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Consequences of landslide dams on alpine river valleys: Examples and typology from the French Southern Alps

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Landslide dams are common features in Alpine areas; they may act as large sediment traps in upper catchments. To document their influence on sediment fluxes, the authors applied a sediment budget approach. The extent of landslide deposits was reconstructed from geomorphic survey and mapping; the cross-section of the landslide mass in its valley was established and the material characterized. The geometry of the reservoir created upstream from the dam and the volume of trapped sediments were assessed with the use of a DEM within a GIS. Subsequently, the geometry of post-depositional erosional features was used to calculate the volume of the eroded landslide mass. Two study cases were investigated, according to their position in the French Southern Alps and to their initiating slope-failure mechanism: the Fontfroide rock-avalanche site, and the early Holocene Chenaillet earth-flow site. From the calculated volumes of sediment filling and dam erosion, it appears that the degree of river incision across the dam mainly varies as a function of local parameters. Landslide dams are persistent features, controlling sediment fluxes long after their occurrence.

Keywords: *French Southern Alps, GIS application, landslide dam, sediment budget*

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Introduction

Landslide dams are common features in mountain environments, and their impacts may be sensitive at all spatial and temporal scales (Costa & Schuster 1988). At local scale, they control the longitudinal profile of rivers and the spatial pattern of sedimentary storage units, whereas at catchment scale, they influence sediment fluxes, transfers and storage. Such controls are well documented in tectonically active mountains such as the Himalayas or the Alps of New Zealand, where the magnitude and duration of landslide dams depend mainly on both uplift and river incision rates, and subsequently on the possibilities of landslide mass removal (Hewitt 1998; 2002; 2006; Fort 2000; 2006; Korup 2002; 2004; 2005). In most of the mountains, however, the interactions between landslide dams and fluvial systems are more complex to decipher. Previous attempts at quantification have shown that large amounts of sediments can be stored in the upper catchments (Hewitt 2002; Schrott et al. 2003), thus interrupting – at least temporarily – the downstream transmission of sediment through the entire system (Hewitt 2006). Therefore, the longevity of landslide dams must be assessed in order to evaluate the subsequent impacts on sediment fluxes at both spatial and temporal scales.

A sediment budget approach is suitable for the aforementioned objective, as it employs conservation of mass to quantify sediment sources, sinks and pathways within a catchment cell (Fig. 1). Geomorphic units are then considered as sediment stores (i.e. talus sheets or cone, avalanche cone, debris cone, rockfall cone, alluvial deposits), for which variations in volumes are assumed to correspond to the volume of sediments removed from the store or supplied to the store. In alpine environments, sediment fluxes are best tackled through process coupling (within hillslopes, from hillslopes to river channel, within river channel, etc.) and sediment cascades throughout the system (Caine 1974; Caine & Swanson 1989; Jordan & Slaymaker 1991; Harvey 2002). The scale-dependence of these process couplings (Chorley et al. 1984; Slaymaker 1991) introduces even more complexity, because of the coexistence and/or the superimposition of small and/or large landforms and sediments resulting from varying stages of landform development (Otto & Dikau 2004). In order to minimize this complexity, we will consider in this paper the impact of landslide dams on two medium-scale alpine catchments, selected so that their basic components (such as lithology, hillslope gradient, dominant processes, etc.) are quite homogeneous at the catchment scale. However, we do not intend to determine the rates at which each geomorphic process is (or was) operating; rather, we try to estimate the total volume of various sediment traps, with particular focus on breaks of slope where aggradation and storage are best developed, to better assess the consequences of post-glacial large-scale mass movements on sediment fluxes and balance at the catchment scale.

The assessment of sediment budgets can be based upon technical, yet expensive, geophysical soundings methods (Evans 1997; Müller 1999; Trimble 1999; Hinderer 2001; Schrott & Adams 2002; Schrott et al. 2003). Alternatively, GIS (geographic information systems) and DEMs (digital elevation modules) facilities may provide useful tools for the synthesis of geomorphic data and volumetric calculations: it simply requires the modelling of geomorphic unit geometry (erosional and aggradational features) that can be derived from morphometric measurements from DEMs (Campbell

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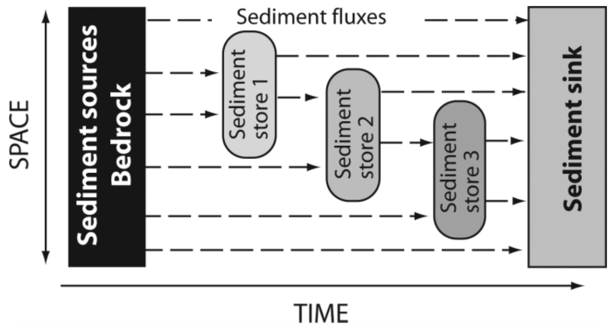

Fig. 1. Conceptual scheme of a sediment budget (Jones 2000).

& Church 2003). We applied the latter approach in this study.

The purpose of this paper is to develop this method in two glaciated alpine catchments to reconstruct the geometry of the reservoir created upstream from the dam and the volume of trapped sediments. By assessing the geometry and volume of post-depositional erosional features (gullying, superficial landsliding, river incision) affecting both the upper catchment and the mass of the landslide dam, we estimate the recovery period over which the effects of the dam may be damped out.

Study sites

Our area of investigation is located in the Upper Durance catchment (French Southern Alps), between the eastern flank of the Massif des Écrins (summits higher than 4000 m a.s.l.) and the Italian border (Fig. 2). Slope instabilities are rather common features in this area because of seismic activity, rugged relief and paraglacial readjustments that have taken place after the Last Glacial Maximum (Cossart et al. 2008). A few landslides caused persistent river damming in association with large ($>10^6\,m^3$) sediment traps, that have offset the sedimentary fluxes at upper catchment scale. To document the duration of landslide dams and their influence on sediment cascade, we selected and compared two sites, where controls on both landsliding and river activity are different (Fig. 3). The first site, the Pré de Madame Carle, located upstream in the Vallouise valley and close to present glaciers, shows the influence of inherited glacial morphology, post-glacial readjustments and current alpine processes in the present hillslope and river profile evolution. In contrast, the second site, located in the Cerveyrette valley, provides an opportunity to document the pattern of landslide/river interactions that are less influenced by former glacial action than by specific lithology (schists) and current seismic activity (Fig. 4). For both sites, chronological (radiocarbon and cosmonuclides) benchmarks are available (Breteaux 1998; Cossart et al. 2008), so that some temporal constraints over which changes in hillslope-channel coupling are taking place can be proposed.

Methods

To document the landslide impacts on sediment fluxes, transfers and storages at the watershed scale, we tried to estimate sediment budgets by combining field survey, DEM and GIS approaches. Sediment fluxes are assessed from the variation in volumes of the sediment storage landforms identified within the basin (Fig. 5). The solutes are assumed to be negligible within the sediment storage as in all high-energy environments (Campbell & Church 2003; Schrott et al. 2003). We proceeded in two steps: first, we reconstructed the geometry of sediment traps and deduced the volume of sediment infill; second, we identified erosional landforms within the landslide sediments and the sediment storage landforms to calculate the export of materials that have taken place since the damming.

Field survey

A geomorphic field survey was first carried out to map both the landslide mass which dammed the valley, the sediment trap created upstream and the post-landslide evolution of adjacent slopes. We established the cross-section of the landslide mass in its valley. Particular attention was paid to the characterization of the dam material (fabric): the grain size of boulders was measured and the percentage of matrix estimated. More recent hillslope failures were also surveyed and mapped with the help of aerial photographs (scale 1:17,000).

We surveyed the nature of the sediments trapped upstream from the dam to distinguish the sediments deposited longitudinally by the river and the sediments supplied from the adjacent, deglaciated footslopes. Footslope evolution was reconstructed in order to identify the main stages of sediment release to the valley floor. Based upon field analysis and photo-interpretation, we identified the various morphosedimentary units covering the lower part of the slopes, such as avalanches or debris cones, alluvial cones and moraines. The identification was based upon well-known criteria (Francou 1988; Bertran 2004): in particular, shape (concave or rectilinear longitudinal profile), particle size distribution and sorting along the slopes, orientation and inclination of the main axis of boulders, fabric of sediments (openwork or not, percentage of matrix) were surveyed. The percentage of vegetation cover was also estimated to document the current degree of geomorphic activity: following Schrott et al. (2003), we considered that a vegetation cover higher than 20% implies low geomorphic activity of the sub-units.

