Deglaciation and postglacial evolution of the Cère Valley (Cantal, French Massif Central) based on geomorphological mapping, ^{36}Cl surface exposure dating and glacier modelling

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Abstract

The landform assemblage in the Cère Valley (Cantal, France) provides one of the most complete sequences for Late Pleistocene glacial fluctuations in the French Massif Central. However, the associated glacial chronology has been debated since the 1980’s. This paper aims to improve the glacial chronology in the Cère Valley using ^{36}Cl surface exposure ages. Geomorphological results define two glacier stadials with reconstructed ELAs of 1078 ± 43 and 1152 ± 34 m above sea level. These results are comparable to those obtained in the Alps or the Pyrenees during the Last Glacial

Maximum (26 to 19.5 ka). However, ^{36}Cl surface exposure ages are centred around the Younger Dryas (YD), between 13 to 11 ka (n = 4). We suggest that these ^{36}Cl ages are not related to a standstill during the YD but rather to the effects of the postglacial evolution of the Cère Valley. We investigate two geomorphological end member scenarios to explain the postponed exposure of sampled boulders: the Aurillac Lake scenario and the latter fluvial incision scenario. While the nature of the geomorphological events leading to the boulder exhumation is not fully resolved, we highlight a long phase of postglacial evolution in the Cère Valley.

1 Introduction

At present, the glacial history of the Cantal-Cézallier-Monts Dore (CCMD) in the French Massif Central is poorly known despite early observations of past glacial imprints (Boule, 1896, 1895; Glangeaud, 1921; Julien and Laval, 1868; Rames, 1873) that led to numerous geomorphological studies (Boisse de Black, 1951; Goër de Hervé, 1972; Valadas, 1984; Van Dorsser, 1986, 1982; Veyret, 1978). This is especially true when it comes to the last glacial extents and timing for which large uncertainties remain (Defive et al., 2019; Etlicher and Goër de Hervé, 1988). The geomorphological reconstructions of the CCMD glacier system were based on a sequence of end moraines located in the main Cantal valleys (Cère, Authre, Jordanne, Alagnon, Rhue) and Monts Dore valleys (Dordogne, Tarentaine) (Boisse de Black, 1951; Goër de Hervé, 1972; Valadas, 1984; Veyret, 1978). Most of the glacial remnants were associated to the last glaciation and are used to define three glacial stadials. The oldest, inferred to correspond to the Local Last Glacial Maximum (LLGM), was defined by the outermost end moraines or till deposits. A younger glacier re-advance, locally named the Recurrence Event, was defined by end moraines located upstream of the LLGM deposits. The end of the Recurrence Event started with the lowland deglaciation, i.e. Artense plateau and lower parts of valleys and plateaus of the CCMD. A final cirque glacier stadial was represented by end moraines located in two main Cantal head valleys: the Impradine and Lagnon valleys (Valadas, 1984). In addition, isolated patches of till were interpreted as pre-LLGM deposits and were associated to Middle-Pleistocene glaciations, based on their location downstream of the LLGM deposits and their more intense weathered aspect (Goër de Hervé, 1972; Van Dorsser, 1982; Veyret, 1978).

The existing chronologies of the deglaciation sequence were constrained by indirect paleoenvironmental data. The timing of the LLGM was correlated to the timing of the glacier maximum extent in the Alps (Veyret, 1978), which is attributed to the global Last Glacial Maximum (LGM) (27.5 to 23.3 ka *sensu* Hughes and Gibbard, 2015). The timing of the last deglaciation in Cantalis constrained by a single radiocarbon age (Veyret-Mekdjian et al., 1978) obtained from the Lugarde kame terrace in the Santoire Valley at 900 m above sea level (a.s.l.) (north of Cantal; Fig. 1 for the location). This kame deposit includes a layer rich in organic matter dated from 17.1 to 15.7 ka cal BP (2 sigma radiocarbon age calibrated with the CLAM v.2.3.2 software and the “IntCal20” calibration curve; Blaauw, 2010; Reimer et al., 2020) that was buried by a till deposit associated with a glacier advance. In addition, indirect chronological boundaries for deglaciation steps were provided by a pollen stratigraphy established in the CCMD deglaciated slopes. The typical Oldest Dryas (18.5 to 15.3 ka *sensu* Degeai and Pastre, 2009) pollinic assemblage defined at the Lake Bouchet at 1250 m a.s.l (Fig. 1 for location) is *Artemisia* optimum with increasing *Juniperus* and *Betula* (Reille and Beaulieu, 1988). This assemblage was reported in the CCMD deglaciated slopes but not directly dated: (i) on the Artense plateau between ~400 to ~1000 m a.s.l. (Vergne, 1991), (ii) on the northern flank of the Cantal at the Taphanel site, 975 m a.s.l. (Ponel et al., 1991; Ponel and Russell Coope, 1990) and (iii) on the southern flank of the Cantal at the Peyre site, 1100 m a.s.l. (Miras et al., 2006) (Fig. 1 for the location). In the Aubrac Mounts, at the Roustières site (1195 m a.s.l.; Fig. 1), radiocarbon ages for this pollinic assemblage range between 17.7 and 15.0 ka cal BP (Gandouin et al., 2016; Ponel et al., 2016). According to these local paleoenvironmental data, two different relative chronologies for deglaciation steps in the CCMD are still debated (Veyret, 1978; Etlicher and Goër de Hervé, 1988):

- after Veyret (1978), the Recurrence Event buried the Lugarde kame terrace during the Oldest Dryas. CCMD lowlands were deglaciated at the end of the Oldest Dryas and the beginning of the Bølling-Allerød (15.3–12.8 ka *sensu* Degeai and Pastre, 2009). Finally, the timing of the cirque glacier stadial was correlated with the Younger Dryas (YD) cold event, between 12.8–11.7 ka (*sensu* Degeai and Pastre, 2009).

- after Etlicher and Goër de Hervé (1988), the Recurrence Event was older than the Oldest Dryas. The till that buried the Lugarde kame terrace was associated with a minor glacier advance after the lowland deglaciation. This advance took place at the latest during the Oldest Dryas. The cirque glacier stadial was correlated with the Oldest Dryas or the Bølling-Allerød.

The latter relative chronology for the CCMD deglaciation steps (Etlicher and Goër de Hervé, 1988) is broadly supported by direct chronological constraints established in the neighbouring Aubrac Mounts by ^{10}Be and ^{26}Al exposure ages (Ancrenaz et al., 2022). In this area, glacial fluctuations from the LLGM to the last glacial advance were reported by geomorphological mapping and were dated between 27 to 17 ka. The full deglaciation of the Aubrac was dated to ~17 ka, during the Oldest Dryas. These findings are comparable to findings obtained at a regional scale. For example, LGM glacier advances were identified in the Alps (Wirsig et al., 2016 and references therein), in the Pyrenees (Calvet et al., 2011; Reixach et al., 2021) and in the Iberian Peninsula (Domínguez-Villar et al., 2013). Glacier recessions started at ~19 ka in the Alps (Wirsig et al., 2016) or ~20 ka in the Pyrenees (Delmas et al., 2011) and the Oldest Dryas was recognized as a glacier recession period over the entire Mediterranean basin (Allard et al., 2021).

The aim of this study is to update the existing indirect and relative chronology for the CCMD glaciation by revising the morphostratigraphic framework in the Cère Valley (Cantal). We combined ^{36}Cl surface exposure dating and former glacier geometry modelling to reconstruct paleo-ELA and associated climatic conditions during the last deglaciation. We chose the Cère Valley (Cantal) because the most complete sequence of glacier fluctuations in the CCMD, and by extension in the Massif Central, is preserved. Four main features were described: (i) the Tronquières moraine, a pre-LLGM glacial deposit, (ii) the Carnéjac terminal moraine and associated proglacial outwash that delimits the LLGM, (iii) the Polminhac recessional moraine delimiting the Recurrence Event and (iv) the Vic-sur-Cère end moraine delimiting a glacier standstill during the deglaciation.

2 Study area

The Cère Valley is one of the deepest (350 to 150 m) and longest (30 km) radial valley of the Cantal stratovolcano. As other Cantal valleys, the Cère Valley was formed by the combined action of fluvial and glacial erosion in favourable volcano-tectonic settings (Valadas, 1984). The upper part of the valley, from the Col de Font de Cère at 1290 m a.s.l. to the Pas de la Cère (~700 m a.s.l.), developed into Miocene trachyandesite along 15 km (Leibrandt, 2011; Nehlig et al., 2001). The lower part of the Cère Valley, from the Pas de la Cère to the Aurillac basin was incised into Oligo-Miocene sediments and Pliocene volcanic breccias (i.e. debris avalanche or debris flow) (Arnaud et al., 2002). Valley slopes were affected by large landslides of various nature (mainly deep-seated gravitational slope deformation and rock fall) but of unknown age, and favoured by geological and topographic settings (Valadas, 1984; Van Dorsser, 1982, 1986).

During the LLGM, the Cantal glacier was a radially drained icefield or icecap (2.5 x 10^3 km^2) with an accumulation zone centred over the north-western part of the Cantal (Goër de Hervé, 1972; Veyret, 1978) (Fig. 1). Radial valleys, such as the Cère Valley, canalized glacier outlets from the central accumulation zone towards the margin. The orographic effect of the Cantal (west windward exposed slopes are much wetter than downwind exposed slopes) is responsible for the dissymmetric extent of valley glaciers (Veyret, 1978). The north-western Cantal valleys were occupied by longer glaciers, up to 30 km, and the eastern valleys were occupied by shorter glaciers, up to 20 km (Fig. 1). To the north, the Cantal, the Cézallier and the Monts Dore glaciers were coalescent forming the CCMD glacier system (Fig. 1). The Cère glacier extended from the Col de Fond de Cère to the Aurillac basin at ~600 m. The particularity of the lower part of the Cère Valley is related to its flat bottom, with infilling of Pleistocene fluvio-glacial sediments (Van Dorsser, 1982; Veyret, 1978) reaching up to 10-20 m thick (Fig. 2).

