14.

duration of the unsteady surge flow, dominated by bed-load transport. In addition, Bathurst and Ashiq (1998) showed that a major dam-break flood can increase the bed-load transport in a river several years after the initial outburst flow.

Catastrophic flood events related to modern or Holocene dam outbursts in mountainous valleys can also produce substantial onland erosion and develop unusually thick hyperpycnites in clastic lakes. These catastrophic deposits are characterized by an erosive base, a laminated and coarsening-upward basal sequence, and a massive to graded upper sequence (Schneider et al., 2004; Chapron et al., 2007). The outburst of the Llanç lake (ca. 40 km [25 mi] long, 400 m [1300 ft] deep) dammed by the Flims sturzstrom (a

12-km³ [3-mi³] rock avalanche deposit) 9400 yr ago produced two outstanding stacked sandy-silt deposits more than 100 km (62 mi) downstream from the Rhine Valley (Switzerland) in the Rhine lacustrine fan of Lake Constance (Pollet and Schneider, 2004; Schneider et al., 2004). These catastrophic deposits retrieved at two locations in Lake Constance at 160 (525 ft) and 180 m (590 ft) water depths (Figure 11) are in sharp contrast with background sedimentation (black spotted lake marls). In Lake Puyehue (Chile), the main impact of the 9.5 magnitude Valdivia earthquake in 1960 was the outburst of an earthquake-induced landslide dam in the Golgol River valley, several weeks after the main seismic shock (Chapron et al., 2006, 2007). This outburst occurred only 5 km

FIGURE 10. Bed-load-dominated hyperpycnal deposits. (A) Log of IODP core 1037B showing succession of hyperconcentrated and concentrated (Ta) flow deposits related to successive floods of Lake Missoula (modified from Brunner et al., 1999). (B) Example of the hyperconcentrated flow deposits (ungraded organic-rich sand) deposited in the Bay of Fréjus (French Mediterranean) by the flood related to the Malpasset Dam break (modified from Mulder et al., 2009). IODP = Integrated Ocean Drilling Program.

Flims outburst-induced hyperpycnal flow deposits in Lake Constance ca. 9400 BP

FIGURE 11. Location of Llanç paleolake temporally dammed by the Flims rock avalanche in the Rhine valley (Switzerland). The outburst of the Llanç Lake formed two successive catastrophic hyperpycnal flood deposits in the Rhine lacustrine fan delta of Lake Constance. As detailed in Schneider et al. (2004), these two hyperpycnites are outstanding features dated to ca. 9400 B.P.

(3 mi) upstream from the Golgol delta in Lake Puyehue, and the related megaflood event initiated a new course of the river in the Golgol alluvial plain, as well as a catastrophic hyperpycnite (ca. 3106 m^3) up to 30 cm (11.8 in.) thick in the proximal basin of Lake Puyehue, facing the Golgol delta. This catastrophic event reworked terrestrial, volcanic, and lacustrine material in the deep proximal basin of this piedmont lake.

Low-magnitude Floods and Reconciliation Processes

Ducassou (2006) and Ducassou et al. (2008) described fine-grained beds generated by convective sedimentation related to successive concentration processes (Figure 12). These beds are made of structureless slightly graded clastic mud (grain size, $<50 \mu\text{m}$) containing lignite fragments, amorphous organic matter patches, and neoformed gypsum. They are almost Azoic and without bioturbation. These beds essentially contain terrigenous particles and reworked microfossils. Rapid sedimentation is indicated by the good preservation of wood fragments, and the lack of planktonic fauna and bioturbation. Forty events are detected during the deposition of sapropel S1 (during ~ 2000 yr), supporting rapid deposition.

The absence of sedimentary structure in these clastic mud beds is not related to the absence of traction be-

cause the grain size of the beds is probably too fine to allow formation of sedimentary structures. The transitional contact between the clastic beds and the interbedded pelagic deposits is more convincing evidence for a short transport distance along the sea floor. The grading of the beds suggests that particle fallout is the most important process in their formation, suggesting that these beds are fine-grained flood-related turbidites.