Geometry of depositional landforms

Valley geometry at time zero. Sediment budgets are assessed over a unit time. The reference time (i.e. 'time zero') corresponds to the pre-damming period. At time zero, we assume the valleys were recently deglaciated, therefore they were still imprinted by a fresh, glacially-shaped morphology, most likely characterized by a U-shaped cross profile, and possibly by rock bars and basins (Fig. 3). The glacial

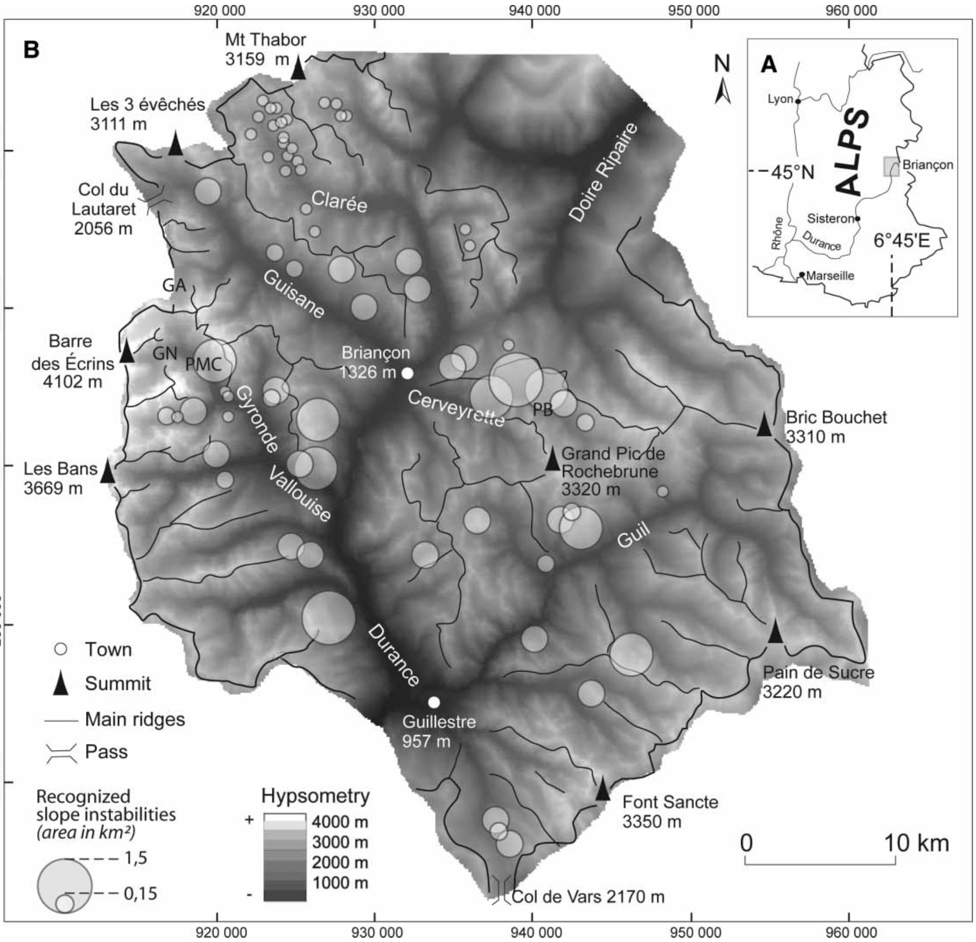

Fig. 2. Location of landslides in the Upper Durance catchment. More than 60 events have been identified, but only a few of them generated river dams (after Cossart 2005). GA = Glacier d'Arsine; GN = Glacier Noir; PMC = Pré de Madame Carle; PB = Plaine du Bourget.

geometry of the valleys at time zero was thus reconstructed based upon a geomorphic model within a raster GIS (ARCGIS) (Fig. 6A & 6B).

First, the pre-damming longitudinal profile is interpolated from the stream power law. A linear regression between the logarithm of distance to the spring and the logarithm of river gradient is assessed upstream and downstream of the sediment trap (Bishop & Goldrick 2000; Brocard 2004) (Fig. 6C & 6D). This profile gives us the altitude of the pre-damming talweg.

Second, some cross-profiles of the buried valley are extrapolated every 100 m. The extrapolation is based upon the Harbor model of a U-shaped glacial valley, assuming that hillslopes can be described by a polynomial law (order 3) (Harbor & Warburton 1993; Schrott & Adams 2002; Campbell & Church 2003; Schrott et al. 2003). Then, according to both the morphometry of slopes located above the buried section and the altitude of the pre-damming talweg, we adjusted our modelled profiles (Fig. 6A). From the obtained profiles, we generated a series of altimetric

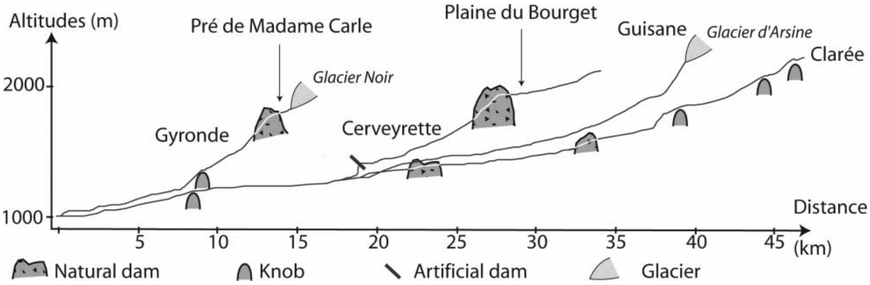

Fig. 3. Long profiles of main tributaries of the Upper Durance catchment. Some of the knickpoints correspond to glacial knobs (rock bars), others are related to landslide deposits. Note that landslide dams mainly occur in the upper part of the catchment, along tributary valleys.

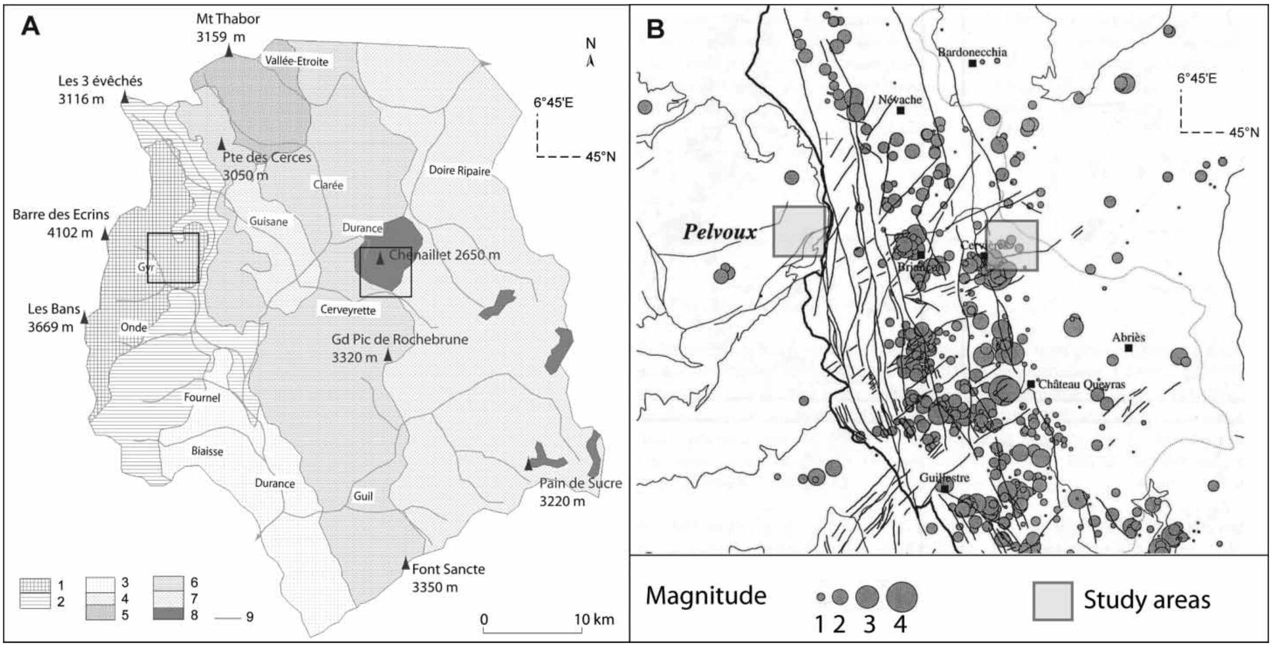

Fig. 4. A. Lithological setting of the Upper Durance catchment. External zone: 1 = granites and gneisses; 2 = sedimentary units (massive limestones). Internal zone: 3 = limestones and schists; 4 = conglomerates and sandstones; 5 = carboniferous sandstones; 6 = limestones and dolomites; 7 = 'Schistes-Lustrés'; 8 = ophiolite complex; 9 = rivers. B. Historical record of earthquakes (after Sue & Tricart 1999). The whole area is subject to seismic activity but the epicentres are preferentially located next to the Durance talweg, along the main Durance fault.

points within the GIS, corresponding to the pre-damming landforms. A TIN model was then created (Delaunay triangulation), and a spline cubic function applied to reconstruct the topography of the time-zero valley (i.e. 'pre-damming DEM'). The horizontal resolution corresponds to a 50 m grid.

