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Glacial erosion dynamics in a small mountainous watershed (Southern French Alps): A source-to-sink approach

Lucile Bonneau [a,b,*], Samuel Toucanne [b], Germain Bayon [b], Stéphan J. Jorry [b], Laurent Emmanuel [a], Ricardo Silva Jacinto [b]

[a] *Université Pierre et Marie Curie, Laboratoire Biominéralisations et Environnements Sédimentaires, ISTeP–UMR CNRS 7193, 75252 Paris, France*
[b] *IFREMER, Unité de Recherche Géosciences Marines, Laboratoire Géophysique et Enregistrements Sédimentaires, F-29280 Plouzané, France*

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A B S T R A C T

In this study we used major element composition, neodymium isotopes ratios (εNd) and concentration of REE to track and quantify the sediment routing in the Var sedimentary system from source (Southern French Alps) to sink (Ligurian Sea) over the last 50 ka. Our data reveal that changes in sediment sources over that period, associated with concomitant changes in the hyperpycnal (i.e. flood-generated turbidity currents) activity in the Var submarine canyon, were mainly driven by paleoenvironmental conditions in the upper basin and in particular by the presence of glaciers during the last glacial period. Based on this evidence, we determined when and how glacier-derived sediments were produced, then excavated and transferred to the ocean, allowing us to ultimately tune offshore sedimentary records to onshore denudation rates. In contrast to large glaciated systems, we found that sediment export from the Var River to the Mediterranean Sea directly responded to climate-induced perturbations within the basin. Finally, we estimated that sediment fluxes in the Var routing system were 2.5 times higher during the Last Glacial Maximum than today, thus confirming that glacier denudation rates exceed fluvial rates and that such a pattern also governs the interglacial–glacial sediment flux cycle in other small mountainous basins.

1. Introduction

Weathering processes and their evolution through time are intensely debated, especially in active mountain belts where tectonic and climate forcings are well expressed at the geological timescale (Molnar, 2004; Koppes and Montgomery, 2009; Willenbring et al., 2013). Glaciers constitute a prominent phenomenon in such environments since they induce high denudation rates, especially in temperate settings (Hallet et al., 1996; Koppes and Montgomery, 2009; Koppes et al., 2015). Nevertheless, the relevance of mountains in the relationship between tectonic, climate and weathering has been recently questioned since variations in denudation rate in highlands over glacial–interglacial cycles could have been counterbalanced by opposite changes in lowlands (Willenbring et al., 2013; Hidy et al., 2014). Many studies attempt to correlate sediment yield/denudation rates and glacier/climate parameters by analyzing global dataset (Koppes and Montgomery, 2009; Willenbring et al., 2013; Koppes et al., 2015) but only a few have addressed this issue by focusing on the temporal variations, at high-resolution, of sediment flux from a single sedimentary system (e.g. Elverhøi et al., 1998; Calvès et al., 2013). As a result, and despite the recent development of conceptual models (Hinderer, 2012; Romans et al., 2016; Jaeger and Koppes, 2016) and numerical simulations (Castelltort and Van Den Driessche, 2003; Simpson and Castelltort, 2012), our understanding remains limited. Many glaciated catchments show a substantial decrease in sediment yield at glacial–interglacial transitions (e.g., in Asia: Clift et al., 2008; Clift and Giosan, 2014; in the European Alps: Hinderer, 2001; Savi et al., 2014; or in small Mediterranean catchments: Woodward et al., 1992, 2008; Adamson et al., 2014) while it is accepted that the ability of rivers to transmit high glacier-derived sediment yield to the sea under glacial arid climate is low (Hinderer, 2001, 2012). As a result, it appears crucial to determine when and how glacier-derived sediments are produced, then excavated and transferred to the ocean, in order to ultimately link offshore sedimentary records to onshore denudation rates. The absence of a large floodplain and of a continental shelf in the mountainous Var sediment routing system (Southern French Alps), usually known to buffer the seaward propagation of the landscape response to tectonic and climate forcings (e.g. Milliman and Syvitski, 1992;

* Corresponding author at: Heidelberg University, Institute of Environmental Physics, 69120 Heidelberg, Germany.
E-mail address: lbonneau@iup.uni-heidelberg.de (L. Bonneau).

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Covault et al., 2013), makes this system a rare and ideal target to focus on this topic at high-resolution. The substantial impact of the growth and decay of the Alpine Ice-Sheet, as well as of the Dansgaard–Oeschger (D/O) millennial-scale climate oscillations, on sediment transfer in the last glacial Var sediment routing system strongly support this assumption (Jorry et al., 2011; Bonneau et al., 2014).

In this study, major/trace element concentrations, and neodymium isotopic ratios (εNd) have been determined in sediments from the Var River basin and its offshore turbidite system, for the last 50 kyr. The combined analysis of terrestrial sources and turbidite activity allows us to provide constraints on the glacial–deglacial pattern of sediment yield associated with a small glaciated basin. When compared to case studies from other larger sediment routing systems, this study brings new insights into how transfer-lag can introduce a bias on the source-to-sink approach at glacial–interglacial time-scale.

