Deposits related to the failure of the Malpasset Dam in 1959
An analogue for hyperpycnal deposits from jökulhlaups

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Sediment cores collected in the Gulf of Fréjus (SE France) contain submarine deposits related to the failure of the Malpasset Dam in 1959. These deposits constitute a dark, sandy terrigenous layer of 10–40 cm thickness lying above an erosion surface. The deposits are composed of ungraded, non-bioturbated sands and silts displaying no apparent sedimentary structure, but rich in organic matter and rock or shell fragments. During the event, this layer prograded onto the inner continental shelf and froze rapidly. These hyperconcentrated flow deposits are related to an unsteady inertia flow generated by a surge-like flood and bedload-dominated hyperpycnal flow. Rapid freezing on flow sides generated lateral, coarse-grained, levee-shape deposits. The deposits related to the failure of the Malpasset Dam are drastically different from classical suspended-load-dominated hyperpycnites deposited by a steady, flood-generated, hyperpycnal flow. However, they are comparable with present-day deposits on a volcanic, ice-covered margin (Icelandic jökulhlaups), with ancient deposits resulting from the pulsating output of subglacial lakes during a deglaciation, or with Martian landforms resulting from sporadic ice–melt events during early Martian times.

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1. Introduction

Submarine turbidity currents can have two main origins (Normark and Piper, 1991). They can result from the transformation of a submarine slide into an initially laminar and then turbulent flow. They can also result from the direct transformation of a river flow entering the sea during a flood, when the suspended sediment concentration is high enough to form a non-buoyant plume (hyperpycnal flows of Bates, 1953; Mulder and Syvitski, 1995; Nakajima, 2006). In this latter case, the flow becomes a turbidity current and its velocity reflects variations of the flood hydrograph at the river mouth. These variations are recorded in hyperpycnal deposits (hyperpycnites of Mulder et al., 2002) that show a coarsening-up interval deposited during the period of increasing discharge and a fining-up-interval deposited during the period of decreasing discharge. Hyperpycnal flows with high suspended sediment load occur preferentially at the mouths of small mountain rivers (Milliman and Syvitski, 1992), and the duration of the floods depends on the climatic environment (Wright et al., 1986; Mulder et al., 1998a,b; Saint-Onge et al., 2003; Warrick and Milliman, 2003; Milliman and Kao 2005; Yu, 2006). For high-magnitude floods, the basal unit can be eroded during peak flood conditions generating a hyperpycnite with missing base resembling a classical Bouma sequence (Bouma, 1962; Mulder et al., 2001b; Mulder et al., 2002).

Catastrophic events can also produce hyperpycnal flows but, in this case, bedload transport is dominant. For example, the sudden emptying of a subglacial reservoir filled by meltwater during the eruption of the Grimsvötn volcano (Iceland) in 1996 produced a jökulhlaup that reached 50,000 m³ s⁻¹ on the Skiedararsandur (Grönvold and Jóhannesson, 1984; Einarsson et al., 1997; Gudmunsson et al., 1997). A total water volume of 3 km³ discharged into the ocean in only two days, with sediment concentration reaching reached 200 kg/m³ (Mulder et al., 2003). Similar triggering can occur at a higher magnitude during the deglacialiation of a major ice-sheet. Brunner et al. (1999) and Zuffa et al. (2000) described deposits related to hyperpycnal outburst of glacial Lake Missoula (Utah) during late Pleistocene (17–12 ka). The 2000 km² lake drained 40 to 80 times generating multiple floods with estimated peak discharges of about 10⁷ m³ s⁻¹ (Mullineaux et al., 1978; Baker and Bunker, 1985; Waitt, 1985). The related deposits were cored during an IODP leg (Shipboard Scientific Party, 1998a,b,c; Brunner et al., 1999; Zierenberg et al., 2000). They show several metre-thick massive, crudely-graded, sand beds corresponding to hyperconcentrated and concentrated flow deposits (Mulder and Alexander, 2001). The contemporaneous emptying of Lake Bonneville in Oregon (estimated volume, 1583 km³; Gilbert, 1878; Malde, 1968) produced a flood with an estimated peak discharge of 425 × 10³ m³ s⁻¹ (Richmond et al., 1965) and transported large basalt boulders of several metres diameter (Malde and Powers, 1962). Dromart et al. (2007) reported steeply-inclined clinoforms in Valles Marineris that could be related to outburst flow occurring during...
Hesperian times (3.5 Ga) when Martian atmospheric pressure was high enough to temporarily allow ice-melting.