3 Methodology

3.1 Glacial features inventory

Our geomorphological mapping aims at deciphering the distribution of late Pleistocene glacial landforms and sediments with special attention to ice-marginal landforms that indicate extents of former glaciers (Kleman and Borgström, 1996). Postglacial deposits, generated by slopes or fluvial processes, such as landslides, colluvial accumulation, alluvial fans or alluvial terraces were also mapped. The mapping was elaborated using (i) the inventory of glacial features from the literature (Boisse de Black, 1951; Valadas, 1984; Van Dorsser, 1982; Veyret, 1978), (ii) aerial photography (25 cm resolution) and Digital Elevation Models (DEM; 1 m resolution from LIDAR) delivered by the Institut national de l'information géographique et forestière (IGN), and (iii) *in situ* (i.e. in the field) verification and description. Mapping was performed using a Geographical Information System (GIS) software (ArcGis).

3.2 Surface exposure dating using ^{36}Cl

3.2.1 Sampling strategy

In the Cère Valley six moraine boulders were identified as suitable objects for surface exposure dating (Fig. 3). One was located on the Cavanhac plateau (sample CTL-04), three on the Carnéjac end-moraine (samples CTL-01, -02, -03) and two on the Polminhac end-moraine (samples CTL-20, -21) (Figs. 2 and 3). Samples for ^{36}Cl dating were collected in the field from top flat surfaces (up to 5 cm thick) of volcanic boulders (basalt and volcanic breccias) using a hammer and a chisel. Sampling was performed on moraine boulders with a broad base embedded in the glacial landform to minimise potential post-depositional disturbance. Sample locations and elevations were recorded using a hand-held GPS with elevations cross-checked with the DEM. Skyline measurements were taken using a compass-clinometer and topographic shielding factors were calculated using the skyline calculator within the CRONUS online calculator (Balco et al., 2008; http://stoneage.ice-d.org/math/skyline/skyline_in.html; accessed on 14th September 2019). Sample information is reported in Table 1.

3.2.2 Sample preparation and age calculation

Samples were crushed and sieved to 250-500 μm at CEREGE (Aix-en-Provence, France). Chlorine was extracted and purified from whole-rock samples to produce AgCl for accelerator mass spectrometry (AMS) analysis, following the procedure described by Schimmelpfennig et al. (2011). About 2 g of the bulk rock and 2 g of the chemically treated sample fractions were sent to SARM (Nancy, France) for chemical composition analyses (Tables 2 and 3). ^{35}Cl/^{37}Cl and ^{36}Cl/^{35}Cl ratios were measured by accelerator mass spectrometry at the 5 MV accelerator ASTER at CEREGE (Arnold et al., 2013). Use of an isotopically enriched carrier allows simultaneous determination of the ^{36}Cl and the natural Cl concentrations of the dissolved samples. For normalisation of the ^{36}Cl/^{35}Cl ratios, an in-house standard with a given ^{36}Cl/^{35}Cl value of $1.42 \pm 0.02 \times 10^{-12}$ was used (Merchel et al., 2011). Blank corrections were performed by subtracting the number of atoms of ^{36}Cl and Cl in the blanks from those in the samples, respectively.

Cl-36 ages were calculated with the Excel® spreadsheet of Schimmelpfennig et al. (2009), using the time-invariant scaling method of Stone (2000) and employing the following ^{36}Cl production rates, referenced to sea level and high latitude (SLHL): 42.2 ± 4.8 atoms ^{36}Cl (g Ca)$^{-1}$ yr^{-1} for spallation of Ca (Schimmelpfennig et al., 2011), 148.1 ± 7.8 atoms ^{36}Cl (g K)$^{-1}$ yr^{-1} for spallation of K (Schimmelpfennig et al., 2014), 13.0 ± 3.0 atoms ^{36}Cl (g Ti)$^{-1}$ yr^{-1} for spallation of Ti (Fink et al., 2000), 1.9 ± 0.2 atoms ^{36}Cl (g Fe)$^{-1}$ yr^{-1} for spallation of Fe (Stone et al., 1996), and 696 ± 185 neutrons (g air)$^{-1}$ yr^{-1} for the production rate of epithermal neutrons from fast neutrons in the atmosphere at the land/atmosphere interface (Marrero et al., 2016a). A high-energy neutron attenuation length of 160 g.cm^{-2} was used.

As the values of several ^{36}Cl production rates are still under discussion, most importantly the one for spallation of Ca (Schimmelpfennig et al., 2011, Marrero et al., 2016a), we also calculated the exposure ages using the calculator by Marrero et al. (2016b), which incorporates default production rates based on Marrero et al. (2016a) and the time-variant ("Lm") rather than the time-invariant ("St") scaling method used in the Excel® spreadsheet of Schimmelpfennig et al. (2009). Due to the variations in the sample compositions and thus target element concentrations (Table 3), this leads to ages being between 0.3

ka younger and 0.2 ka older than when applying the above-described methods. These differences do not affect our chronological reconstructions.

Typical value for erosion rates of crystalline rocks are comprised between 0.5 to 2.5 mm.ka^{-1} in alpine environments (Balco, 2011) with a suggested value of 2 mm.ka^{-1} at mid-latitude for homogenous rocks (André, 2002). Our sampled surfaces come from volcanic breccia boulders (CTL-02, -03, -04, -20) composed of diverse volcanic clasts embedded in a fissile matrix (Figs. 3B-3E). Erosion processes through physical or chemical weathering are expected to be efficient and conducive to higher erosion rates than for homogenous crystalline rocks. For example, in Gran Canaria, exposure ages and erosion rates obtained from basaltic clasts embedded in volcanic breccias were calculated using ^{3}He (Williams et al., 2005). Results ranged from 2.7 to 23.9 mm.ka^{-1} for exposure ages between 25.6 to 226.2 ka. We applied three different erosion rates to our ^{36}Cl surface exposure ages: 0, 10 and 20 mm.ka^{-1} to quantified effects of various erosion rates.

3.3 Reconstruction of former glacier geometry, associated ELA and paleoclimatic conditions

3.3.1 3D glacier reconstruction and ELA estimation

The geometry of the former Cère glacier was modelled in 3D using the GlaRe ArcToolBox for ArcGIS (Pellitero et al., 2016) for the three glacial stadials recognized in the field (section 3.2; Fig. 4). This model assumes a perfect plasticity behaviour for glacier ice and applies the numerical iterative solution to the Van der Veen’s equation (Benn and Hulton, 2010). The basal shear stress value generally lies between 50 kPa and 150 kPa (Benn and Evans, 2010). The appropriate basal shear stress value was estimated to match the reconstructed ice thickness according to geomorphological markers on valley sides, i.e. lateral moraines. Ice-thickness profiles were reconstructed along 70 flowlines that were manually digitized along the main glacial valley trunk and its network tributaries. Glacier surface was interpolated using the *Topo to Raster* method to produce a 100 x 100 m cell-size resolution DEM of the former glacier surface topography. A valley-shape correction factor (*f*) of 0.7 (average *f* value obtained from 79 valley cross sections) was applied to account for the valley morphology effect.

Paleo-Equilibrium Line Altitudes (Paleo-ELAs) were estimated using the ELA Calculation ToolBox for ArcGIS (Pellitero et al., 2015) and the Area-Altitude Balance Ratio (AABR) method. Different BR values were associated with different glacier/climate relationships and a range of 1.0 to 2.5 with 0.5 intervals was applied to consider the global BR value reported in Rea (2009). The mean with its standard deviation was then reported for each glacial stadial.

The Cère Valley topography was affected by landslides, especially deep-seated landslides. The topography of the paleo-glacier bed has an influence on the 3D glacier modelling and the ELA estimation (Pellitero et al., 2016, 2015). In absence of a robust chronology for the landslides, glacier modelling was run with both the post-landslide topography (i.e. the current topography) and the pre-landslide topography. The pre-landslide topography was reconstructed following the methodology exposed in Rodríguez-Rodríguez et al. (2018).

3.3.2 Paleoclimatic reconstructions

As no glaciers are currently present in the Massif Central, a direct comparison between the current ELA and former ELAs was impossible. In order to estimate the amplitude of ELA changes and to quantify the effect of oceanic influences that control the Cantal climate (Jubertie, 2006), the current theoretical ELA was assessed using current climatic conditions derived from 21 climatic stations located in western Cantal (Figs. 1 and 4A). Climatic conditions were extrapolated to higher altitude using a linear regression and plotted against the Ohmura equation (Fig. 4C) which provides a relationship between the Mean Summer Temperature (MST in °C) and the Mean Annual Precipitation (MAP in mm.yr^{-1}) at the ELA (derived from an inventory of 70 glaciers in the world; Ohmura et al., 1992). By graphic read out, the intersection between the extrapolated current climatic conditions above Cantal summits and the Ohmura equation yielded a MST of 7.6 ± 0.3°C and a MAP of 3162 ± 163 mm.yr^{-1}. These climatic conditions were converted to elevation in m, using current altitudinal lapse rates of 840 mm.yr^{-1}.km^{-1} and 5.0 °C.km-1 (Fig. 4A). A similar lapse rate for MST has been reconstructed reflecting potential effects of dominant south-western influences in the Cère Valley (Valadas, 1984) to 5.5°C.km-1 (Genevois et al., 2022). This yielded a current theoretical ELA at 2759 ± 28 m (Fig. 4C). Higher altitudinal lapse rate for MST (i.e. 5.5°C.km-1) decreasing the current theoretical ELA to 2634 m a.s.l. Once the ELA was calculated for current climatic conditions and for former glacial stadials, MST values were calculated according to -90% to 0% change of MAP compared to present, using the Ohmura equation (Ohmura et al., 1992) and current climatic gradients. This assumption did not account for paleo-climatic gradients, prevailing during the LGM and the Last Glacial-to-Interglacial Transition (LGIT) in Europe (Heyman et al., 2013; Peyron et al., 1998).