Depositional landforms. The quantification of stored sediments is based upon the subdivision of the trap into simple geometric landforms (Fig. 7). We consider separately what is stored below and above the level of the present valley floor.

The volume of sediments trapped below the level of the present valley floor is calculated from a comparison of the pre-damming DEM with the current altitude of the valley floor. These sediments correspond to alluvial floodplain deposits and footslope deposits. Hillslopes and alluvial deposits are commonly interfingered; however, at the model scale, their limit may be simplified and represented by a vertical plane (Fig. 8). A cut-and-fill process within ARCGIS 3D Analyst was applied to measure the sediment thickness and the volume of trapped sediments, represented by a raster map. A combination of the latter with the vector map representing footslope and alluvial deposits allowed the volumes corresponding to every store to be assessed.

The volume calculations of the stores located above the valley floor are based upon geometric modelling. In the high alpine environments studied here, footslope sedimentary stores mainly consist of landslide depositional landforms and/or cone-shaped or sheet landforms (torrential cone, talus-avalanches cones, scree talus). They are modelled as simple geometric landforms to calculate their total volumes (Fig. 7), including porosity and all grain sizes, without correction (Martin 2003). The pre-depositional

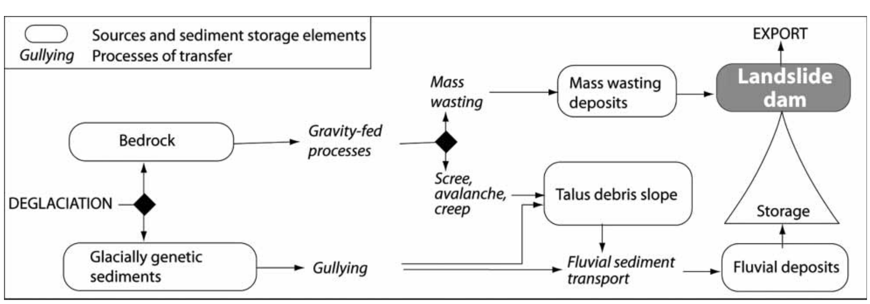

Fig. 5. Conceptual scheme for assessing sediment budget in catchments affected by a landslide dam. The deglaciation is the reference time (time zero) for assessing the budget; particular attention should be paid to the reconstruction of the valley topography just after the disappearance of the glacier.

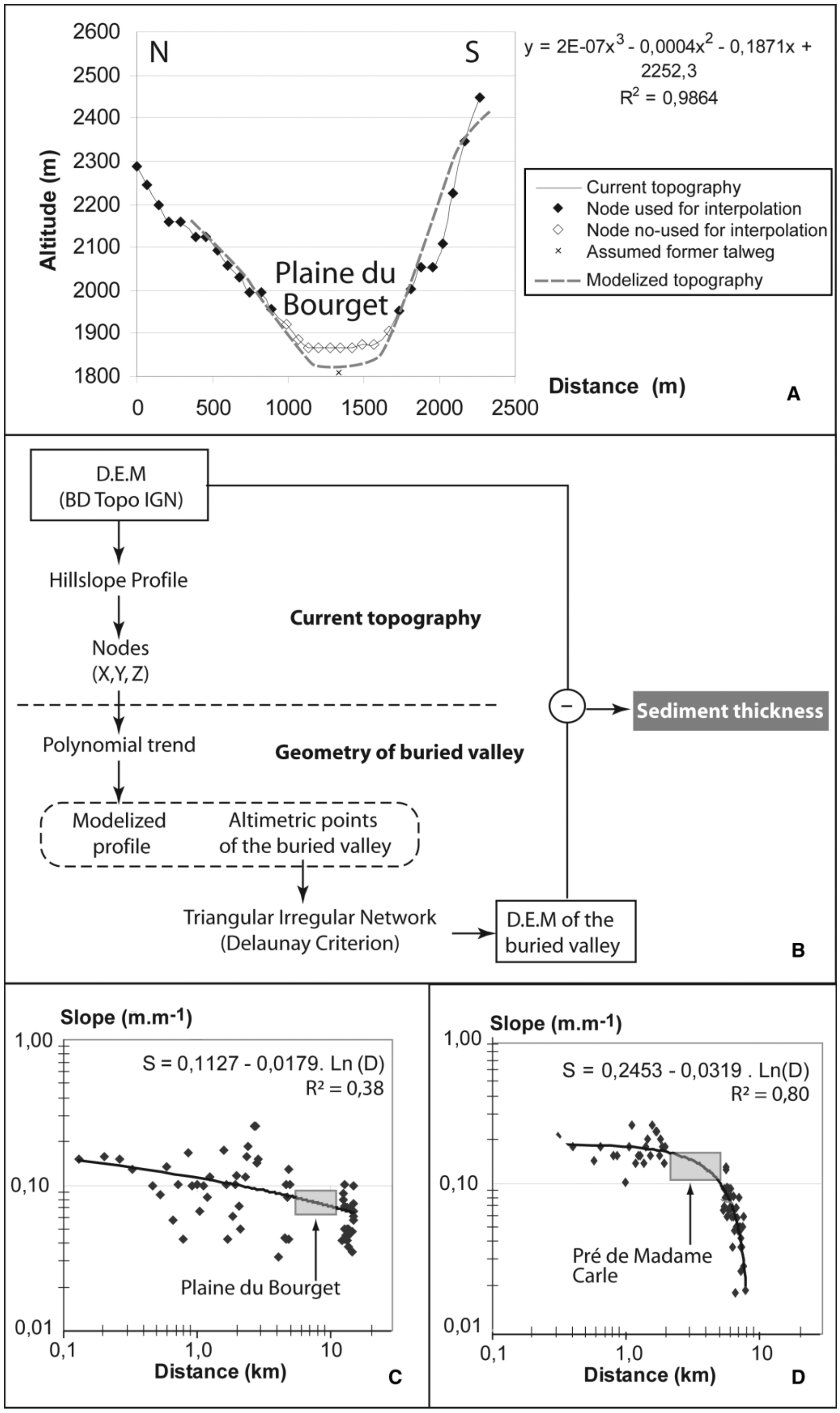

Fig. 6. Methods for quantifying a sediment budget and for modelling long profiles. A. Reconstruction of a glacially shaped valley according to hillslope geometry and the probable altitude of the pre-damming talweg. This profile corresponds to the Cerveyrette valley (see Fig. 9). B. Quantification of the thickness of sediments stored within the valley floor. Current DEM is compared with the interpolated DEM, which corresponds to time zero topography. C and D: Modelling of Cerveyrette and Gyronde long profiles before the occurrence of the landslide dams. The dots correspond to local measurements of slopes, surveyed at regular intervals. The location of buried sections is shown with grey boxes; C. Cerveyrette valley: the trend line is significant; D. Gyronde valley: the trend line fits very well with local measurements.

