Preservation of the last aggradation phase in climate-driven terraces: Evidence from Late Quaternary reach-specific fluvial dynamics of the Allier River (France)

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ABSTRACT: There is limited knowledge about the preservation of aggradation phases in Quaternary fluvial records. Previous numerical modelling of erosion and deposition in Late Quaternary Allier River (France) generated the prediction that this river has reach-specific fluvial dynamics related to climate-driven tributary sediment-flux dynamics. To test this prediction, new optically stimulated luminescence (OSL) samples were collected of the Late Quaternary Fx terrace at five locations along a stretch of 60 km. OSL dates of both quartz and feldspar sand grains indicate that all relatively basalt-poor sediments display significantly different ages for each reach (ranging from 36.3 ± 2.0 to 21.1 ± 2.3 ka). The more basalt-rich terrace body consistently yields ages in the range 21.1 ± 1.7 to 16.1 ± 1.5 ka, suggesting contemporaneous aggradation along the whole studied Allier reach during this interval. Our own new OSL date of a Tartaret eruption around 16.8 ± 2.5 ka also fits this time window, suggesting a direct link with volcanic activity. However, there are many more dated volcanic events that coincide with the older basalt-poor units, making it less likely that a direct link between terrace-sediment basin and collisional basin and volcanic activity exists. The timings of the dated depositional events in MIS 3 and 2 all match with simulated climate drivers and published landscape erosion rates. Counterevidence, the volcanic Chaîne des Puys area supplied more sediment during the cold and dry Last Glacial Maximum. Basalt content in the Allier terrace sediments reflects climate-related sediment-flux dynamics upstream. The scarcity of older basalt-poor sediment bodies from MIS 4 and 3 in the Fx terrace suggests that less sediment was supplied and/or the intermittent erosional phases in the Allier were very effective at removing them. We hypothesize that this observation of predominant preservation of the last aggradation phase could be a common phenomenon in most climate-driven terraces. © 2020 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd

KEYWORDS: river terrace; numerical model; pattern-oriented sampling; Quaternary; erosion rate; sediment supply; volcanism; aggradation; preservation

Introduction

All around the world, sediments from MIS 2 are commonly found in the youngest fluvial terraces (Bridgland, 2000; Veldkamp et al., 2007; Counts et al., 2015; Winsemann et al., 2015; Olszak, 2017). Attempts to extract more detailed climate information from these terrace records is often biased towards reconstructing the timing of incisional phases (Cordier et al., 2014; Vandenbergh, 2015; Kolb et al., 2017). These changes are often linked to a change in fluvial style, typically a shift from cold-stage braided rivers to warm-stage meandering rivers. Recently, a study of Tana River in Kenya demonstrated that also in an equatorial fluvial system, without major shifts in its fluvial style, more sediments accumulated within the floodplain during a cold stage compared to a warm stage (Schoorl et al., 2019).

Fluvial landscape evolution reconstructions and modelling have many challenges (Temme et al., 2017; Veldkamp et al., 2017). Recently, it has become clear that the field-based and model-based communities should work more closely together. The approach of pattern-oriented sampling has been advocated by Brient et al. (2018) to bridge this gap.
The underlying idea is that numerical modelling should guide fieldwork more in terms of where and what type of information is to be collected, in order to allow more direct spatial-temporal pattern matching between simulation outcomes and the reconstructed field conditions. Up to now, location selection for landscape and fluvial reconstruction has been biased by the availability and access of records (typical quarries and large natural outcrops), leading to systematically ignoring areas with less accessible sedimentary records.

A numerical modelling exercise (using the 1D longitudinal profile FLUVER2 model; Veldkamp and van Dijke, 2000) was used, and published and generally accepted external drivers (climate: Guioet et al., 1989, 1993; base level: Bintanja et al., 2005; crustal movement: Westaway, 2004) for the last 50ka of the upper Allier basin in the Massif Central in France (Veldkamp et al., 2016), displayed significant reach-specific differences in fluvial dynamics and expression for the past 50ka. When a major tributary joins the Allier, the local erosion/deposition dynamics pattern can change. There are also episodes during which deposition or erosion appears to be contemporaneous along the whole modelled reach. The numerical modelling exercise also indicated that using only terrace morphological units is insufficient to reconstruct the more complex sedimentary dynamics in time. The simulation results indicated where and how additional sampling could take place. In reality, this is not straightforward because the FLUVER2 model is only 1D and does not simulate preservation: it simulates alternating erosion/deposition events in time along the longitudinal profile. Despite this limitation, the following specific predictions were made using the FLUVER2 model (Veldkamp et al., 2016, p. 2266):

- Sediment fluxes in the Allier basin are climate-controlled.
- The timing of aggradation events changes along the longitudinal profile in relationship with tributaries.
- The time lags (transitions) in the fluvial records are different along the longitudinal profile.

These predictions were based on three different transects, for which some calibration (occurrence of alternating erosion/deposition and the vertical aggradation space) and quasi-validation (modelled and observed age of fluvial sediments) was done. Overall, the simulations demonstrated the potential relevance of reach-specific dynamics, an observation shared with Attal et al. (2011), Geach et al. (2015), Kolb et al. (2017) and Takahashi and Sugai (2018). Surprisingly, not many field studies address this issue systematically. The few that do are often faced with difficulties of correlation of sedimentary units and their inherent age uncertainties related to the dating techniques used (Briant et al., 2012; Maddy et al., 2012a). More often, it is assumed that all terrace units can be correlated along a longitudinal profile for many (up to hundreds) kilometres (Merritts et al., 1994; Pazzaglia, 2013).