Wave-modified Hyperpycnites

Wright et al. (1986), Myrow et al. (2002), and Lamb et al. (2008) described deposits from the Pennsylvanian in north-central Colorado showing both reverse and normal grading and sedimentary structures, suggesting oscillatory flow (large-scale hummocky cross-stratification, quasi-parallel lamination, combined flow-ripple lamination) interpreted as storm-influenced hyperpycnal flow deposits. In that case, a storm would be at the origin of both storm waves and flooding rivers. The abundance of sole marks (flute and gutter casts) and ripple cross-stratification suggests that the unidirectional flow was dominant. The paleoenvironmental reconstruction shows that the system was fed by a fan delta. Sediments in hyperpycnites include numerous plant fragments coming from the highlands located in the drainage basin. Wood fragments provided the tool marks, indicating flow direction.

FIGURE 12. Structureless slightly graded clastic mud beds resulting from reconcentration processes by convective sedimentation during floods in the Nile deep-sea fan (modified from Ducassou, 2006 and Ducassou et al., 2008).

SPATIAL EVOLUTION AND TIME DISTRIBUTION OF FLOOD DEPOSITS

Coarse-grained Flood Deposits

Spatial evolution of coarse-grained flood deposits (bed-load-dominated hyperpycnal flow deposits) has been synthesized in a sigmoidal bar model by Mutti et al. (1996). These bars are formed during major floods at the mouth of a channeled system by the transfor-

mation of a concentrated flow into a more dilute turbulent flow. Mutti et al. (1996) defined six facies (Figure 13) numbered from 1 to 6 from the proximal (river mouth) to the distal part. The base of the bar lies on erosion surfaces (scours). Facies 1 corresponds to nonstratified pebbles with or without sandy matrix. It results from the frictional freezing (*en masse* deposition) of the coarse basal part of a hyperconcentrated flow (Mulder and Alexander, 2001). Facies 2 is a coarse sandstone containing pebbles in the proximal part and cross-bedding with stratification dip increasing in the direction of progradation. Stratification planes are enhanced by pebbles and gravels and become convex-up distally. This facies is deposited by bed-load transport in a hyperconcentrated flow, in which flow dilution allows individual transport of particles. Facies 3 is made of nonstratified coarse-to-medium sandstone with a crude fining up that would correspond to a concentrated flow deposit. Facies 4 corresponds to medium sandstone with horizontal or slightly undulated planar bedding. Facies 5 corresponds to fine to very fine sandstone with horizontal planar and cross-bedding (ripples). Facies 4 and 5 correspond to deposition by traction plus fallout deposition. Facies 6 corresponds to a clay interval (fall-out deposition).

In Saint-Antonin outcrops (du Fornel, 2003; Joseph et al., 2005), the longitudinal facies evolution approximates the Mutti et al. (1996) model. However, beds containing gravel and pebble layers show a clear inverse and then normal grading without an erosion surface and can be interpreted as hyperpycnites (Mulder et al., 2002). The storm-wave-modified hyperpycnites described by Lamb et al. (2008) show that proximal bed forms record mainly an oscillation-dominated motion and distal bed forms record mainly a unidirectional current-dominated motion, consistent with a distal decrease of the wave impact on the hyperpycnal flow as it moves along the shelf floor.