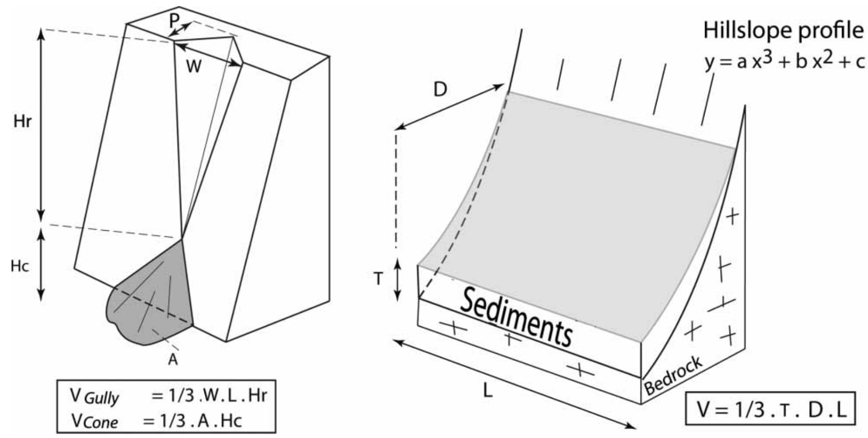

Fig. 7. Volumetric calculations for simple landforms (after Campbell & Church 2003). W = width; P = Depth; H = Height; A = Surface area; D = Distance; L = Length; T = Thickness.

landform is assumed to correspond to the geometry of the 'time-zero' valley. The calculation requires basic measurements (height, width, etc.) provided by a DEM (50 m-grid generated by Institut Géographique National (IGN)), coupled with field measurements (Leica laser telemeter).

Geometry of post-damming erosional landforms

Erosional landforms first correspond to gullies running down most of the length of mountain slopes, eroding bedrock, colluvium, and landslide deposits. They also correspond to the trenches incised within the landslide dam. In both cases, gullies or trench shapes are modelled as a triangular prism, thus allowing the volume of eroded sediment to be calculated. The width and length of the gullies were measured at every 500 m long segments, both in the field (Leica laser telemeter) and on orthorectified and georeferenced aerial photographs (scale 1:17,500). The depth of the gullies was estimated with the same high resolution DEM provided by IGN (altitude uncertainty less than 5 m).

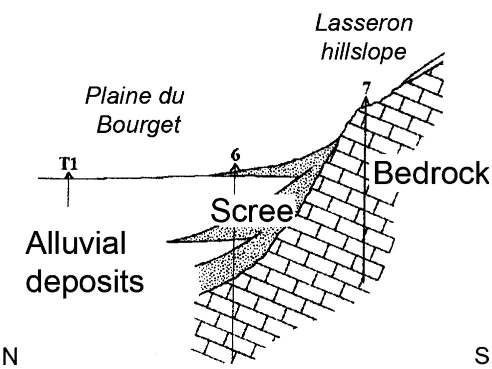

Fig. 8. Simplified evaluation of the limit between interfingered, hillslope and alluvial – lacustrine deposits.

Results

The Cerveyrette valley and the Chenaillet earthflow dam

Geomorphic setting, slope instabilities and cause of failure. The Cerveyrette valley (3286–1200 m a.s.l.), a left bank tributary of the Durance River, is characterized by prominent topographic contrast opposing the south-facing, counter dip slopes of the Lasseron Massif (2702 m a.s.l.), forming high cliffs of massive dolomites, to the north-facing dip slopes of the Chenaillet Massif (2650 m a.s.l.), shaped in weak, poorly cohesive bedrock such as 'Schistes – Lustrés' (highly foliated calcschists in the area) or serpentinized peridotites (oceanic crust klippe), that are particularly prone to mass movement (Fig. 9A). In addition, the east-west trending Cervières fault cuts the lower part of this Chenaillet hillslope (Barféty et al. 1995). At the end of the Last Glaciation Maximum (LGM), the 500 m thick Cerveyrette glacier tongue melted rapidly and left this part of the valley ice-free *c.*12,000 years ago (Cossart 2000; 2005).

A large, 3.5 km long, slide-earthflow occurred after glacial retreat, most probably caused by the combined effects of post-glacial debuttressing and liquefaction (soaking by snowmelt waters) of the serpentinite bedrock, and possibly helped by a very probable earthquake trigger in relation to the activity of the Cerveyrette fault (Fig. 4B) (Sue & Tricart 1999), particularly if it is considered that the landslide mass dammed the upstream part of the Cerveyrette valley 'efficiently' (i.e. instantaneously). The preserved landforms suggest the rapidity and magnitude of the event. Sourced from a 1.85 km^2 rotational slide crown (2320 m a.s.l.), the earthslide–earthflow that was set in motion represents an earth volume of $c.3 \times 10^7 m^3$, composed of a few large peridotite and pillow-lava boulders embedded in a very abundant serpentinite matrix, that flowed down to the Cerveyrette valley (1856 m a.s.l.). The tongue was at least 100 m thick, as indirectly evaluated by the relative altitude of the 1.5 km long levees bounding the earth tongue down to

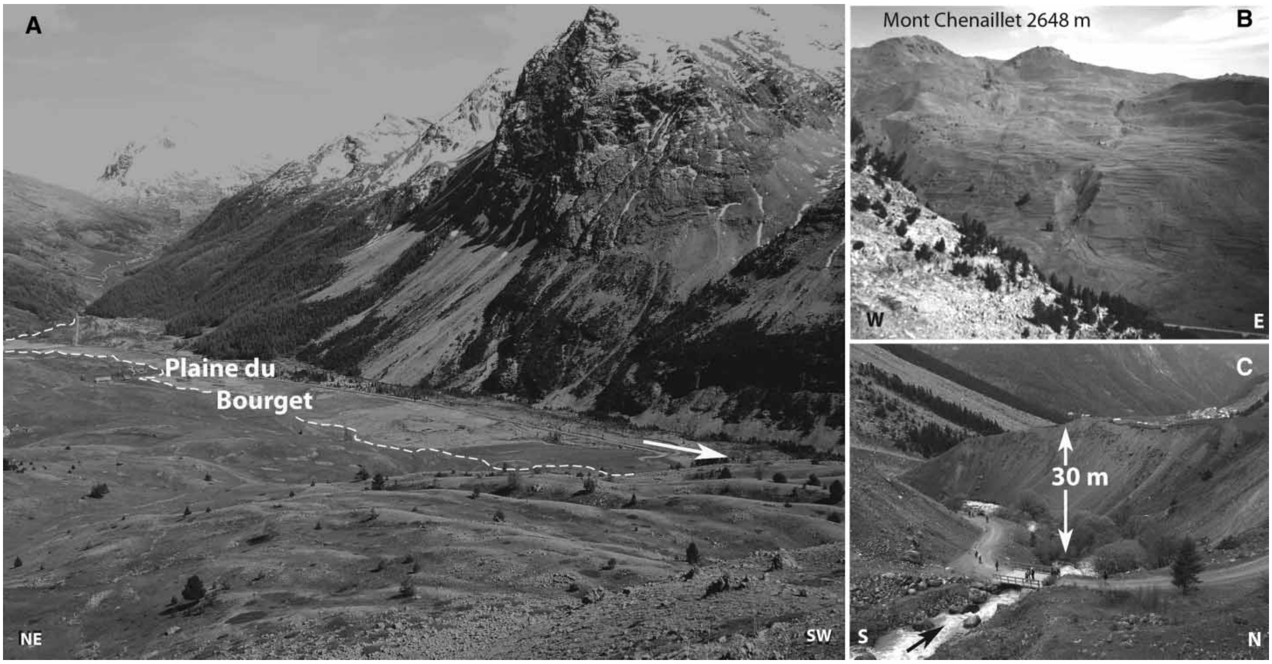

Fig. 9. Views of the Chenaillet area, in the Cerveyrette valley. A. Plaine du Bourget which corresponds to the aggradational plain blocked by the Chenaillet earthflow. Note the contrast between steep massive hillslopes (left flank) and deformed ridge-shaped hillslopes (right flank) (Photo: Monique Fort, 2003). B. View of the Chenaillet mountainslope, affected by *sackung* deformation; note the stepped morphology. Runoff adjusts to such deformations by local incisions and gullies, supplying sediments to the valley floor (Photo: Etienne Cossart, 2002). C. Cerveyrette River channel, incised across the landslide dam (Photo: Monique Fort, 2005).

the valley (Breteaux 1998), and by the depth (>80 m) reached by the sediment cores performed along the axis of the Cerveyrette valley. Downstream, the earthflow was constrained by the Lasseron cliffs, and hence was diverted westwards so that it flowed 1 km down the Cerveyrette valley to the site of Les Aîttes.