The FLUVER2 model also suggests a potential stacking of many depositional events during the last 50ka for the Allier. This is illustrated by the simulated erosion–deposition dynamics for selected transects (Veldkamp et al., 2016). It shows that in time, more aggradation events (approximately 60% of the simulated time) take place than erosional events. When the erosional events are mainly localized in the main channel, this could lead to a stack of depositional events in the floodplain, that can potentially be preserved as a terrace body when the floodplain is incised. Based on this modelling outcome, we additionally hypothesize, as a fourth prediction, that a detailed analysis of a terrace body will display a stack of various episodes with climate-controlled aggradation events.

It is the objective of this study to systematically sample similar terrace units in different connected reaches in the Allier system to test the four aforementioned general predictions.

**Study Area**

The study object is a 60km stretch of the Allier River system (in the upper Loire River basin) between the towns of Coudes and Vichy in central France (see Figure 1). The Allier River terrace record has been extensively mapped (BRGM, 2011) and described (Larue, 1979; Pastre, 1987, 2005). The Allier River is the main tributary of the Loire River and drains the igneous and metamorphic Massif Central. The higher-altitude western basin contains several Tertiary to Holocene volcanic provinces (Cantal, Mont Dore and Chaîne des Puys), while the eastern basin, drained by the Dore River tributary, has no Quaternary volcanic activity. Compared to the eastern basin, the western basin is higher (up to 1886m compared to 1480m in the Dore basin) and is known to have supported some mountain glaciers and minor plateau ice sheets in the Sancy–Mont Dore Massif during the late Quaternary cold stages (Veyret, 1986; Etlicher and De Goër De Hervé, 1988).

The original terrace inventories for this stretch of the Allier used predominantly geomorphological characteristics for mapping and consequently terraces were subdivided based on relative height above the current river bed, with Fz being the current river bed and stepping backward alphabetically to the highest and oldest identified Fs terrace (Pleocene). In time, it became evident that these geomorphological terrace chronologies were too simplistic and subdivisions based on more detailed morphology and sedimentology were used, leading to sublevels (not always mapped on the available geological maps). For example, the Late Quaternary Fx terrace was subdivided into a higher Fxa and lower Fxb level. Subsequently, sand mineralogy (Van Dorsser, 1969; Pastre, 1987) and sand bulk geochemistry (Veldkamp and Kroonenberg, 1993a) were used to create further subdivisions of terrace bodies.

The most comprehensive and up-to-date Allier River terrace compilation and geochronology is described in Pastre (2005), where the geochronological control mainly comes from 14C, U/Th series dates combined with dates (TL, K/Ar, Ar/Ar) of known volcanic eruptions. In general, the area has known Quaternary net crustal uplift, causing the fluvial incision of the Allier River and terrace preservation (Veldkamp, 1992; Westaway, 2004). This crustal uplift was not uniform for the whole area, causing regional and local specific terrace preservation and variable relative heights of older terraces above current floodplain level (see Pastre, 2005; Larue, 2008).

The Late Quaternary chronology of the Fx terrace level (considered to be MIS 4 to 2) is fragmented and based on local 14C dates on organics, and U-series dates of travertines (Rihs et al., 2000; Veldkamp et al., 2004). The Fx terrace is characterized by units with significant differences in ‘volcanic’ fragments, and microscopic examination demonstrated that the volcanic sand grains are mainly dark basaltic groundmass fragments ranging from 20 to 60% of the total sand fraction (van Dorsser, 1969). These differences are also clearly visible in outcrops (see inset photo in Figure 2) and allow direct and easy separation of the different units in the field. The standard architecture observed in the Fx terrace outcrops is that the lower and usually thinner units are relatively basalt-poor, with palaeosols occasionally developed in them. These units, if present, are always overlain by apparently uniform, often gravelly and more basalt-rich sediments. So far, there has never been any direct dating of these more basalt-rich units.
The first systematic attempt to reconstruct a chronology for Fx based on $^{14}$C on organic remains was done by Raynal (1984). Since then, $^{14}$C dating has improved considerably and new calibrations have been made. Consequently, many of the older (pre-1990s) reported $^{14}$C ages have unknown quality and accuracy, and therefore cannot be compared directly with modern age estimates and other dating techniques. However, there are a handful of reliable $^{14}$C accelerator mass spectrometry (AMS) dates from organic macro remains which are associated with Fx terrace sediments.

Surmely et al. (2002) present some recent radiometric dates ($^{14}$C AMS reported as calibrated age), from archaeological sites near Longues, for Allier River overbank deposits on the Fx terrace (12 m above current river bed and overlying the basalt-rich top layer). The two reported dates are cal. 15630 ± 120BP and a dated reindeer phalanx of cal. 12290 ± 60BP. These dates indicate that the upper Fx sediments were deposited before 15630 years BP, a timing confirmed by incision rates estimated before 15630 years BP, a timing confirmed by incision rates (mainly due to volcanic component changes). One theory considers these changes to be controlled by climate change-related sediment supply changes. The higher volcanic source areas, in the western part of the basin, are considered to have produced more (basalt-rich) sediment during glaciation and deglaciation phases than the lower-lying areas in the basin (Veldkamp, 1992; Veldkamp and Kroonenberg, 1993a). This climate control was partially confirmed by estimating $^{10}$Be erosion rate signals from the terrace stratigraphic units, where the basalt-rich units displayed higher denudation rates (Schaller et al., 2002). Our modelling exercise of FLUVER2 used this as general model input hypothesis (Veldkamp et al., 2016).