In this paper, we use the catastrophic flood event resulting from the failure of the Malpasset Dam as an analogue for bedload-dominated hyperpycnal flows generated by sudden flash floods occurring during natural dam breakage or similar outburst events to describe the nature and distribution of the resulting marine deposits and to interpret the associated transport and deposition processes.

2. Regional setting

The study area is located in the western Mediterranean basin (Fig. 1) at the southern geological limit of Calcareous Provence where massive Cretaceous carbonates outcrop. The study area also includes a part of the Tanneron and Estrel massifs (Fig. 2A). The Tanneron is a Hercynian massif containing granites, gneiss and coal deposits and the Estrel is formed by Permian volcanic deposits. The eastern part of the study area is occupied by a Permian depression that forms the western end of the Estrel Massif and shows sedimentary and volcanic Permian deposits.

The combined Argens and Reyran rivers discharge into the Gulf of Fréjus, which is approximately 4 km wide (Fig. 1). Both rivers originate in the Calcareous Provence; the Reyran crosses the Tanneron and Estrel massifs, while the Argens crosses the Permian depression before merging with the Reyran less than 400 m upstream of the river mouth. Bellaiche (1965) described the Quaternary sediments deposited in the Gulf of Fréjus after the Last Glacial Maximum, which constitute a conglomerate disappearing at a water depth of about 80–90 m corresponding to the late glacial coastline (Bellaiche, 1969a). The conglomerate is about 10 cm thick and is covered by terrigeneous transgressive deposits (Flandrian transgression). The late Holocene surface sediments are composed of a soft, dark-beige mud with high water content which thins towards the continental shelf edge (Bellaiche, 1965; Bellaiche et al., 1969). The shallowest extent of these late Holocene muds (mud-line of Bellaiche, 1969b) was located at a water depth of 15 m prior to the Malpasset Dam breakage (Nesteroff, 1965) and 23 m following the event (Bellaiche, 1969a). At water depths shallower than 15 m, the mud is replaced by coarse shoreface deposits (Bellaiche, 1969a). Seaward of the shelf break, the Argens–Reyran river system continues through the deep Fréjus canyon (Fig. 1).

2.1. The 1959 flood

The Malpasset Dam was a 60-m-high arch-dam built between 1951 and 1954, located 14 km upstream of the river mouth. On December
Fig. 2. A: Thickness of erosion and deposition on the continent between Malpasset dam and the city of Fréjus (from Bellaiche, 1965) after the 1959 event. B: Simulation of the wave created on land after the dam breaking (Hervouet, 2000). C: Simplified geological map across the drainage basin of Argens and Reyran rivers.
2nd, 1959, the Dam broke and discharged $49 \times 10^6$ m$^3$ of water into the lower Reyran valley at a velocity of up to 20 m s$^{-1}$. The maximum depth of erosion reached locally 10 m immediately downstream of the dam (Bellaiche, 1969a) and more than 5 m in the city of Fréjus as shown by the limits of urban destruction. Numerical modelling using the Telemac 2D model (Hervouet, 2000; Fig. 2B) suggests that the flood had a total duration of about 20 min. The event caused 439 casualties, mainly located in the city of Fréjus.