Bed-load/Suspended-load Hyperpycnal Flow Deposits

A synthetic model of longitudinal evolution of hyperpycnal facies can be made (Figure 13). It differentiates bed-load-dominated hyperpycnal and suspended-load-dominated hyperpycnal transport. The resulting deposits depend on the suspended-load/bed-load ratio. This ratio is related to the flood hydrograph. Short and intense climatic-event-related flash floods generate a fast increase of the flow velocity at the river mouth. In this case, hyperpycnal flows are preferentially high-capacity flows dominated by

FIGURE 13. (A) Geometry of a flood-related sigmoidal bar (modified from Mutti et al., 1996 and du Fornel, 2003). (B) Synthetic model of longitudinal evolution of hyperpycnal facies. It differentiates bed-load-dominated hyperpycnal and suspended-load-dominated hyperpycnal transport (vertical path). The resulting deposits depend on the suspended-load/bed-load ratio. This ratio is related to the flood hydrograph. Horizontal path shows main flow evolution from distance to river mouth. This evolution includes the decrease of both flow competency and capacity with distance, the increase of suspended-load versus bed-load transport, the increase of grain sorting, the progressive replacement of en masse deposition by traction, and then particle fallout and the change in grain fabric. Q = water discharge; MF = mass-flow deposit.

bed-load transport. Long-duration floods have a flat hydrograph generating low-velocity flows dominated by suspended load.

The main differences in deposits between bed-load-dominated and suspended-load-dominated hyperpycnal flows are as follows (vertical path in Figure 13):

- coarse-grained mouth-bar progradation is replaced by fine-grained hyperpycnites
- increase of bypass on the continental shelf and upper slope
- decrease in flow competency
- increase of sediment sorting

Instantaneous catastrophic events or outburst flows (dam breaks and jökulhlaups) can be included in this model; they generate very sudden floods with high-velocity flows favoring bed-load transport. As suggested by Mulder et al. (2009) using the example of

the Malpasset Dam break, the hydrodynamics of a catastrophic outburst flow is instead similar to a mass flow or a surgelike turbidity current instead of to a classical flood. The resulting deposit depends on the initial grain size but is first a frictional mass flow deposit in the proximal part (ungraded conglomerate or sandstone). The upper part of the flow can transform into a concentrated flow depositing a Ta Bouma facies with a crude grading. If the exceptional event is of moderate size, such as in the Malpasset example, the deposits stop at this stage and are limited to the continental shelf. If the event is outsized, such as in the case of the Missoula Lake outburst, the flow can reach the continental slope and proceed toward the abyss. The flow becomes accumulative and may transform into a true turbidity current, generating classical bypass on the upper slope and depositing classical turbidites on the deeper part of the continental slope and rise (Piper and Normark, 2009).

Flood Deposits of Climatic Origin

Short-duration floods related to instantaneous climatic events (thunderstorm or hurricane) will generate hyperpycnal flows dominated by bed-load transport. Deposition will occur close to the river mouth by rapid progradation of the mouth bar (Mutti et al., 1996).

The main flow evolution with increasing distance from the river mouth is as follows (horizontal path in Figure 13):

decrease of both flow competency and capacity.
increase of suspended-load versus bed-load transport.

increase of grain sorting.

en masse deposition progressively replaced by traction and then particle fallout.

change in grain fabric: no fabric in mass flow, then crude fabric, and then no fabric.

Bed-load-dominated hyperpycnal flow first moves as mass flows. Deposits include massive pebble-to-gravel conglomerates with no internal fabric of clasts and no sedimentary structures (defined as facies 1 in Mutti et al., 1996). They correspond to the frictional flow described by Mulder and Alexander (2001). With distance, clasts begin to be transported individually, generating a crude to clear imbricate fabric in the deposits, corresponding to facies 2 as defined in Mutti et al. (1996). With distance, suspended-load transport becomes larger than bed-load transport. Clast imbrications progressively disappear, and classic hyperpycnites can form. They resemble the hyperpycnites defined by Mulder et al. (2003) in modern marine environments, but with a coarser grain size (Figure 6). They show the classic basal coarsening-up unit and the top fining-up unit. The peak of the flood is marked by the maximum grain size corresponding to a gravel bed or lamina, or coarse sand layer in the deposit (defined as facies 2 in Mutti et al., 1996). When suspended load dominates (defined as facies 3–6 in Mutti et al., 1996), the hyperpycnal flow forms fining-up deposits with facies that mimic the classic Bouma sequence. This deposition is a classic example of a suspended-load depletive waning flow. Suspended-load-dominated flows form classical hyperpycnites (Figure 6). In the proximal part, a small gravel bar with facies similar to those formed by bed-load-dominated hyperpycnal flow can form if coarse material is present. If only fine material is present, no deposit occurs in the