Alternatively, there is a second hypothesis, linking the high volcanic content in the terraces directly to volcanic events. Pastre (2005) used the volcanic mineralogy of dated volcanic events and the Allier terrace sand mineralogy to date them, by assuming a direct relationship between volcanism and events and the Allier terrace sand mineralogy to date them, by assuming a direct relationship between volcanism and

FIGURE 1. Location of the study area and sample sites. Background DEM from low (green) to high (brown) (source: https://www.geoportail.gouv.fr/carte). The main river and main tributaries are indicated, as well as the six sample locations and Le Bouchet lake. [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 2. Photograph of the different sand deposits in the Allier Fx terrace out of one outcrop (Les Martres d’Artière). The dark sand is three times richer in basalt than the more brownish sand. [Colour figure can be viewed at wileyonlinelibrary.com]
### Table I

| Sample location | Total dose rate (Gy ka⁻¹) | Validity |
|-----------------|---------------------------|----------|
| Tartaret 3.14 ± 0.14 | questionable | A fading correction was applied for this sample. |
| Lempdes up 3.87 ± 0.20 | likely OK | OK |
| Lempdes down 3.38 ± 0.15 | Likely OK | Likely OK |
| Lempdes mid 3.51 ± 0.15 | Likely OK | Likely OK |
| Les Martres down 3.15 ± 0.14 | Likely OK | Likely OK |
| Les Martres mid 2.76 ± 0.12 | Likely OK | Likely OK |
| Culp 2.76 ± 0.12 | Likely OK | Likely OK |
| Montagniers down 3.81 ± 0.17 | Likely OK | Likely OK |
| Mariol Ditch 4.22 ± 0.20 | Likely OK | Likely OK |
| Mariol 3.84 ± 0.20 | Likely OK | Likely OK |

For each sample the used total dose rate, used methods and age estimates (ka) and the validity of the age estimate are given.

Methods

Fieldwork

Given the existing modelling outcomes, it was deemed crucial to sample the same terrace units along the longitudinal river profile at multiple locations. As hypothesized specifically, transitions between different sediment bodies can give insight into the timing of deposition and existing time lags. In order to be able to sample at multiple locations, it is essential not to be dependent on specific materials such as organic remains and travertines, since these materials are quite rare in the studied system. We have therefore decided to use OSL techniques despite their challenges, to allow direct dating of burial ages (Wallinga and Cunningham, 2015).

We selected five locations of the morphological Fxa terrace unit along a 40-km stretch of the Allier River between Coudes and Vichy, including several confluences (see Figure 1; Table I gives more specifics about sample locations, including UTM coordinates).

The Fxa terrace unit is well mapped by the BRGM (on 1:50 000 geology maps) and is typically found at 12 to 20m above the current river bed. Every selected section contained a basalt-rich top unit and a lower basalt-poor unit, with the exception of Culhat where a weathered Fw terrace underlies the basalt-rich unit. All sections were logged and described. At each location, all apparent breaks and abrupt transitions in this terrace unit were sampled.

To test if volcanic activity in the high (periglacial) headwaters could be an alternative trigger, we analysed recent dating (40Ar/39Ar and TL) for palaeomagnetic reconstructions by Laj et al. (2014) and additionally sampled materials from the Tartaret volcano for OSL dating to check for a possible direct volcanic link (Maçaire et al., 1992). Several scoria cone remnants are still visible, and one or more lava flows are preserved in the landscape over a stretch of 24km. We sampled silty sediments that were trapped in the scoria when the oldest lake was draining through the scoria cone, and sampled two basalt samples with granitic xenoliths.

OSL dating

We used OSL dating to determine the last moment of full daylight exposure of sand-sized quartz and/or K-rich feldspar extracts derived from deposits taken along the Allier River. For dating late Quaternary river deposits, OSL dating of quartz (Huntley et al., 1985) is the preferred method as it combines favourable properties such as signal stability and at the same
time sufficient bleachability of the targeted signal within fluvial sediment transport (e.g. Wallinga, 2002). Especially when small aliquot measurements are combined with dedicated statistical analyses, OSL dating of quartz is a robust method to determine the burial age of river terrace sediments (e.g. Rittenour, 2008; Cunningham and Wallinga, 2012). In settings, however, where the quartz is sourced from close proximity plutonic, metamorphic or volcanic bedrock, as is the case in the Allier River setting, quartz OSL signals tend to be weak, if not unsuitable. This can hamper successful dating of the corresponding samples. Luminescence dating of K-rich feldspar extracts using infrared (IR) stimulation provides an alternative for these samples. However, IR-stimulated feldspar luminescence has two major drawbacks compared to quartz OSL. First, the signals tend to be thermally unstable (termed anomalous fading; Spooner, 1994), which can lead to age underestimation. Second, signals bleach at lower rates compared to quartz OSL (Godfrey-Smith et al., 1988; Thomsen et al., 2008), making insufficient bleaching and thus age overestimation more likely. To overcome these drawbacks, new measurement protocols have been developed in recent years that make use of a more stable post-infrared infrared (pIRIR)-stimulated feldspar signal (Thomsen et al., 2008). This pIRIR approach can be combined with single-grain analyses of K-rich feldspars to extract the grain population with the lowest (ideally zero) age inheritance (Reimann et al., 2012). A specific challenge for applying feldspar pIRIR approaches to poorly bleached sediments is that the method can be tailored either to enhance bleachability of the IR/pIRIR signals by reducing preheat and stimulation temperatures (Kars et al., 2014) or to enhance stability of the IR/pIRIR signals by increasing preheat and stimulation temperatures (Li and Li, 2011; Buylaert et al., 2012), but not both.

Dating results and specific models and assumptions are given in Table S1 of the online Supporting Information. All obtained OSL dates are listed in Table 1.

Results

We describe all sampled sections and their locations, together with the OSL sample results.