Mean July Temperature (MJT) data reconstructed from chironomid assemblages of the Oldest Dryas and the YD at the Roustières sites were used to estimate theoretical MAP at the ELA (Figs. 1 and 4). These data indicate a MJT of 6 to 10 °C for the Oldest Dryas and 10 to 13 °C for the YD. These two periods are drier than today according to pollinic assemblages (Gandouin et al., 2016; Ponel et al., 2016). First, paleo-MJT were converted into MST using the current linear relationships (0.98 factor; Fig. 4B). Then the summer cooling was estimated by comparing paleo-MST with current MST recorded by local climatic stations. This cooling was applied to the current climate in the Cère Valley to obtain theoretical MST during the period of interest. No correction for altitude was performed as the Roustières site altitude frame reconstructed ELAs for the Carnéjac and the Polminhac stadials. The Ohmura equation was used to calculate the associated MAP. As the Roustières elevation (1196 m a.s.l.) approximates the ELA reconstruction elevations for the Carnéjac and the Polminhac stadials, no elevation correction was performed on calculated MST and MAP.

4 Results

4.1 Glacial geomorphology

No significant glacial deposits were found in the upper part of the Cère Valley. Here, multiple head valleys with amphitheatre morphologies have developed in trachyandesitic rocks (Fig. 5A). These topographic settings were associated with limited ice accumulation, except for the Fond d’Alagnon glacial cirque in the Alagnon Valley which ice contributed to the Cère Valley glacier by a glacier transfluence towards the Fond de Cère pass (1290 m) (Fig. 5A). In contrast in the lower part of the Cère

Valley, large glacial landforms constituting a specific landform assemblage, such as moraines and proglacial outwash were found, particularly in the Aurillac basin (Fig. 6). Geomorphological observations allowed to partly reconstruct the deglaciation sequence despite disturbances caused by slope deposits (alluvial fans, colluvial accumulation and landslides) or fluvial processes (incision and aggradation of the valley floor) which may have masked, reworked or buried glacial landforms and associated deposits (Fig. 6).

All glacial and associated deposits identified in this work were located between the Tronquières moraine and the Pas de la Cère. The Tronquières moraine in the Aurillac basin (644 m a.s.l.; Figs. 2 and 6) materialise the maximal extent of the Cère glacier. According to geological cores (Fig. 2), these deposits are composed of diamicton 2 to 4m thick, interpreted as till of undetermined age. Three levels of terrace above the current Cère river: +10, +20, +30 m (Figs. 2 and 6) were identified on the eastern slope of the Tronquières moraine, at the Cère and the Jordanne rivers confluence. Around 5.5 km upstream of the Tronquières moraine, the Carnéjac end moraine (640 m a.s.l.) forms a transverse topographic ridge in the Cère Valley. This landform was associated to fluvio-glacial deposits forming a three-kilometre-long perched (+15 to +5 m) terrace above the current Cère river. Near the proximal Carnéjac end moraine slope, clayey sediments were reported (Figs. 2 and 6), interpreted as potential lacustrine deposits. The Polminhac end moraine (650 m a.s.l.), located 14 km upstream of the Tronquières moraine, is constituted of two individua, smooth and parallel ridges across the valley, Tronquières moraine (Fig. 2). An alluvial cone partly masked this end moraine. On the Cère Valley slopes, the La Pradelle lateral moraine (925 m a.s.l.) was identified (Figs. 6 and 7) and is associated to the Carnéjac stadial. In addition, isolated patches of till and isolated erratic boulders were found at the Vézac pass (665 m a.s.l.), at the Puy des Arbres pass (880 m a.s.l.) and at the Curebourse pass (1000 m a.s.l.). These glacial deposits attest of tansfluences of the Cère glacier towards secondary valleys (Fig. 6). The Vic-sur-Cère landform is interpreted as an alluvial fan in relation to a marked gully. These glacial landforms allow to define at least three glacier stadials. The Tronquières stadial for which the Tronquières moraine give a minimal extent. As no new observation were performed, the earlier assumption that associated these deposits to pre-LLGM glacial advance was not modified (Veyret, 1978). However, tills were identified between the Troquières moraine and the Carnéjac end moraine. Based on their fresh aspects, i. e. no weathering traces, these deposits are associated to the LLGM. The Carnéjac and the Polminhac stadials were associated to two glacier standstills during the deglaciation.

Between the Carnéjac end moraine and the Pas de la Cère, large landslides affected the valley slopes. The largest one was the Vixouze landslide in which till deposits filled longitudinal gullies that were subsequently moulded by subglacial erosion (Figs. 5C, 5E, 6 and 7). These observations suggest that the Vixouze landslide, and by extension other smaller landslides in the Cère Valley, occurred before the Carnéjac stadial.

4.2 Chronological results

All samples have $^{36}Cl/^{35}Cl$ ratios in the range of 8.9 – 14.8 x 10^{-14} compared to two process blanks (BKCTL-01 & -02) with $^{36}Cl/^{35}Cl$ ratios of 2.32 ± 0.6 and 0.12 ± 0.04 x 10^{-15}, respectively. Typical uncertainties for raw AMS data are 1.7 – 3.0% for $^{35}Cl/^{37}Cl$ and 6.2 – 9.3% for $^{36}Cl/^{35}Cl$. Measurement results, calculated concentrations and surface exposure ages with their uncertainties are reported in Table 4.

For samples CTL-01 and CTL-03, the correction of surface exposure ages with a 10 and a 20 mm.ka^{-1} erosion rates led to older ages (Table 4; Fig. 8. In these samples, Cl concentrations are low (~30 ppm; Table 4). All other samples (CTL-02, -04, -20 and -21) give younger exposure ages when applying 10 and 20 mm.ka^{-1} of erosion rates (Fig. 8). This is counter-intuitive when correcting exposure ages for erosion but these samples have high Cl concentrations (between ~99 – 521 ppm; Table 4). This high Cl concentration induce higher ^{36}Cl concentration in the subsurface than at the surface through low-energy-neutron capture by ^{35}Cl.

Surface exposure ages corrected with a 10 mm.ka^{-1} erosion rate were assumed to best reflect boulders erosion since their exposure. The stratigraphically oldest erratic boulder (CTL-04) is isolated and located on the Cavanhac plateau and has an exposure age of 13.5 ± 3.9 ka (Table 4). This sample was taken from an erratic boulder associated with LLGM retreat, before the Carnéjac stadial (Figs. 3D, 6 and 8). Three moraine boulders embedded in the Carnéjac end moraine were sampled (Table 4; Figs. 3A-3C, 6 and 8). Sample CTL-01 was taken from a basaltic boulder characterized by fractures and jigsaw cracks (Fig. 6A). Samples CTL-02 and CTL-03 were taken from volcanic breccia boulders (Figs. 3B and 3C). Surface exposure ages are clustered: 12.6 ± 1.2 ka (CTL-01), 12.0 ± 2.2 ka (CTL-02) and 12.2 ± 1.1 ka (CTL-03), whereby only CTL-02 was a Cl-rich sample. Two volcanic breccia boulders were sampled from the inner ridge of the Polminhac end moraine (Figs. 3E–3F, 6 and 8): CTL-20 (Cl-rich sample) yielded a maximum exposure age of 12.1 ± 2.6 ka and CTL-21 an exposure age of 0.9 ± 0.3 ka. Due to its position near the Cère river (~40 m) and its small size (~0.2 m^3 above ground), the CTL-21 boulder is interpreted as an exhumed boulder associated with probable latter fluvial or anthropogenic end moraine erosion.

We note that ^{36}Cl surface exposure ages from two distant (~8 km) end moraines: the Carnéjac and the Polminhac moraines, are well clustered to ~12 ka (n = 4; Fig. 8). The interpretation of these ages is discussed in section 5.

4.3 Glacier modelling

We performed 3D reconstructions of the paleo- Cère glacier with the position of Carnéjac and Polminhac end-moraines. We extended glacier flow-line to the Font d'Alagnon glacial cirque to account the presence of glacier transfluence at this place (Fig. 5A). The elevation of the La Pradelle lateral moraine (Figs. 6 and 7B) indicate a paleo-ice thickness of 280 m, compatible with a basal shear stress of 25 kPa for the lower part of the Cere valley during the Carnéjac stadial. However, typical value of basal shear stress for valley glaciers were 50 – 150 kPa (Benn and Evans, 2010). Our low value for basal shear stress supports rapid basal sliding compatible with deformable sediments at the glacier bed. Such deformable sediments could be represented by Oligocene and Miocene uncemented clayey sediments or Late Pleistocene deposits, which composed the lower Cère valley floor (Fig. 2 and 6). For the uppermost half of the valley a basal shear stress value of 100 kPa was used. We note that topography of the glacier bed changed before and after the landslides. However, the two distinct topographic configurations did not significantly affect the reconstructed paleo-glaciers and associated ELAs. An ELA of 1078 ± 43 m a.s.l. for a pre-landslides topography was calculated, whereas an ELA of 1091 ± 43 m a.s.l. for a post-landslides topography (Table 5). Because we found till, associated to the Carnéjac stadial, in transversal gullies of the Vixouze landslide (section 4.1): (i) we hypothesise that the age of majority of landslides in the Cère Valley are associated to pre-Carnéjac stadial periods and (ii) we chose the post-landslides topography to reconstruct the Carnéjac and the Polminhac stadials. The glacier modelling of the Polminhac stadial was processed using the same basal shear stress values as for the Carnéjac stadial. Only the main flowline was adjusted to match the respective end moraine.

During the Carnéjac stadial, only the Curebourse pass was reached by the paleo-glacier that potentially flowed over into the Goul valley (Figs. 6 and 7). The other two transfluences identified in the field were probably active during the LLGM or at times when more ice accumulated in the valley. Reconstructed ELAs for the Carnéjac stadial (1091 ± 43 m a.s.l.) and for the Polminhac stadial (1152 ± 34 m a.s.l.) are indistinguishable within uncertainties (Table 5). These ELA values were comparable to those reconstructed in Western Europe during the LGM (see Kuhlemann et al. 2008 for a synthesis).

Based on the MJT for the Oldest Dryas and the YD from the Roustières site, the associated MJT at the ELA were calculated and summarized in Table 5. Results indicate a 9.2 to 5.4 °C cooling for the Oldest Dryas with a +141 to +230% MAP at the ELA and a 5.4 to 2.6 °C cooling for the YD with a +230 to +305% MAP at the ELA compared to today (Table 5). During these two periods, the reconstructed MAP gives wetter climate than today, which is not consistent with local and regional paleoenvironmental data. This discrepancy is partially due to temperature being not cold enough to calculate the MAP at the ELAs. The source of this incompatibility is discussed in the following section.