Other slope instabilities can be observed along the south-oriented slope. Another earthflow is quite prominent upstream (downslope of the Bousson Pass), the occurrence of which is also related to the presence of serpentinite bedrock. It may have developed at the same time as the Chenaillet earthflow, yet its runout was not voluminous enough to dam the Cerveyrette valley. Between the Bousson and the Chenaillet-Les Aîttes earthflows the depth of hillslope is affected by an extensive rockflow, as evidenced superficially by the presence of backslope antiscarps and depressions (sometimes occupied by shallow lakes or ponds) and/or stepped scarps distinctive of a still active *sackung* (sagging) process. Current geomorphic evolution is also controlled by small-scale landslides affecting the former dismantled slide-earthflow material locally, and by extensive gullies cutting across the full length of the hillslope (Fig. 9B), irrespective of the bedrock nature (either peridotites or earthflow material), and which brings more material to the junction with the Bourget plain (Plaine du Bourget), in the form of small debris fans.

Post-landslide evolution of the sediment trap. The Plaine du Bourget (Figs. 9A and 10) developed in response to the damming of the Cerveyrette valley by the Chenaillet earthflow. The landslide mass was sufficiently voluminous to dam the upper Cerveyrette valley efficiently and cause the aggradation of sediments upstream from the earthflow tongue. The exact nature of the trapped sediments is only known in the distal part of the trap, very close to the earthflow dam, where longitudinal, bottomset lacustrine sediments are interfingered with colluvial, scree deposits (Fig. 8) (Barféty et al. 1995; and unpublished EDF report by Lemoine[1], quoted in Breteaux 1998), built up at the foot of the >1000 m high dolomitic Lasseron cliff. Most of the trap was infilled with alluvial gravels and silts derived from the upper Cerveyrette catchment, fed by alpine periglacial and/or locally glaciated hillslopes (the component grain size reflecting the contrast in lithology between the dolomites of the left bank and the 'schistes lustrés' of the right bank). This large amount of debris aggraded as a prograding fan-delta, progressively encroaching the lake. Other debris inputs constraining the width of the lake derived from the steep slopes of Lasseron as scree and avalanche cones and tali (Fig. 9A), partly buried under the Bourget plain level. The current flatness of the Plaine du Bourget (longitudinal slope *c.* 1–2%), together with the well-developed micro-topography of a meandering stream (abandoned meanders, oxbow lakes), suggest the lacustrine body may have extended approximately 2 km upstream from the dam. Today, the local base level is still controlled by the Chenaillet earthflow dam, despite the fact the dam is already incised by the Cerveyrette, by retrogressive erosion (Fig. 9C).

Sediment budget assessment. The sediment budget can be established as follows (Fig. 11). In our scheme we tried to

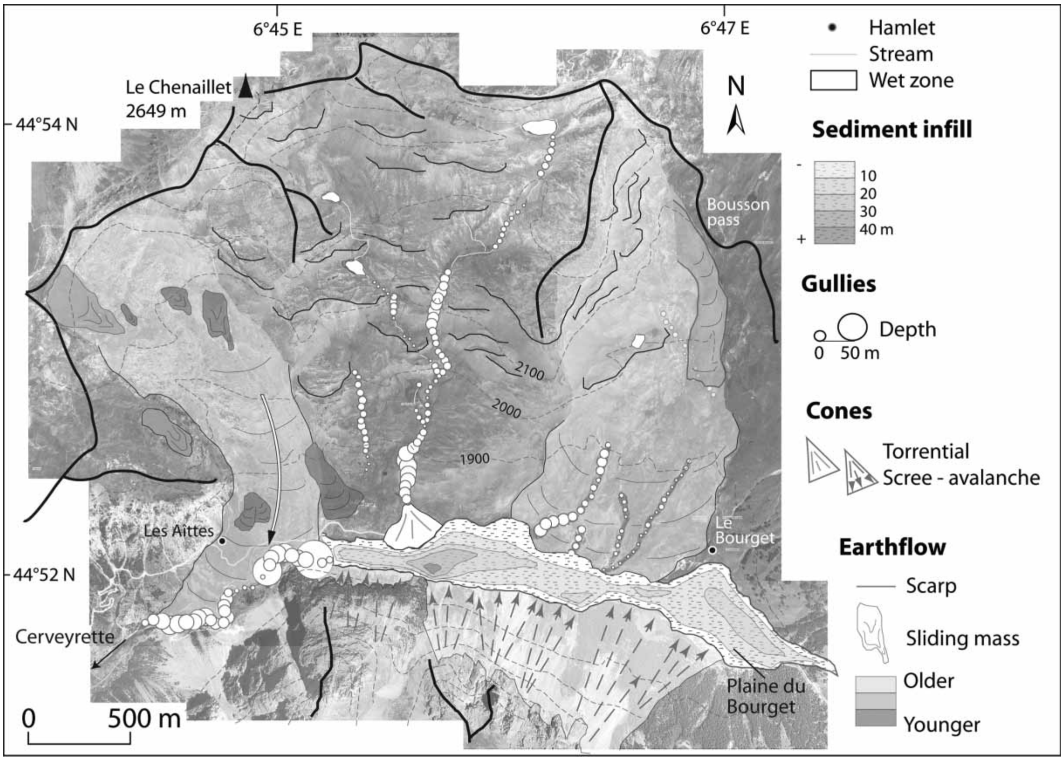

Fig. 10. Geomorphic map of the Chenaillet area and reconstruction of sediment thickness. Note the various generations of landslides and the gullies that are still active.

identify each storage unit as precisely as possible, opposing both right and left flanks of the Cerveyrette valley to its longitudinal axis, and separating masses in transit from those trapped upstream from the Chenaillet earthflow dam. The Chenaillet earthflow dam represents a volume of *c*.21 × $10^6 m^3$ of diamictic material accumulated across the Cerveyrette valley.

The projection of the present hillslope gradient down to the talweg suggests the pre-damming valley was quite wide

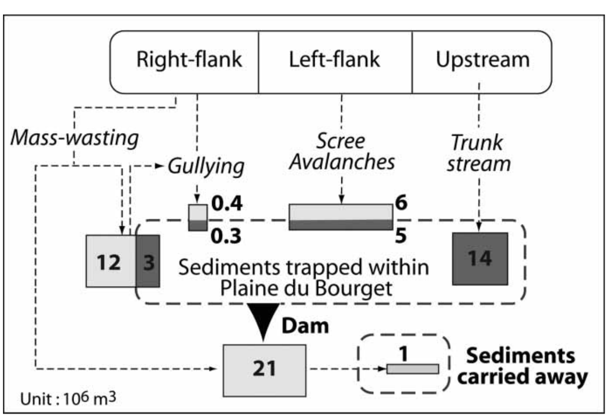

Fig. 11. Sediment budget in the Chenaillet area $>20.10^6 m^3$ are still stored within the valley. Even though impressive, the incision of the landslide dam represents a minor export of sediments.

($>$500m) 2 km upstream from the dam. Hence, in our calculations we assumed that both the landslides and scree deposits extended down to the former axis of the valley. If the extent of talus cones on the left bank is quite easy to delineate (we projected a vertical plane, as shown on Fig. 8), there is more uncertainty relating to assessing the volume of the slides–earthflows derived from the schistose Chenaillet flank of the Cerveyrette (error margin of *c*.10–15%). The buried volume of the footslope deposits derived from the left flank represents about half ($5 \times 10^6 m^3$) of the total scree ($11 \times 10^6 m^3$). Further, the Bousson earthflow runout extended downslope below the present Cerveyrette floodplain; our computation gave an estimated volume of $3 \times 10^6 m^3$ trapped and buried under fluvial deposits (about one-quarter of the total earthflow volume, with an error margin of about 10–15%). Finally, the larger part of the Plaine du Bourget is built up with fluvio-lacustrine sediments representing a volume of $14 \times 10^6 m^3$, almost twice the volume of adjacent slope deposits. Collectively, the Plaine du Bourget corresponds to a large and complex sediment store of *c*.$22.3 \times 10^6 m^3$. This store, developed between the Late Pleistocene and ~5000 BP, first interrupted and then considerably reduced the sediment flux downstream.