proximal part, which becomes a bypass zone. Fine-grained material is transported down the continental slope and forms the fine-grained hyperpycnites (Figure 6) (Mulder et al., 2003). In moderately dirty rivers, reconcentration processes dominate, forming fine-grained turbidites (ungraded clastic beds described by Ducassou et al., 2008).

Simultaneously or alternatively, the rapid progradation of mouth bars during floods and particularly when bed-load transport is important can generate sediment failures. The study of bed-load transport along the Yellowstone River showed that floods generate substantial stream-bank erosion and hillslope mass wasting (Holnbeck, 2005). Large quantities of coarse material (sand to cobbles) are entrained by the flows and became flood-bar deposits. When generated close to the river mouth, river-bar failures related to mouth-bar progradation generate submarine flow and classic turbidity currents, as observed by Bornhold et al. (1994) in west Canadian fjords, and these currents deposit classic turbidites (Bouma sequences). This suggests that hyperpycnites and turbidites can be interlayered in sedimentary series (see, e.g., Mulder et al., 2001b, and Saint-Onge et al., 2003, for the Saguenay Fjord; see Mas, 2009, for the Var).

SIGNIFICANCE OF HYPERPYCNAL FLOOD DEPOSITS IN THE GEOLOGIC RECORD

Sedimentary Structure and System Scale in Lacustrine Environments

During the last deglaciation, frequent and powerful clastic hyperpycnal flows in lakes originating from large alpine rivers (e.g., Rhone, Rhine, and Danube rivers) not only allowed the rapid progradation of deltas in proglacial lakes, but also developed migrating, and sometimes meandering, channel levee systems along prodeltas that fed fan lobes in the deep lacustrine basins (Houbolt and Jonker, 1968; Chapron et al., 1996, 2009; Schröder et al., 1998; Van Rensbergen et al., 1998, 1999; Popescu et al., 2001). These lacustrine deposits filled many large alpine valleys, and only fine-grained particles originating from homopycnal or mesopycnal flows could be exported downstream into fluvial systems when the lake basins became smaller. Some of these large valley lakes were completely filled and are today flat alluvial plains. Some large alpine valley lakes are still directly filled by hyperpycnal flows from large alpine rivers; other

FIGURE 14. Chirp seismic profile across the Lake Le Bourget deep basin (see location in Figure 9) illustrating seismic facies associated with mesopycnal and hyperpycnal flood deposits in the tributaries within the Holocene drape (Seismic Unit 5) and at the end of the Late Glacial period (Seismic Unit 4). High clastic supply during deglaciation enhanced the impact of earthquakes (formation of the Hautecombe Disturbed Unit [HDU]; Chapron et al., 1996, 2005; van Rensbergen et al., 1999). The HDU is here characterized by two almost contemporaneous slides remolding mesopycnal flood deposits and developing one debris-flow deposit (Df) and two megaturbidites in the deep basin (MT1 and MT2).