5 Interpretations and discussion

5.1 ^{36}Cl surface exposure ages interpretation: boulders exhumation related to a postglacial event?

Cl-36 surface exposure ages obtained in the Cère Valley range between 13 to 11 ka (Table 4) and are coeval with the YD (n = 3 for the Carnéjac end moraine and n = 1 for the Polminhac end moraine). Sample CTL-04 from the stratigraphically oldest boulder gives an older surface exposure age with a broad uncertainty (Table 4; Fig. 8). This exposure age could reflect a minimum age for the LLGM end but it is not further discussed here as it is a single dated erratic boulder.

The association of the Carnéjac or the Polminhac end moraines to the YD cold event is not plausible considering that:

- the existing relative and local chronologies for the CCMD glacier fluctuations (Veyret, 1978; Etlicher and Goër de Hervé, 1988). These early chronological hypotheses are supported by local paleoenvironmental data and surface exposure ages (^{10}Be and ^{26}Al) from the nearby Aubrac Mountains (Ancrenaz et al., 2022). Both paleoenvironmental and exposure ages support a deglaciation of the CCMD at the end of the Oldest Dryas (Fig. 8). During the YD, either only cirque glaciers occurred in the CCMD according to Veyret (1978) or the CCMD was fully deglaciated according to Etlicher and Goër de Hervé (1988).
- the ELAs and associated paleoclimatic conditions reconstructed for these two stadials in the Cère Valley (between 1078 ± 43 to 1152 ± 34 m; Table 5), are comparable to reconstructions from the Alps or the Pyrenees during the LGM or the early LGIT (Ivy-Ochs et al., 2008; Kuhlemann et al., 2008; Reixach et al., 2021).

Two explanations to this apparent time lag between the expected glacial chronology of the CCMD and the ^{36}Cl surface exposure ages obtained in the Cère Valley (this study) are considered. First, existing relative glacial chronologies for the CCMD underestimate the intensity of glacial advances during the YD. This means that associated climatic conditions in the CCMD were colder than expected to sustain these two major glacier stadials. Nevertheless, local paleoenvironmental data converge towards robust reconstructions of the YD in the CCMD (Juvigné et al., 1996; Miras et al., 2006; Miras and Guenet, 2013; Ponel et al., 1991; Vergne, 1991), and are not consistent with our mapped glacier advances.

The second hypothesis relies on uncertainties regarding the geomorphological events leading to the exhumation of the sampled boulders. Indeed, boulders embedded in end moraines could record incomplete exposure histories (Heyman et al., 2011) induced by geomorphological evolution of the end moraine. Two processes could lead to underestimated surface exposure ages: erosion of the sampled surfaces and incomplete exposure. Effects of erosion of the sampled surface were quantified by correcting surface exposure ages for various erosion rates and results show comparable ages (Table 4; Fig. 8). Generally, incomplete exposure is regarded as the main liming effect in the use of surface exposure ages (Heyman et al., 2011). Incomplete exposure encompasses effects of post-depositional burial or exhumation that led to underestimated surface exposure ages. For example, end moraine slopes destabilization after the deglaciation is considered as a main process leading to incomplete exposure of boulders, by boulder rolling, burial or latter exhumation through erosional processes (Allard et al., 2020; Heyman et al., 2011; Putkonen and Swanson, 2003; Tomkins et al., 2021; Zreda et al., 1994).

In the Cère Valley, ^{36}Cl surface exposure ages obtained for the Carnéjac end moraine and the Polminhac end moraine were (i) interpreted as non-related glacial event and (ii) constrained between 13 – 11 ka. We argue that these boulders experienced the same incomplete exposure history with a first phase of burial with complete shielding and then a simultaneous exhumation related to a unique and rapid geomorphological event concerning both the Carnéjac and the Polminhac end moraines. This geomorphological event took place after the deglaciation of the Cère Valley. This hypothesis is further developed in the following section.

5.2 Geomorphological scenarios for the postglacial evolution of the Cère Valley

Geomorphological observations concerning the postglacial evolution of the lower Cère Valley, between the Aurillac basin and the Pas de la Cère (Fig. 2 for location), are summarized here:

- geomorphological activities on valley slopes such as gullies incision, alluvial fans (Vic fan; Fig. 6), shallow landslides and colluvial accumulation,
- the valley floor is composed by up to 15 to 20 m of Pleistocene sediments, i.e. till, fluvio-glacial, fluvial or slope deposits, according to geological cores (Fig. 2).
- three terrace levels were identified in the Aurillac basin (+10, + 20 and + 30 m; Fig. 6).
- between the Carnéjac end moraine and the Pas de la Cère, two flat topographic levels on the valley floor are reported at 640 m: related to the Carnéjac end moraine and at 660 m: related to the Polminhac end moraine.
- finally, clayey deposits against the proximal slopes of the Carnéjac end moraines were identified and were interpreted as lacustrine clay from a moraine dammed proglacial lake by Veyret (1978).

The resulting landform-sediment assemblage is interpreted as a typical paraglacial landscape (Ballantyne, 2002). The Cère Valley filling is related to the water sediment continuity perturbation during its postglacial evolution, inducing intensive aggradation dynamics between the Carnéjac end moraine and the Pas de la Cère. Intense slope activities due to paraglacial conditions is enhanced by the overall lithologies of the Cère Valley tributaries (heterogenous volcanic breccias and trachytic rocks) favourable to glacial debuttressing, landsliding and fluvial erosion which support a perturbated water sediment continuity by enhanced sediment supply in the Cère Valley.

To explain the synchronous ^{36}Cl surface exposure ages from the Carnéjac (n = 3) and the Polminhac (n = 1) end moraines separated by 8 km, we combined our (i) literature review, (ii) geological cores compilation and (iii) field work, to propose two complementary geomorphological scenarios: the Aurillac proglacial Lake and the postglacial Cère river fluvial incision. The two scenarios encompass potential evolutions of the Cère Valley leading to boulders burial. These scenarios rely on two major assumptions: the Carnéjac and the Polminhac stadials were coeval to glacier-favourable periods identified in the Aubrac Mounts between 25 to 17 ka and the Cère Valley deglaciation is coeval with the Aubrac Mountains deglaciation ~17 ka (Ancrenaz et al. 2022). In addition, potential effects of anthropogenic disturbances (agricultural activities and urbanization) were not accounted for in these scenarios.

The Aurillac proglacial Lake scenario

The Tronquières moraine (644 m a.s.l.) is assumed to be LLGM deposits. During the Cère glacier retreat the Tronquières moraine could have dammed the valley, enclosing the Aurillac basin and producing a moraine-dammed proglacial lake: the Aurillac Lake (Fig. 9). The lake surface altitude reached between 640 to 660 m a.s.l. (deepest part between ~50 and ~70 m in the Aurillac basin), was 18 km long at its maximum with a total surface ranged between 32 and 44 km^2. The following Carnéjac and Polmihnac stadials and their associated end moraines were deposited in a glacilacustrine environment (Fig. 9). The Aurillac Lake shielded, at least partially, boulders from the Carnéjac and the Polminhac end moraines from cosmic rays. At some point during deglaciation, the Tronquières moraine was breached by the Cère river, lowering the Aurillac proglacial Lake level and exposing the boulders. Carnéjac and Polminhac end moraines dammed the valley, producing secondary lakes that did not shielded end moraine crests and sampled boulders. As the Tronquières moraine was breached, fluvial terraces in the Aurillac basin are constructed while minor lakes subsisted in the Valley (Fig. 9). In this scenario, ^{36}Cl surface exposure ages from the Carnéjac and the Polminhac boulders (13 to 11 ka) are considered maximum ages for their exhumation and correspond to the timing of the Aurillac Lake drainage.

Postglacial fluvial incision scenario

After the LLGM, the Cère Valley glacier retreated and the Carnéjac and the Polminhac stadials occurred during deglaciation. As no moraine-dammed lakes were present in the Aurillac basin, the Carnéjac and the Polminhac end moraines are deposited in ice-marginal environment. The construction of alluvial terraces in the Aurillac basin were coeval with the Cère Valley deglaciation. After the full deglaciation, the Carnéjac and the Polminhac end moraines produced moraine-dammed lakes associated with aggradation dynamics by lacustrine sedimentation in the valley floor. These dynamics are enhanced by intense slope activities. During this period of aggradation, end moraines were stable landforms and sampled boulders were buried and fully shielded by at minimum 4 m of till. The end of aggradation dynamics was associated to a change in the hydro-sedimentary dynamic, leading to the Cère river fluvial incision of end moraines. This erosional phase was responsible of the end moraines destabilization leading to boulders exhumation. In this scenario, ^{36}Cl surface exposure ages (13 to 11 ka) reflected the end moraines stabilization after an intensive erosional phase associated to the end of postglacial aggradation dynamics.

Each of these two scenarios have limitations. For the Aurillac proglacial Lake scenario, the true age of the Tronquières moraine is still uncertain. However, the identification of fresh aspect tills in the Aurillac basin associated to the LLGM (this study) offset the pre-LLGM hypothesis from Veyret (1978). In addition, no lacustrine deposits were identified with certainty in the Aurillac basin. For the postglacial fluvial incision scenario, the well-preserved topography of the Carnéjac and the Polminhac end moraines was the main limitation, that indicated limited post-deposition erosion of these landforms. Furthermore, the important size of the sampled boulders (Fig. 3) favoured limited effects of postglacial exhumation trough end moraine erosion (Heyman et al., 2016).

Despite these limitations, our two scenarios highlight the wide range of postglacial geomorphological events that could have affected the lower Cère valley morphology and then could have impacted the ^{36}Cl surface exposure ages of the boulders. The true postglacial evolution is probably a combination of the two geomorphological scenarios: moraine-dams breaching and consecutive fluvial incision. More precisely, it is highly probable that proglacial lakes between the Carnéjac and the Polminhac end moraines have subsisted for a longer time than the lake between Aurillac and Carnéjac (Fig. 9). This is suggested by the distinct evolution between the Aurillac basin, affected by a longer fluvial incision (three terrace levels for nearly 40 m of vertical incision), compared to the Carnéjac - Polminhac - Pas de la Cère area, where no fluvial terraces are observed (very limited incision of 10 m at the Carnéjac moraine).