As soon as the blockage of the valley occurred, the downstream part of the Cerveyrette torrential river (west of the Chenaillet dam) started adjusting its longitudinal profile by retrogressive erosion, hence progressing upwards from about the site of the present village of Cervières up to the

Chenaillet earthflow tongue. The present situation is a 30 m deep incision through the landslide dam (Figs. 9C and 10). Upstream from the dam, the post-landslide evolution consists mainly of linear incisions into hillslopes by small gullies flowing down the south-oriented Chenaillet slope (Fig. 9B). The measured eroded volume of the gullies is $c.0.8 \times 10^6 m^3$, a value that can be compared to the estimated volume ($0.4 \times 10^6 m^3$) of the debris cones built up at the junction with the Plaine of Le Bourget, thus suggesting that (1) another part $\approx 0.3 \times 10^6 m^3$) is buried and (2) that only a small part of this sediment flux was transferred as suspension load directly to the cascading sediment system.

The present situation corresponds to a total sediment removal and export of only $10^6 m^3$ (*c*.1/60 of debris – either weathered bedrock and/or till remnants – displaced since the Late Pleistocene). Whereas the largest (in the case of gullies) if not the total (in the case of talus scree or avalanche) amount of removed debris from the slopes is still trapped upstream from the dam, most of the sediment carried away results from the still active, yet sporadic dissection of the landslide dam (see Discussion). In this context, the solute and suspended load derived from the upper catchment (Cerveyrette River and gullies inputs) probably represent a significant part that is still to be specified.

The Pré de Madame Carle and the Fontfroide rock-avalanche dam

Geomorphic context and causes of failure. The Torrent de Saint Pierre valley, where the Pré (meadow) de Madame Carle site is nested, originates from the eastern flank of the Massif des Écrins. This area, corresponding to a sub-catchment of the Vallouise valley, is characterized by high differences of elevation between summits and valley floor that can exceed 2500 m (Fig. 12A) and locally reach 4000 m a.s.l. (Barre des Écrins, 4102 m a.s.l.). This very rugged terrain, with slope gradients ranging from 100% to 130%, is distinctive of the local geology and glacial history. The valley, which belongs to the alpine outer crystalline zone (Barféty & Pécher 1984), is deeply cut into massive, yet locally densely fractured, granitic and gneissic bedrock (Fig. 13A) that was carved out by mighty, 600–900 m thick, glacial tongues that developed during the last glaciation. The recession of ice induced paraglacial stress release that exerted a direct influence on rock-slope failures (Cossart 2005).

Today, the valley is dammed by the large Fontfroide rock-avalanche supplied from the left-bank of the valley and abutting against the northern rock face of the Pelvoux Massif (3943 m a.s.l.). The rock-avalanche runout accumulated as a steep, 150 m high, cone-shaped mass (Fig. 13B), the volume of which was estimated to be $c.10.0 \times 10^6 m^3$ according to Colas (2000), though with uncertainty about its exact thickness (likely ranging from order 10 m upstream to 200 m downstream). The avalanche material is a mixture of large blocks (commonly over 10 m^3) and matrix (shattered rocks produced by interclast collisions during rapid downslope transport of mobile debris), which is compacted and confined in the deep valley floor. The largest boulders are up to 15 m in length. They are particularly abundant in the distal part of the deposit. The present accumulation is the result of at least two stages of failure, as attested by sedimentological, morphological, petrographic, and dating evidence (Cossart et al. 2008), that were influenced by paraglacial stress release and joint development. The initial failure appears to have occurred immediately after deglaciation (6.5 ^{10}Be ka, cosmonuclide dating), and affected the lower slopes that had experienced maximum glacial loading and were subject to the greatest stress release. The calculated glacial loading stresses were of particularly high value at this site ($\sigma = \sim 5000$ kPa, $\tau = \sim 300$ kPa) (Cossart et al. 2008). The volume of the dam was incremented by other failures that occurred several millennia after deglaciation (1.5 ^{10}Be ka); in the latter cases, destabilization and failure propagated upslope into a zone of steeper slope gradients, as attested by petrographic evidence. These later failure events were largely sourced from above the maximum altitude of former glacier cover, and hence it appears they are unlikely to reflect the direct influence of paraglacial stress release.

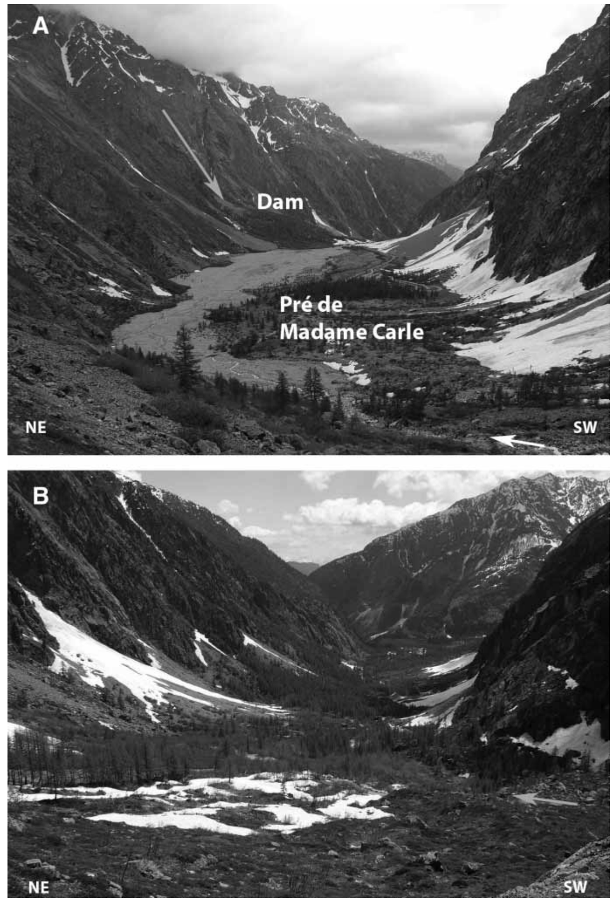

Fig. 12. Views of the Torrent de Saint Pierre valley. A. Downstream view of the Pré de Madame Carle, aggradational plain and the Fontfroide rock-avalanche deposits in the background (Photo: Monique Fort, 2003). B. View of the surface fabric of the Fontfroide deposit; incision by the Torrent de Saint Pierre (the alignment of which is marked by the arrow) is limited by the percentage of large boulders (Photo: Monique Fort, 2003).

Post rock-avalanche evolution of the sediment trap. Debris runout associated with the first event accumulated on the