2. Regional setting

The Var River (SE France) and its main tributaries (Tinée, Vésubie, Esteron and Cian rivers) drain a total area of 2800 km^2, from the Southern French Alps to the Ligurian Sea (Western Mediterranean). No hydropower dams are present in the catchment area. The Var drainage area is characterized by a steep slope (mean 23°) and a mean/maximum altitude of ca. 1200 m and 3200 m, respectively. Typical hillslope erosional processes of steep mountainous and formerly glaciated catchments (gullies, landslides, etc.) are observed all over the basin (Julian, 1977). The Var drainage area is mainly composed of Mesozoic carbonate rocks (mainly limestones and marls) locally covered by Cenozoic sandstones, marls and limestones (Kerckhove and Monjuvent, 1979; Rouire et al., 1980; Fig. 1). Paleozoic External Crystalline Massifs form the upper reaches in the eastern part of the drainage area (Mercantour Massif). They are composed of occidental (Tinée, TMC) and oriental (Malinvern-Argentera, OMC) metamorphic complexes that outcrop in the NE part of the Tinée sub-basin and in the upper Vésubie sub-basin, respectively, and of the Argentera granite. Locally, Permian pelites are found in unconformity on the edge of the External Crystalline Massifs and in the central part of the drainage area. The lower Var valley corresponds to the filling of the Messinian Var valley during Plio-Quaternary, and is now occupied by a braided gravely channel bordered by steep hillslopes. The Var delta, that is very limited in extent (5 km^2), is built on the edge of the narrow (virtually absent off the river mouth) continental shelf (Piper and Savoye, 1993). The modern sediment yield is estimated at 1.63 Mt/yr, i.e. a specific sediment flux of 580 t/km^2/yr (Mulder et al., 1997, 1998). The discharge of the Var River is characterized by a significant seasonality. High water discharges occur during spring when snow melts, and during autumn when rainfall is high. Heavy rainfall can produce floods, with peak discharges of the Var River exceeding 1000 m^3/s, i.e. 20 times the mean annual discharge (50 m^3/s).

The Var River mouth is directly connected to the head of a submarine canyon. The Var canyon joins the Paillon canyon to form a single valley that feeds a channel-levee system (Var Sedimentary Ridge, VSR) ended by a distal lobe which extends to the continental slope of Corsica Island (Fig. 1). Turbidites on the VSR originate from the overflow of (i) turbidity currents that follow a large (earthquake-related) mass wasting initiated at the top of the continental slope in unconsolidated sediments (Mulder et al., 1998; Migeon et al., 2011), and (ii) hyperpycnal currents triggered during high magnitude floods of the Var River (Piper and Savoye, 1993; Mulder et al., 1997, 1998). All the characteristics described above make the Var sedimentary system a potential reactive system (Covault et al., 2013) and a unique target to investigate forcings on sediment flux. Recently, a climate-related pattern has been highlighted in the feeding of the offshore part of the Var sediment routing system over the last 75 kyr (Jorry et al., 2011; Bonneau et al., 2014) through the direct correlation between the turbidite activity on the VSR and climate conditions in the Var catchment at the scale of both glacial–interglacial and D/O cycles. Such a direct connection between climate and deep-sea sedimentation is likely to be carried by hyperpycnal activity of Var river floods that is highly dependent of the balance between water discharge and sediment load (Mulder and Syvitski, 1995; Mulder et al., 1997, 1998). High hyperpycnal activity observed during the last glacial seems mainly to have been caused by the presence of glaciers in the Var valleys and high sediment-concentrated glacial outwash (Piper and Savoye, 1993; Bonneau et al., 2014). We discuss this assumption below.

3. Material and methods

3.1. Sampling method

Chemical analyses were performed on the <63 μm fraction of both marine and riverine sediments. This grain-size fraction encompasses that of marine sediments deposited on the VSR (Savoye et al., 1993), as well as that of the suspended sediment load of the Var River (Gennesseaux, 1966). Some marine ($n = 9$) and riverine ($n = 7$) samples were separated into the 0–45 μm and 45–63 μm grain-size fractions in order to test the possibility of a relationship between grain size and sediment sources.

3.2. Sampling method in the Var River watershed

A total of 43 sediment samples were collected on the river bed of the Var River and its tributaries, in order to determine the geochemical signature of the main lithological units and to quantify the sedimentary mixing that may occur along the onshore sediment route. Because fine-grained sediments (<63 μm) in the river bed are generally not abundant because of winnowing during floods, sheltered areas (i.e. low-energy meanders, base of boulders) have preferentially been sampled. Bulk sediments were passed through a 63-μm sieve on site to obtain several tens of grams of fine sediments. Each sample is regarded as representative of sediments delivered by the upstream drained area.

3.3. Sampling method in sediment cores

We studied two cores collected during the ESSDIV cruise (2008) onboard the R/V *Pourquoi pas?*: a 22 meter-long core recovered on the top of the middle VSR (ESSK08-CS01), and a 24 meter-long core recovered on the southern VSR (ESSK08-CS13). The sediments consist of alternations of millimeter to decimeter-scale turbiditic sandy/silty sequences and hemipelagic muds. The chronostratigraphic framework is well-constrained, and based on ^{14}C-AMS dates and the tuning of the planktic foraminifera *Globigerina bulloides* δ^{18}O record to the NGRIP record (see Jorry et al., 2011; Bonneau et al., 2014 for details).

For this study, the upper part (i.e. silty-clay size fraction) of 91 turbidite sequences in core ESSK08-CS01 ($n = 53$; between 0–30 kyr BP) and core ESSK08-CS13 ($n = 38$; between 30–50 kyr BP) were sampled in order to obtain a mean resolution of ca. 500 yr on the studied time period.

3.4. Analytical methods

3.4.1. Major and minor element composition

Major element concentrations were measured in selected riverine ($n = 21$) and marine ($n = 11$) samples. The chemical composition of bulk sediment samples was determined by wavelength-dispersive X-ray fluorescence (WD-XRF) using a Siemens SRS 303