The chronological signal recorded by our ^{36}Cl ages, between 13 – 11 ka, occurred 5 ka after the deglaciation and records an abrupt change in the water sediment continuity in the Cère Valley. We interpret the chronological signal as an exhumation age of the sampled boulders, due to the end of aggradation dynamics and the beginning of fluvial incision that demarcated the end of the postglacial evolution of the Cère Valley (Figs. 8 and 9). By comparison, in deglaciated valleys of the Alps, the postglacial valley filling duration was estimated to up to 7 ka (Brardinoni et al., 2018), that is consistent with our scenarios. The end of the valley filling is mainly controlled by the timing of the tributaries deglaciation, slope stabilization and climatic conditions (Brardinoni et al., 2018; Ravazzi et al., 2012). A combination of all three factors was expected to ended the postglacial adjustment of the Cère Valley (13 - 11 ka).

6 Conclusions

The Cère Valley was occupied by a glacier and sediment assemblages provided an opportunity to reconstruct glacial fluctuations in the CCMD. Revision of geomorphological arguments allows to identify three glacial stadials. The Tronquières moraine marks the last maximal extent of the glacier but it was not possible to identify if it was deposited by a pre-LLGM glacier advance or a LLGM glacier advance. As a working hypothesis we attributed the glacial deposits in the Aurillac basin to the LLGM. Two other glacier stadials: the Carnéjac and the Polminhac stadials are defined by end moraines that materialize two major glacial events. Large landslides in the Cère Valley pre-existed to at least, these two glacier stadials (presence of till in landslide counter slopes). ^{36}Cl surface exposure ages from one erratic boulder, three boulders embedded in the Carnéjac end moraine and two boulders embedded in the Polminhac end moraine were obtained. Results are coeval to the Younger Dryas and range between 13 to 11 ka. The ages are too young considering the hypothesised ages of these end moraines according to existing relative glacial chronologies in the CCMD and the direct glacial chronology from the nearby Aubrac Mountains. Moreover, 3D reconstructions and associated ELAs with prevailing climatic conditions (MST and MAP) calculated for the Carnéjac and the Polminhac stadials are comparable to those calculated for the LGM and the early LGIT in the Alps and the Pyrenees.

To explain the time lag between ^{36}Cl surface exposure ages and expected end moraine ages, we investigated geomorphological scenarios that could have led to a latter exhumation of the sampled boulders. Using geomorphic observations, geological cores and ^{36}Cl surface exposure ages, two scenarios were presented: the Aurillac proglacial Lake scenario and the postglacial fluvial incision scenario. Each scenario explains plausible causes of boulders burial and then exhumation by one unique geomorphological event. The geomorphological scenario judged as the more plausible indicated that after the Cère Valley glaciation, between 25 to 17 ka, moraine-dammed lakes and intensive slope activities under paraglacial conditions conducted to the Cère Valley fill. During this period, the Carnjéac and the Polminhac end moraines were stable landforms with sampled boulders buried and shielding from cosmic rays. This postglacial evolution (>17 to ~12 ka) ended by the Cère river fluvial incision, eroding the base of the end moraines which lowered their surfaces and exposed sampled boulders (~12 ka). However, future geomorphological investigations in the CCMD are needed to validate and complete this scenario.

This work highlights that our ^{36}Cl surface exposure ages are related to a major geomorphological event at the Cère Valley scale, during its postglacial evolution. Those geomorphological processes need to be fully understood and are complementary to direct chronologies and 3D glacier reconstructions to correctly reconstruct glacial fluctuations. In other formerly glaciated Cantal valleys, as the Alagnon Valley, the same landform assemblage is identified (flat valley floor filled by Pleistocene sediments). This highlights the potential complex postglacial evolution of several Cantal valleys that is still poorly known and for which this work provides a few first order hypotheses.

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9 Tables

Table 1. Characteristics of boulders for ^{36}Cl surface exposure dating.

Sample ID	Latitude DD	Longitude DD	Elevation (m a.s.l.)	Boulder lithology	Sample density ($g.cm^{-3}$)	Shielding factor	Sample thickness (cm)
CTL-01	44.9108	2.5019	639	basalt	3.0	1	2.0
CTL-02	44.9112	2.5014	646	breccia	2.6	1	3.5
CTL-03	44.9111	2.4984	640	breccia	2.6	1	2.6
CTL-04	44.9200	2.4945	818	breccia	2.6	1	1.1
CTL-20	44.9503	2.5897	649	breccia	2.6	0.9985	4.6
CTL-21	44.9509	2.5913	648	basalt	3.0	0.9985	5.9

Table 2. Bulk composition of samples before chemical treatment, analysed at the SARM-CRPG (Nancy, France) by ICP-OES (major elements), ICP-MS (trace element), atomic absorption (Li), colorimetry (B) and spectrophotometry (Cl). Values in italics are averages from samples CTL-02, -03 for sample CTL-04.

Sample ID	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MnO %	MgO %	CaO %	Na_2O %	K_2O %	TiO_2 %	P_2O_5 %	LOI %	Total Cl (ppm)	Li (ppm)	B (ppm)	Sm (ppm)	Gd (ppm)	Th (ppm)	U (ppm)
CTL-01	53.8	18.3	8.3	0.2	1.1	5.4	4.6	3.4	1.7	0.7	2.3	125	19.4	5.1	10.6	7.9	10.8	3.0
CTL-02	51.4	15.9	9.4	0.1	2.6	6.6	2.9	2.2	2.3	0.7	6.3	285	18.5	5.0	10.4	8.4	9.1	2.6
CTL-03	51.1	17.8	9.1	0.2	2.1	7.2	3.8	2.8	2.1	0.6	2.5	98	13.9	5.2	9.2	7.2	8.5	2.3
CTL-04	*51.2*	*16.9*	*9.3*	*0.1*	*2.3*	*6.9*	*3.3*	*2.5*	*2.2*	*0.6*	*4.4*	*192*	*16.2*	*5.1*	*9.8*	*7.8*	*8.8*	*2.4*
CTL-20	53.9	15.6	7.2	0.2	4.8	5.6	4.8	3.6	1.5	0.4	1.9	225	18.8	6.5	6.6	5.4	17.1	5.0
CTL-21	43.2	13.3	12.2	0.2	10.9	10.5	3.5	1.5	2.9	0.7	1.1	760	6.4	2.3	8.1	6.7	6.9	1.7

Table 3. Concentrations in major element (in %) and in Cl (in ppm) in sample splits after acid etching, analysed at the SARM-CRPG (Nancy, France) by ICP-OES.

Sample ID	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MnO %	MgO %	CaO %	Na_2O %	K_2O %	TiO_2 %	P_2O_5 %	LOI %	Total Cl (ppm)
CTL-01	59.39	18.69	5.27	0.06	0.63	3.79	5.25	4.14	1.72	< L.D.	0.89	99.81
CTL-02	56.75	16.41	6.03	0.09	2.83	7.65	3.41	2.63	2.27	0.16	1.47	99.69
CTL-03	55.20	15.60	9.24	0.11	2.70	6.28	3.86	3.41	2.90	< L.D.	0.45	99.75
CTL-04	58.50	16.01	6.24	0.09	2.18	6.12	3.55	3.42	2.27	0.14	1.80	100.30
CTL-20	57.13	17.78	5.02	0.08	2.60	8.75	3.20	2.18	1.43	0.15	2.15	268.53
CTL-21	56.36	19.23	4.20	0.06	1.84	7.71	3.89	2.56	1.68	0.20	1.76	98.74

Table 4. Relevant data for chemical ^{36}Cl extraction, AMS results and ^{36}Cl exposure ages.

Sample ID	Sample weight (g)	Mass of Cl in spike (mg)	[$^{35}Cl/^{37}Cl$]	[$^{36}Cl/^{35}Cl$] (10^{-14})	Number of atoms Cl (10^{-19})	[Cl] in sample (ppm)	[^{36}Cl] (10^6 atoms)	[^{36}Cl] (10^4 at.g^{-1})	Age (ka)* including P uncertainties ε = 0 mm yr^{-1}	Age (ka)* including P uncertainties ε = 10 mm yr^{-1}	Age (ka)* including P uncertainties ε = 20 mm yr^{-1}
Plateau de Cavanhac											
CTL-04**	43.59	1.8117	3.459 ± 0.059	11.1 ± 0.8	38.60 ± 7.03	521 ± 95	35.80 ± 6.42	82.14 ± 14.73	16.9 ± 3.9 (4.9)	13.5 ± 3.9 (4.9)	13.3 ± 3.9 (4.9)
Moraine de Carnéjac											
CTL-01	42.97	1.8020	8.703 ± 0.150	14.8 ± 0.9	2.25 ± 0.13	31 ± 2	7.07 ± 0.48	16.44 ± 1.11	12.0 ± 1.2 (1.3)	12.6 ± 1.2 (1.3)	13.9 ± 1.2 (1.3)
CTL-02**	44.09	1.8020	3.757 ± 0.067	9.5 ± 0.7	20.20 ± 2.34	270 ± 31	17.38 ± 2.10	39.42 ± 4.76	13.6 ± 2.2 (3.0)	12.0 ± 2.2 (3.0)	12.1 ± 2.2 (3.0)
CTL-03	40.41	1.8096	8.684 ± 0.262	13.7 ± 0.8	2.27 ± 0.16	33 ± 2	6.57 ± 0.44	16.26 ± 1.09	11.8 ± 1.1 (1.3)	12.2 ± 1.1 (1.3)	13.2 ± 1.1 (1.3)
Moraine de Polminhac											
CTL-20	45.07	2.0010	3.807 ± 0.115	8.9 ± 0.5	20.56 ± 3.60	269 ± 47	17.01 ± 2.65	3.78 ± 0.59	13.6 ± 2.6 (2.6)	12.1 ± 2.6 (2.6)	12.3 ± 2.6 (2.6)
CTL-21**	45.15	1.9998	4.961 ± 0.149	1.8 ± 0.2	7.57 ± 0.72	99 ± 9	1.64 ± 0.18	0.36 ± 0.04	0.96 ± 0.3 (0.3)	0.9 ± 0.3 (0.3)	0.9 ± 0.3 (0.3)
BKCTL-01	-	1.7632	376.034 ± 9.772	0.23 ± 0.06	-	-	-	-	-	-	-
BKCTL-02	-	1.9914	212.416 ± 8.504	0.012 ± 0.004	-	-	-	-	-	-	-

* No snow correction.
** Cl- rich sample

Table 5. Synthesis of Carnéjac and Polminhac Equilibrium Line Altitude (ELA) reconstructions and associated climatic conditions using local Mean July Temperature (MJT) for the Younger Dryas and the Oldest Dryas.