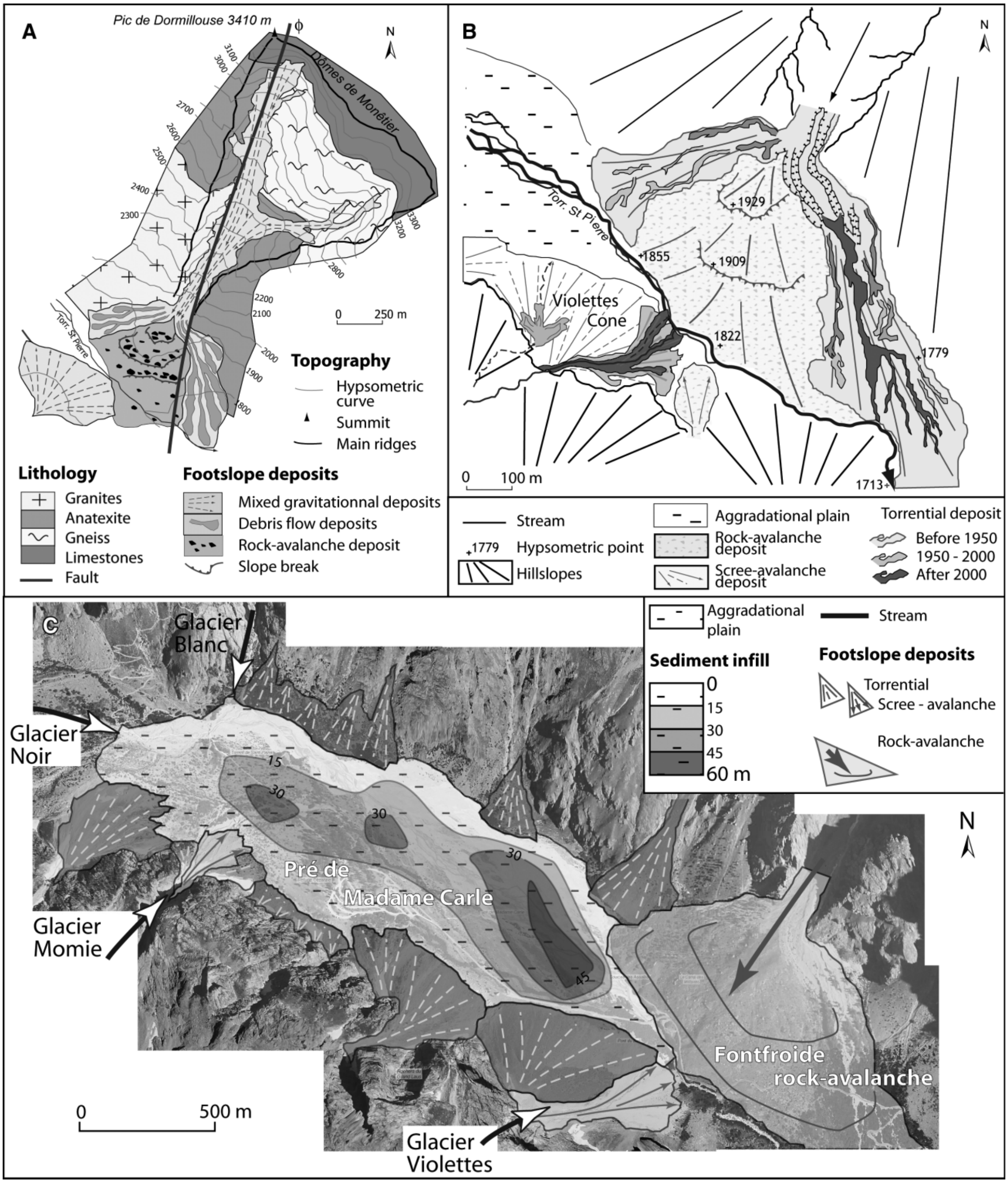

Fig. 13. Geomorphic components and sediment stores in the Pré de Madame Carle area. A. Topographic and geological context (Barféty & Pécher 1984). B: The Fontfroide rock-avalanche deposit and the opposite Violettes cone, restricting the possibilities of enlargement of the Torrent de Saint Pierre channel. Note the active debris flows, more specifically the eastern track bypassing the upper catchment. C: Mapping of hillslope and longitudinal sediments and reconstruction of their thickness.

valley floor, damming the river and creating a sediment trap, today occupied by an aggradational plain (the Pré de Madame Carle) that was and still is fed longitudinally by glacio-fluvial waters originating from both the Glacier Blanc and Glacier Noir margins. Additional inputs were supplied from the south by the Momie Glacier and Violettes Glacier meltwaters. The Fontfroide landslide dam is the local base level and, as such, controls the elevation of the aggradational plain upstream. The plain area is *c*.64 ha, half of which is covered by vegetation today, the percentage of which may vary according to changes in geomorphic activity – more specifically to changes in the rates of glacial melting and lateral undercutting by the braiding of Torrent de Saint-Pierre.

Laterally, the Pré was also supplied with debris by adjacent valley-side footslope deposits (avalanche, rockfall, proglacial stream, and debris flow) accumulated in the form of cones or talus. Scree–avalanche deposits are quite developed (58 ha) and probably started being deposited earlier than debris torrent and debris flow products (9 ha), that are currently active processes, as evidenced by the mapping of debris flows during the 20th century (Fig. 13B). An asymmetry is observed between both left and right flanks of the valley:

(1) On the right flank the sediment stores are larger (surface area of 51 ha; height *c.*200 m) and are characterized by a higher rate of activity. They are mainly made of scree–avalanche deposits ('transition deposits'; cf. Jomelli & Francou 2000), supplied from steep (ranging from 100% to 130%) mountain slopes of the Mont Pelvoux. Debris torrent deposits are locally cut-and-filled within these deposits, and develop downstream water chutes fed by the Violettes and Momie glaciers. Vegetation cover, located on the distal parts of the cone, represents less than 10% of the storage area, hence confirming a high rate of process activity.
(2) On the left flank the stores represent 27 ha. They consist of smaller cones, 50–150 m high, made up of scree–avalanche deposits, derived from steep, deglaciated mountain slopes (ranging from 80% to 130%). These cones are currently partly covered by vegetation (20–30% of the area).

Along the Pré de Madame Carle, the Saint Pierre stream solid discharge is composed of glacial flour, sands and small gravels (<30 cm long axis), mainly transported during late spring and summer high flows. Larger boulders are very rare and when present they are part of the channel armouring. There is no coupling between the mountain slopes and the Saint-Pierre stream channel, except at the Violettes cone foot (Fig. 13B and 13C) (see the following), so that most of the debris is still aggrading along the edges of the 'Pré'.

Quantification and implications for sediment budgets. According to the reconstruction of both longitudinal and lateral profiles, the thickness of the 'Pré' sediment infill is *c.*20–50 m and the trap corresponds to a large sedimentary assemblage of $53 \times 10^6 m^3$ (Fig. 14), with about half of this volume corresponding to the Fontfroide rock-avalanche deposit ($23 \times 10^6 m^3$).

Within the Pré de Madame Carle, the upstream aggradation complex ($31 \times 10^6 m^3$) can be subdivided equally between the sediments stored within the alluvial plain ($15.5 \times 10^6 m^3$) and the sediments stored within the footslopes ($15 \times 10^6 m^3$) supplied by mountain slopes. The asymmetry between the right ($11 \times 10^6 m^3$) and left ($4 \times 10^6 m^3$) flanks of the valley is quite obvious.

Today, the Fontfroide dam is well preserved and effective due to the blocky and massive nature of its components piled up against the Pelvoux rocky wall. Its stability, hence its impounding effect, are additionally reinforced by the presence of the Violettes glacio-torrential debris fan, the location of which right across the Fontfroide rock-avalanche accumulation does not leave any space for the Torrent de Saint Pierre other than a narrow, 3–5 m deep entrenched channel, thus allowing only a small amount of

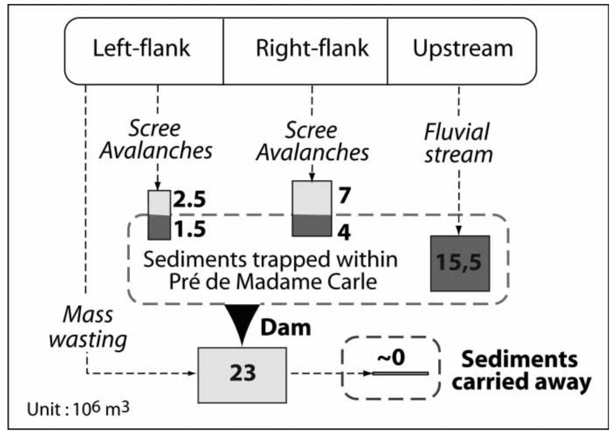

Fig. 14. Sediment budget in the Pré de Madame Carle area. The incision of the dam, thus the export of sediments, is negligible.

debris to be exported out of the system. The removed volume may be estimated to be $0.1 \times 10^6 m^3$, which is negligible compared to the volume of sediments stored upvalley. This sediment output can be broken down into three components: (1) the suspended load carried by the Torrent de Saint Pierre and mainly supplied by glacial meltwaters of Glacier Blanc and Glacier Noir and secondarily by Glacier de la Momie; (2) the debris flow products derived from Glacier des Violettes, because the debris fan and tracks are directly connected to the Torrent de Saint Pierre; (3) most debris flow products issued from the upper slopes of the Fontfroide rock-avalanche are flowing eastward, following the steeper, south-eastward sloping track, hence bypassing the Pré de Madame Carle trap (Fig. 13B). The amount of sediment export is still to be precisely calculated, but at first estimate it does not represent more than 1% of the overall budget since the occurrence of the dam, 6400 years ago.

Finally, the incision depth of the Torrent de Saint Pierre can be considered as negligible compared to the thickness of the rock-avalanche runout. In fact, the largest gneissic boulders are controlling the potential linear incision and act as sound rock, making the dam very resistant. Therefore, collectively, this would mean that the dam is still a very efficient barrier controlling the sediment fluxes and outputs of the system.