2.2. Subaerial deposits

Aerial photographs taken just after the catastrophe show that subaerial deposits formed a large sheet of silty to sandy mud that covered most of the city of Fréjus and surrounding areas (Fig. 3). These deposits have been mapped by Bellaiche (1969a; Fig. 2C). They cover a wide area beginning $\sim 8$ km (straight-line distance) from the coastline and represent an estimated volume of 4,515,400 m$^3$. The thickness of deposits varies from a few centimetres to more than 1.5 m (Fig. 2C). In many locations, erosion and sedimentation appear to have been simultaneous processes. In particular, soft coastal deposits (loose sand) were eroded and transported downstream in the Mediterranean Sea.

3. Data and methods

The data were collected during the Carma cruise (2001) on the N/O Tethys 2 using both a traditional Kullenberg corer and a Barnett interface gravity multi-corer (Barnett et al., 1984). 16 interface cores and 11 Kullenberg cores with lengths varying from 1.2 to 2.65 m were collected on the continental shelf and Fréjus Canyon (Fig. 4). These corings add to the database of 353, 1.5 m-long Kullenberg cores collected on the continental shelf by Bellaiche (1965). For the Carma cruise cores, a 1 cm-thick slab was sampled along each core and was X-radiographed using the Scopix system (Migeon et al., 1999) combining an X-ray imaging system and image analysis software. Grain size...
was measured using a laser diffractometer Malvern Mastersizer. In addition, large thin sections were made to aid interpretation.

Analysis of the detrital petrography was performed after sieving at 90 and 150 μm. The age of the most recent deposits was provided by counting the activity of radiogenic isotopes: 137Cs (resulting from subaerial nuclear tests) and 210Pbexc (half-life = 22.4 yr) were counted over 20 h using a high-resolution gamma spectrometer with a semi-planar detector. 210Pbexc = total 210Pb – 226Ra. No activity can be detected after a period corresponding to five to six times the half-life at the maximum (Jouanneau et al., 1988; Gouleau et al., 2000). The appearance of 137Cs marks the beginning of nuclear tests in atmosphere (year 1952). The peak of 137Cs corresponds to the most intense testing period (1963). In coarse deposits, sediments were sieved at 150 μm to concentrate the fine fraction. This method is appropriate in this study because we do not calculate sedimentation rates but simply need to verify the young age of the uppermost deposits in the cores.

4. Results

11 interface cores collected on the continental shelf during the Carma cruise and 48 cores from Bellaiche (1965) contain an organic-rich layer of 10–40 cm thickness (Fig. 5), deposited above olive-grey to dark olive-grey bioturbated mud (Fig. 5). This organic-rich layer is limited by a basal sharp or erosive surface and is dominated by coarse sand to silt grain sizes. The grain size analysis shows that the hemipelagic mud has a constant grain size (e.g. cores MT01, MT02, MT03 and MT05 in Fig. 6). This constant grain size allowed easy identification of the base of the Malpasset Dam deposits. For cores containing this deposit, grain size distributions show bimodal curves with peaks at 80 μm and 120 μm. The maximum grain size is about 45 μm for the d50 curve and between 160 and 245 μm for the d90 curve. All the cores containing this layer are located on the inner continental shelf between 6°44′30″E and 6°46′00″E and 43°25′30″N and 43°24′00″N. Most of these coarse deposits are located at water depths shallower than 23 m (Fig. 4).