A: Lempdes-Abat

In an outer bend of the Allier River near Lempdes-Abat, an almost 22 m vertical outcrop containing fluvial and slope deposits is located (Figure 1) in an Fxa terrace (Figure 3, ages in ka BP). The fluvial well-sorted sandy layers were sampled for OSL and specific attention was paid to the top basalt-rich sandy unit embedded in more localized fluvial and slope deposits. The sequence is capped with almost 2 m of slope material which contains a specific 14C 13700 years cal. BP tephrA layer that has been mapped and recognized in the Limagne area (Juvigné et al., 1992; Fourmont et al., 2006). The tephrA at our site has been sampled and labelled ‘Dallet’ in Figure 2; Juvigné et al., 1992). All obtained new OSL ages are indeed older than 13700 years BP and demonstrate increasing age with burial depth.

The typical Allier River, basalt-rich sand layer yields two age estimates of quartz 18.2 ± 1.1 and feldspar 16.9 ± 1.2 ka (MIS 2), which agree within 1-sigma uncertainty with each other and are thus statistically indistinguishable. We decided to use the quartz OSL age to estimate the most likely depositional age range of 19.3–17.1 ka for the basalt-rich sediments. About 4 m lower, a basalt-poor unit has a burial age of 33.8 ± 3.1 ka and a 6 m lower unit yields an age of 36.3 ± 2.0 ka.

B: Les Martres-d’Artière

Just before the Artière–Allier River confluence, an area is found where many deep gravel pits are located within the Fxa terrace (Figure 4). Although the exposures are over 20 m thick, we focused on the more recent sediments and on the transition of relatively basalt-poor Allier River sediment to basalt-rich sediments on top. At this transition we were able to obtain two different OSL ages. The underlying relatively basalt-poor unit yields an age of 26.8 ± 2.3 and the overlying basalt-rich unit gave an age of 21.1 ± 1.7 ka. Lower in the quarry where the basalt-rich sediments are thicker, in a gully an age of 18.9 ± 1.6 ka was obtained, indicating an age range of 22.8–17.3 ka (overlapping in the 19.4–20.5 ka range) for the two basalt-rich samples. All samples indicate a MIS 2 age of deposition.

FIGURE 3. Lempdes-Abat sample location. A schematic lithostratigraphical description is given and illustrated with photos. Successful OSL dates are given for either quartz or feldspar. See Table 1 for UTM coordinates. [Colour figure can be viewed at wileyonlinelibrary.com]
C: Culhat

At Culhat we sampled an abandoned gravel pit in the Fxa terrace which had extensive outcrops 30 years ago. In Figure 5 we have included a photo of the former outcrop. This indicates a basalt-rich top layer covering a cryogenically disturbed palaeosol developed in a relatively basalt-poor fluvial deposit. The degree of weathering resembles the sites described by Veldkamp and Kroonenberg (1993a) as Fx1, now known to be MIS 6 (Pastre, 2005). Currently, only a relatively shallow outcrop remains (Figure 5). We sampled at 3 m below the terrace surface in the basalt-rich gravelly unit. This sample yielded excellent matching ages for both quartz and feldspar grains of 18.1 ± 1.1 and 18.0 ± 1.3 ka, respectively. Again, this is an MIS 2 age range of 19.2–18.0 ka with comparable age estimates as observed upstream in the basalt-rich units upstream at Les Martres-d’Artière (B) and Lempdes-Abat (A).

D: Les Montagniers

Another sample location was near the Allier-Dore confluence, which is located 15 km downstream of Culhat. It is located within the current Dore valley as an Fxa terrace at a road cut where about 2 m of fluvial sediments (mainly sands) are exposed, with a clear subdivision of a basalt-rich gravelly top layer overlying a basalt-poor more sandy layer (Figure 6). We sampled near the transition and found a quartz age for the underlying basalt-poor sand (could be due to local Dore influence) of 21.1 ± 2.3 ka. The overlying basalt-rich layer was feldspar dated to 18.5 ± 1.6 ka, which matches remarkably well with the dates for the basalt-rich layers in the other profiles. Again, we observe a MIS 2 deposition of a basalt-rich fluvial Allier unit.

E: Mariol

Near Mariol (Figure 7) in a ditch in the Fxa terrace we sampled, right below a loamy topsoil, a basalt-rich sand layer that showed clear signs of post-depositional mixing, presumably linked to bioturbation. Our best estimate of the age based on the oldest age population (FMMoldest) is 16.1 ± 1.5 ka. However, we recognize that this age might be slightly underestimated because of the mixing. Only 600 m away is the Mariol North site, where along the Fxb terrace scarp a gravelly outcrop of the Fx terrace is exposed. One sample was extracted that yielded a feldspar age of 23.9 ± 2.0 ka. Assuming we are dealing with a single sediment body, these two ages yield a burial age range of 25.9–14.6 ka. Thus, deposition of
the fluvial sediments during MIS 2 is very likely. The morpho-
logical differences between Fxa and Fxb seem to express differ-
ent post-depositional incision phases.

Le Tartaret scoria sample

We did not date the volcanic material directly but focused on
the silty/sandy material trapped in the scoria cone material of
the northern Tartaret volcano cone. This material yielded an
age estimate of 16.8 ± 2.5ka, indicating that the Tartaret vol-
cano was already active during MIS 2. Many published dates
indicate Late Glacial ages and younger. These are all radiocar-
bon dates on organic materials that were more common during
the Late Glacial than during MIS 2. Our OSL date (including
uncertainties) overlaps with the age estimate of 13.7 ± 1.6ka
BP by Pilleyre et al. (1992).

Discussion

Longitudinal trends in timing of aggradation and
erosion events

The schematic profiles and a longitudinal profile are plotted in
Figure 8, indicating which units are preserved at which location. The red marked ages are from published 14C on macro
remains.