Discussion

Assessment of sedimentary budget

Our results are a first attempt at evaluating the sedimentary budget of alpine valleys using an approach combining field survey and DEM and GIS facilities. However, some difficulties were encountered, in the precise computation of trapped sediments and in the evaluation of the outputs, and more specifically of the fine components exported as suspended load by the hydrosystem. If Milliman & Syvitski (1992) consider the suspended load generally to represent only *c.*15–20% of the total solid load, Meybeck &

Vörösmarty (2005) suggest a larger range of values depending on the scale of river basin and type of natural fluvial filters (in this case, landslide dams). Moreover, in mountains streams, uncertainties remain for characterizing material ranging in size from 0.1 to 1 mm that may move as bed load or suspended load depending on flow conditions (Martin 2003). In our study, the position of the basins in headwaters of their respective fluvial systems favours the trapping of coarser particulates, conversely increasing the relative part of suspended and dissolved load as exported sediments. At local scale, the contrasted lithology between the two basins (schists versus crystallines) results in a distinct suspended load output, which is larger in the Cerveyrette valley than in the Vallouise valley.

Method

Our method has proved to be quite efficient. On the one hand, we are well aware that there are some uncertainties concerning the bedrock geometry but former studies have shown that geophysical soundings are not necessarily better tools; they quite often give minimal values (Hoffman & Schrott 2002). Moreover, in the case of U-shaped glacial valleys, the buried topography can be better reconstructed from well-preserved glaciated mountain slopes that are still exposed above the aggradational plain (Dadson & Church 2005), hence reducing the uncertainty. On the other hand, we found good agreement between available borehole data and our morphometric analysis (Chenaillet case study), like Schrott & Adams (2002) and Brocard (2004). Our computation provides an order of magnitude of the depth of the buried valley. Since the modelled topography of the valley floor is at a higher altitude than the theoretical pre-damming longitudinal profile (Fig. 6A), our estimations may possibly be minimal values.

Sediment budget assessment versus cause of rock slope failure

The assessment of sediment budgets relies on some assumptions implying different possibilities of talus slope formation. Hoffmann & Schrott (2002) suggest three options: the tali are either older or younger than the valley fill, or concurrent with it. In the Chenaillet example, sediment cores have shown that there was a concurrent accumulation of alluvial valley filling and slope formation. This may be explained by the distinctive steepness of the Lasseron cliffs, supplying a large and continuous amount of frost- and tectonically-shattered clasts to talus screes, whereas the south-oriented, schists-ophiolitic slope is affected by a quite steady rock- or earth-flow deformation. By contrast, the valley-slope relationship appeared less clear in the case of the Pré de Madame Carle example, in the absence of any available geophysical investigation. However, three lines of evidence suggest the Fontfroide rock-avalanche occurred rapidly after the deglaciation, and therefore before any filling of the valley: (1) the failure plane is located in the zone of maximum glacial loading, (2) the timing of failure is very much influenced by paraglacial stress release, and (3) the pronounced cross-sectional dissymmetry of the valley bottom occurs where there is a sharp knick point in the longitudinal profile, a situation that suggests the runout preserved an empty, glacial valley. We therefore presume that in such a paraglacial context the filling of the trap was, at least in the early stage, collectively controlled by valley-slope debris and proglacial gravels, in a timing and supplying rate well in accordance with the published models (Church & Ryder 1972; Ballantyne 2002). Other examples of paraglacial readjustment have also been reported in the French Alps, such as the La Madeleine rock avalanche ($c.10 \times 10^8$ m^3), that took place in the Arc valley between 13,000 and 10,000 years ago (Letourneur et al. 1983; Marnezy 1999). Upstream from the dam, a >150 m deep lake developed that rapidly filled up with lacustrine and deltaic sediments, which today are partly dissected and on display along the Arc River channel.

Other alpine case studies suggest that the causes of instabilities and valley damming cannot be restricted to paraglacial effects. Firstly, geological parameters are important, as pointed out in the Chenaillet example: there, the current seismotectonic activity of the Cervières fault appears as an essential controlling factor which, if combined with other environmental factors (slope, bedrock type, high hydrostatic pore pressure in relation with snowmelt), may impact the cascading sedimentary system over a long period. In another example, documented by Brocard (2004), the Drôme River (French Pre-Alps) was dammed 500 years ago by the Claps translational rock slide affecting massive, stratigraphically jointed Portlandian (Tithonic) limestones; here also, the litho-tectonic context was crucial. The resulting lake that developed upstream was filled rapidly and today the river percolates throughout the accumulation of large limestone boulders. Secondly, climatic changes are also recognized as an important cause of landslide development, such as in the Italian Alps (Soldati et al. 2004), independently of exceptional meteorological events that may locally trigger catastrophic slope failure.

Whatever the cause of rock slope failure, more geophysical soundings and/or borehole data would allow not only a better estimate of the sediment budget (narrowing error bars) but also a better understanding of the damming development through the detailed description of infilled (lacustrine or other) sediments.

Morphosedimentary changes and landslide stability

The morphosedimentary changes that have affected the functioning of the sediment cascade are another matter of uncertainty, very much in relation to the more or less effective stability of the landslide dam. In our two examples, we have pointed out the difficulty of assessing the present outputs throughout the impounded section of the valley.

The interruption of sediment cascade caused by the two studied landslide dams created large sediment traps (volume = order 10^7m^3) that are still efficient several millennia after their formation, as attested by their low (to very low) incision, controlled and considerably reduced by channel river bed armouring (presence of rock slope rubble). These sediment traps are all the more effective in that they take place in upper alpine catchments where the stream power is rather low and inefficient for the removal of the large boulders composing the whole mass of the dam. As a consequence, these dams are perturbing the paraglacial pattern of sediment delivery, creating segmented river systems: narrow gorges or persistent landslide barriers alternating with, and the cause of, the development of wide sediment stores upstream, that are a major control on sediment fluxes downstream.

In contrast to large river systems developed in highly tectonically active mountains, that are capable of breaching the dams hence re-establishing the longitudinal continuity of the sediment flux (Hewitt 1998; Fort 2000; Fort et al. 1989; Korup 2002; 2005), our two case studies show that Holocene landslide dams counteract fluvial bedrock incision over long periods and control the sedimentary cascade. In both the Fontfroide and Chenaillet examples, the impoundment stage within the 'disturbance cycle' (cf. Slaymaker & Owens 2004; Hewitt 2006) is still effective, so that the development of features such as 'defended' river terraces (upstream from the dam; Hewitt 2002) or landslide-derived sediment pulses (downstream) in relation to dam degradation and/or break (Fort 1987) are not observed.

Another control on landslide dam longevity is its resistance to erosion. In this respect, our cases studies illustrate two types of situation. Whereas the Fontfroide rock avalanche behaves as a stable and rather immune barrier to vertical erosion (presence of huge blocks), the Chenaillet earthflow has been quite deeply dissected by retrogressive erosion, yet the sediment storage of the Plaine du Bourget has not been affected so far. Indeed, this retrogressive erosion progresses upwards sporadically, in relation to extreme meteorological events such as the >100 years recurrence of floods such as the flood of 1957 that destabilized the entire hydrosystem, re-established efficient hillslope-channel coupling, and was characterized by exceptional stream power values (Tricart 1961; Arnaud-Fassetta et al. 2005).

Conclusions

Our study confirms that upper alpine areas are characterized by high rates of sediment production. For instance, in our case study if the largest volume was supplied immediately by large rock failures following glacial retreat, we observed evidence of more recent slope instabilities that are still ongoing, in particular active gullying and debris flow processes related to the progressive recession and melting of present glaciers and to exceptional meteorological events. All these processes are contributing to the sediment cascade removing either glacially inherited, or frost-shattered, or mass-wasting, collapsed debris.

After deglaciation the occurrence of landslide dams interrupted the sediment cascade through creating large sediment traps (volume = order $10^7 m^3$) that are still efficient several millennia after their formation, as attested by their low (to very low) incision. This incision is controlled and considerably reduced by river bed armouring, all the more efficient in that the stream power of these upper alpine rivers is rather low and does not allow the removal of the large boulders composing the whole mass of the dams. The resulting segmented river system allows, in between narrow gorges or persistent landslide barriers, the development of wide sediment stores upstream that exert a major control on sediment fluxes downstream.

From the calculated volumes of sediment filling and dam erosion, it appears that the degree of river incision across the dam mainly varies as a function of local parameters: longitudinal slope and drainage pattern; type, size and permeability of the dam; and current rate of sediment supply from upstream and adjacent slopes. In alpine headwaters contexts, landslide dams are persistent features, controlling the sediment fluxes long after their occurrence.

Note

[1] M. Lemoine (1952) 'Deuxième rapport géologique sur les sondages de la Chau (barrage de la Cerveyrette) effectués au cours de la campagne 1950', unpublished EDF (Marseille) report, 15 pp.

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