Vertical grain size distribution (Fig. 6) shows either no grading or a crude coarsening-up trend, for example on MT 10 and 9. No sedimentary structure or bioturbation is visible in the dark layer. Binocular and thin section analysis show that the dark layer contains abundant quartz, mica, feldspar, pebble, rock fragments (essentially Permian pelites and gneiss), and frequent gastropods (Turritella) of 3–5 cm length. It contains also numerous vegetal remains (pine-cone, etc.).
described in studies of the surface deposits previous to the 1959 event (Nesteroff, 1965; Bellaiche, 1969a). (4) This dark layer lies on the beige mud interpreted as late Holocene deposits by Bellaiche (1969b). (5) These recent deposits form a seaward-prograding wedge with thickness decreasing from 30 to 0 cm. Nesteroff (1965) showed that the shallowest extent of the late Holocene mud was close to isobath 15 m. Bellaiche (1965) suggests that the shallowest extent of the mud line after the dam break was located between isobaths 20 and 23 m. Our new data show that the deposits related to the dam break extend slightly deeper than isobath 30 m. However, at a water depth deeper than 20–25 m, the dark layer is thin and probably discontinuous (Bellaiche did not detect it in cores) suggesting that the flow spread at this location. These results suggest that the dark layer covered the older Holocene mud, leading to the deepening of the mud line. (6) The presence of a sharp or erosive basal surface suggests an energetic process for the deposition of this dark layer. (7) The grain-size of the deposits is very similar to the grain size of the deposits deposited onland after the dam broke (Bellaiche, 1969a). (8) The $^{210}$Pb$_{exc}$ and $^{137}$Cs dating show that the dark sandy-silt layer is covered with centimetre-thick mud drapes with an age of <100 years.

The analysis of the detrital petrography shows that the origin of the deposit is the Tanneron massif (gneiss) and the Permian depression (red Permian clasts). Abundance of quartz, mica and feldspar is characteristic of the rocks surrounding the dam and deposited in the Reyran River. The heavy minerals are typical both of the Argens River and the Fréjus beach. Only the zircon and the monoclinic pyroxenes suggest a source from the Reyran River (Bellaiche, 1969a). This is explained by the fact that Argens and Reyran rivers merge 400 m upstream of the river mouth and that a large part of the Fréjus beach sand was reworked and transported downstream during the flood, as shown on the subaerial photograph (Fig. 2). This erosion of Fréjus beach is also consistent with the two peaks in the grain-size distribution curve.

The transversal and longitudinal variations in deposit thickness are very informative regarding the flow behaviour. The thicker deposits observed on both sides of the point where the flow entered the sea suggest that the flow behaved as a typical planar jet flow of Bates (1953) or inertia-dominated flow of Wright (1977). The quick thinning and disappearing of the deposits seaward (in less than 4 km) is consistent with such a behaviour. This behaviour is typical of a fast-moving, high-concentration, bedload-dominated flow. The shear resistance is higher on the sides of the flow, where freezing occurs more rapidly and more intensely, generating coarse deposits with a levee shape while the flow continues to bypass along the main axis of transport where the driving force exceeds the shear resistance (Fig. 4). This kind of deposit has been described in friction-dominated (hyperconcentrated flow and debris flow deposits) both in subaerial (Johnson, 1970, 1984) and submarine (Middleton and Hampton, 1973) environments.

These results suggest that the coarse, dark deposit observed in cores was generated by the violent flood caused by the Malpasset Dam failure, and, in that sense, they correspond to a fast hyperpycnal flow. However, the deposits do not show the classical coarsening and fining-up intervals described by Mulder et al. (2003) in hyperpycnites. The explanation probably relates to the nature, magnitude and brief duration of the processes. The 1959 flood corresponds to a typical surge-like flood. This means that the peak discharge occurred suddenly without any preliminary period of increasing discharge (the waxing flow of Kneller, 1995; Kneller and Branney, 1995). In addition, the energy of the surge suggested by the height of the flood wave generated erosion before rapid deposition. Deposits on the continent have a sheet-like shape suggesting that the flow behaved as a hyperconcentrated flow (inertia flow) with deposition occurring through freezing (“en masse” deposition; Middleton and Hampton, 1973; Lowe, 1979, 1982). Deposition was thus too fast to generate any sedimentary structure. The rapid freezing was probably intensified