The Fx Lempdes-Abat section demonstrates a fluvial aggra-
dation phase from maximum 38.3 to 30.7ka, or a minimum
of only 36.9 to 34.3ka if both samples represent the same unit,
followed by a phase of local slope deposits which is followed
by fluvial aggradation somewhere between 18.1 and 17.1ka
of basalt-rich Allier River sediments (if we accept both quartz
and feldspar ages), followed by slope deposition including the
basalt surface around 18.7 ka, again indicating that no further Kroonenberg, 1993a), indicating that this soil was still at the local accumulation of slope material with volcanic tephra during the last slope-material accumulation. There are no indications of major erosional events.

The Fx terrace at the Les Martres-d’Artière section demonstrates only MIS 2 sediments which have a time gap of at least 2 to 10 ka between deposition of the basalt-poor sediments somewhere between 29.1 and 24.5 ka and the basalt-rich sediments, which were dated between 22.8 and 17.3 ka, or 20.5 and 19.4 ka if the two units represent the same aggradation phase. If the two dated basalt-rich units are considered separate, then at this location the existence of gullies cut into the older sediments infilled with younger basalt-rich sediments could indicate periods of erosion-incision in MIS 2.

At Culhat there is only much older (MIS 6) weathered fluvial material (Fw terrace unit) underlying the basalt-rich terrace deposits. Because there is a partially preserved palaeosol in these older fluvial sediments (see figure in Figure 5), it suggests that there was no earlier MIS 4 or 3 deposition at this location. The 13C cal. age of 18.7 ka was obtained on organic material from a gully in the palaeosol unit (Veldkamp and Kroonenberg, 1993a), indicating that this soil was still at the surface around 18.7 ka, again indicating that no further basalt-poor sediments were deposited at Culhat before the basalt-rich depositional event somewhere between 19.2 and 17.0 ka.

The Les Montagniers section also has a sharp transition of basalt-poor to basalt-rich fluvial sediments, but here at the transition no significant time gap can be discerned. The age ranges of the basalt-rich (20.1–16.9 ka) and the basalt-poor sediments (23.4–18.8 ka) overlap. Because we are close to the Allier-Dore confluence, the lower basalt content in the lower unit might be attributed to a higher Dore component in the sediment (there is no basalt in the Dore catchment). This might be related to incomplete sediment mixing from the two rivers, representing the same aggradation event. The MIS 3 terrace sediments were not observed at this location.

At Mariol we considered the intermediate basalt-rich Fxa and Fxb terrace deposits. The lower unit (25.9–21.9 ka) has an older age than the higher unit (17.6–14.6 ka). However, the top sample location is possibly influenced by bioturbation, making the age result merely a minimum estimate. A buried gully with basalt-poor sediments yielded a 13C cal. age of 29.5 ka (Veldkamp and Kroonenberg, 1993a), indicating a time gap of 4–7 ka between the basalt-richer and -poorer phases. Summarizing, the sampled Fx locations all have different ages of the underlying basalt-poor terrace deposits with varying time gaps between the basalt-rich and -poor units. This seems to suggest that the basalt-poor units reflect reach-specific dynamics (either reach-specific deposition or erosion), while the basalt-rich top unit has comparable age estimates for all sampled locations between minimum 17.6–21.9 ka or maximum 14.6–25.9 ka (if we consider all age estimates including the Mariol sites, as separate aggradation events). However, when we combine the age estimate uncertainties, we can easily group all basalt-rich units into only two brief aggradation events. Namely, 22.8–21.9 and 17.6–17.3 ka if we assume two phases in Les Martres and two phases in Montagniers or, alternatively, one phase 20.1–19.4 ka and a second phase 17.6–17.1 ka (this without the bioturbated Mariol site and a single aggradation phase for both Les Martres and Les Montagniers).

The observed time gaps between the preserved fluvial aggradation events range from 15 to 10 ka. The basalt-richest top unit seems to have been deposited contemporaneously along the 60 km longitudinal profile between 18.7 and 15.6 ka. This age estimation, based on 13 OSL age estimates, almost exactly overlaps with the 13C age estimate range based on four samples, confirming that indeed this terrace unit can be correlated over 60 km. The very last aggradation event (MIS 2) which has the highest basalt content and caps all other Fx sedimentary units is best preserved.

Evaluating the ‘volcanic eruption trigger’ hypothesis

One of the hypotheses concerning the deposition of large amounts of basalt-rich terrace sediments involves a link with active basaltic eruptions during their formation. In case of one specific eruption, one would expect a significant increase of basalt content at one specific confluence (van Gorp et al., 2013). The properties of the Fx terrace unit richest in basalt are plotted along the longitudinal profile to observe possible trends associated with tributaries (see Figure 9). The Couze Chambon is the tributary draining the Tartaret volcano (Lac Chambon area), while the Veyre, Artière and Morge drain, from south to north, various parts of the Chaîne des Puys volcanic chain which had many Quaternary