		Current climatic conditions at ELA altitude		Roustières site (1196 m a.s.l.)			
				Younger Dryas climatic conditions at ELA		Oldest Dryas climatic conditions at ELA	
	ELA (m)	MST (°C)	MAP (mm.yr^{-1})	MST (°C)	MAP anomaly (%)	MST (°C)	MAP anomaly (%)
Carnéjac stade (post-RSF topography)	1091 ± 43	15.5 ± 0.2	1771 ± 36				
Carnéjac stade (pre-RSF topography)	1078 ± 43	15.5 ± 0.2	1760 ± 37	9.5 - 12.4	+230 - +305	5.7 - 9.5	+141 -+230
Polminhac stade	1152 ± 34	15.2 ± 0.2	1823 ± 29				
Today	2759 ± 28	7 ± 1	3162 ± 159	-	-	-	-

10 Figures

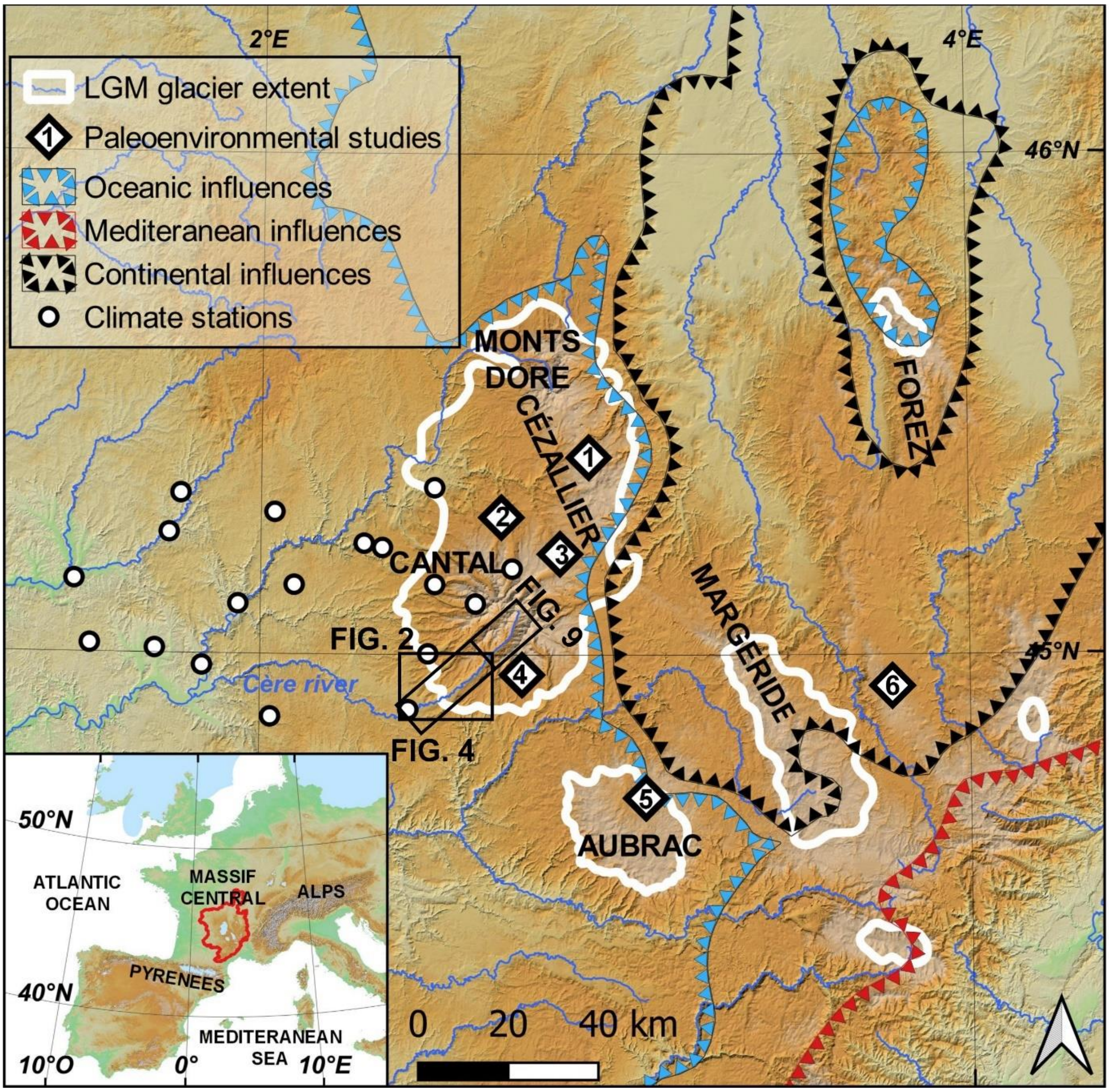


Figure 1. Location map of the Cère Valley in the Cantal-Cézallier-Mont Dores glacial system (CCMD), with Local Last Glacial Maximum (LLGM) extent in the Massif Central (Ehlers et al., 2011), and main actual atmospheric influences. Numbers correspond to localities cited in the main text: 1) Godivelle, 2) Lugarde kame terrace from where the ^{14}C age was obtained, 3) Taphanel, 4) Peyre, 5) Roustières, 6) Lake Bouchet.

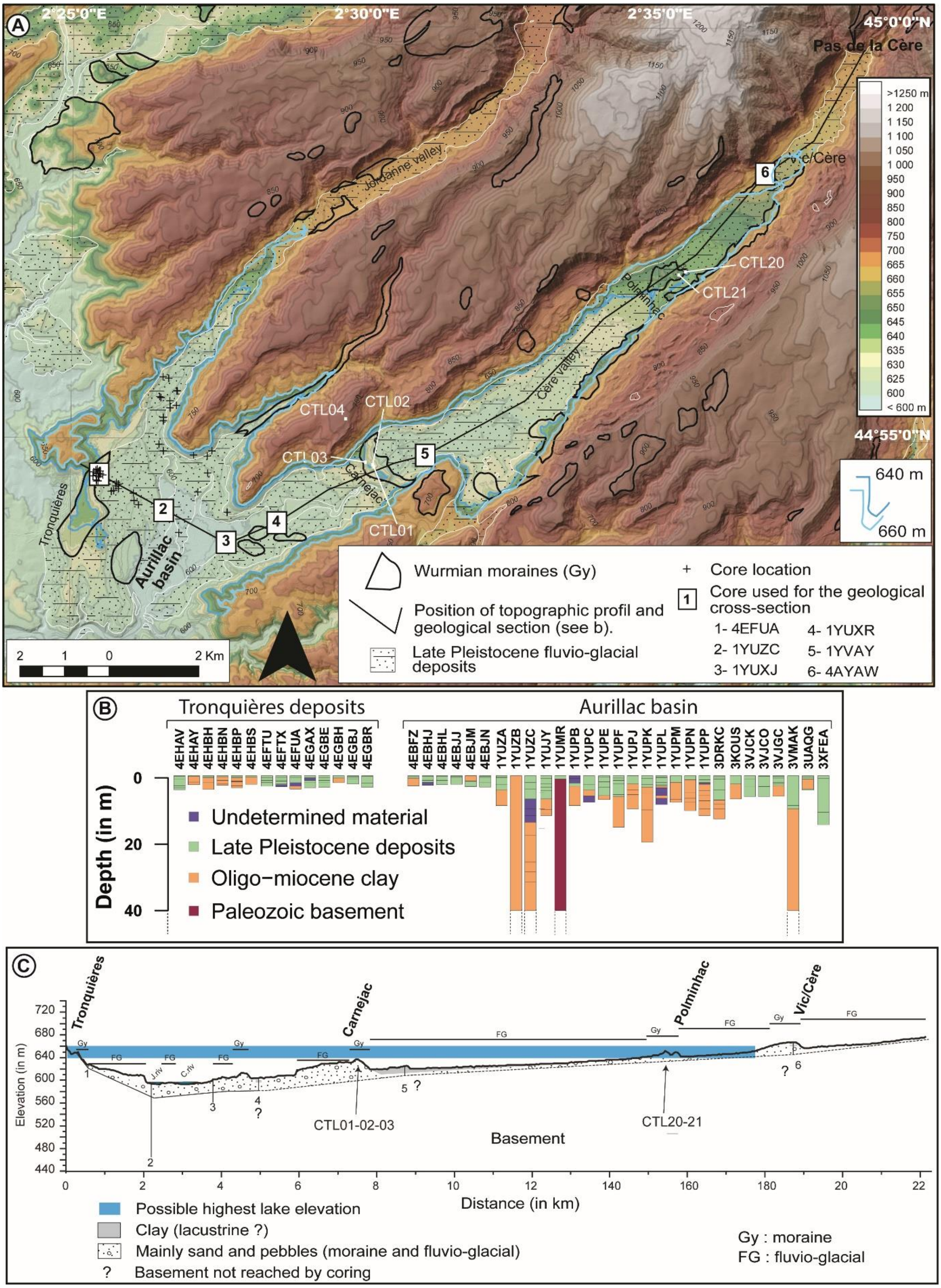


Figure 2. A. Map of glacial and associated deposits in the lower Cère Valley, between the Pas de la Cère and the Aurillac basin, according to the 1:50000 geological survey map (Brousse et al. 1972) and location of geological cores (data available at http://infoterre.brgm.fr). B. Interpretation of geological cores from the Tronquières moraine and the Aurillac basin. C. Interpreted geological cross-

section of the lower Cère valley, using geological survey map (1:50000) and most develop geological cores.