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**Fig. 5.** Interface cores showing the sequence deposited by the Malpasset Dam failure in MT 9 photograph, X-ray (Scopix) image; grain size curve (d90 values).
when flow spread, at a water depth of 20–25 m, i.e. at the location where Bellaiche (1969a) identified the post-event mudline. The continuity between subaerial and submarine deposits suggests that the process did not drastically change when the flow entered the sea. No grading is visible in the dark layer in cores MT9 and MT10 suggesting that no preferential fallout of particles occurred during deposition. This is consistent with the presence of a progradational wedge of sand deposited above the hemipelagic mud as described by Bellaiche (1969a; Fig. 7). The deposits are similar to the massive sand beds described by Zuffa et al. (2000) related to the Missoula Lake floods. However, these authors also described thinner beds with a crude grading corresponding to the Ta interval of the Bouma sequence (Bouma, 1962) or the concentrated flow deposits of Mulder and Alexander (2001). The lack of grading in the Malpasset Dam deposits can be explained by the small magnitude of the event when compared to the Lake Missoula events. Freezing of the flow was too fast to permit any differentiation at the upper flow interface. Another difference with deep-sea hyperpycnites (Mulder et al., 2001a, 2002) is the restricted extent of the deposits to the inner continental shelf. None of the cores collected in the Fréjus Canyon show recent deposits. Four explanations can be provided for this point: (1) the coarse particle sizes of the sediment deposited in the Reyran and Argens rivers and transported during the flood. Most of the coarse particles come from Hercynian and Permian crystalline massifs, and are composed of rock clasts and dense quartz, micas and feldspar with a grain-size ranging between sand and medium silts. This suggests that these particles were transported as bedload rather than suspended load. (2) The short duration of the event. A surge like flood lasts only a few minutes, and is typically unsteady, first instantaneously waxing, and then quickly waning. This kind of behaviour does not allow bedload transport over a long distance. To be transported over long distances, coarse particles require events of long duration and sustained intensity. (3) As shown by aerial photographs and sediment analysis onland (Bellaiche, 1965), a large amount of the sediments transported during the flood were deposited on the continent. Only a small part of the particles eroded in the Reyran valley were transported into the marine environment. Most of the submarine deposits come from erosion downstream of the Reyran–Argens junction and from erosion
of sand on the Fréjus Beach. (4) The fast spreading and freezing of the flow.

6. Conclusions

The Malpasset Dam failure provides a good example of a surge-like hyperpycnal flow. When entering the sea, its behaviour provides a typical example of an inertia-dominated flow. The deposits related to this sudden flooding event can be found both on land and at sea. In the marine environment, the main deposits are restricted to a narrow and shallow strip between the shoreface and −23 m isobath. Deposits extend more sparsely down to isobath −30 m. An organic-rich, fining-up sandy-silt layer of a few decimetres thickness that prograded over the late Holocene mud constitutes the flood-related deposits. The detrital petrography clearly indicate a source from the Reyran and Argens rivers and erosion of the beach of Fréjus.

The deposits associated with the Malpasset Dam failure strongly differ from classical hyperpycnites because:
- The process relates to an intense, unsteady surge-flow of short duration, very different from the steady flow sustained over days to weeks during a seasonal river flood;
- Suspended load is very low; the flow is essentially bedload-dominated.

Consequently, the process is closer to a slide-triggered, surge-like flow forming a hyperconcentrated flow, with the only difference being the presence of fresh water in the Malpasset surge and saltwater in a slide-triggered turbidity current. The Malpasset flood deposit is a good analogue for surge-like floods generated by the breaking of natural dams, such as those producing jökulhlaupts, or deposits resulting from sudden discharge of subglacial lakes during deglaciation because:
- Most of the floods in these subglacial environments result from the rapid draining of a reservoir, usually a fresh-water subglacial lake;
- The nature of eroded particulate material (volcanic rock in Iceland, moraine deposits on a glaciated margin) generates primarily coarse particles prone to bedload transport.

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