**FIGURE 8.** Allier River longitudinal profile and schematic correlation of the five sample locations. [Colour figure can be viewed at wileyonlinelibrary.com]
basaltic eruptions. Both the Dore and Buron tributaries drain the granitic eastern basin where no Quaternary volcanic activity took place. The OSL age ranges (11 samples) are plotted with their error range in blue bars. We also plotted coarse sand bulk-chemistry characteristics for the basalt-rich terrace unit. TiO$_2$ and MgO elements are typical indicators for basalt content, while Na$_2$O (associated with albitic feldspars) is grain-size dependent (Veldkamp and Kroonenberg, 1993b). We can observe from the Na$_2$O horizontal trend that we are dealing with similar grain sizes (coarse sands with medians between 800 and 2000μm). The combined TiO$_2$ and MgO trend increases up to a maximum of slightly more than 5% of the total bulk geochemistry, and from 40 to 45km (the zero point reference is the Couze Chambon–Allier confluence) downstream their content decreases to slightly above 2% at 63km. This compositional trend is related to the tributary inputs along the studied reach. The Couze Chambon tributary followed by the Veyre, Artière and Morge all drain the western volcanic basins. This is witnessed by a steady increase of the basalt elements (TiO$_2$ + MgO) downstream (Veldkamp and Kroonenberg, 1993b), with the highest content at the Allier–Morge confluence. From the Dore confluence downstream, there is a steady decrease in basalt elements. The gradual compositional change between tributaries is caused by delayed sediment mixing of sediment fluxes downstream from a confluence (Veldkamp, 1991, chapter 3.3). Since there is no significant increase at one specific tributary, or a gradual decrease from the Couze Chambon downstream, it seems unlikely that one specific volcanic eruption is responsible for the higher basalt content in the upper Fx terrace unit.

In order to evaluate this in more detail, we linked the longitudinal profile characteristics to known basaltic eruptions within the tributary basins during MIS 2. The Chaîne des Puys volcanic range has been built up over the last 90ka, including two periods of heightened activity between 25 and 15ka, when the Allier sediments richest in basalt were deposited. However, there were also volcanic eruptions with lava flows in the tributaries during the periods when the relatively basalt-poor units were deposited. Figure 10 is our own compilation of the number of dated MIS 3 to 1 eruptions in the Chaîne des Puys, using higher temporal resolution than Boivin and Thouret (2014).

Our compilation (based on Nowell et al., 2006; Miallier et al., 2012; Laj et al., 2014) confirms the high-volcanic-activity episodes as indicated by Boivin and Thouret (2014). When we plot the Fx terrace unit basalt composition (TiO$_2$ + MgO) against eruption frequency in the Chaîne des Puys (see Figure 10), we observe no obvious relationship between volcanic activity and Allier sediment composition in time. Taken together, this evidence strongly indicates that it is unlikely that volcanic activity is directly responsible for the high basalt content in the MIS 2 Allier Fx terrace unit. However, since all main tributaries (Couze Chambon, Artière and Morge) had contemporaneous volcanic eruptions in the relevant time frame of 18.7 to 15.6ka BP, we cannot completely rule out that those volcanic eruptions together caused an increase in basalt content of the Allier terrace sediments. The fact that other periods had more volcanic eruptions without a detectable increase in basalt content (see Figure 10) makes this a rather implausible hypothesis. This lack of basalt influx also depends on the connectivity of the Chaîne des Puys area to the Allier downstream. It might be that ongoing volcanic activity did not leave a downstream signature in the Allier sediments because there was limited hillslope–floodplain connectivity in the tributaries (Wainwright, 2006).

**FIGURE 9.** Allier River longitudinal profile (60km) starting at the Couze Chambon–Allier confluence, indicating the ages of the dated Fx terrace units, the compositional change in sand bulk geochemistry (TiO$_2$ + MgO, %) indicating basalt content and their association with tributaries (Volc. indicates tributary with mainly volcanic lithologies; Gran. indicates igneous and metamorphic lithologies). Blue bars indicate correlations of dated units along the Allier River. (Colour figure can be viewed at wileyonlinelibrary.com)
Evaluating the ‘climate drive’ modelling predictions

The numerical modelling exercise using climate drivers (Veldkamp et al., 2016) yielded three different predictions that we will now evaluate based on the new dating results. A detailed comparison with predicted age estimates is difficult as the simulation was focused on the last 50 ka while our new age estimates are only in the range 38–15 ka. Although we focused on the basalt-poor to basalt-rich transitions, we have sampled every exposed terrace unit and did not encounter older MIS 3 sediments. This suggests that limited sediments in the age range 50–38 ka are preserved, indicating significant erosional phases and/or limited preservation. In general, when we compare our new age estimates with the predictions of aggradation (Veldkamp et al., 2016, figure 9), we can observe (see Figure 11) that the model suggests a much wider range of ages with aggradation, while the data indicates a more limited range of ages in the preserved sediments. Because the FLUVER2 model does not simulate preservation, this might explain the main difference between model and field conditions, that only the last major aggradation event is fully preserved. Overall, it seems that the model tends to overpredict large aggradation events, compared to the actual sedimentary record. Also, the timing of some depositional events (given uncertainties) overlaps with predictions of incision, indicating a poor model accuracy. We will therefore only evaluate the broad trends given the inherent uncertainties of the OSL age estimates.

Prediction 1: Sediment fluxes in the Allier basin are climate-controlled.

OSL ages of the terrace sands are plotted in a graph (Figure 11) of the modelled sediment supply (simulated as hill-slope erosion, which is a function of slope, altitude, precipitation and catchment size) (Guiot et al., 1989, 1993; Veldkamp et al., 2016, figure 10). It can be observed that the preserved sedimentary events match closely with modelled (small) peaks in sediment supply during relatively cold and dry periods in MIS 2. This match suggests that depositional events along the Allier are all climate-controlled and not related to deglaciation. Such climate control has been observed for many other European systems (Bridgland and Westaway, 2008; Maddy et al., 2012b; Cordier et al., 2014; Zieliński et al., 2019). The remaining question is why the 20.5–16.9 ka depositional event seems to be so much bigger (in terms of preserved sediment volume, see Figure 8) and richer in basaltic fragments. This aggradation event was predicted for all three simulated reaches. All tributaries (including the non-volcanic Dore) demonstrate a higher sediment supply during this episode. An alternative explanation of the limited occurrence of older events is the issue of preservation, implying significant erosion in between the aggradation events. The local records give a mixed impression. At some locations there is clear evidence...
of erosional phases (Les Martre d’Artière and Mariol), while others contain a palaeosol (Culhat) and slope materials (Lempdes-Abat) indicating no to limited erosion in between the depositional phases.