lakes located in marginal valleys became disconnected from large alpine rivers during deglaciation. Lake Le Bourget (French northwest Alps (Figure 9) is such a marginal valley, where, since the early Holocene, only sporadic major Rhone River floods spread hyperpycnal flows over the alluvial plain and surrounding swamps (Chapron et al., 2005). These sporadic floods do not now develop channel levee systems but have produced centimeter-thick fine-grained hyperpycnites in the deep basin during periods of major environmental change, such as during the Little Ice Age. Similar cold and wet periods associated with the advances of Mont Blanc glaciers enhanced glaciofluvial regimes and high lake levels (Arnaud et al., 2005; Chapron et al., 2005; Debret et al., 2010). These periods of enhanced flooding developed outstanding high-amplitude reflections on Chirp seismic profiles over long distances from the tributary to the deep basin (Figure 14). Today's global warming in mountain ranges favors the melting of glaciers and development of proglacial lakes at the head of large catchment areas, as well as landslides along large valleys because of reduced permafrost. These significant

environmental changes, together with earthquake activity, may favor the development of catastrophic floods in large valleys related to the outburst of temporary dammed lakes. Examples presented in this chapter show that these catastrophic floods can be erosive over long distances, both on land and in sub-aquatic basins.

Depositional System Scale in the Marine Realm

Hyperpycnal flows are involved in the construction of two major structures shaping the continental clastic margins: submarine canyons and fan deltas.

Canyons are steep-sided submarine valleys that are deeply incised into continental slopes and sometimes shelves (Shepard and Dill, 1966). Some canyon heads, such as in the Zaire and the Capbreton canyons, penetrate into the river estuary. This latter canyon was connected to the Adour River until AD 1310, but was anthropically disconnected afterward (Klingebiel and Legigan, 1978). Four hypotheses have been listed for canyon formation (Mulder et al., 2004): (1) the subaerial/shallow-water hypothesis (Mediterranean canyons) as shown by the Messinian fan delta

deposits related to the Var deep-sea turbidite system (Clauzon, 1978; Clauzon et al., 1995); (2) retrogressive erosion as suggested by the presence of failure scars on canyon heads and flanks (e.g., Gaudin, 2006; Gaudin et al., 2006); the frequent alignment of pockmarks in the direction of the canyons or a deep-sea channel beyond the head (Le Moigne, 1999) is consistent with this hypothesis; (3) canyons that are bypass areas along prograding margins (Pratson and Haxby, 1996); (4) erosion by downslope-eroding sediment flows (Pratson et al., 1994). This last hypothesis suggests that hyperpycnal flows would be an important process in excavating canyons and preserving their morphology despite margin progradation. Hyperpycnal flows could also be involved in the prograding margin hypothesis (hypothesis 3). The role of hyperpycnal flows in canyon formation and in the preservation of their morphology is supported by the record of continuous activity of particle-laden flows in canyons connected to deep-sea fans, in which hyperpycnites have been detected; for example, the Var system (Genesseeux et al., 1971) and the Zaire system (Droz et al., 1996; Hiscott et al., 1997; Savoye et al., 2000; Kripounoff et al., 2003). Piper and Normark (2009) suggest that large hyperpycnal flows create broad straight valleys with relatively uniform width. Smaller hyperpycnal flows would be responsible for the maintenance of canyons and slope valleys observed seaward of deltas or ice-covered margins during sea level rise.

The frequent sinuous shape of channels in channel levee complexes also suggests the involvement of hyperpycnal flow in canyon persistence. The frequent sinuous shape of submarine channels is explained by the natural flow behavior in response to the resistance of a hummocky sea floor at its basal interface (Gorycki, 1973). In addition, Leopold and Maddock (1953), Schumm (1981), and Rigaut (1997) suggest that meanders would occur only on moderate-to-low slopes under the action of high-energy low-concentration flows maintained during long periods, that is, hyperpycnal flows. However, recent results (Corney et al., 2006; Keevil et al., 2006) suggest that deposition in the inside bend of meanders results from a particular velocity and density gradient of turbidity currents (Clark and Pickering, 1996). The highest velocity in the basal part of such a current suggests a centrifugal force at the base of the current that is the opposite of what happens in river flows. Meander bars in channels would not be point bars, and long-duration currents would not be necessary to explain the frequent sinuous shape of deep-sea

channels. The Amazon example (Pirmez and Inram, 2003) shows that frequent turbidity currents can have the same impact on channel levee construction as more sustained flows.