Figure 3. Photographs of erratic boulders sampled for ^{36}Cl surface exposure dating. Fractures of CTL-01 boulder are highlighted with white dashed lines.

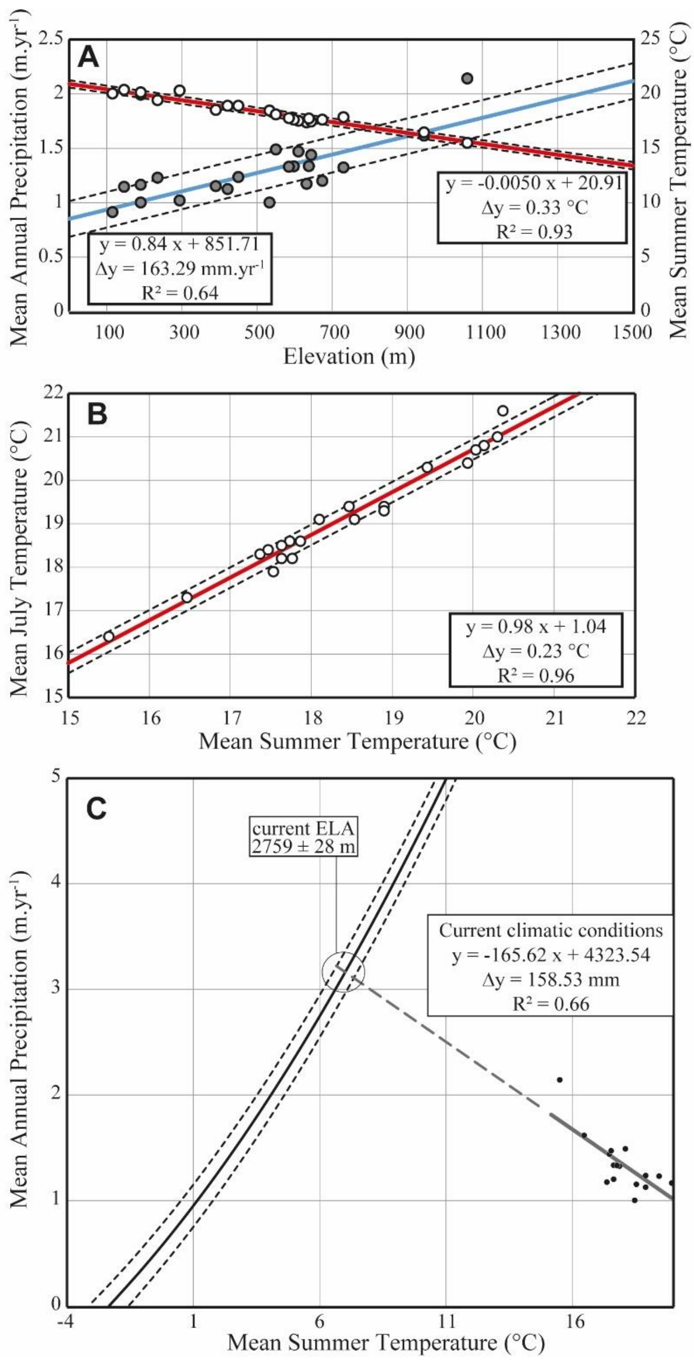


Figure 4. Climatic conditions in the western Cantal. A) Mean Summer Temperature (MST) and Mean Annual Precipitation (MAP) from the 21 climatic stations, plotted against elevation and associated elevation gradients. Black dots are mean annual precipitation. White dots are mean annual temperatures. B) Linear regression of Mean July Temperature (MJT) against Mean Summer Temperature (MST). C) Calculated current theoretical ELA from interpolation of the 21 climatic stations against the Ohmura equation.

Figure 5. Photographs of geomorphological features in the Cère Valley. A) The Fond d'Alagnon glacial cirque and the Alagnon glacier transfluence towards the Cère Valley. B) Basal till deposits (LLGM) at the Vézac pass. C) Fossilized alluvion under basaltic table in the Vixouze landslide constituting slide masses. D) Ice-marginal deposits (LLGM) forming terraces at the Vézac pass. E) View of the lower Cère Valley, showing the extent of the Vixouze landslide.

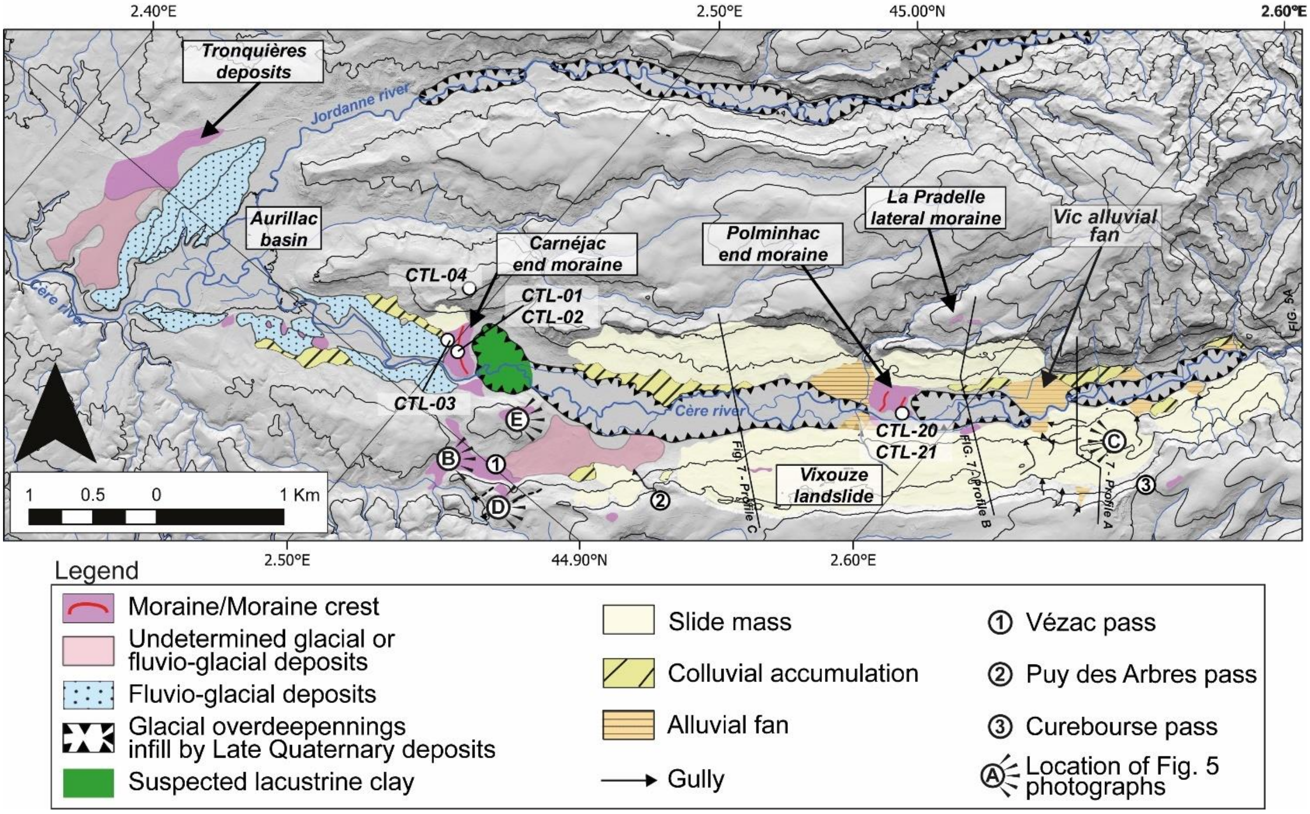
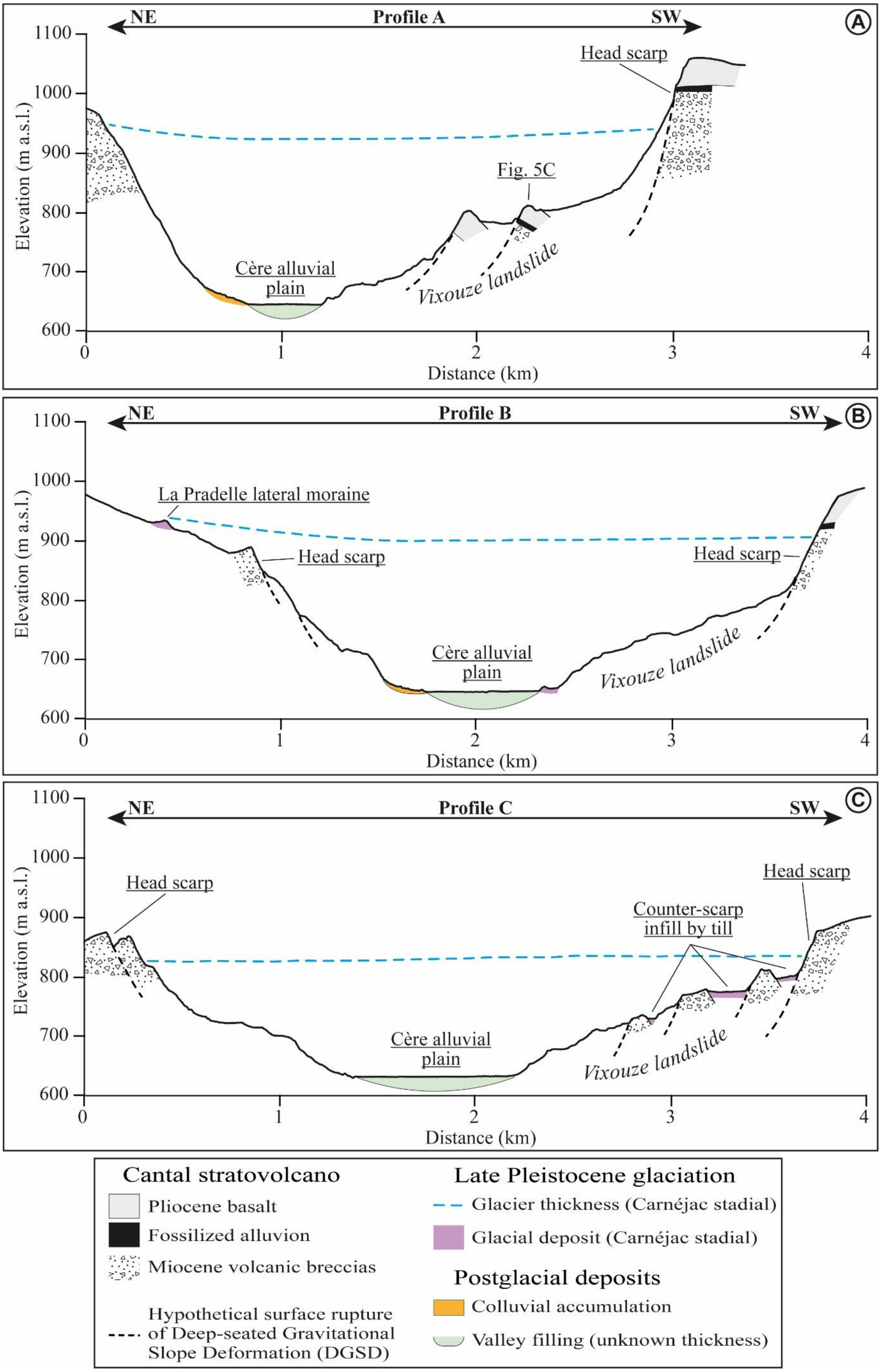