There are some independent erosion-rate estimates available based on $^{10}$Be of quartz grains sampled from the youngest Fx and Fy terraces and current river bed near the Allier–Dore confluence. They yielded an approximately 15ka delayed/averaged climate-dependent landscape erosion signal (Schaller et al., 2002) which was supported by a lake sediment budget estimate for the last 13ka (Macaire et al., 1997, 2010).

A similar longer-term and more detailed sediment supply record has been reconstructed for the Le Bouchet lake (see Figure 1 for location) (Degeai and Pastre, 2009).

In Figure 12 we combined the modelled sediment supply curve for the higher western volcanic tributaries (Veldkamp et al., 2016) with the $^{10}$Be erosion rates curve of Schaller et al. (2002) and the Le Bouchet lake landscape erosion curve (Degeai and Pastre, 2009). In the same figure we also plotted the Allier sediment composition change. Although direct comparison is difficult, due to the different temporal units, there is a general similarity (given the significant temporal uncertainties) of the erosion rate curve when we move the $^{10}$Be curve 15ka back in time. The sediment composition seems to move in synchrony with these changes. During periods with high erosion rates in the upper volcanic tributary catchments, the basalt content of the Allier sediments increased proportionally.

The three times increase in erosion rates at Le Bouchet lake from approximately 35ka to around 20ka seems related to a three times higher basalt content in the Allier sediments. The $^{10}$Be and simulated changes are less, only an increase by a half, but they appear to be synchronous. This lower rate might be due to the fact that the $^{10}$Be denudation rate is an average for the whole basin including the lower-lying low-relief areas. It is known from more recent $^{10}$Be denudation rate investigations (Schaller et al., 2016) that the denudation rates are related to the overall relief within the fluvial basin.

To summarize, several independent records and our previous numerical simulation demonstrate an increase (between 0.5 to 3 times) of erosion rates in the upper (volcanic) catchments of the Allier tributaries between 25 and 15ka BP, leading to aggradation events with an increased basalt content downstream in the Allier river bed.

Prediction 2: The timing of aggradation events changes along the longitudinal profile in relationship with tributaries.

Our results demonstrate that the older relatively basalt-poor terrace units do display reach‐specific deposition (or preservation) in Figure 9. Some reaches have no evidence of deposition events, while others have contemporary local depositional events, yielding a discontinuous pattern of sediment ages along the longitudinal profile. The blue bars in Figure 9 indicate the age range with preserved deposition. The only exception is the basalt-rich terrace unit that can be consistently traced along the longitudinal profile with in general thick accumulations (up to 20m) (Figure 8) within a limited time frame of a few thousand years. It has to be noted that also the FLUVER2 simulations showed contemporaneous deposition along the whole longitudinal profile during this period. But this also applies for all other events during the 30–20ka period which were not observed in the field data. Every peak in the hillslope-erosion curve (see Figure 11) is related to contemporaneous aggradation along the studied reach (see also Veldkamp et al., 2016, figure 8).

It is known that terraces are diachronic features, and modelling exercises (Veldkamp and Tebbens, 2001; Van Balen et al., 2010) demonstrate that this typically leads to a decrease of age in the downstream direction of hundreds to a few thousands of years along hundreds of kilometres of river profile. Such a trend cannot be confirmed in our case due to the uncertainties of our dating estimates, but a depositional time frame of maximum 3000 years can be observed.

So, we can conclude that the reach-specific differential timing of deposition and/or preservation seems valid for the basalt-poorer events. The exception is the large basalt-rich depositional event, that supplied large amounts of basalt-rich sediments resulting in large-scale aggradation along the Allier within a relatively short period of 33ka, after which incision occurred along the whole studied reach and the Fx terrace unit was formed.

![FIGURE 12. Compilation of simulated landscape erosion rates (Veldkamp et al., 2016). $^{10}$Be denudation rates (Schaller et al., 2002) and reconstructed erosion rates from Lac du Bouchet record (Degeai and Pastre, 2009). Allier Fx terrace sediment composition in time as ($\text{TiO}_2 + \text{MgO}, \%)$ (Veldkamp, 1991, p. 96) is added to demonstrate relationships. Uncertainties are from publications and personal communication (Jean-Philippe Degeai). [Colour figure can be viewed at wileyonlinelibrary.com]](image-url)
Prediction 3: The time lags (transitions) in the fluvial record are different along the longitudinal profile.

When we look at the time gaps in the preserved Fx terrace records, it appears that we have three different reaches. The reach between the Couze Chambon–Allier and Artière–Allier confluence (with temporal gaps of 15–8ka); the reach between Artière–Allier and the Allier–Dore confluence reach (no significant depositional time gaps discerned), followed by the reach downstream of the Allier–Dore confluence where a 5ka gap is observed. These trends seem not only to confirm the time-lag transition predictions but also the reach specificity of the erosion and deposition. These differences can also be related to different tectonic units (Viveen et al., 2013, 2014; Woolderink et al., 2019; Maddy et al., 2020). The knickpoints visible in the longitudinal profile in Figure 8 suggest such a factor, giving the uniform easily erodible lithologies in the Limagne graben. Future detailed analysis of the role of neotectonic activity might reveal additional tectonic controls on Allier terrace formation and preservation.