In addition, the shape of the canyon or the channel is probably strongly correlated to the type of sediment transport, suspended load or bed load. Abbado et al. (2005) show that the anastomosed shape of the Columbia River is related to the frequent avulsion of shallow-channel/small-elevation levees in a river system dominated by bed-load transport. Large sandar (e.g., Skeidarársandur in Iceland) and, in general, river systems in periglacial environments are anastomosed, and bed load is the dominant process of transport (Blum and Törnqvist, 2000; Gomez et al., 2000). Typical examples are the Yukon and Copper Rivers in Alaska and the Waimakariri River in New Zealand. The upper part of the Var Canyon shows an anastomosed network of small channels, with the channel floor covered by coarse sand and gravel (Parize et al., 1989; Savoye and Piper, 1991).

Fan deltas are coarse-grained prograding sedimentary deposits that form in subaquatic environments (marine or lake). The presence of submarine bioturbation or fauna differentiates them from alluvial fans. However, fossil tracks are rare in very coarse-grained facies. These fan deltas form in shelf or slope waters where they might connect to a deep-sea submarine fan (see classification in Westcott and Ethridge, 1990). A Gilbert-type delta is a fan delta composed of coarse sediments (pebbles) with steeply dipping ($30\text{--}35^\circ$) foresets. This type of delta would form from a mountain river depositing sediment into a freshwater lake. All fan deltas are directly connected to a river system and are constructed by the stacking of deposits generated by successive high-energy flash floods (bed-load-dominated hyperpycnal flows). In detail, Gilbert-type deltas are constructed by rapidly decelerating hyperpycnal flows (bed-load-dominated hyperpycnal flows) or flows with a small density contrast between the flow body and the surrounding water, that is, the inertia-dominated homopycnal flow described by Bates (1953) or the jet flow described by Wright (1977). Deep-sea submarine fans are constituted by the stacking of both classic failure-related turbidites (Bouma type) and hyperpycnites. Interbedding of Bouma sequences and hyperpycnites in the Var system (Migeon, 2000; Migeon et al., 2001), the Zaire system (Migeon, 2000), and the Arabian Sea (Bourget et al., 2010a, b) show that the two initiation processes (failure transformation or direct river transfer) can interact in the same deep-sea environment.

CONCLUSIONS

Hyperpycnal floods occurring in modern and late Quaternary lacustrine and marine sedimentary environments are frequent and can extend into deltaic environments. Flood events are generally erosive in shallow waters and contribute to the development of channel levee systems. In deep waters, the deposits (hyperpycnites) can reach fan lobes and be distinguished from classical turbidites by the occurrence of organic debris of continental origin at their base and by the preservation of a coarsening-upward basal sequence associated with the waxing flow of the flood event.

Hyperpycnal flood deposits can result either from suspended-load- or bed-load-dominated hyperpycnal flows triggered by climatic events such as heavy rainfall or snowmelt, or by catastrophic events such as jökulhlaups or dam outbursts in the drainage basin. In addition, reconcentration processes affecting low-magnitude floods along deltaic slopes can develop suspended-load hyperpycnal flows in deep-marine waters. Consequently, most of the world's rivers (>80%) could generate hyperpycnal flows in the submarine environment. Given that hyperpycnal flows are sustained, bed-load transport can be important and clean sandy lag deposits can occur along the floor of hyperpycnal-dominated channels.

Large hyperpycnal floods are documented in both lacustrine and marine environments in association with significant environmental changes, such as fluctuations of continental glaciers. The current global warming in mountain ranges, together with earthquake and volcanic activities, may thus favor the development of temporary dam lakes (proglacial moraine dam lakes caused by melting glaciers; landslide dam lakes caused by reduced permafrost) and expose fluvial valleys, lakes, and coastal regions to catastrophic hyperpycnal flood events in the near future.

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