Figure 6. Map of glacial and slope deposits and location of the ^{36}Cl samples in the lower part of the Cère Valley.



Profile A
NE
SW
A
Head scarp
Fig. 5C
Cère alluvial plain
Vixouze landslide
Elevation (m a.s.l.)
Distance (km)
Profile B
B
La Pradelle lateral moraine
Head scarp
Head scarp
Cère alluvial plain
Vixouze landslide
Profile C
C
Head scarp
Head scarp
Counter-scarp infill by till
Cère alluvial plain
Vixouze landslide
Cantal stratovolcano
Pliocene basalt
Fossilized alluvion
Miocene volcanic breccias
Hypothetical surface rupture of Deep-seated Gravitational Slope Deformation (DGSD)
Late Pleistocene glaciation
Glacier thickness (Carnéjac stadial)
Glacial deposit (Carnéjac stadial)
Postglacial deposits
Colluvial accumulation
Valley filling (unknown thickness)

Figure 7. Transverse profiles of the lower Cère Valley showing relationships between Deep-seated Gravitational Slope Deformations (DGSDs) and the former glacier. A. Transversal profile located upstream the Vic alluvial fan. B. Transversal profile located upstream the Polminhac end moraine. C. Transversal profile located upstream the Carnéjac end moraine. For precise location of profiles see Figure 6.

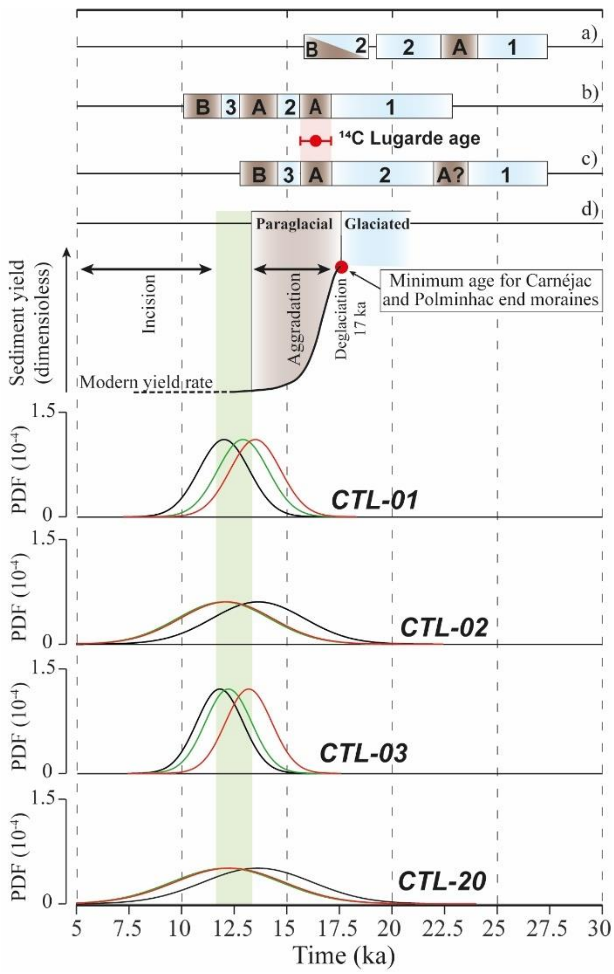


Figure 8. Camel plots of ^{36}Cl exposure ages under different erosion rate scenarios (black line: 0 mm.ka^{-1}, green line: 10 mm. ka^{-1}, red line: 20 mm. ka^{-1}) against local glacial chronologies and the chronological scenario of postglacial evolution of the Cère Valley. Camel plots were generated using the Matlab code from G. Balco (https://cosmognosis.wordpress.com/2009/07/13/matlab-code-for-camel-diagrams/). a) Glacial chronology of the Aubrac plateau icefield from ^{10}Be and ^{26}Al exposure ages (Ancrenaz et al., 2022). b) Relative glacial chronology established by Veyret (1978) for the CCMD last glaciation. c) Relative glacial chronology established by Etlicher and Göer de Hervé (1988) for the CCMD last glaciation. 1: Local Last Glacial Maximum, 2: Minor glacier advance, 3: Cirque glacier stade, A: Glacier retreat, B: Full deglaciation. d) Schematic representation of the sediment yield during the paraglacial period (modified from Ballantyne, 2002) against our chronological scenario for the deglaciation, the postglacial and the 'modern' periods. The convergence of ^{36}Cl exposure ages (green box) is interpreted as the end of the paraglacial period and the beginning of the 'modern' period (see text for more details).

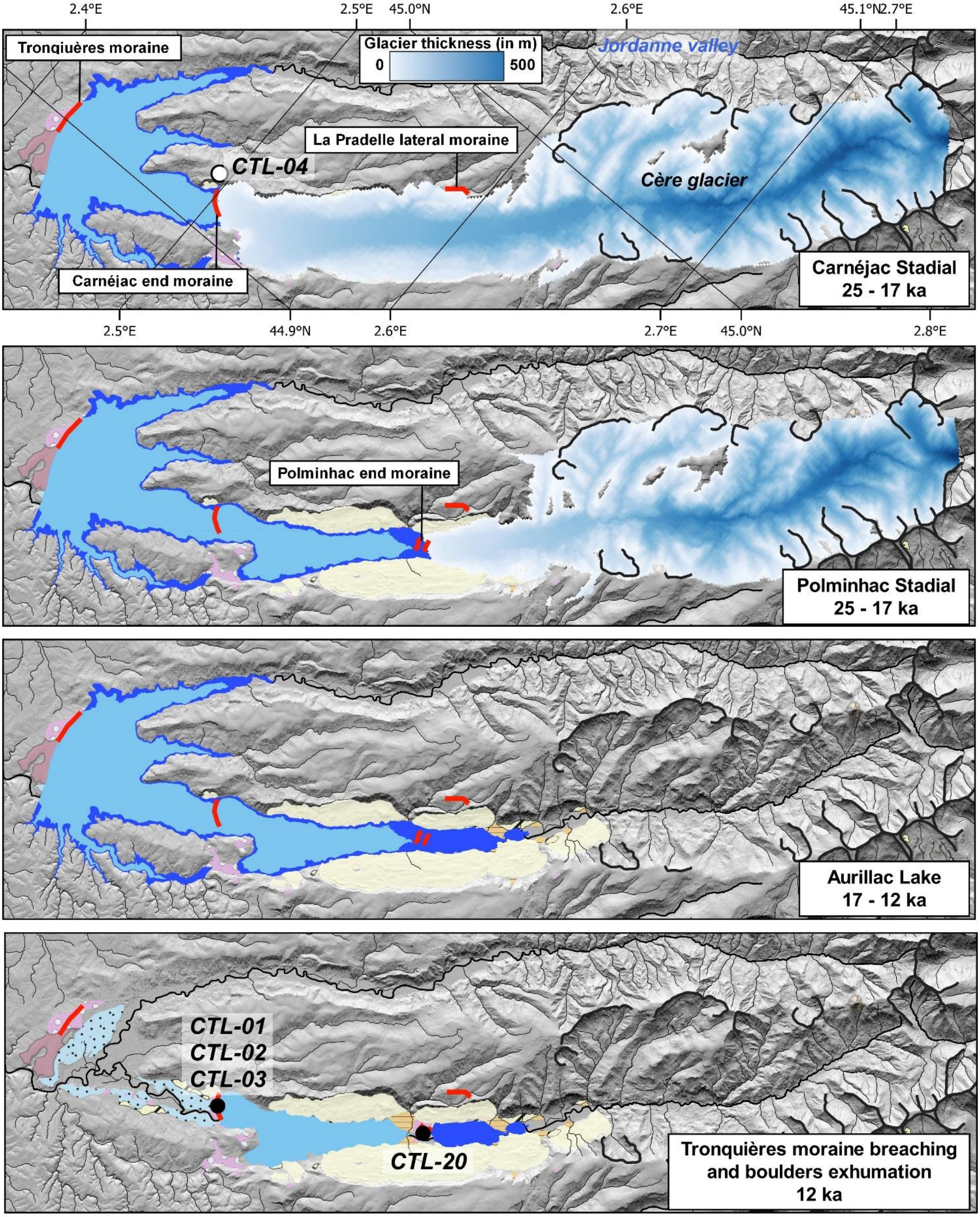


Figure 9. Reconstruction of the last deglaciation in the Cère Valley according to the Aurillac proglacial Lake scenario. Two lake levels were represented: 640 m in light blue and 660 m in dark blue. Black lines delineated glacial cirques. For the legend see Fig. 6.