Overall, we find strong evidence that supports our model assumptions and outcomes, namely that the Late Quaternary Allier system dynamics were predominantly climate-driven. There is a discrepancy between the number of predicted contemporaneous deposition events along the studied 60km reach. We only observed one event. All other predicted events occurred either in specific reaches or were only preserved in a specific reach. We only found units in the Fx terrace in the age range of 38–15ka, suggesting that either no older deposition events occurred or that they occurred but were not preserved. The observation that the last MIS 2 unit overlies a palaeosol in MIS 6 Allier sediments suggests that no earlier MIS 3 or 2 deposition took place at that location. This could suggest that initially during MIS 4 and 3 fewer sediments were supplied to the Allier. Apparently, more clastic sediments were supplied during the coolest and driest stages of the LGM. This might be caused by the gradual buildup of permafrost and shifts in vegetation cover towards less cover, leading to larger sediment supplies during snow/ice melt and precipitation events in the summer over a permanent permafrost in the upper reaches of the volcanic tributary catchments.

There is no clear evidence for a direct link between volcanic activity and either sediment-flux magnitude or sediment composition. The most basalt-rich Allier sediments coincide with a period of reduced volcanic activity, but we cannot rule out a contributing role of active volcanism, for which several mechanisms can be suggested. First, all three known MIS 2 eruptions led to lava flows into the river valleys, facilitating direct sediment transfer to the Allier downstream. Second, the Tartaret volcano might have erupted below the fringes of a small ice-sheet, triggering a large water and sediment pulse in the Couze Chambon. Third, the tephra from Tartaret’s eruption may have triggered accelerated snow melt during summer due to the dark tephra cover, leading to increased fluvial activity across the Chaine des Puys. Another more indirect mechanism is the temporary blockage of rivers, causing a disconnection within a catchment, followed by a large sediment pulse due to the breaching of the lava blockage, thus triggering a headward erosion wave upstream (see van Gorp et al., 2015). Depending on the duration of the blockage, this mechanism could explain why sediment fluxes can happen during periods with limited new eruptions, allowing the fluvial system to remove blockages and reconnect to its upper (volcanic) reaches.

Evaluating the additional prediction that a stack of various climate-controlled aggradation events is preserved within a terrace record.

All the above discussed evidence together makes it clear that in no Allier Fx terrace is a stack of all modelled climate-controlled aggradation events preserved. There is evidence that early aggradation events during MIS 4 and 3 only occurred locally and/or are preserved. Local palaeosols indicate that at some locations no deposition occurred before MIS 2. The increasing amount of basaltic components from MIS 3 to 2 in the preserved terrace sediments also suggests less supply of sediments from the headwaters to the Allier in MIS 3 compared to MIS 2, limiting the likelihood of significant aggradation events in MIS 3. We have not found any MIS 4 sediment. The MIS 3 events that did occur are reach-specific and heavily eroded, suggesting limited magnitude and/or effective erosional phases after each earlier depositional event. Combined, our reconstructed record does suggest that the MIS 2 aggradation event was a large-scale significant event that occurred along the whole studied Allier, that is well preserved in the Fx terraces. Earlier modelled depositional events either did not take place of have been eroded since. This gradual increase of magnitude and preservation of aggradation events during the Late Quaternary might point to a mechanism that is also valid for other climate-driven fluvial systems.

Implications of the field data for future numerical modelling

Although we sampled new sites to obtain independent age estimates, our OSL dates unfortunately have insufficient temporal resolution, due to the sediment characteristics, to allow accurate estimation of erosion and deposition timing. Numerical modelling has a higher apparent resolution, making it impossible to establish direct reliable correlations.

The next challenge will be to step up from a 1D numerical model (FLUVER2; Veldkamp and van Dijk, 2000)) to a 2D model, which will also allow modelling of sediment composition and flux magnitudes (Schoorl et al., 2014; Veldkamp et al., 2017). It will be interesting to compare the dynamics of the Allier and Dore systems and to simulate one to two tributaries in more detail to predict possible field record properties to be investigated in more detail. This 2D approach will allow us to explore the volcanic trigger hypothesis in more detail, in a similar fashion to van Gorp et al. (2015).

Conclusions

Our modelling-based fieldwork allowed us to test our modelled predictions in more detail. We were able to confirm some of the predicted fluvial-system characteristics. The timing of terrace-sediment deposition or its preservation (erosion) appears to be climate-controlled. MIS 3 and 2 sediment fluxes occurred during relatively cold and dry periods. Only for the last MIS 2 unit is there evidence that it was deposited contemporaneously along the studied 60km Allier reach. This unit contains the highest basalt content and was deposited between 18.7 and 15.6ka. This is the only terrace unit suitable for detailed long-distance correlation purposes in the Allier system. The basalt richness of the terrace deposits appears not to be directly related to the frequency of volcanic activity but to climate-driven landscape erosion in its upper volcanic reaches. The older, more fragmentary Fx units seem to display reach-specific patterns of deposition and/or preservation. Comparison with known landscape-erosion records suggests that the reconstructed deposition was mainly active during late MIS 3 and MIS 2, something our model simulations did not predict. This might point to either a long-term delayed landscape...
response (as suggested by Forzoni et al., 2014), and/or to very effective erosional phases in between, removing the evidence of older depositional events. It suggests that the Allier Fx terrace record mainly preserved the final coolest and driest climatic conditions, and does not preserve a full record spanning MIS 4 to 2, as often suggested in conceptual terrace models (Bridgland and Westaway, 2008; Cordier et al., 2014). This observation might be more generally applicable for other fluvial terrace records. We therefore postulate that in most climate-driven terraces, the last aggradation phase is predominately preserved. This observation might also help to separate the different drivers of terrace formation, which are not always only climate-related (Maddy et al., 2020).

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

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